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RESULTS AND SYNTHESIS OF INTEGRATED GEOLOGIC STUDIES OF THE CARBONIFEROUS LISBURNE GROUP OF NORTHEASTERN ALASKA

FINAL REPORT

By
Keith F. Watts

May 1995

Performed Under Contract No. DE-AC22-89BC14471

University of Alaska, Fairbanks
Fairbanks, Alaska

Bartlesville Project Office
U. S. DEPARTMENT OF ENERGY
Bartlesville, Oklahoma

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Analysis of Reservoir Heterogeneities Due to Shallowing-Upward Cycles in Carbonate Rocks of the Pennsylvanian Wahoo Limestone of Northeastern Alaska

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Assistant Secretary for Fossil Energy

Robert E. Lemmon, Project Manager
Bartlesville Project Office
P.O. Box 1398
Bartlesville, OK 74005

Prepared by
University of Alaska, Fairbanks
Tectonics and Sedimentation Research Group
Department of Geology and Geophysics
Geophysical Institute
Fairbanks, AK 99775

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ABSTRACT

The primary objective of this project was to develop an integrated database to characterize reservoir heterogeneities resulting from numerous small-scale shallowing-upward cycles (parasequences) comprising the Pennsylvanian Wahoo Limestone. The Wahoo Limestone is the upper part of an extensive carbonate platform sequence of the Carboniferous Lisburne Group which is widely exposed in the Brooks Range and is a widespread hydrocarbon reservoir unit in the subsurface of the North Slope of Alaska. A leading goal is to determine lateral and vertical variations in the complex mosaic of carbonate facies comprising the Wahoo. In order to understand the overall basin history and its relationship to the stratigraphic and structural framework, aspects of rock units adjacent to the Wahoo, the underlying Endicott Group and Alapah Limestone and overlying Echooka Formation are also discussed.

This report presents the results of research accomplished by a team of specialists in carbonate petrology, biostratigraphy, and diagenesis. It includes an overview of the regional geological framework; a discussion of biostratigraphic results; a summary of diagenetic studies; and preliminary results of comparative studies of a cored well in the Lisburne oil field. A computerized database system (the *Wahoo* database) was developed and is explained in a users manual. Several appendices summarize some of the data entered into the *Wahoo* database. Regional studies provide an understanding of lateral facies relationships and how position on a southward-facing carbonate ramp affected the nature of carbonate shallowing-upward cycles (parasequences). The parasequences are interpreted in terms of depositional environments and sea-level fluctuations and used to develop detailed facies models. Conodont biostratigraphy provides an independent means of correlation and age dating. Conodont biofacies analyses are related to paleoenvironments as determined by carbonate microfacies analysis. Analyses of diagenesis have allowed recognition of a number of subaerial exposure surfaces, providing another important means of correlation. The *Wahoo* database has allowed us to record and present a huge amount of petrographic and other data and is just beginning to realize its potential as a tool for quantifying and understanding lateral and vertical variations in the carbonate petrology of the parasequences.

Our correlation scheme, using sequence and parasequence (cyclic) stratigraphy, biostratigraphy, and cement stratigraphy, allows us to interpret the depositional history and paleogeographic evolution of the region and to develop predictive facies models and paleogeographic maps. Our detailed analysis of the Wahoo Limestone provides a basis for interpreting correlative rocks in the adjacent subsurface of the coastal plain of ANWR, a potential hydrocarbon lease-sale area. In a broader sense, our work serves as an excellent generic example of carbonate shallowing-upward cycles (parasequences) that typify carbonate sediments. Our regional approach of using detailed carbonate facies analyses of numerous carbonate cycles to develop refined facies models could be applied to other cyclic carbonates.

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EXECUTIVE SUMMARY / INTRODUCTION

This report summarizes the major advances made on our integrated stratigraphic studies of carbonate shallowing-upward cycles supported by the Department of Energy (contract DE-AC22-89BC14471) and a consortium of oil industry sponsors. The primary objective of the project was to develop an integrated database to characterize reservoir heterogeneities resulting from numerous, small-scale, carbonate, shallowing-upward cycles (parasequences) comprising the Carboniferous Wahoo Limestone. The Wahoo Limestone is the upper part of an extensive carbonate platform sequence of the Carboniferous Lisburne Group which is widely exposed in the Brooks Range and is a widespread hydrocarbon reservoir unit in the subsurface of the North Slope of Alaska (see Figs. 1-1 & 1-2). The ultimate goal was to determine lateral and vertical variations in the complex mosaic of carbonate facies comprising the Wahoo Limestone.

With the support of a consortium of petroleum industry sponsors, our work on the Lisburne Group began in 1986 and will continue in the future, as we expand the scope of our studies beyond ANWR into other parts of the Brooks Range and the subsurface of the North Slope, with comparative studies elsewhere in the circumarctic region. This final Department of Energy report summarizes the data produced between September 1989 and July 1993 (the duration of our DOE contract), but also incorporates findings from previous studies at UAF (1986 to 1989) and other cited workers. Some aspects of the research are completed and available as student theses or pre-publication drafts of manuscripts. Other parts of the research are still underway as ongoing student thesis projects and manuscripts in preparation. As such, parts of this report are a final progress report on studies that will be completed in the near future. Other aspects of our ongoing studies are in earlier stages of development and will be discussed more briefly.

The project involves a number of carbonate researchers from four institutions (Table 0-1). University of Alaska Fairbanks (UAF) researchers, Dr. Keith Watts and his students (Randall Carlson, Paul Gruzlovic, Andrea Krumhardt, Teresa Imm, Mary Eckstein, and Sue Morgan) analyzed more than 25 stratigraphic sections of the Lisburne Group in the Arctic National Wildlife Refuge (ANWR), using sequence/parasequence stratigraphy together with carbonate microfacies analyses to interpret their depositional history. Conodont biostratigraphy and biofacies data, provided by Dr. Anita Harris (U.S. Geological Survey) and Andrea Krumhardt (MS UAF, 1992), serve as independent means of correlation that was compared with data on foraminiferal biostratigraphy provided by Dr. Bernard Mamet (University of Montreal). Subaerial exposure surfaces and associated variations in cement stratigraphy analyzed by Randall Carlson (and advisors Dr. Robert Goldstein and Dr. Paul Enos at the University of Kansas) further constrained our correlations. Recently, Sue Morgan (UAF Ph.D. student) begun comparative studies of correlative rocks from a well at the Lisburne oil field in order to test our ability to use cyclic stratigraphy for regional correlations, and to examine the relationship

Table 0-1

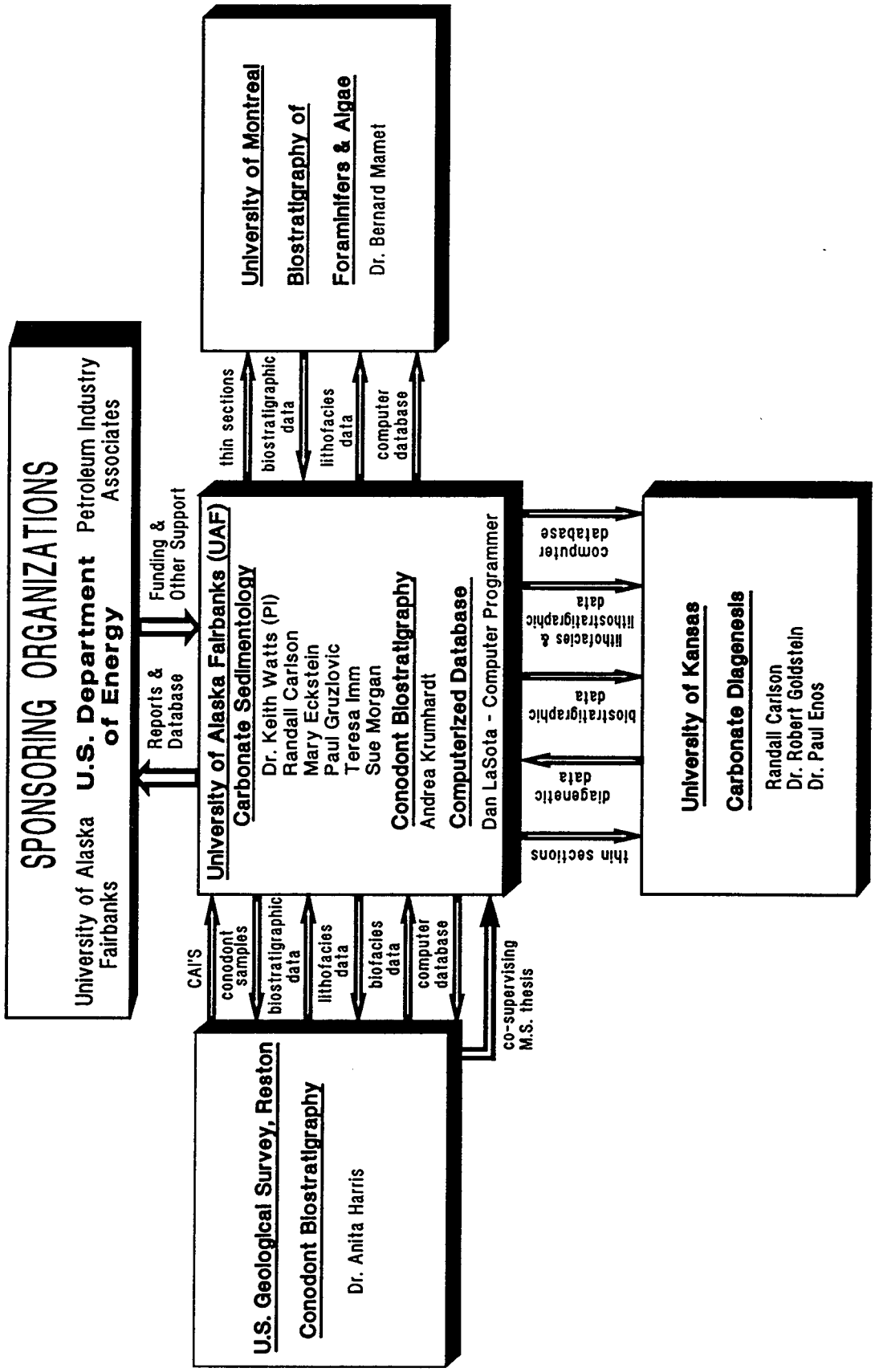


Table 1- Organizational chart summarizes the relationships between different researchers and organizations involved in the Wahoo research program. Industrial sponsors of Tectonics and Sedimentation ANWR Research Program have included Amoco, ARCO Alaska, BP Alaska, Chevron, Conoco, Elf Aquitane, Exxon, Japan National Oil Corporation, Mobil, Murphy, Phillips, Shell, Texaco, and Unocal.

between cyclic stratigraphy and reservoir properties. To help integrate this broad range of studies, a computerized database system was developed by Dan Lasota and Keith Watts (UAF) to accommodate information on carbonate petrology, biostratigraphy, and diagenesis derived from our analyses of the thousands of samples collected in this project.

Our detailed analysis of the sequence/parasequence stratigraphy, biostratigraphy, and cement stratigraphy of the Wahoo Limestone has allowed us to develop predictive facies models and paleogeographic maps to interpret the Carboniferous depositional history and paleogeographic evolution of ANWR. This provides a basis for interpreting correlative rocks in the adjacent subsurface of the coastal plain of ANWR, a potential hydrocarbon lease-sale area.

In a broader sense, our work is a comprehensive study of carbonate shallowing-upward cycles (parasequences) that typify carbonate sediments. The ultimate goal of our integrated studies was to construct sea level curves modeling the carbonate cycles and to determine our ability to use cyclic stratigraphy as a means of correlation. Unfortunately, possible inconsistencies between biostratigraphic data and our preliminary correlations based on sequence/parasequence stratigraphy indicate that, without adequate biostratigraphic control, sequence/parasequence stratigraphy should be used with caution. In order to determine whether relative sea-level fluctuations recorded in the Wahoo Limestone resulted from glacioeustatic sea-level fluctuations, we compared our relative sea-level curves with those developed for Carboniferous rocks elsewhere (e.g. Ross and Ross, 1988). A general lack of correlation indicates that either local or regional depositional or tectonic factors influenced relative sea-level fluctuations in the Wahoo Limestone. Alternatively, age-control problems resulting from a diachronous biostratigraphic indicators (due to migration or paleoenvironmental control on first occurrences) may inhibit correlation with existing eustatic curves.

This report is organized into a number of chapters, each summarizing results of the different tasks completed for this DOE contract. Most chapters are separate papers complete with abstracts and conclusions. This allows readers interested in specific aspects of the research to focus on appropriate chapter(s) without reading the entire report, but results in inherent redundancies. Chapter 1 discusses the regional stratigraphic framework, considers the criteria used in carbonate microfacies analyses for interpreting depositional environments, and presents interpretations of sequence and parasequence stratigraphy. Chapter 2 presents an overview on conodont biostratigraphy and biofacies results from an important reference section, considers the regional implications of other conodont data, and presents a CAI map of ANWR. Chapter 3 provides an overview of diagenetic studies, focusing on subaerial exposure surfaces and cement stratigraphy. Chapter 4 presents preliminary results of a subsurface study of carbonate microfacies and cyclicity in the Wahoo Limestone at a well in the Lisburne oil field at Prudhoe Bay. Chapter 5 is a manual explaining how to use the *Wahoo* computerized database that contains information on samples and localities, petrographic analyses, conodont analyses, diagenetic

information, and well log measurements. Chapter 6 summarizes these results and consider their significance to understanding the petroleum geology of the Lisburne. Although we have made significant advances in our understanding of the Lisburne Group, many or our interpretations are preliminary and will change as ongoing studies are completed and more data become available.

SIGNIFICANT ACCOMPLISHMENTS

- Development of a regional geological and paleogeographic framework of understanding for the Carboniferous Lisburne Group of northern Alaska.

- Determination of the position of the Mississippian-Pennsylvanian boundary in the Wahoo Limestone using conodont biostratigraphy. We have also begun to develop a conodont zonation scheme for northeastern Alaska (Krumhardt et al., in review). Conodont biofacies analyses along with paleoenvironmental interpretations using carbonate microfacies provide new insights on depositional environments. Conodont color alteration indices are a measure of the thermal history of ANWR.

- Recognition of numerous subaerial exposure surfaces in the Lisburne Group that aid correlation between sections. Variations in cement stratigraphy as determined by cathodoluminescence can be related to some of these surfaces, providing information on the timing of cementation.

- Preliminary analysis of the Wahoo Limestone of the Lisburne oil field. This project ultimately will compare the carbonate cycles and sequence stratigraphy of this subsurface section with correlative rocks exposed in ANWR.

- Development of the *Wahoo* computerized database system which holds information on over 12689 samples from 105 localities with 3055 carbonate microfacies (petrographic) analyses, 342 conodont analyses, 378 diagenesis analyses, and 5842 well log measurements. A manual in this report explains how to utilize this powerful integrated database.

- Comparison of the results of sequence/parasequence stratigraphy, conodont biostratigraphy, and cement stratigraphy to develop a synthesis of the Carboniferous paleogeography and depositional history of ANWR.

- Completion of two master's thesis projects (Gruzlovic, 1991 and Krumhardt, 1992). Two Ph.D. projects (Carlson and Morgan) and a Master's thesis project (Eckstein) are nearing completion.

- Presentation of several papers at international conferences (Watts et al., 1990, 1992; Krumhardt and Harris, 1990, Krumhardt et al., 1992; Carlson, 1990; Carlson et al., 1991; Carlson and Goldstein, 1992; Imm, 1990) and preparation of manuscripts for submission as USGS publications and to scientific journals.

CONCLUSIONS

• The Lisburne Group, together with the underlying Endicott Group clastics, can be subdivided into three major depositional sequences (transgressive-regressive successions). These sequences are useful for correlation across ANWR and to Prudhoe Bay.

• The lowest sequence begins with the progressive onlap of terrigenous (Endicott) and carbonate sediments over the regional sub-Mississippian unconformity. The widespread deposition of the Alapah Limestone represents the culmination of the most extensive carbonate platform in the Lisburne Group. Progradation of intertidal carbonates and associated subaerial exposure surfaces mark the sequence boundary in the uppermost Mississippian. This sequence boundary may correspond to the Kaskaskia-Absaroka cratonal sequence boundary of Sloss (1963, 1988).

• The second sequence begins with rapid establishment of open-marine carbonates of the lower Wahoo Limestone member. Most of the sequence formed on a carbonate ramp fluctuating between below and above wave-base conditions. The Mississippian-Pennsylvanian boundary coincides with a short-duration subaerial exposure surface and the beginning of an overall regressive trend. The rest of the sequence represents a progradational highstand systems tract with a maximum regression and sequence boundary indicated by local cryptalgalaminate and an increase in terrigenous quartz in the lowest upper Wahoo Limestone. Redeposited Mississippian conodonts above the Mississippian-Pennsylvanian boundary could have been derived from erosion along tidal channels (possibly up to 15 m deep) or from beneath a correlative unconformity located farther to the north.

• The third sequence, representing most of the upper Wahoo Limestone, begins with local intertidal and more widespread restricted-platform limestones. The sequence boundary and an associated influx of terrigenous quartz can be correlated with an unconformity and thick interval of terrigenous sediment at Prudhoe Bay. Numerous parasequences in the unit can be grouped into parasequence sets that help define the evolution and paleogeography of the Wahoo carbonate ramp. However, individual parasequences cannot be correlated with a high degree of confidence because of the effects of paraconformities and autocyclic migration of carbonate facies.

• A regional unconformity beneath the Echooka Formation has considerable erosional relief and represents a hiatus of approximately 38 m.y. Widespread subaerial exposure associated with this unconformity essentially killed the Lisburne carbonate platform (i.e., its calcareous organisms). Major carbonate production was never reestablished, possibly because of paleoclimatic changes associated with the northward plate tectonic drift of northern Alaska. This unconformity apparently indicates regional uplift of the Lisburne platform and may be related to correlative unconformities throughout the circumarctic region (Beauchamp, 1992).

• Conodont biostratigraphy has precisely defined the position of the Mississippian-Pennsylvanian boundary within the lower Wahoo Limestone member (Sequence B) at an important reference section. Established foraminiferal biostratigraphy is inconsistent with respect to conodont-based time-rock boundaries in this reference section. However, existing Carboniferous conodont zonations are not readily applicable because most zonal indicators are absent, so a local zonation scheme was developed.

• Subaerial exposure surfaces provide another means of correlation and figure importantly in the early cementation of the Lisburne Group. Subaerial exposure surfaces in the Alapah Limestone are easily explained within a sequence stratigraphic framework, whereas those in the Wahoo Limestone are more problematic.

• Existing sea-level curves for the Carboniferous are contradictory and generally do not match the sea-level fluctuations apparent in the Lisburne Group. However, the most dramatic change in depositional conditions in the Lisburne (Alapah to Wahoo transition) occurs in the latest Mississippian and may coincide with the Kaskaskia-Absaroka sequence boundary (Sloss, 1963, 1988).

• The Lisburne Group at Prudhoe Bay can be subdivided into three depositional sequences that correspond to those in the Lisburne of ANWR, but formed adjacent to a landmass where influxes of terrigenous sediments mark the sea-level lowstands.

• The *Wahoo* computerized database is a powerful research tool that has allowed us to compile a large amount of data that is included with this report.

• The Lisburne Group exposed in ANWR is generally tightly cemented and supermature. Fracturing due to Brookian deformation could enhance the overall reservoir potential of the Lisburne Group, particularly intervals of relatively brittle dolomite. Sabkha dolomites and cavernous porosity in the upper Alapah Limestone may form attractive reservoir rocks if not occluded by late stage cements.

SIGNIFICANCE FOR EOR RESEARCH PLAN

Our research on cyclicity addresses a number of issues which are important to DOE's fossil energy program as outlined in the Program Research and Development Announcement for this contract (DE-RA22-88BC1420). Our research provides "generic crosscutting descriptions of formations to permit design of cost-effective and environmentally acceptable production methods." In documenting the three-dimensional anatomy of the Wahoo Limestone (both primary and diagenetic characteristics), we define the spatial variability in the outcrop equivalent of reservoir rocks that may affect movement of fluids (oil and gas, etc.). The regional scope of the research will allow integration of reservoir heterogeneity studies within a regional structural and stratigraphic framework. Our analyses permit us to determine depositional environments and to relate primary heterogeneities to

sedimentary processes for predictive purposes and develop models required to characterize reservoir heterogeneity. In particular, we formulated predictive geological and microfacies models which help provide a scientific basis for predicting well spacing and enhanced oil/gas recovery potential in poorly known or potential oil and gas fields.

In addition, our work meets a number of needs outlined in the report, "Research needs for hydrocarbon fuels" (CONF-8705179; DE87014555), sponsored by the U.S. Department of Energy. Our research provides a 3-D analysis of the outcrop equivalents of reservoir rocks, focusing on sequence analysis and rock properties, facies analysis, and diagenesis. Although the research applies to a known reservoir (the Lisburne field), it also pertains to frontier areas—Alaska's North Slope in ANWR, providing information on regional unconformities, and tectonic and paleoenvironmental controls on basin evolution. By involving a number of carbonate specialists and biostratigraphers, this project takes an integrated approach for basin analysis and provides conceptual facies models, paleogeographic maps, analyses of depositional systems and history, geochemistry of cements, thermal history (CAI), and diagenetic history. Ongoing analyses of a well from the Lisburne field will allow us to compare 3-D rock characteristics and selected reservoir properties. Education and training of graduate students involved in the project helped provide professional geologists to implement industrial and governmental programs for satisfying the nation's future energy needs. Furthermore, our research program is an excellent example of how cooperative DOE/industry support of projects significant to industry and DOE missions can improve the research base existent in our universities, and further develop and utilize the academic manpower resource for basic research on energy problems.

CHAPTER 1

REGIONAL STRATIGRAPHIC FRAMEWORK OF THE LISBURNE GROUP OF ANWR

By K.F. Watts (University of Alaska Fairbanks, Principal Investigator)

A.G. Harris (U.S. Geological Survey, Reston, Virginia)

R.C. Carlson, M.K. Eckstein, P.D. Gruzlovic, T.A. Imm, A.P. Krumhardt, D.K. Lasota and S.K. Morgan (University of Alaska Fairbanks)

J.A. Dumoulin (U.S. Geological Survey, Anchorage, Alaska)

R.C. Carlson, Paul Enos, and R. H. Goldstein (University of Kansas, Lawrence, Kansas)

B. L. Mamet (University of Montreal, Montreal, Quebec, Canada)

ABSTRACT

The Carboniferous Lisburne Group, a major carbonate platform succession, is widely exposed in the Brooks Range and forms an extensive hydrocarbon target in the subsurface of the North Slope of Alaska. Gradationally beneath carbonates of the Lisburne Group, terrigenous sediments of the Mississippian Endicott Group (conglomerate and sandstone of the Kekiktuk Formation overlain by the Kayak Shale) were derived from local and northern (Ellesmerian) source areas. Locally, at the Endicott-Lisburne transition, sandy limestones of the Itkilyariak Formation record another phase of siliciclastic influx that lies above and/or is a lateral equivalent of the Kayak Shale and Lisburne Group in areas adjacent to paleotopographic highs. This siliciclastic to carbonate transition represents a major transgressive succession that onlaps northward over the sub-Mississippian unconformity, a regional angular unconformity and sequence boundary in northern Alaska. The age and nature of onlap depend upon the paleotopography of the underlying sub-Mississippian rocks and regional passive margin subsidence.

The Lisburne Group is a thick succession of carbonate rocks subdivided into the Alapah Limestone and overlying Wahoo Limestone, both having informal members. The lower Alapah Limestone has numerous parasequences (small-scale carbonate cycles) superimposed on an overall transgressive succession. Locally, parasequences at the base of the Alapah contain restricted-platform (lagoonal) algal limestones overlain by intertidal fenestral mudstone and cryptalgal dolomite. Upsection, parasequences contain cross-stratified skeletal grainstones that formed as high-energy shoals. In the middle Alapah, fossiliferous limestones formed mostly below wave base in open-marine to open-platform environments. The upper Alapah, composed of dark-colored, spiculitic dolomite and lime mudstone with replaced evaporite nodules, represents an extensive restricted platform that locally prograded or aggraded to sea level, as indicated by intertidal to supratidal cryptalgalaminate with fenestral fabric. The Mississippian and Pennsylvanian lower member of the Wahoo Limestone is a mappable cliff-forming unit composed of bryozoan/pelmatozoan limestone that formed in an open-marine setting on a high-energy carbonate ramp with good circulation and normal salinity. The Pennsylvanian upper member of the Wahoo Limestone is characterized by numerous small-scale parasequences superimposed on an overall transgressive-regressive succession. The top of the Lisburne Group is marked by another major unconformity beneath the Permian Echooka Formation that represents a significant hiatus (~38 m.y.) and major erosional surface. The Lisburne can be subdivided into three depositional sequences: the lowest and thickest sequence includes the entire Endicott Group and most of the Alapah, the second and thinnest sequence approximates the lower Wahoo, and the highest sequence is most of the upper Wahoo. Type 1 sequence boundaries beneath the Endicott and above the Lisburne are major regional unconformities, whereas type 2 sequence boundaries within the Lisburne are recognized as major regressions indicated by carbonate facies analysis.

INTRODUCTION

This paper discusses stratigraphic framework, depositional history and paleogeography of the Lisburne Group in the northeastern Brooks Range, and provides a regional synopsis of its three-dimensional anatomy. The influence of underlying geology that forms the foundation for the Lisburne platform also is considered. Of more general interest, well-developed parasequences (carbonate cycles ubiquitous in shallow-marine carbonates), particularly in the Pennsylvanian upper Wahoo Limestone, are interpreted in terms of relative sea-level fluctuations and provide insights for developing detailed facies models underpinning paleogeographic reconstructions. This information will help assess the petroleum potential of the unit in the subsurface of the Arctic National Wildlife Refuge (ANWR) and also pertains to the Lisburne oil field at Prudhoe Bay.

The Carboniferous Lisburne Group of northern Alaska formed on a large carbonate platform that extended across northern Alaska eastward into Canada and westward toward northeastern Russia (Fig. 1-1). In northern ANWR, the stratigraphic organization of the Lisburne Group is similar to the subsurface stratigraphy at Prudhoe Bay, indicating that these two areas generally formed along depositional strike (Figs. 1-1 & 1-2; Armstrong and Mamet, 1974; Watts et al., 1987). The Lisburne Group forms a producing hydrocarbon reservoir at Prudhoe Bay and is a potential hydrocarbon objective for the entire North Slope region (Bird and Jordan, 1977; Okland et al., 1987; Bird et al., 1987). The coastal plain of ANWR overlies promising source and reservoir rocks and structures and is considered to be the most prospective unexplored potential onshore hydrocarbon area in North America (Bird and Magoon, 1987).

The thick succession of Lisburne Group carbonates apparently formed on a broadly subsiding, southward-facing (relative to present coordinates), passive continental margin (Bird and Molenaar, 1987). The Lisburne gradationally overlies fluvial and marginal marine sediments of the Endicott Group, together forming a major depositional sequence that lapped northward over the regional angular sub-Mississippian unconformity (Fig. 1-3). The paleotopography of the sub-Mississippian rocks controlled depositional patterns in the overlying sequence (Endicott and Lisburne; Fig. 1-3). The top of the Lisburne is truncated by another regional unconformity beneath the Permian Echooka Formation (Hubbard et al., 1987; Crowder, 1990). The thickness and age of the upper part of the Lisburne Group is controlled, in part, by the depth of sub-Permian erosion.

The Lisburne Group is subdivided into the Mississippian Alapah and Wachsmuth Limestones (Bowsher and Dutro, 1957) and the Mississippian to Pennsylvanian Wahoo Limestone (Brosgé et al., 1962; Watts et al., 1990). Most previous studies of the Lisburne were conducted by Armstrong (carbonate sedimentology) and Mamet (foraminiferan biostratigraphy). Their pioneering studies established the basic stratigraphic framework for the Lisburne Group,

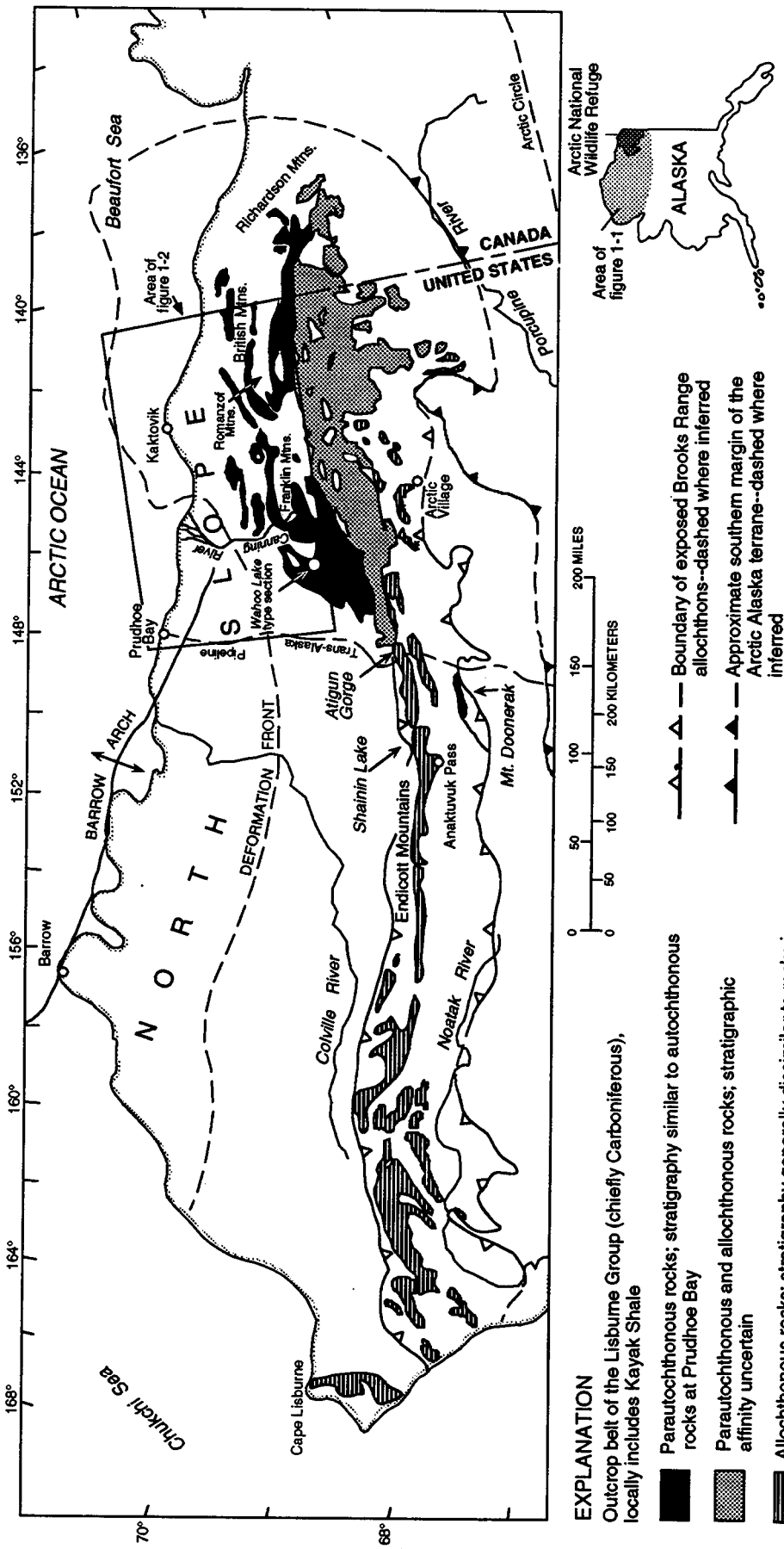


Figure 1-1. Geologic map showing the distribution and tectonic affinities of the Lisburne Group exposed in the Brooks Range. Compiled from Grybeck et al., 1977 (Alaska Lisburne Group), Norris, 1982 (Canada Lisburne Group), Craig et al., 1985 (Barrow Arch and deformation front), Mull et al., 1987b (allochthons), and Wesley Wallace, pers comm. (parautochthon vs. allochthon).

Figure 1-2

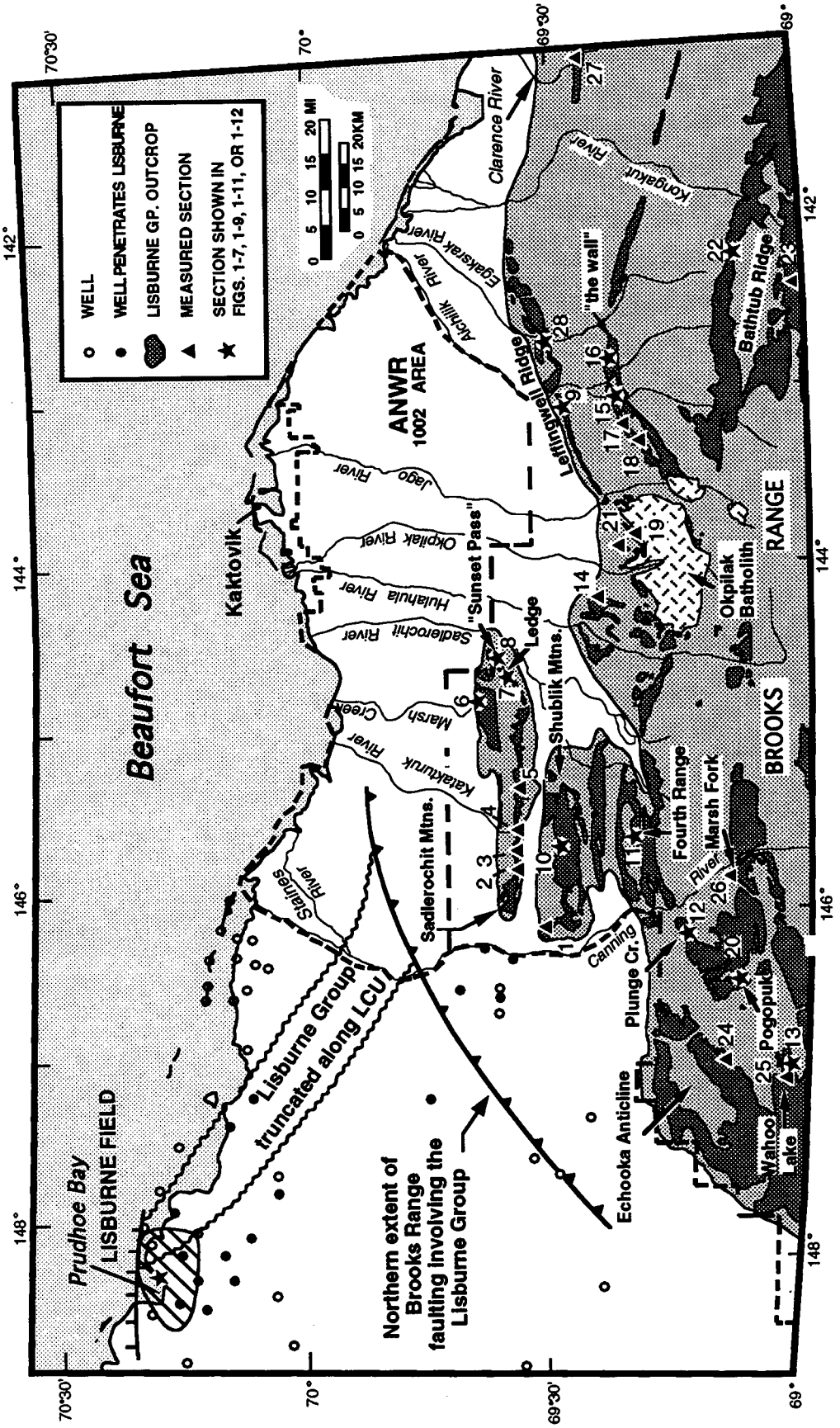


Figure 1-2. Map showing outcrop belts of the Lisburne Group in ANWR and locations of measured sections. The general location of the truncation of the Lisburne Group beneath the Lower Cretaceous unconformity (LCU) is also shown extending southeastward from Prudhoe Bay (modified from Bird et al., 1987).

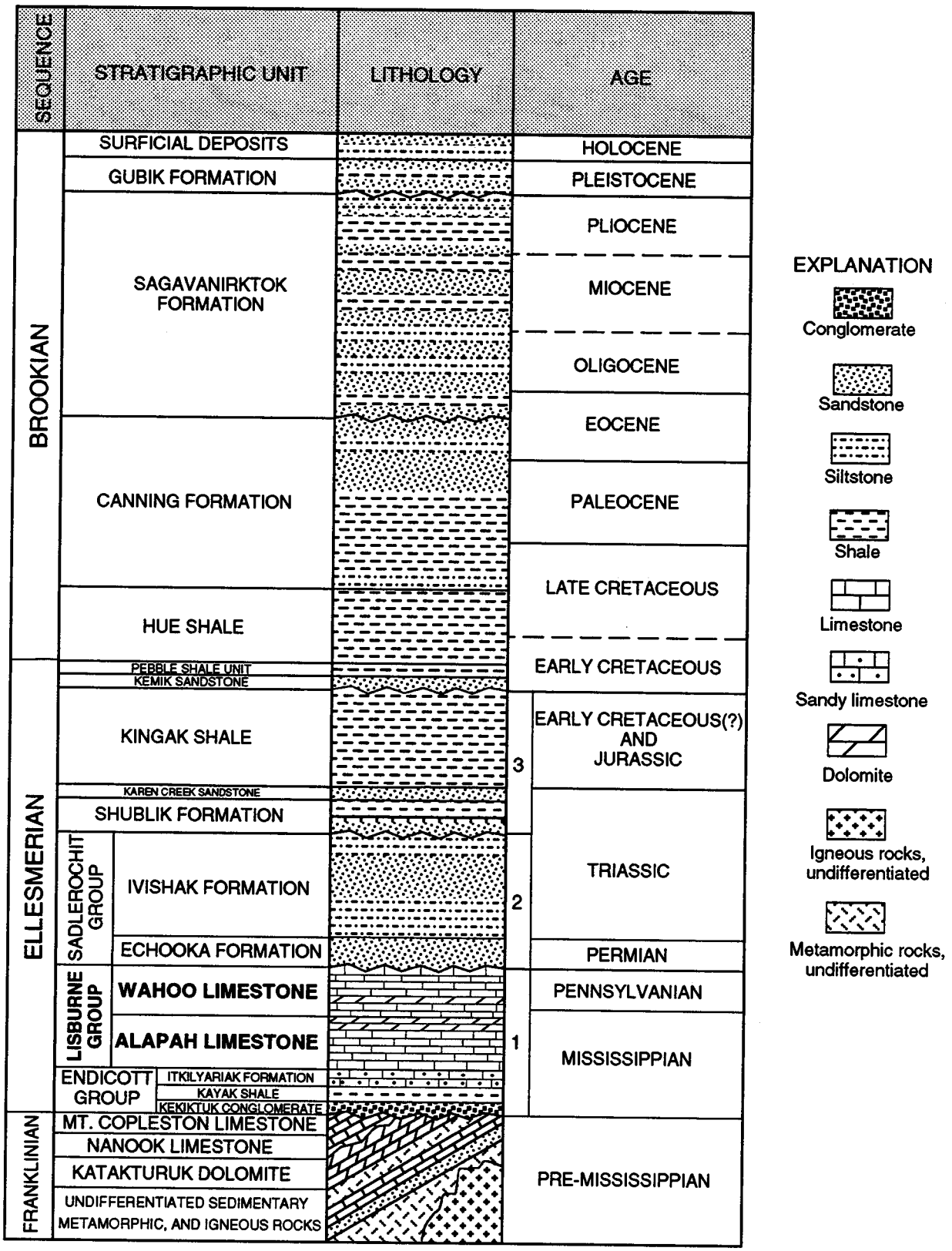


Figure 1-3. Generalized stratigraphy of the northeastern Brooks Range, ANWR (modified from Bird et al., 1987).

including carbonate microfacies analyses of paleoenvironments (Armstrong, 1972, 1974, Armstrong and Mamet, 1970, 1974, 1975, 1977, 1978; Mamet and Armstrong, 1972; Wood and Armstrong, 1975; Armstrong and Bird, 1976). Our detailed microfacies analyses provide new insights on the depositional history and paleogeography of the different subunits of the Lisburne Group in the northeastern Brooks Range. Analyses of its sequence and parasequence stratigraphy has allowed us to develop detailed facies models and paleogeographic maps. Conodont biostratigraphy has been particularly useful for precisely determining the location of the Mississippian-Pennsylvanian boundary and for resolving problems with stratigraphic nomenclature (Krumhardt et al., 1992, in press). Our work in the northeastern Brooks Range (ANWR) adds to knowledge about the Carboniferous geology of Arctic Alaska and its relationship to the rest of the circumarctic region.

REGIONAL GEOLOGICAL SETTING

The thick succession of mostly sedimentary rocks exposed in the northeastern Brooks Range (Fig. 1-3) correlates with the subsurface stratigraphic sequence of the North Slope petroleum province that contains the huge hydrocarbon reservoirs at Prudhoe Bay (Bird and Molenaar, 1987). The stratigraphic succession of northern Alaska has been subdivided into three major sequences (Grantz and May, 1983; Bird and Molenaar, 1987, Moore et al., 1992), using terminology originally established in the Canadian Arctic (Lerand, 1973). The Precambrian to Devonian Franklinian Sequence (hereafter referred to in more general terms as sub-Mississippian rocks) is a complex assemblage of mostly sedimentary rocks that were variably deformed and weakly metamorphosed during pre-Mississippian deformational events. Although the sub-Mississippian rocks of ANWR have been referred to as basement, little-deformed and unmetamorphosed sedimentary rocks such as the Precambrian Katakturuk Dolomite (a potential hydrocarbon reservoir) are neither economic nor crystalline basement. The sub-Mississippian unconformity is an angular unconformity that truncates a variety of sub-Mississippian rocks and has significant erosional relief (Watts et al., 1988). These sub-Mississippian rocks are a complex assemblage of lithologic units that typically dip southward relative to the unconformity and range in age from Precambrian to Devonian (Figs. 1-3 & 1-4; Reiser et al., 1978, 1980; Blodgett et al., 1986; Wallace and Hanks, 1990).

The overlying Mississippian to Lower Cretaceous Ellesmerian Sequence consists of a thick succession of marine carbonate and terrigenous sediments that formed along a south-facing, broadly subsiding continental margin. The Endicott and Lisburne Groups together comprise the first depositional sequence that lapped northward over the sub-Mississippian unconformity during the initial phases of passive margin subsidence. The composition and facies relationships of the basal clastics of the overlying Endicott Group indicate that they were derived locally in part and that they filled paleovalleys on the sub-Mississippian unconformity (LePain, 1993). However, most terrigenous clastic sediments of the Ellesmerian Sequence were transported southward (relative to present day coordinates) and were derived from continental highlands previously located north of, and later were

rifted away from, the present continental margin bounding northern Alaska (Grantz and May, 1983; Hubbard, 1987). The Early Cretaceous rifting event that caused this separation also was important in the uplift and development of the Barrow Arch, a significant structural high along Alaska's northern margin. Erosion along the Barrow Arch lead to the progressive truncation of Ellesmerian and older rocks beneath the Lower Cretaceous unconformity (LCU) to form the structural/stratigraphic trap for the Prudhoe Bay oil fields, including the Lisburne field (Fig. 1-1; Jamison et al., 1980).

The Cretaceous to Cenozoic Brookian Sequence consists of detritus eroded from the Brooks Range orogen, transported northward, and deposited in the adjacent foreland basin. This direction of sediment transport is the opposite direction from that in the Ellesmerian Sequence.

The northeastern Brooks Range is part of the extensive Brooks Range fold and thrust belt that stretches across northern Alaska from Canada to the Lisburne Peninsula and may be a continuation of the Cordillera of western North America (Fig. 1-1; Wallace and Hanks, 1990). Throughout most of the Brooks Range, the Lisburne Group and associated rocks are allochthonous, being parts of north-vergent thrust sheets (Fig. 1-1; Armstrong and Mamet, 1978). In the northeastern Brooks Range (ANWR), the Lisburne is parautochthonous and similar to autochthonous rocks in the subsurface at Prudhoe Bay (Figs. 1-1 & 1-2; Armstrong and Mamet, 1977, 1978). Because these parautochthonous rocks are not displaced much, palinspastic reconstructions are relatively straight-forward and their paleogeography and depositional history can be deciphered. Palinspastic reconstructions in the allochthonous rocks are more problematic, but understanding major facies changes in the allochthonous Carboniferous Lisburne and its equivalents will be essential for unraveling the complex geology of the Brooks Range (Mayfield et al., 1988).

ENDICOTT GROUP

The Endicott Group (Kekiktuk Conglomerate and Kayak Shale) is the lower part of a transgressive systems tract that onlapped northward over the sub-Mississippian unconformity and continues into the Lisburne Group (Fig. 1-4). Because it is intimately associated and coeval with the Lisburne, we will consider some general aspects of the Endicott Group. The basal Kekiktuk Conglomerate consists of quartzose sandstone and conglomerate and becomes finer grained and more shaly upward (Brosgé et al., 1962; Nilsen, 1981; LePain and Crowder, 1989). The Kekiktuk Conglomerate passes gradationally upsection into the Kayak Shale, which grades up into carbonates of the Lisburne Group (LePain et al., 1990; LePain, 1993). In ANWR, a localized interval of calcareous quartzose sandstone and sandy fossiliferous limestone assigned to the Itkilyariak Formation occurs at the transition between the Endicott and Lisburne or between the Lisburne and sub-Mississippian rocks where the Kekiktuk and/or Kayak are missing.

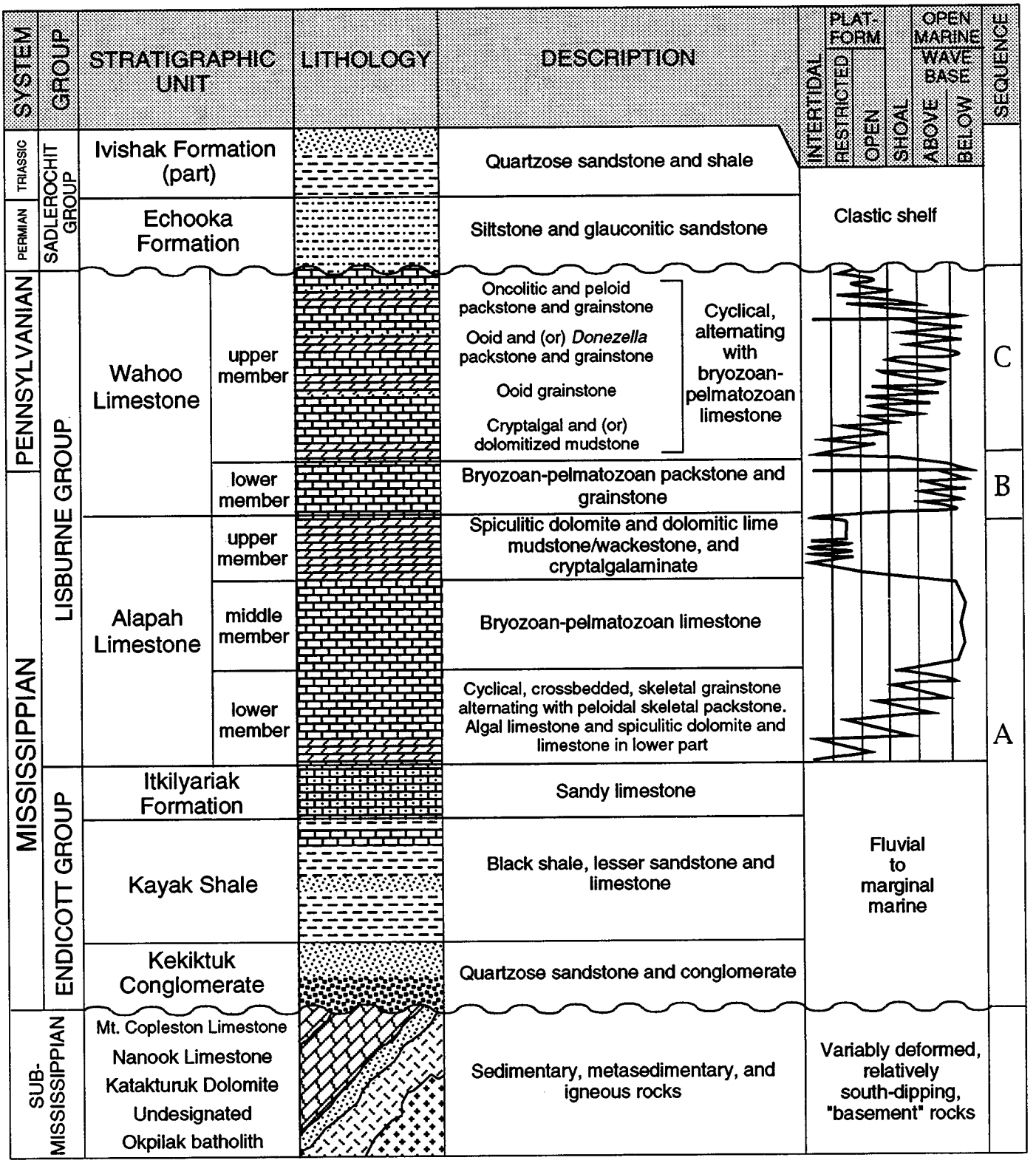


Figure 1-4. Generalized stratigraphy of the Carboniferous Endicott and Lisburne groups and the Permian to Triassic Sadlerochit Group in northern ANWR (modified from Krumhardt, 1992).

KEKIKTUK CONGLOMERATE AND KAYAK SHALE

The Kekiktuk Conglomerate (Formation) of the Endicott oil field near Prudhoe Bay fills a Visean-age (Meramecian to early Chesterian, Late Mississippian) fault-bounded basin (Woidneck et al., 1987). The organization of the Kekiktuk in ANWR is different with thinner, generally coarser-grained, laterally variable terrigenous clastics suggesting deposition in paleovalleys cut into sub-Mississippian rocks (LePain, 1993). The stratal organization, terrestrial plant fossils and rare coal beds indicate deposition in fluvial environments and a humid climate. The gradational transition into the Kayak Shale marks the beginning of a major marine transgression that inundated northern ANWR in Visean time (Meramecian, Late Mississippian). Farther south (near loc. 23, Fig. 1-2), limestones in the Kayak are Tournaisian (Osagean) in age, indicating earlier marine conditions in this area (Anderson, 1993).

The Kayak Shale consists of black organic-rich shale and siltstone with lesser sandstone and limestone. Much of the organic matter was derived from land plants. Limestone interbedded with shale in the upper part of the unit is similar to limestone in the overlying Lisburne Group, indicating normal-marine conditions but with a periodic influx of terrigenous mud. Armstrong and Mamet (1975) recovered foraminifers and algae from limestones in the Kayak Shale in ANWR that range in age from late early Visean (Osagean, Mamet microfossil Zone 11) to late Visean (early Chesterian, Zone 16). Because the contact is gradational and time transgressive, it is difficult to consistently determine the position of the lithostratigraphic boundary in different measured sections. In this paper, we arbitrarily define the base of the Lisburne Group to be above the last significant (> 1 meter-thick) interval of shale in the Kayak Shale or the last bed of sandy limestone of the Itkilyariak Formation. In most places, the contact is easily mapped along the base of the cliff-forming Lisburne Group, which contrasts with the slope-forming Kayak Shale. In the southern part of the ANWR study area, thick intervals of limestone occur in the Kayak Shale. Locally, in northern ANWR (locs. 10 & 11, Fig. 1-2), limestones in the upper Kayak contain cryptalgal laminate and calcite pseudomorphs after gypsum, indicating intertidal an hypersaline conditions respectively (Gruzlovic, 1991).

Interpretation of Kekiktuk Conglomerate and Kayak Shale

The Kekiktuk Conglomerate of ANWR has been interpreted as fluvial deposits that filled local paleovalleys cut into older rocks underlying the sub-Mississippian unconformity (LePain, 1993). An upward transition from braided fluvial to meandering fluvial deposits in the unit indicates a progressive rise in base level associated with the beginning of a major marine transgression that lapped northward in ANWR. The gradational transition into black shale of the Kayak Shale and local marine sandstones in the upper Kekiktuk and within the Kayak indicates the progressive flooding of paleovalleys and formation of estuaries (LePain, 1993).

Preceding the onlap of the Lisburne Group, black organic-rich terrigenous muds of the Kayak Shale were deposited in marginal marine environments having restricted circulation (LePain et al., 1990; LePain, 1993). During the Osagean to early Chesterian, a shallow restricted marginal marine environment was bounded on the north by the Sadlerochit Mountains paleotopographic high (Barrow Arch?) and on the south by the northward advancing Lisburne carbonate platform.

The water depths and paleogeography associated with the Kayak Shale allowed low-energy sedimentation of organic-rich muds. The coeval Lisburne platform to the south possibly created a barrier to circulation, so the Kayak may have formed in relatively shallow lagoonal conditions. Restricted water circulation and oversupply of organic matter caused dysaerobic or anaerobic conditions (Oschmann, 1991). Much of the organic matter was terrestrial, produced on humid flood plains of the Endicott Group. Locally, shallow-water environments had sufficient oxygen to support a normal-marine fauna (including pelmatozoans, bryozoans, and corals) as indicated by limestones within the Kayak Shale, particularly near its gradational contact with the Lisburne Group. At other localities, the presence of cryptalgal laminate and evaporite pseudomorphs in limestones in the Kayak indicate very shallow intertidal conditions (and climatic changes?). However, variations in water depth may have been inherited from paleovalleys and intervening basement highs, as indicated by localized deeper-water(?) spiculite at the Kayak/Lisburne transition (see below).

ITKILYARIAK FORMATION

The Itkilyariak Formation exposed in northern ANWR is a localized, discontinuous interval of relatively coarse sandy (quartzose) fossiliferous limestone and calcareous quartzose sandstone at the top of the Endicott Group (Mull and Mangus, 1972). It is widespread in the subsurface in the Prudhoe Bay region and in the eastern National Petroleum Reserve in Alaska (Mull and Mangus, 1972; Armstrong and Mamet, 1974; Jamison et al., 1980; Woidneck, 1987). In outcrop, the unit is significantly different than in the subsurface; it is locally exposed in the eastern Sadlerochit Mountains (the type locality) and near the Okpilak batholith, but has not been recognized in other areas. Although the Itkilyariak Formation originally was defined as part of the Endicott Group (Mull and Mangus, 1972), it passes gradationally upward into clean limestones of the Lisburne Group and is most easily mapped as part of the Lisburne Group.

At the type locality in the eastern Sadlerochit Mountains, the Itkilyariak Formation is a thin interval (5-10 meters) of sandy and silty limestone that lies unconformably on sub-Mississippian low-grade metamorphic rocks. The unit cannot be traced laterally for more than a few tens of meters. In adjacent exposures, Lisburne Group carbonates directly overlie the sub-Mississippian unconformity. Nearby (1 km southwest), unusual carbonate breccias fill karstic(?) cavities cut into the underlying Precambrian Katakturuk Dolomite and contain clasts derived from this unit.

In eastern ANWR between the Okpilak and Aichilik rivers (Fig. 1-2), sandy limestones of the Itkilyariak Formation contain very coarse to granular, subangular quartz. These beds of coarse-grained, sandy pelmatozoan grainstone/packstone alternate with dolomitized lime mudstone and bryozoan wackestone. The interbeds of sandy limestone occur in successions up to 40 meters thick and are best developed immediately north of the Okpilak batholith (loc. 21, Fig. 1-2). Although the quartz is similar to that in the underlying granite, no feldspars have been recognized, perhaps indicating that they were weathered away due to a humid Mississippian climate (LePain, 1993). Other localities to the east of the Okpilak batholith contain lesser amounts of sandy limestone above an interval of black siltstone of the Kayak Shale (locs. 17 & 18, Fig. 1-2; see also Mull and Mangus, 1972).

Interpretation of the Itkilyariak Formation

The type locality in the eastern Sadlerochit Mountains is unusual and represents localized transgressive lag deposits derived from the underlying sub-Mississippian basement. At the northern Okpilak batholith localities, sandy limestones of the Itkilyariak Formation resulted from the inception of carbonate sedimentation above a sandy substrate. A continued but diminishing influx of quartzose sand and/or reworking of the sandy substrate caused the quartz to be mixed with pelmatozoans and other fossil fragments in high-energy grainstones that formed in the nearshore environment. These mixed sandy grainstones occur as high-energy storm deposits that were redeposited in low-energy open-marine or open-platform environments now represented by bryozoan wackestone and bafflestone. East of the Okpilak batholith, the influx of coarse terrigenous sand above shale and siltstone of the Kayak Shale indicates a relative sea-level fall and/or rejuvenation of localized(?) source areas. In all cases, the mixed sediments of the Itkilyariak Formation were deposited adjacent to or over paleotopographic highs that served as sources of terrigenous sediments that were mixed with carbonates in nearshore marine environments. In the subsurface of Prudhoe Bay, terrigenous sediments in the Itkilyariak and less commonly in the Lisburne were derived from the adjacent Colville high (Armstrong and Mamet, 1974; Jamison et al., 1980).

LISBURNE GROUP OF NORTHERN ANWR

In the northeastern Brooks Range, the Carboniferous Lisburne Group has been formally subdivided into the Alapah Limestone and Wahoo Limestone (Brosgé et al., 1962; Armstrong and Mamet, 1975). Although these formations are different in northeastern ANWR than at their type localities due to lateral facies changes, the dark-colored slope-forming Alapah Limestone and the light-colored, cliff-forming, fossiliferous Wahoo Limestone can be traced across most of ANWR (Fig. 1-4). However, some previous studies (Armstrong and Mamet, 1975, 1977) may have used biostratigraphic criteria to define a Mississippian Alapah and a Pennsylvanian Wahoo, rather than using consistent lithostratigraphic criteria (see below). The Mississippian-Pennsylvanian boundary actually occurs in the lower part of the Wahoo Limestone, rather than at any mappable change in lithology (Figs. 1-4

& 1-5). In the north, the contact between the Alapah and Wahoo is relatively sharp, but farther to the south, the contact is increasingly gradational.

In this report, the Alapah Limestone is subdivided into three informal members (lower, middle and upper) based on differences recognized primarily through microfacies analyses (Fig. 1-4). The Wahoo Limestone is subdivided into two informal members (lower and upper) based upon composition, stratigraphic organization and mappable outcrop characteristics (Figs. 1-4 & 1-6). Although these lithologic units are distinguished readily in northern ANWR, basinward lateral facies changes across the Lisburne carbonate platform cause some subunits to pinch out, change in character, and/or develop more gradational contacts. However, establishing such localized informal subunits will help to characterize the mosaic of carbonate facies comprising the Lisburne and the paleogeographic evolution of the carbonate platform on which it formed.

The age of the basal Lisburne Group becomes progressively younger to the north (Armstrong and Mamet, 1977, 1978; Mamet and Armstrong, 1972), signifying northward-directed onlap/transgression that accompanied initial subsidence of the Ellesmerian passive margin (Fig. 1-5). In most parts of northern ANWR, the Alapah Limestone is underlain conformably by the Endicott Group. However, the youngest ages of the basal Lisburne Group occur where it directly overlies the sub-Mississippian unconformity without intervening terrigenous sediments of the Endicott Group. The delayed onlap and/or the presence of clasts derived from underlying sub-Mississippian rocks indicate paleotopographic highs in the areas of the eastern Sadlerochit Mountains and Okpilak batholith. Farther to the south and west in the Endicott allochthon, shallow-marine carbonates with abundant replacement chert of the older Wachsmuth Limestone underlie the Alapah Limestone, and form the basal unit of the Lisburne Group (Bowsher and Dutro, 1957). Overall, the Lisburne generally thickens to the south, in response to earlier onlap and more rapid subsidence rates. The age and thickness of the upper Wahoo is controlled, in part, by the depth of erosion along the regional sub-Permian unconformity (Armstrong, 1974; Watts et al., 1987).

WACHSMUTH LIMESTONE

The Wachsmuth Limestone and Alapah Limestone were originally defined near Shainin Lake in the central Brooks Range (Bowsher and Dutro, 1957), where they were reexamined as part of our regional framework studies (see below). Brosgé et al. (1962) extended the Wachsmuth and Alapah nomenclature into the southern and western parts of ANWR but noted lithologic differences from the type locality. However, the Wachsmuth has not been recognized as a mappable lithologic unit anywhere but at the type locality, where it is difficult to distinguish from the Alapah Limestone. In the southern part of our ANWR study area (Marsh Fork, loc. 26, Fig. 1-2), a cherty limestone unit was classified tentatively as the Wachsmuth by previous workers (Mamet and Armstrong, 1972; Armstrong and Mamet, 1975). Their age determinations (early Meramecian; Mamet Zone 12 and Zone 12/13)

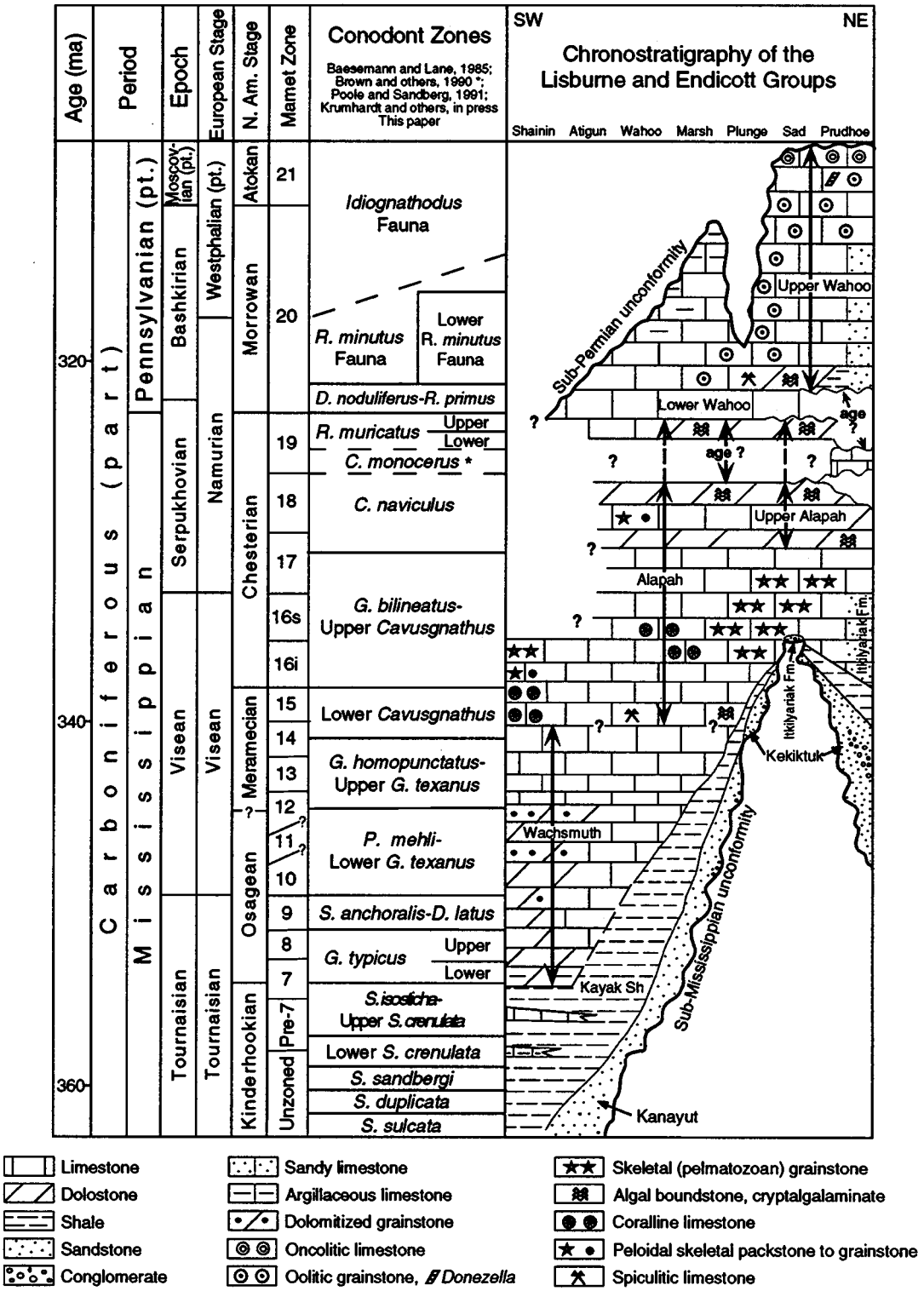


Figure 1-5. Chronostratigraphy of the Lisburne Group. See Chapter 2 for detailed chronostratigraphic charts and discussion of biostratigraphic criteria used for age determinations. Localities on Fig. 1-2 include: Sad." (loc. 8), Plunge (loc. 12), Wahoo (loc. 13), Marsh (loc. 28). Atigun is near Trans-Alaska Pipeline and Shainin is in the central Brooks Range (Fig. 1-1). See also Figs. 1-7, 1-9, 1-11, 1-12, 1-14, 1-30, and 1-31.

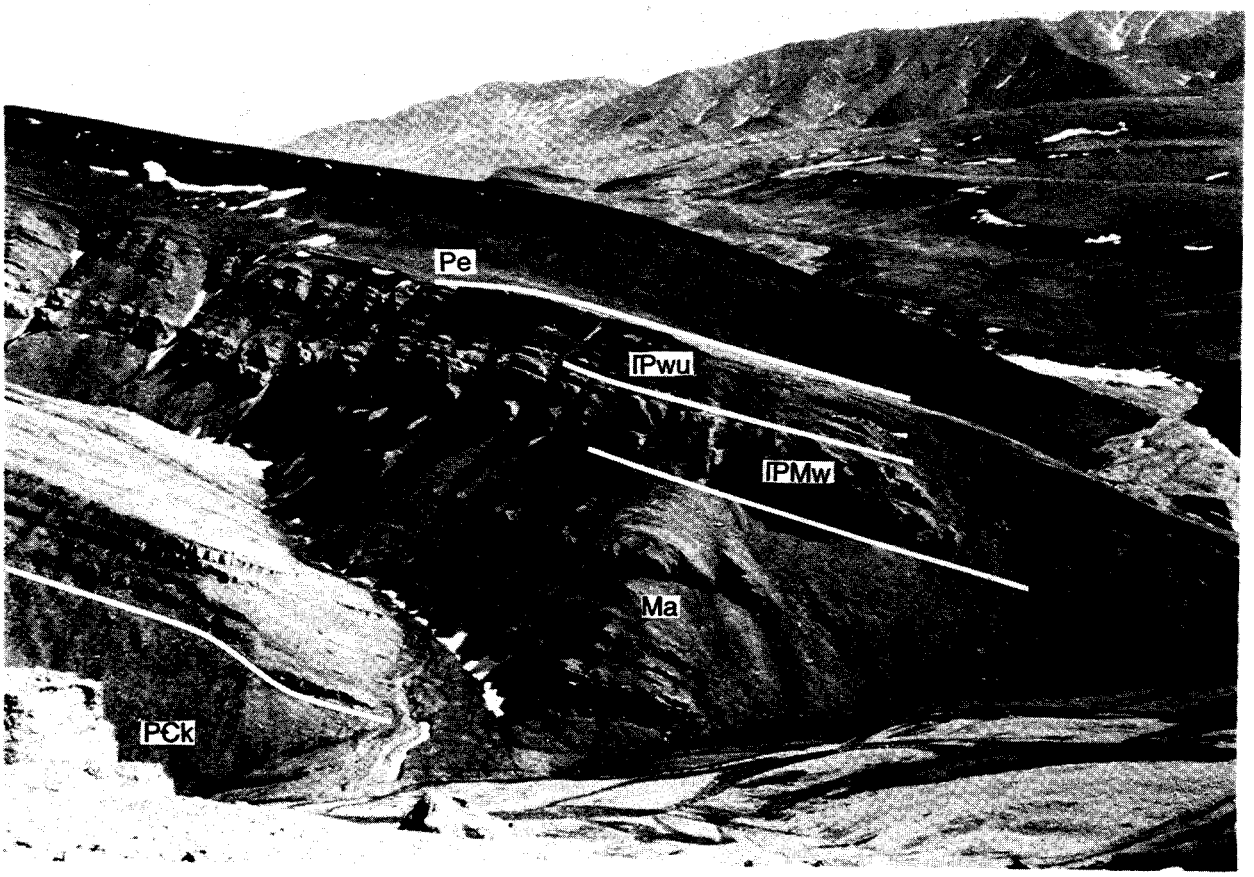


Figure 1-6. The subunits of the Lisburne Group are well exposed in the western Sadlerochit Mountains along Katakturuk Gorge (loc. 4, Fig. 1-2). PЄk—Precambrian Katakturuk Dolomite; Ma—Mississippian Alapah Limestone; IPMwl—Mississippian to Pennsylvanian lower Wahoo Limestone; IPwu—Pennsylvanian upper Wahoo Limestone, Pe—Permian Echooka Formation.

correspond to the youngest part of the type Wachsmuth (Osagean/Mamet Zone 8 to late Meramecian/Zone 14) and may be the basis for the correlation. A conodont sample from a dolostone in the lower part of the Lisburne at this section yielded conodonts that indicate an Osagean to Meramecian age (17.5 meters above an interval of siliceous shale and bedded chert assigned to the Kayak). However, the Marsh Fork rocks are dominated by cherty spiculitic(?) and peloidal(?) dolostone and coralline skeletal wackestone and packstone, and are significantly different than the cherty and dolomitic skeletal grainstone and wackestone that characterize the type Wachsmuth (see below). Because of the apparent lack of a mappable lithologic correlation, we include these cherty carbonates in the lower part of the Alapah Limestone.

ALAPAH LIMESTONE

The Alapah Limestone in ANWR is a thick sequence (> 250 meters / 800 ft.) of Upper Mississippian (Meramecian and Chesterian, possibly Osagean) limestone and dolomite. In most of northern ANWR, it gradationally overlies the Endicott Group, but locally overlies pre-Mississippian rocks. Based on microfacies analysis in northern ANWR, the Alapah Limestone can be subdivided into three informal members: 1) the lower Alapah member that passes upward from algal limestone to cross-stratified skeletal grainstone of the informal "Egaksrak grainstone" unit; 2) the middle Alapah member that consists primarily of bryozoan-pelmatozoan limestone; 3) the upper Alapah member that consists primarily of spiculitic dolomite and lime mudstone with minor cryptalgalaminate. Boundaries between all of these units are gradational and lateral changes in thickness and lithofacies are evident between different measured sections (Fig. 1-7; Gruzlovic, 1991).

The age of the basal Alapah Limestone is diachronous. In the southern part of the ANWR study area (Marsh Fork, loc. 26, Fig. 1-2), foraminifers and algae indicate that the lower part of the Lisburne is at least early Meramecian in age (Zone 12; Mamet and Armstrong, 1972; Armstrong and Mamet, 1975), but our conodonts from lower in the Lisburne indicate an Osagean to Meramecian age (we tentatively include these cherty limestones in the basal Alapah rather than the Wachsmuth Limestone, see above). In northern ANWR (Sadlerochit Mountains, locs. 2, 4 & 8, Fig. 1-2), the basal Alapah is Chesterian (Zone 16_i-16_s; Mamet and Armstrong, 1972). In the intervening area, the basal Alapah is late Meramecian (Zone ≥ 13 and $<16_i$) in the Fourth Range and early Chesterian in the central Shublik Mountains (Zone 16_i; Bernard Mamet, written communication, 1989). Conodonts yield consistent but less precise ages of late Meramecian to early Chesterian in both the central Shublik Mountains and Fourth Range areas (see Chapter 2). Thus, the age of the basal Alapah becomes younger to the northeast (north-northeast in ANWR) and is consistent with an overall transgression generally proceeding from southwest to northeast across northern Alaska (Fig. 1-5), as first proposed by Armstrong and Mamet (1970).

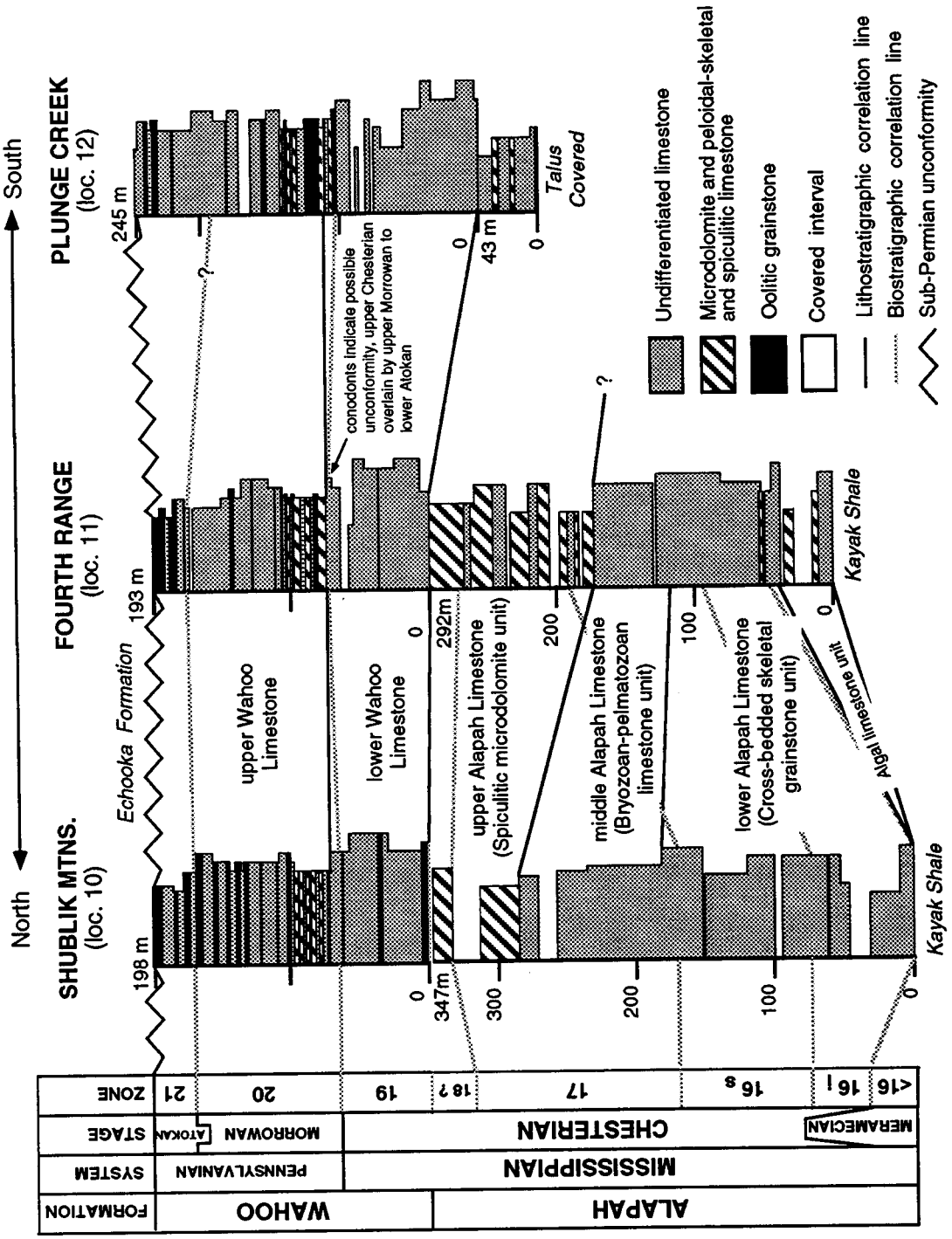


Figure 1-7. Correlation of Lisburne Group along the central part of the Canning River transect (modified from Gruzlovic, 1991). This north to south series of stratigraphic sections extends southward from the Shublik Mountains ("Sunset Pass" section) to the northern Franklin Mountains, generally down depositional dip on a south-dipping carbonate ramp (locs. 10 - 12, Fig. 1-2). This diagram does not account for new conodont data that may indicate an intraformational unconformity within the lower Wahoo at the Fourth Range (see Chapters 2 and 6).

The age of top the Alapah Limestone is less well constrained, being composed of relatively unfossiliferous dolomite and spiculitic limestone, but is probably late Chesterian. In the north (loc. 4, Fig. 1-2), the age of the upper part of the Alapah Limestone is late Chesterian based on foraminifers and algae (Mamet Zone 18). Slightly to the south, in the central Shublik Mountains and in the Fourth Range (locs. 10 & 11, Fig. 1), the age of the upper Alapah is at least middle Chesterian (Mamet Zone 17) and possibly is late Chesterian (Mamet Zone 18; Bernard Mamet, written communication, 1989; Gruzlovic, 1991). Conodonts indicate that the top of the Alapah is younger, being within the *Rhachistognathus muricatus* Zone and equivalent to Mamet Zone 19 (latest Chesterian, see Chapter 2) at several ANWR localities (locs. 8, 9, 11, 13, 15, 16, 22 & 27, Fig. 1-2). Several collections contain *Adetognathus latus*, indicating that the uppermost Alapah is within the Upper *muricatus* Subzone (loc. 8, 9, 11, 15, 16, & 27, Fig. 1-2).

Lower Alapah member—Algal limestone and "Egaksrak grainstone"

Black calcareous shale and argillaceous limestone of the Kayak Shale pass gradationally upward into progressively more pure limestones of the lower Alapah Limestone member (Figs. 1-4 & 1-7). The contact is placed arbitrarily above the highest significant shale (>1 meter), typically forming a distinct break in slope. Limestones are commonly spiculitic packstone, wackestone, and mudstone and locally contain colonial corals. The lower Alapah in the northern part of ANWR can be further subdivided into a lower algal limestone subunit and an upper subunit composed of cyclical cross-stratified grainstone, informally termed the Egaksrak grainstone. In the algal subunit, calcareous algae occur in wackestone, packstone, and bafflestone and are associated with calcispheres and ostracods (Fig. 1-8a). Pseudomorphs of quartz and calcite after evaporites (gypsum rosettes) indicate hypersaline conditions (Fig. 1-8d). In the north (locs. 11 & 27, Fig. 1-2), the basal Alapah is cyclic with algal bafflestone passing upward into cryptalgal-laminated (stromatolitic) dolomites or lime mudstones with fenestral fabric (Fig. 1-8c; Gruzlovic, 1991). Subaerial exposure surfaces in the unit are indicated by laminated crusts, collapse breccias and early fractures (see Chapter 3). The algal limestone subunit is up to 30 meters in thickness.

Gradationally overlying the algal limestones, the informal "Egaksrak grainstone" unit of the lower Alapah Limestone contains distinctive intervals of cross-stratified, skeletal grainstone that define three to seven distinct carbonate cycles (parasequences). These grainstone intervals are particularly well developed near the Egaksrak River (loc. 16, Figs. 1-2 & 1-9), where they gradationally overlie and are interbedded with muddy carbonates containing gastropods, oncolites and a generally impoverished fauna. Beds of well-sorted, highly abraded medium- to coarse-grained, bioclastic and peloidal grainstones have large-scale cross-stratification (Figs. 1-8b & 1-10a; 10 to 30 cm amplitude foresets) and represent high-energy bioclastic shoals that migrated repeatedly across northern ANWR. In parasequences in the upper part of the unit, the grainstones alternate with skeletal packstone and wackestone containing a more varied fauna, including pelmatozoans

and bryozoans. The contacts of the Egaksrak grainstone unit are gradational and chosen arbitrarily at the base of the lowest thick grainstone interval and at the top of the highest thick grainstone interval (Fig. 1-9). It ranges in thickness from 79 to 173 meters.

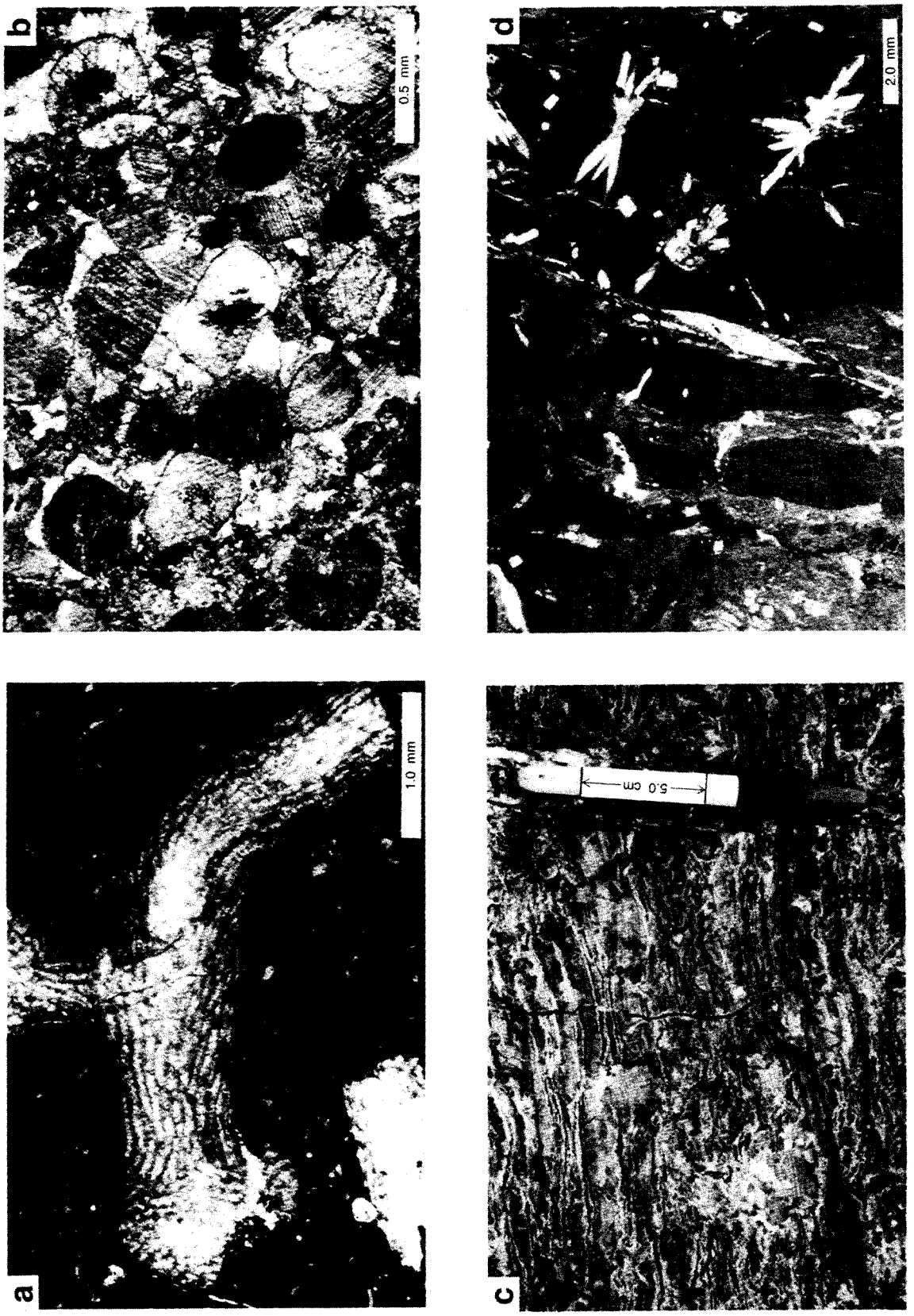
As noted above, the age of the basal lower Alapah Limestone member is diachronous. The algal limestone and Egaksrak grainstone units are confined to northern ANWR and are younger (Meramecian to Chesterian, >Zone 13 and < Zone 16) than the basal Alapah Limestone/Lisburne Group to the south. In southern ANWR (locs. 22, 23 & 26), conodonts indicate that the basal Lisburne/Alapah is Osagean(?) to Meramecian and that intervals of limestone in the underlying Kayak Shale are of Kinderhookian to Osagean age. However, limestones of the lower part of the Alapah in southern ANWR are lithologically most similar to the middle Alapah Limestone member of northern ANWR (see below), indicating northward retrogradation of open-marine/open-platform environments (i.e., a transgression). In the Fourth Range (loc. 11, Fig. 1-2), the algal limestone unit (basal Alapah) is middle to late Meramecian (≥ Mamet Zone 13 but < Zone 16), as are similar limestones within the upper Kayak Shale in the Shublik Mountains (loc. 10, Fig. 1-2; Gruzlovic, 1991). The Egaksrak grainstone unit in both these areas begins in the lower Chesterian (Zone 16i). In the Sadlerochit Mountains, an interval of algal limestone is not present and the basal Alapah (Egaksrak grainstone unit) is Chesterian in age (Zone 16) because of onlap onto the Sadlerochit high. The age becomes younger eastward across the Sadlerochit Mountains from Zone 16i in the west to Zone 16s in the east (locs. 2-8, Fig. 1-2; Armstrong and Mamet, 1977). The top of the member is Chesterian in age, varying between Zone 17 in the north (Sadlerochit and Shublik Mountains, locs. 2, 4, 8 & 10, Fig. 1-2) and Zone 16s to the south (Fourth Range, loc. 11 on Fig. 1-2; Gruzlovic, 1991). In eastern ANWR (loc. 16, Fig. 1-2), conodonts indicate an imprecise late Meramecian to Chesterian age for the Egaksrak grainstone.

Lateral facies changes in this diachronous unit are best described by considering two transects across the Lisburne platform, the first along the Canning River and the second near the Aichilik River, respectively in western and eastern parts of the ANWR study area (Fig. 1-2). In the northern Canning transect (western Sadlerochit Mountains, locs. 2 & 4, Fig. 1-2), the lower Alapah Limestone consists of three cyclical repetitions of limestone (including cross-stratified grainstone), shale, and local sandstone. In this area, the Endicott Group beneath the Lisburne Group shows considerable lateral variations in thickness and lithofacies (Imm and Watts, 1987). In the eastern Sadlerochit Mountains (near loc. 8, Fig. 1-2), the Alapah directly overlies the sub-Mississippian unconformity, with locally intervening mixed siliciclastic and carbonate sediments of the Itkilyariak Formation. To the south along the Canning River transect (Shublik Mountains, loc. 10, Fig. 1-2), the number (7?) and overall thickness (182m) of cycles containing cross-stratified grainstone (Egaksrak grainstone of the lower Alapah) increase. Farther to the south (Fourth Range, loc. 11, Fig. 1-2), a thinner (78m) succession of cyclic Egaksrak grainstone is

Figure 1-8. Photomicrographs of the Alapah Limestone.

A - Algal boundstone contains large branch of the algae, *Ungdarella* in a dark lime mud matrix. Lower part of Alapah Limestone in the Fourth Range (25.0 meters above base of section AK13M, loc. 11, Figs. 1-2 and 1-7; from Gruzlovic, 1991).
B - Pelmatozoan-bryozoan-peloidal grainstone contains highly abraded and rounded grains with micritic envelopes. Lower Alapah Limestone in the Fourth Range (65 meters above base of section AK13M; loc. 11, Figs. 1-2 and 1-7; from Gruzlovic, 1991).
C - Cryptalgal laminite has spar-filled fenestral fabric. Upper Alapah Limestone in the eastern Sadlerochit Mountains ("Sunset Pass", below section AK22M; near loc. 8, Fig. 1-2).
D - Pseudomorphs after radiating gypsum crystals in microdolomite above an intraclastic breccia containing imbricated clasts of microdolomite. Upper Kayak Shale in the central Shublik Mountains (0.5 meter above base of section AK11M; loc. 10, Figs. 1-2 and 1-7; from Gruzlovic, 1991), cross-polarized light.

Figure 1.8.



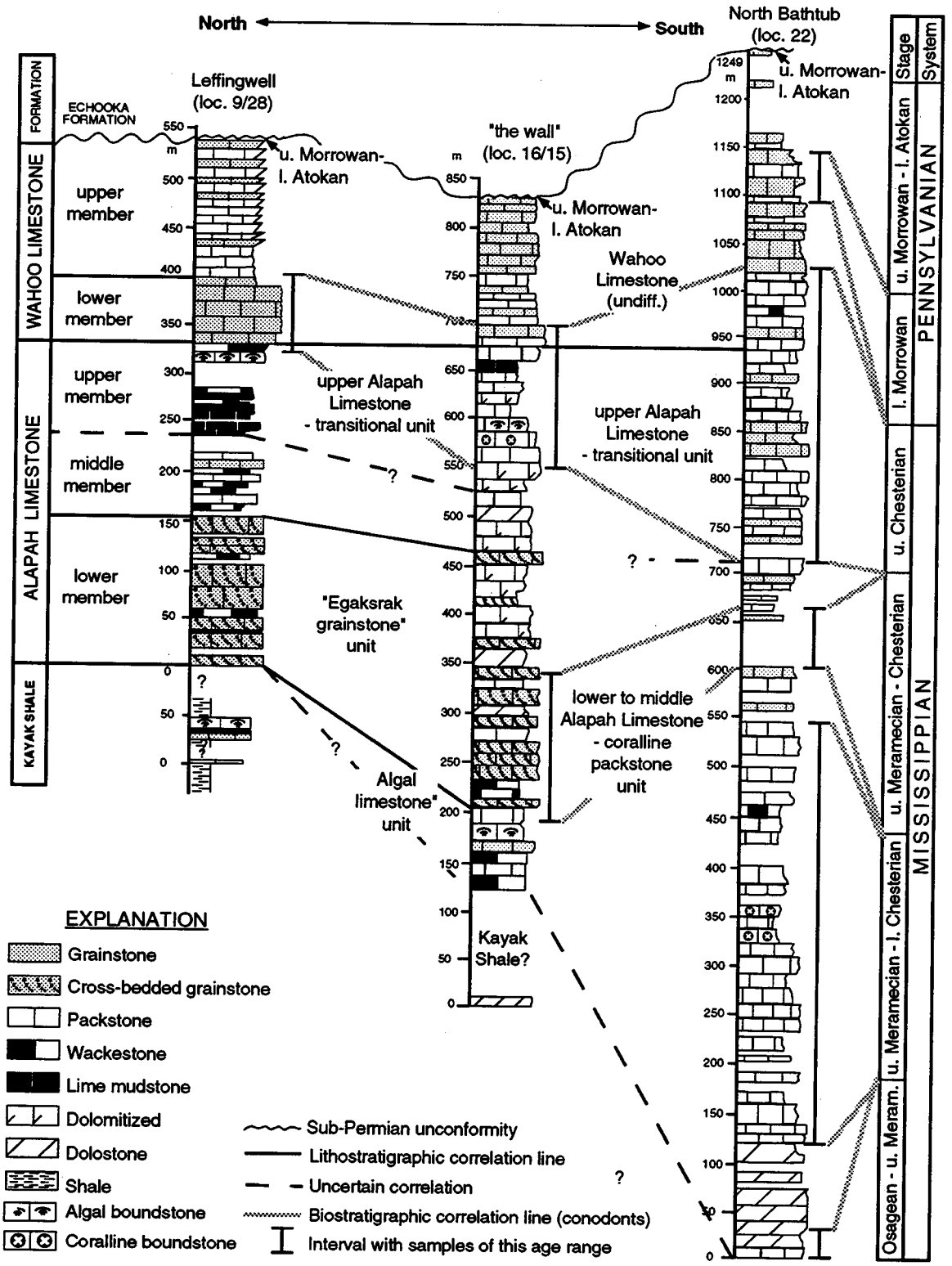


Figure 1-9. Stratigraphic correlation for the Lisburne Group along the Aichilik River transect (locs. 9, 28, 15, 16 and 22, Fig. 1-2), generally down depositional dip on a southward-sloping carbonate ramp, shows major thickness changes in the Lisburne Group. The composite stratigraphic section for "the wall" near the Aichilik River has an uncertain amount of overlap between its component sections.

underlain by an older succession of cryptalgalaminate with other algal and muddy (lagoonal?) carbonates. In the southernmost section (Marsh Fork, loc. 26, Fig. 1-2), the Egaksrak grainstone and algal limestone units of the lower Alapah are not recognized and the lower part of the Alapah is composed of cherty limestone and coralline (open-marine/open-platform) packstone to mudstone.

Along the northern part of the Aichilik transect (Leffingwell Ridge, loc. 28, Figs. 1-2 & 1-9), a >150 meter-thick interval of Egaksrak grainstone is dominated cross-stratified grainstone containing highly abraded bioclasts and lesser ooids. A similar thick interval dominated by cross-stratified grainstone occurs farther to the east near the Canadian border (Clarence River, loc. 27, Fig. 1-2) and is underlain by well-developed cryptalgalaminate. Southward along the Aichilik transect (Egaksrak "wall", loc. 16, Figs. 1-2 & 1-9), seven intervals of cross-stratified skeletal grainstone of the Egaksrak grainstone unit are particularly well developed within a 173-meter-thick succession that overlies cryptalgalaminate and other algal and muddy (lagoonal?) carbonates. Farther downdip in the southern part of the ANWR study area (loc. 22, Figs. 1-2 & 1-9), the Egaksrak grainstone is not recognized and coralline (open-marine/open-platform) limestones comprise the lower part of the Alapah Limestone.

Middle Alapah member—Bryozoan-pelmatozoan limestones

The middle Alapah Limestone is dominated by muddy limestones that contain a normal-marine fauna (including bryozoans, echinoderms, corals, etc.). Parasequences (carbonate cycles) are not apparent. The thickness ranges from 55 to 105 meters along the northern Canning transect. The age of the unit in northern ANWR is early(?) to middle Chesterian (Zone 16s(?)-17)on the basis of foraminifers and algae (Gruzlovic, 1991). Packstone is the most common lithology with lesser grainstone and wackestone. Lime mud is abundant in these carbonates and can be preferentially dolomitized. Fossiliferous packstone of the middle Alapah gradationally overlies the lower Alapah and similar lithologies alternate with the upper intervals of cross-stratified grainstone in the lower Alapah; the contact is defined arbitrarily at the top of the highest grainstone interval. The contact with the upper Alapah is more abrupt but considered conformable with an upsection decrease in diversity of marine fauna and an increase in peloidal dolomicrite that contains spicules, calcispheres and ostracods (Gruzlovic, 1991). Pseudomorphs after evaporite nodules locally occur near the top of the middle Alapah.

In northern ANWR, the middle Alapah member shows irregular thickness variations. Along the northern Canning River transect, it is almost two times thicker in the north than in the south (105 meters versus 55 meters) over a present distance of 12 miles/19 kilometers between the Shublik Mountains and Fourth Range (~27 km/ 17 miles original distance correcting for tectonic shortening; C. Hanks and W. Wallace, pers. comm.; locs. 10 & 11, Figs. 1-2 &1-7). The lower Alapah in these localities shows a similar northward-thickening trend. These northward-thickening trends are not compatible with a simple southward-facing carbonate

ramp. Differential subsidence could have produced the northward-thickening trend if the Fourth Range subsided less than in the central Shublik Mountains. Alternatively, slower sedimentation rates toward the south also could have produced the thickness variations. However, subaerial exposure surfaces near the top of the upper Alapah apparently represent a regionally correlatable, nearly horizontal datum (see below and Chapter 3) that would favor differential subsidence and imply tectonic movements. Depositional patterns in the Alapah indicate considerable variability, possibly related to paleotopography along the sub-Mississippian unconformity surface and/or possible displacement along pre-existing(?) faults. During the Visean (Meramecian to early Chesterian), active faulting occurred at the Endicott oil field (Woidneck et al., 1987; Hubbard et al., 1987).

In southern ANWR (North Bathtub and Marsh Fork, locs. 22 & 26, Fig. 1-2), the Egaksrak grainstone and algal limestone subunits of the lower Alapah Limestone member apparently do not occur. In these areas, a thick interval of packstone containing pelmatozoans, bryozoans, corals, and algae (the lower coralline packstone unit, Fig. 1-9) is most similar to the middle Alapah member of northern ANWR. Pervasive dolomitization and silicification in the lower part of both sections could have obscured what may have been the lower Alapah member. However, most of the differences are probably due to lateral facies changes, with the coralline packstone unit being deposited in open-marine to open-platform conditions that were seaward of the bioclastic shoals of the Egaksrak grainstone unit to the north. The coralline packstone unit has a thickness of up to at least 730 meters, indicating that normal marine conditions existed on the southern part of the carbonate platform for a long interval of time and/or that the this area subsided more rapidly than areas farther to the north.

Available age data indicates that the middle Alapah is older in the south than in the north, implying lateral facies changes and age equivalence to the lower Alapah (i.e., normal marine limestones seaward of coeval bioclastic shoals). In southern ANWR, conodonts indicate that the age of the coralline packstone unit (the lower and middle Alapah) is Meramecian (possibly Osagean) at the base and is probably Chesterian at the top. Because of these lateral facies changes, the informal lithostratigraphic subdivisions of the Alapah (lower, middle and upper members) established for northern ANWR cannot be consistently and logically applied in southern ANWR. Using this terminology, the Alapah of southern ANWR would begin with the middle member rather than the lower member. In future publications, it may be necessary to establish more formal nomenclature using geographic names such as the Egaksrak grainstone member (rather than lower, middle and upper Alapah members) in order to better describe the organization of the Lisburne, particularly its lateral facies changes.

Upper Alapah member—Spiculitic dolomite and limestone

In northern ANWR, the upper Alapah Limestone member primarily consists of dark, poorly exposed dolomite and lime mudstone (Fig. 1-5 & 1-8b). An

impoverished fauna includes sponge spicules, ostracods, calcispheres, and minor pelmatozoan fragments. Dolomite preferentially replaces lime mud (mostly finely crystalline dolomicrite) and may have formed in a variety of diagenetic settings including by penecontemporaneous dolomitization (such as in sabkha dolomites) and later burial dolomitization (Jameson, 1989). Although intervals of dolomite are scattered throughout the Lisburne Group, the dolomicrite of the upper Alapah appears to be the most widespread and most likely to have formed due to early dolomitization (i.e., sabkha dolomite). Dead oil commonly occurs in intercrystalline and vuggy porosity in the dolomite, making the unit the most promising reservoir rock in the Lisburne Group (Bird and Jordan, 1977; Jamison et al., 1980; Bird et al., 1987). Bird and Jordan (1977) trace this widespread interval of relatively porous dolomite across much of the North Slope. Other characteristic features include evaporite nodules replaced by quartz and/or calcite and disseminated laths and molds of anhydrite in dolomicrite (Fig. 1-10b). Several intervals of cryptalgalaminate (flat-laminated stromatolite) and fenestral fabric in the upper part of the unit may serve as a correlatable marker interval and are interpreted to indicate repeated subaerial exposure events (see Chapter 3). Cavernous porosity and collapse breccias formed due to the dissolution of carbonates (and possibly evaporites), possibly during subaerial exposure of the unit (Fig. 1-10c). Early cracks and disruption of algal textures in the cryptalgalaminate occur in the uppermost Alapah immediately below the Wahoo Limestone, indicating up to four subaerial exposure surfaces (see Chapter 3).

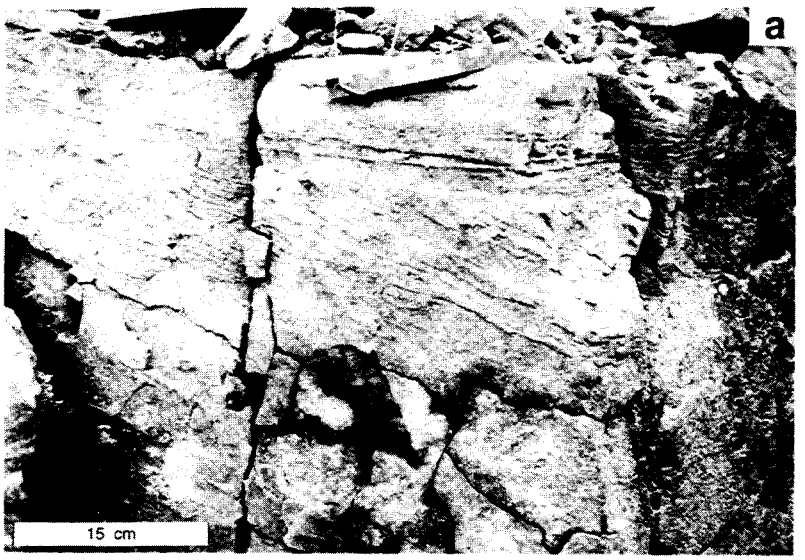
Foraminifers and algae indicate that the age of the upper Alapah member is at least middle Chesterian (Zone 17) and possibly late Chesterian (Zone 18) in northern ANWR (Fig. 1-7; Gruzlovic, 1991). However, conodonts indicate that the upper Alapah is younger, being in the Upper *muricatus* Subzone in several northern ANWR localities (loc. 8, 9, 11, 15, 16, & 27, Fig. 1-2) and within the *Rhachistognathus muricatus* Zone in southern ANWR (loc. 13 & 22, Fig. 1-2), and equivalent to Mamet Zone 19 (latest Chesterian, see Chapter 2).

Along the northern Canning River transect (Shublik Mountains and Fourth Range, locs. 10 & 11, Fig. 1-2 & 1-7), the upper Alapah Limestone member shows a significant southward-thickening trend, increasing from 65 meters to 119 meters over a present distance of 19 km/12 miles (~27 km/ 17 miles original distance correcting for tectonic shortening, C. Hanks and W. Wallace, pers. comm.). A southward change in lithology also occurs with spiculitic dolomicrite of the upper Alapah being interbedded with muddy bryozoan-pelmatozoan dolomitic limestone (wackestone and packstone). Similar lithologic changes and southward-thickening trends are evident along the Aichilik River transect (Leffingwell Ridge and Egaksrak wall", locs. 28, 15 &16, Fig. 1-2 &1-9).

In southern ANWR (Wahoo Lake and near Bathtub Ridge, locs. 13, 22 & 23, Fig. 1-2, 1-9), a transitional unit in the upper Alapah Limestone member contains dark dolomite and lime mudstone and wackestone interbedded with light-colored limestones containing a normal-marine fauna, including pelmatozoans and corals.

Figure 1-10. Outcrop photographs of the Alapah Limestone.
A - Large-scale cross-lamination in the lower Alapah Limestone, central Sadlerochit Mountains (near loc. 5, Fig. 1-2).
B - Silicified and calcitized geodes in the upper Alapah may represent replaced evaporite nodules, Leffingwell Ridge (138 meters above base of section AK95M; loc. 9, Fig. 1-2).
C - Collapse breccia in the upper Alapah Limestone; float in the western Shublik Mountains (near loc. 1, Fig. 1-2).

Fig. 1-10



This transitional unit in the uppermost Alapah represents a gradational change to the normal-marine conditions that prevailed in the Wahoo Limestone. Overall, the Lisburne Group is considerably thicker in the south than in the north (1100 meters compared to 620 meters); much of the thickening is due to the greater thickness of the upper Alapah and its transitional unit (e.g., locs. 9 & 22, Figs. 1-2 & 1-9; presently 35 miles/60 km apart). Additional accommodation space may have resulted from greater subsidence rates to the south, allowing accumulation of a thicker succession of carbonates. Less accommodation space was available in the north where the platform prograded or aggraded above sea-level, inhibiting carbonate sedimentation. A barrier to circulation may have separated the restricted platform in northern ANWR from the relatively open platform in southern ANWR, but has not yet been documented. Alternatively, the better circulation conditions in the south may have resulted from a more seaward position on a broad carbonate platform and the restricted conditions to the north may have resulted from the dampening of tides and waves across an extensive shallow carbonate platform (Shaw, 1964; Irwin, 1965; Enos, 1983).

DEFINITION OF THE ALAPAH-WAHOO BOUNDARY

In northern ANWR (locs. 1-11, Fig. 1-2), the contact between the dark, recessive-weathering Alapah Limestone and the light-gray weathering cliffs of the Wahoo Limestone is sharp, with a marked contrast in lithologies (Figs. 1-6 & 1-11). Following the original definition of the Wahoo Limestone (Brosgé et al., 1962), we place the basal Wahoo contact above the highest dark fine-grained carbonate (dolomicrite or muddy limestone) and below the lowest continuous coarse-grained fossiliferous limestone (pelmatozoan packstone to grainstone) of the lower Wahoo Limestone member (see below) that typically forms a cliff. This mappable boundary is based on lithologic and weathering characteristics and is independent of biostratigraphy and age interpretations (Fig. 1-13). At the type locality and other southerly localities (locs. 12, 13, 22 & 25, Fig. 1-12), the Alapah-Wahoo contact is more gradational, with the upper part of the upper Alapah being a transitional unit having characteristics of both formations, being composed of alternating fossiliferous limestones and dark, fine-grained limestone and dolostone. This transitional unit is interpreted to be a seaward lateral equivalent of restricted-platform carbonates of the upper Alapah.

Unfortunately, the boundary between the Alapah and the Wahoo limestones was not defined consistently in previous publications, as illustrated at an important reference section in the eastern Sadlerochit Mountains (Fig. 1-14). We agree with Armstrong (1972) and Wood and Armstrong (1975) who placed the boundary at the base of the cliff-forming, skeletal limestone unit (our lower Wahoo, see below). In other publications (Armstrong and Mamet, 1975, 1977), the Alapah-Wahoo contact is placed at the Mississippian-Pennsylvanian boundary as determined by foraminiferan biostratigraphy (columns 2 & 3, Fig. 1-14). At this reference section, the Mississippian-Pennsylvanian boundary (as determined by both conodont and foraminiferan biostratigraphy) occurs within the continuous cliff of the lower

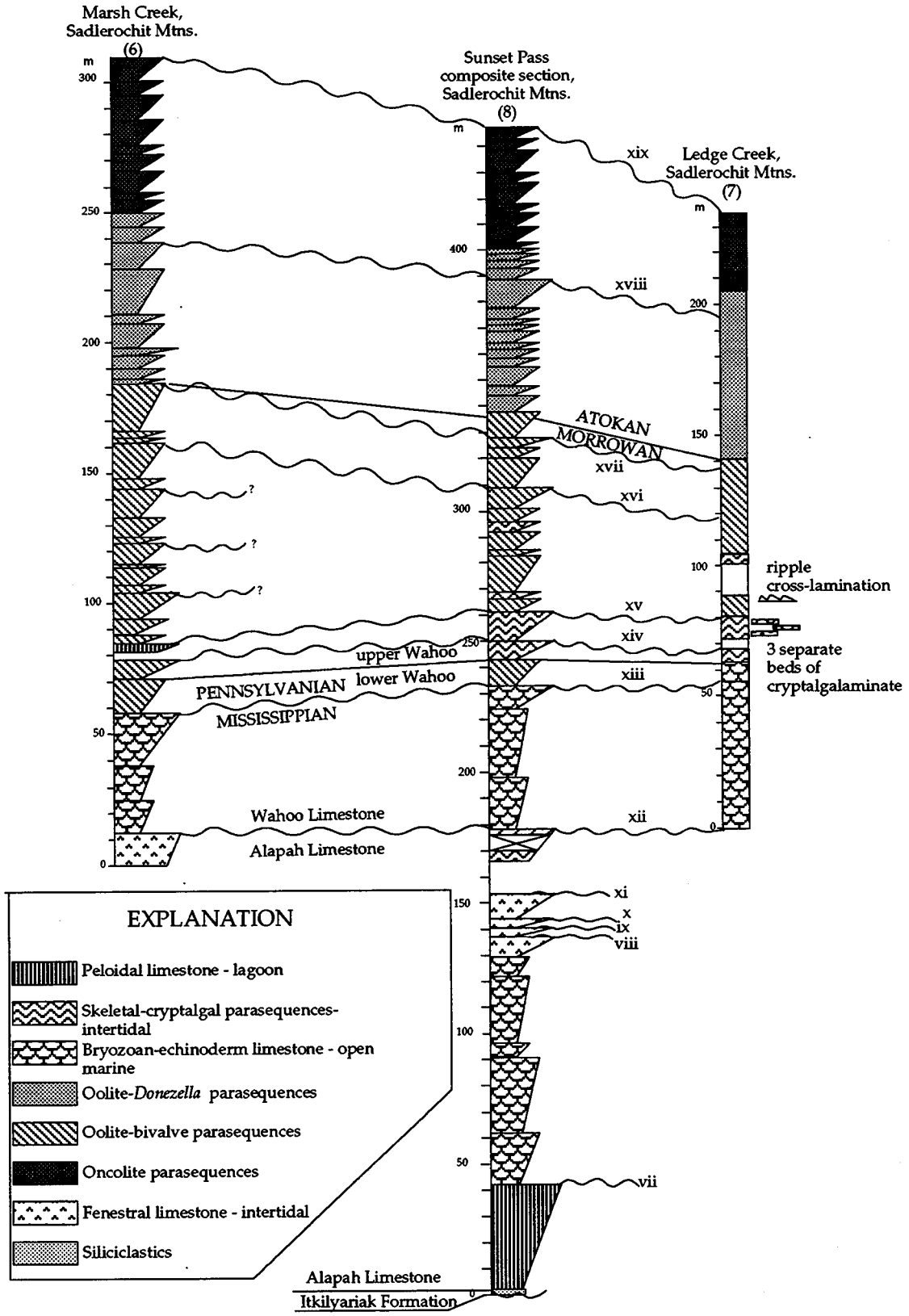


Figure 1-11. Stratigraphic correlation diagram for three sections measured in the northeastern Sadlerochit Mountains shows the subunits of the upper Wahoo that are exposed adjacent to the coastal plain of ANWR (locs. 6-8, Fig. 1-2, modified from Carlson, 1987).

Figure 1-12

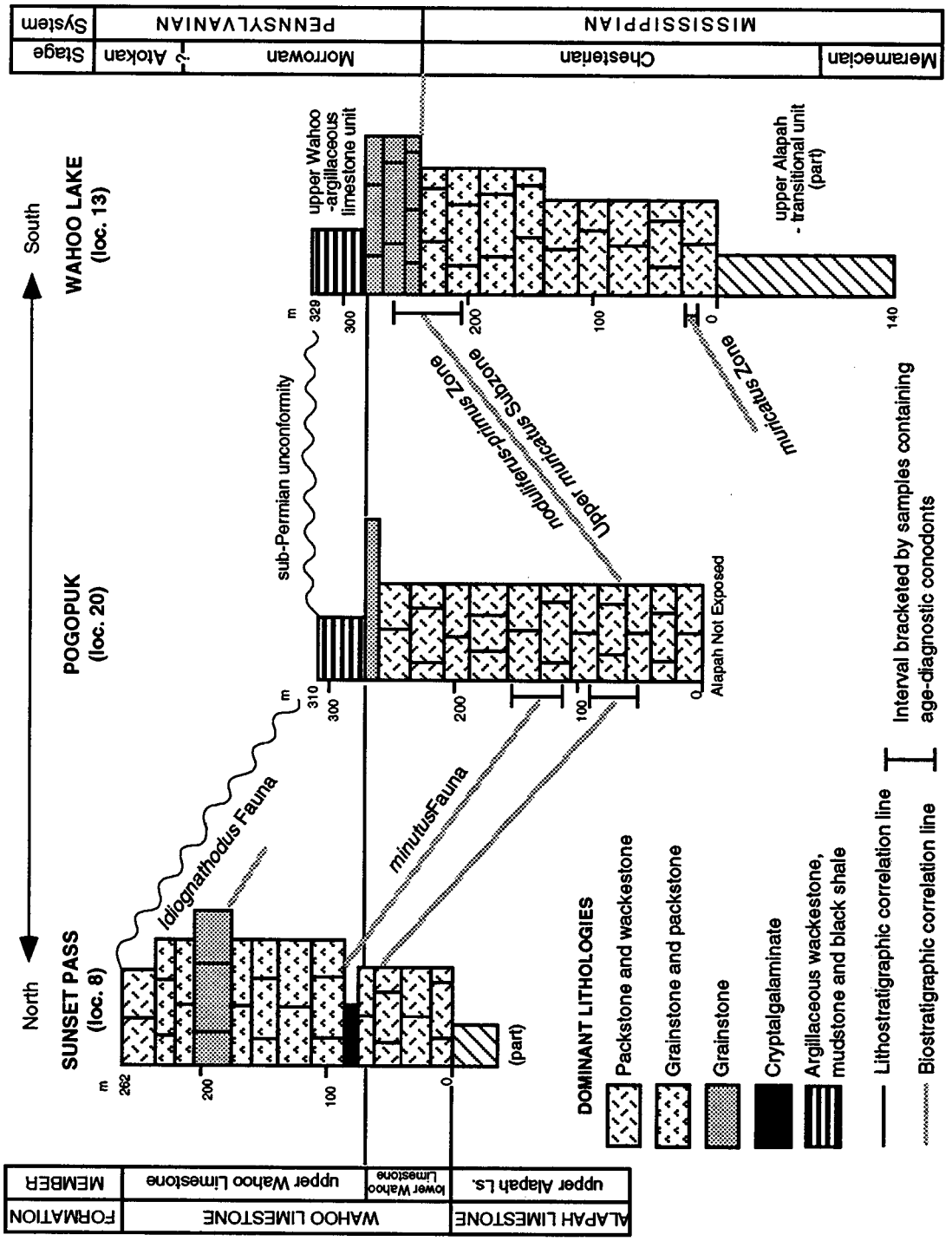


Figure 1-12. Preliminary stratigraphic correlation diagram compares the Wahoo Limestone of northern ANWR (Sunset Pass) with a section near the Wahoo type locality (loc. 13, Fig. 1-2)). The thin dark limestone unit of the upper-Wahoo at the type locality and Pogopuk Creek section (loc. 20, Fig. 1-2) is different than the cyclical carbonates of the upper Wahoo member in northern ANWR (eastern Sadlerochit Mountains; loc. 8, Figs. 1-2 and 1-11).

Wahoo Limestone and lacks any mappable lithologic or topographic expression (Fig. 1-13c; see below, discussions on the lower Wahoo Limestone and in Chapter 2; Krumhardt, 1991). Our definition of the boundary is more consistent with the original definition of the Wahoo Limestone (Brosgé et al., 1962) and corresponds to a mappable and significant change in lithology (Fig. 1-13).

At the top of the Alapah Limestone in the north (locs. 4 & 9, Fig. 1-2), a zone of recrystallized limestone occurs immediately below the contact. In other northern areas (locs. 8 & 10, Fig. 1-2), cavernous porosity (up to 10 meters across) filled with large calcite crystals along this contact indicates dissolution. Conodonts from the uppermost Alapah in the Sadlerochit Mountains are much more recrystallized and bleached than those in the adjacent Wahoo, suggesting that uppermost Alapah was a conduit for hydrothermal solutions. In the Shublik Mountains, blocks (up to 6 meters across) of lower Wahoo have collapsed into these caverns, indicating later post-Wahoo dissolution. Farther to the south (locs. 12 & 13, Fig. 1-2), the Alapah-Wahoo contact is gradational and difficult to locate precisely. Interestingly, cave sediments and speleothem cements fill cavernous porosity in the transitional unit of the upper Alapah near Wahoo Lake (loc. 25, Fig. 1-2).

WAHOO LIMESTONE

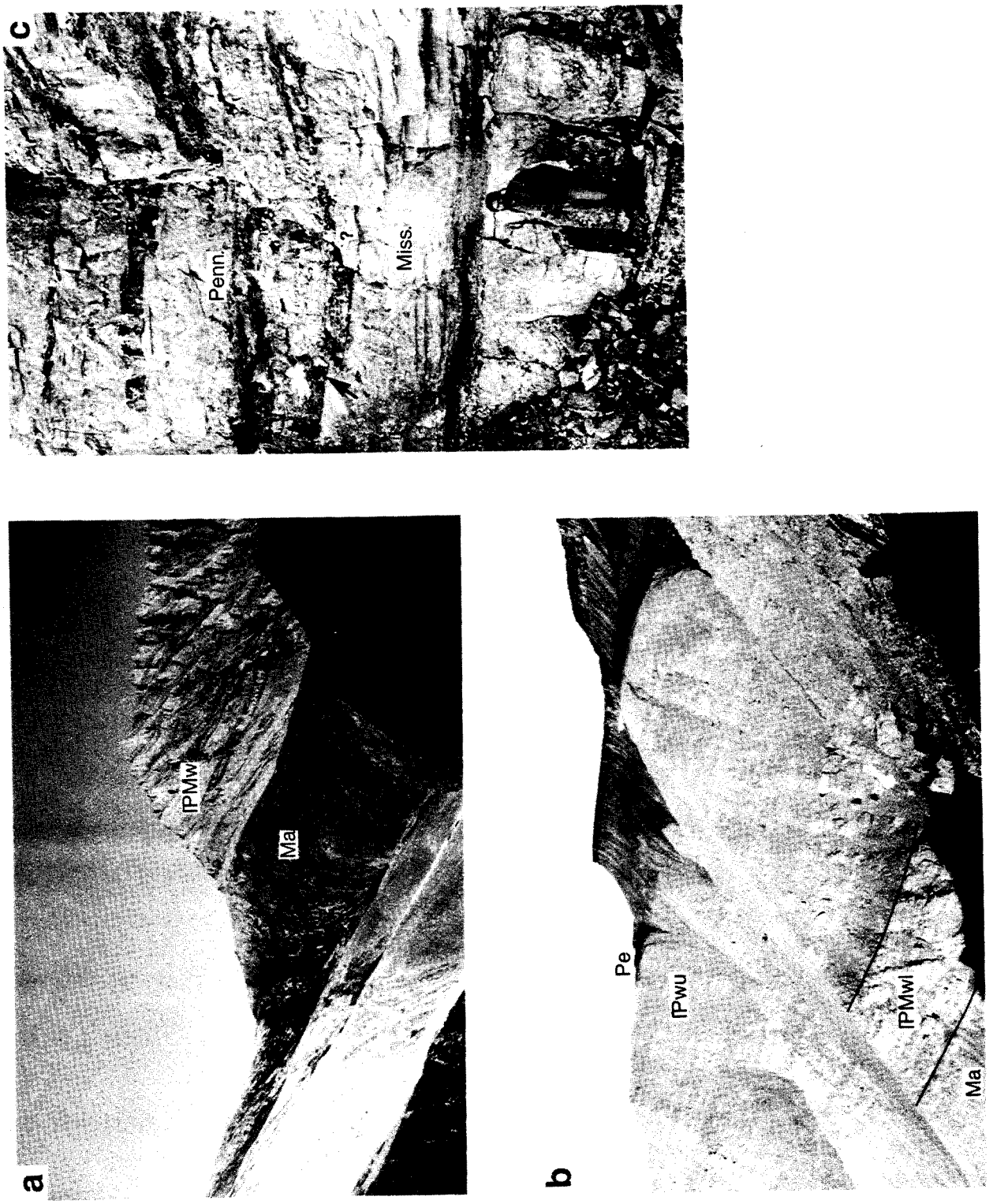
The Wahoo Limestone (0 to >330 meters in thickness) overlies the Alapah Limestone and is composed primarily of limestone with lesser dolomite and very minor intervals of shale and siltstone. At the type locality near Wahoo Lake, the Wahoo Limestone is a thick (330 meters) interval of light-weathering, cliff-forming, fossiliferous limestone that overlies the darker weathering Alapah Limestone (Fig. 1-13; Watts et al., 1989). The Wahoo ranges in age from Mississippian (Chesterian) to Pennsylvanian (late Morrowan to Atokan) rather than the original Pennsylvanian (?) and Permian age assignment of Brosgé and others (1962). The youngest bona fide Wahoo at the type locality is late Morrowan to early Atokan in age (Fig. 1-12; Armstrong et al., 1970; Watts et al., 1992). Watts et al. (1989) reassigned the calcareous beds of Permian age to the Echooka Formation in their redefinition of the upper member of the Wahoo.

In northern ANWR, the Wahoo Limestone can be subdivided informally into lower and upper members (Fig. 1-4). The Mississippian and Pennsylvanian lower member of the Wahoo Limestone is composed of massive, cliff-forming, fossiliferous limestone. The Pennsylvanian upper member of the Wahoo Limestone is characterized by ledge-and-slope topography resulting from differential weathering of small-scale carbonate cycles (parasequences; Figs. 1-4 & 1-6). The type section of the Wahoo most closely resembles the cliff-forming, fossiliferous, limestones of the lower Wahoo member (Watts et al., 1989). Problems in the definition of the Alapah-Wahoo boundary and age-dating for the lower Wahoo Limestone may be due, in part, to lateral facies changes in the unit. The cyclic carbonates of the upper Wahoo in northern localities (locs. 1-12, Figs. 1-2 & 1-12)

Figure 1-13. Outcrop photographs of the lower Wahoo Limestone.

A - The Wahoo Limestone (ℙMw) exposed near the type section is a very thick, light-colored, cliff-forming unit which overlies the dark-colored, slope-forming Alapah Limestone (Ma; near locality 13, Figs. 1-2 & 1-12).
B - In the eastern Sadlerochit Mountains, the lower member of the Wahoo Limestone (ℙMwl) is similar to rocks comprising the type Wahoo Limestone, forming a light-colored cliff above the slope-forming Alapah Limestone (Ma). The upper member of the Wahoo Limestone (ℙwu) in the Sadlerochit Mountains is quite different from any rocks in the type section of the Wahoo Limestone, being a thick succession of cyclic carbonates that has a characteristic ledge-and-slope topography. The dark-colored Echooka Formation (Pe) unconformably overlies the Wahoo Limestone (loc. 8, Figs. 1-2, 1-11, & 1-12).
C - The Pennsylvanian-Mississippian boundary occurs within the lower member of the Wahoo Limestone in the eastern Sadlerochit Mountains. Note the erosional scour (arrow) beneath a distinctive marker bed formed by recessive-weathering bryozoan packstone with abundant chert nodules (55 meters above base of Wahoo Limestone at section AK22M; loc. 8, Figs. 1-2, 1-11, 1-12, & 1-14). The ? beneath the chert interval indicates the position of a sample containing possible Pennsylvanian conodonts but the lowest definitive Pennsylvanian conodonts (Penn.) occur above the chert interval.

Figure 1-13



differ from the upper part of the Wahoo at the type section due to seaward lateral facies changes (Watts et al., 1989, see below).

lower Wahoo Limestone

The lower Wahoo Limestone forms a distinct cliff of light-colored limestone above the dark, slope-forming upper Alapah Limestone (Fig. 1-13a & b). The lower Wahoo is composed of mostly thick- to very thick-bedded, light- to medium-gray, bryozoan-pelmatozoan limestone with rare intervals of oolitic grainstone and peloidal-skeletal packstone in the upper part. The basal lower Wahoo contains peloids and spicules along with other skeletal grains. The lower Wahoo is cyclic containing four to five parasequences which can be correlated throughout the study area. However, variations in lithology in these parasequences are subtle and best defined by microfacies analysis.

The upper contact of the lower Wahoo Limestone member is located at the top of the cliff formed by the lower Wahoo and is marked by a transition into the ledge-and-slope topography of the upper Wahoo Limestone. In northern ANWR (locs. 1-10, Fig. 1-2), this contact is sharp, but farther to the south (locs. 11 & 12, Figs. 1-2 & 1-7), the contact is gradational (Gruzlovic, 1991). The first occurrence of orangish- to greenish-weathering, dolomitic-bryozoan wackestone to packstone of the upper Wahoo also is used to distinguish this boundary. In the eastern Sadlerochit Mountains (locs. 6-8, Fig. 1-2 & 1-11), the contact between the lower and upper members of the Wahoo Limestone appears to be planar, but locally has possible erosional relief (Carlson, 1987). Interestingly, redeposited conodonts of Late Mississippian age occur below and immediately above this contact, indicating erosion and the reworking of Upper Mississippian sediments during earliest Pennsylvanian time (loc. 8, Fig. 1-2 & 1-14). However, no unconformity is apparent based on conodont biostratigraphy; the *noduliferus-primus* Zone spans the lower-upper Wahoo boundary (see Chapter 2). At the Fourth Range (loc. 11, Fig. 1-2 & 1-7), a possible unconformity in the upper part of the lower Wahoo is indicated by conodonts of late Morrowan to early Atokan age that directly overlie rocks of the latest Chesterian age (*R. minutus* Fauna above the Upper *R. muricatus* Subzone, see Chapter 2 and 6).

The lower Wahoo varies in thickness from 60 meters in the north to more than 100 meters in the south (locs. 9 & 12, Fig. 1-2). Thick relatively massive limestones of the lower Wahoo comprise up to 281 meters of the type Wahoo, and are underlain by at least 140 meters of the transitional unit of the upper Alapah and overlain by 48 meters of a localized thin-bedded dark argillaceous limestone unit of the upper Wahoo (loc. 13, Fig. 1-2).

The lower Wahoo Limestone is of Mississippian and Pennsylvanian age on the basis of foraminiferan and conodont biostratigraphy. The position of the Mississippian-Pennsylvanian boundary as determined by foraminiferan biostratigraphy has been reported inconsistently by previous workers, as illustrated by an important reference section in the eastern Sadlerochit Mountains (loc. 8, Fig.

1-2 & 1-14). Previous studies indicate that the lower Wahoo Limestone is Chesterian in age (Zones 18 & 19) and may range into the Morrowan (Mamet Zone 20; Armstrong, 1972; Armstrong and Mamet, 1975, 1977; P. Brenckle, pers. comm., 1990). The precise position of the Mississippian-Pennsylvanian boundary in previous studies is unclear because of an interval lacking diagnostic foraminifers below the first occurrence of definitive Morrowan foraminifers (Carlson, 1987). However, our samples indicate that the age-diagnostic foraminifer for Zone 20, *Globivalvulina bulloides*, appears within the lower Wahoo (Fig. 1-14). The conodont biostratigraphy of this reference section indicates that the Mississippian-Pennsylvanian boundary lies 15 meters below the contact between the lower Wahoo Limestone and the upper Wahoo Limestone (Fig. 1-14; Krumhardt and Harris, 1990; see Chapter 2). The Mississippian-Pennsylvanian boundary occurs 55 meters above the base of the lower Wahoo Limestone member at the base of a distinct interval of peloidal-skeletal wackestone with reddish-brown, nodular, replacement chert. Just above the chert interval, a peloidal-skeletal grainstone contains the lowest definitive Pennsylvanian conodonts in the study section. Immediately beneath the chert interval, a skeletal grainstone contains possible Pennsylvanian conodonts. Definitive Mississippian conodonts were identified 50 centimeters lower. The uppermost Mississippian limestones are latest Chesterian in age (Upper *muricatus* Subzone; see Chapter 2). Although conodonts do not indicate any appreciable time gap, minor paleotopography (0.5 to 1 meter) is evident beneath the chert interval and diagenetic features suggest subaerial exposure along this surface (see Chapter 3).

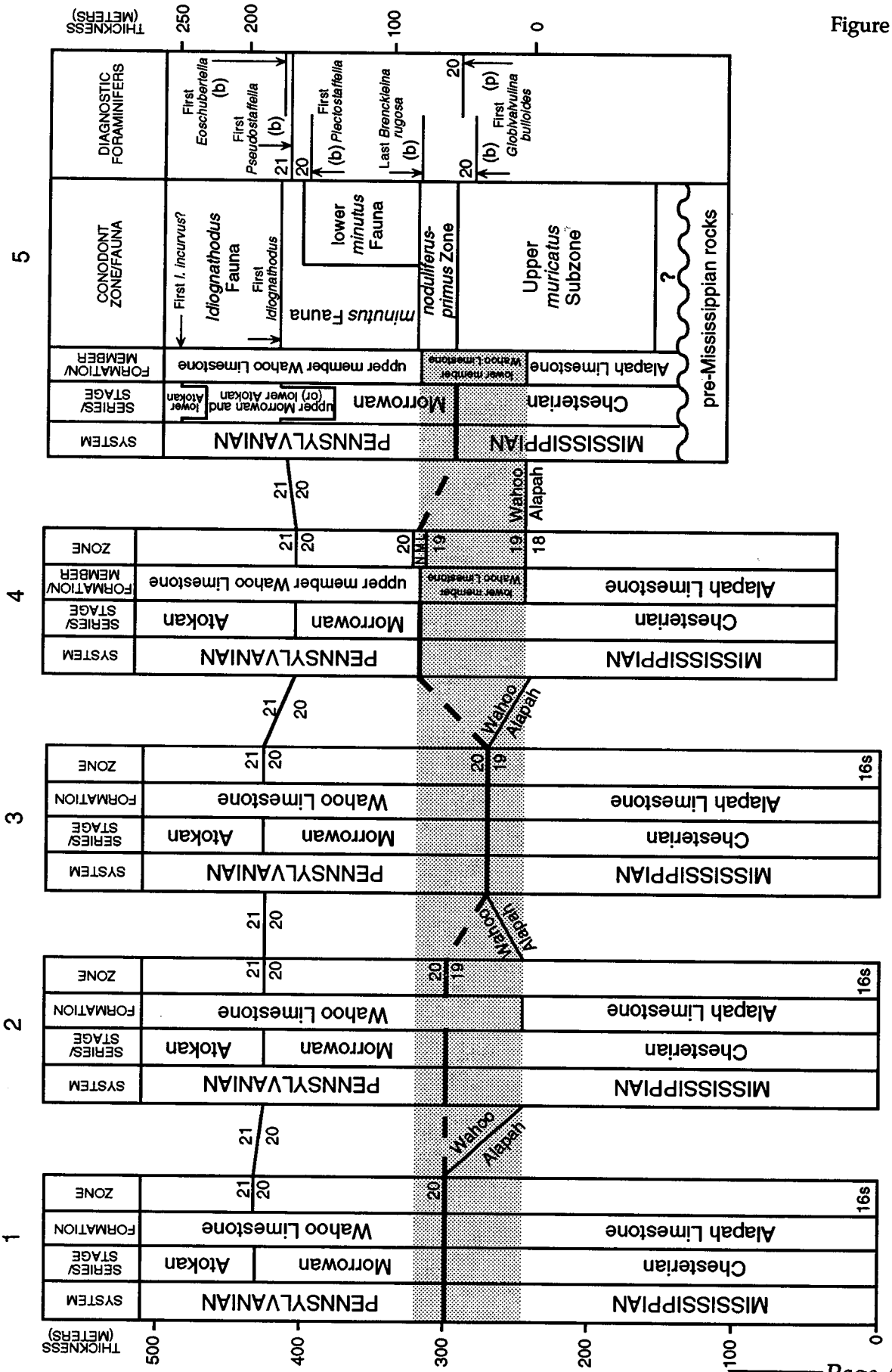
upper Wahoo Limestone

The informal upper member of the Wahoo Limestone is composed of mostly yellowish-, brown- and gray-weathering, medium- to thick-bedded limestone with minor intervals of yellow- to orange-weathering dolomite and dark-gray- to olive-weathering shale. Parasequences (small-scale carbonate cycles) are common throughout the upper Wahoo and are characterized by slope-forming shales, spiculitic dolomites, and muddy, dolomitic, skeletal limestones alternating with ledge-forming, skeletal and oolitic grainstones. These parasequences are similar to those in reservoir rocks in the Lisburne oil field at Prudhoe Bay (Fig. 1-4; Okland et al., 1987; Carlson, 1987; Carlson and Watts, 1987; Kaldi et al., 1990; Jameson, 1990b, in revision; see below and Chapter 4).

The boundary between the informal lower and upper members of the Wahoo is placed between the resistant, gray-weathering limestones of the lower Wahoo and the slope-forming, yellow- to orange-weathering dolomite and highly dolomitic limestones of the upper Wahoo (Figs. 1-12 & 1-13b). In the eastern Sadlerochit Mountains (loc. 1-6 to 1-8, Fig. 1-2 & 12-11), the basal upper Wahoo Limestone contains quartz silt and fine sand and local cryptalgal laminate that signify deposition in restricted to intertidal environments near a source of terrigenous sediment (Fig. 1-4). This represents the maximum regression in the Wahoo and corresponds to a sequence boundary (see below). Most of the upper Wahoo represents a major transgressive-regressive succession (depositional sequence) with

Figure 1-14. Comparison of lithostratigraphic, biostratigraphic, and time-rock boundaries between section 8 and the nearby "Sunset Pass" section analyzed in previous reports shows inconsistencies in stratigraphic nomenclature and age determinations for the Wahoo Limestone. Prior to Carlson (1987; column 4), all interpretations for the Sunset Pass section were based on one composite section (Armstrong et al., 1970, sections 68A-4A, 4B); Carlson's section is along the same traverse. The Alapah Limestone-Wahoo Limestone boundary is at the same stratigraphic level in columns 2, 4, and 5 but differs from columns 1 and 3. Foraminiferan zonal boundaries in columns 1-4 were determined by B.L. Mamet; foraminiferan data for column 5 are from P.L. Brenckle (b) and Sylvie Pinard (p). In column 5, the first occurrence of the diagnostic foraminifer that approximates the base of the Pennsylvanian, *Globivalvulina bulloides*, is at least 12 meters below the first *Declinognathodus noduliferus*, the conodont species that marks the base of the Pennsylvanian. P.L. Brenckle also noted the last occurrence of *Brenckleina rugosa* well above its known range in the conterminous United States (at or very slightly above the base of the Pennsylvanian). The Morrowan-Atokan boundary is poorly constrained by conodonts. The foraminifer *Pseudostaffella* sp. is used to approximate this boundary in the Midcontinent and Cordillera of the conterminous United States (Lane and Manger, 1985; Groves, 1986). In the study section it appears 14 meters above the lowest occurrence of its plectostaffellid ancestor and 75 meters below the first definitive Atokan conodont. Column 1 is from Armstrong et al. (1970) and Armstrong and Mamet (1977); column 2 from Armstrong (1972; 1974) and Wood and Armstrong (1975); column 3 from Armstrong and Mamet (1975) and Mamet and Armstrong (1984); column 4 from Carlson (1987); column 5 from Krumhardt et al. (in press)-thickness measured from base of Wahoo Limestone. Heavy dashed line shows relative position of Mississippian-Pennsylvanian boundary for the various studies. NML refers to "No Man's Land" (an interval lacking age-diagnostic foraminifers) as used by B.L. Mamet in Carlson (1987) and Gruzlovic (1991). Shading indicates the position of the lower Wahoo Limestone as defined in this report and by Krumhardt (1992).

Figure 1-14


THICKNESS (METERS)
500
400
300
200
100
0
1
2
3
4
5
SYSTEM
SERIES/ STAGE
FORMATION
ZONE
PENNSYLVANIAN
MISSISSIPPIAN
Morrowan
Atokan
Chesterian
Wahoo Limestone
Alapah Limestone
upper member Wahoo Limestone
lower member Wahoo Limestone
upper Morrowan and (or) lower Atokan
lower Atokan
16s
Wahoo
Alapah
NML
CONODONT ZONE/FAUNA
DIAGNOSTIC FORAMINIFERS
First I. incurvus?
Idiognathodus Fauna
First Idiognathodus
minutus Fauna
lower minutus Fauna
nodulifer-us-primus Zone
Upper muricatus Subzone
pre-Mississippian rocks
First Eoschubertella (b)
First Pseudostaffella (b)
First Plectostaffella (b)
Last Brenckleina rugosa (b)
First Globivalvulina bulloides (b)
(p)

the deepest water facies in the middle part of the unit. Numerous small-scale parasequences are superimposed on this large-scale transgressive-regressive succession (Fig. 1-4).

The age of the upper Wahoo in ANWR is Early to Middle Pennsylvanian (Morrowan - Atokan), as indicated by the presence of the foraminifers *Globivalvulina bulloides* and *Psuedostaffella* (first appearances mark the base of the Morrowan and Atokan respectively; Zones 20-21, Paul Brenckle, personal communication, 1987). Our biostratigraphic zonation using conodonts (see Chapter 2) indicates ages of early Morrowan (*noduliferus-primus* Zone), Morrowan (*R. minutus* Fauna), and late Morrowan to early Atokan (*Idiognathodus* Fauna). The age of the uppermost Wahoo is controlled by depth of erosion beneath the Echooka Formation and is youngest (Atokan) in northern ANWR and generally older (Morrowan and Chesterian) to the south and west (Watts et al., 1992). A slightly thicker and younger Atokan-age succession occurs at Prudhoe Bay (Armstrong and Mamet, 1974; Stanulonis and Tran, 1992; Jameson, 1990a, 1990bin revision).

A disconformity separates the Lisburne Group from the overlying Echooka Formation of Permian age. Regionally, this disconformity is an irregular surface with significant erosional relief (Crowder, 1990; Watts, 1992). The contact between the Lisburne and Echooka is typically planar; carbonate rocks of the Lisburne are overlain by terrigenous siltstone, shale, and/or glauconitic quartzose sandstone of the Echooka (Crowder, 1990). Less commonly, erosional relief is apparent beneath channel-fill conglomerates in the basal Echooka. Clasts in the conglomerates include limestone and chert derived from the Lisburne. Even though the Lisburne platform was exposed subaerially, karst features are uncommon (Crowder, 1990; Carlson, 1990; Watts, 1991, 1992). Erosion along the disconformity produced significant variations in thickness and age of the uppermost Wahoo. The upper Wahoo Limestone is most complete in the eastern Sadlerochit Mountains where erosion beneath the post-Lisburne unconformity was least (locs. 6-8, Fig. 1-2 & 1-11). The entire Wahoo here is not as thick as at the type section (262 meters versus 330 meters in thickness), but the Pennsylvanian (Morrowan to early Atokan) part of the section is thicker (207 meters versus ~180 meters). In some areas, such as west of the Trans-Alaska Pipeline (Fig. 1-1), the Pennsylvanian part of the Lisburne entirely absent but may not have been deposited (Armstrong and Mamet, 1978; Watts et al., 1992).

The upper Wahoo Limestone can be subdivided into parasequences based on carbonate microfacies analyses and interpretations of paleoenvironments and associated changes in water depth. The boundaries between parasequences correspond to abrupt changes in lithology, whereas vertical facies changes within the parasequences typically are gradational. Most commonly, the parasequence boundary is defined as a marine flooding surface where deeper-water deposits sharply overlie shallower water deposits. Parasequences having similar characteristics are grouped into parasequence sets that can be related to their position within the overall transgressive-regressive succession of the upper Wahoo. The

nature of the parasequences and parasequence sets varies depending on location on the Lisburne carbonate platform.

Because definition of parasequences is based on paleoenvironmental interpretations and consideration of depositional history, we will discuss the criteria used to make paleoenvironmental interpretations before describing and interpreting the sequence and parasequence stratigraphy of the Wahoo. To better understand the relationships between different depositional environments and their response to sea-level fluctuations, we will first consider the geometry of carbonate platforms and how platform geometry evolved throughout the deposition of the Lisburne Group.

CARBONATE PLATFORM GEOMETRY OF THE LISBURNE GROUP OF ANWR

The geometry of carbonate platforms varies depending on tectonic setting, climate, the nature of organic buildups and other factors (Read, 1982, 1985). A **carbonate shelf** is a relatively flat-topped carbonate platform, typically with rimmed margins formed by reefs or some other barrier bounded by slopes that drop relatively steeply into deeper water. A **carbonate ramp** slopes gently (<1 °) seaward into progressively deeper water without a break in slope. In this report, **carbonate platform** is used a general term for extensive shallow-water areas that were created by carbonate-producing organisms, and includes both carbonate shelves and ramps (c.f. Read, 1982, 1985). A knowledge of platform geometry provides a conceptual basis for understanding the distribution of different carbonate facies and associated paleoenvironments that are discussed in the next section of this report.

A carbonate shelf has extensive shallow subtidal areas that may be either an open platform with normal-marine conditions (salinity, oxygenation, nutrients, etc.) or a restricted platform with poor circulation leading to harsh environmental conditions. Usually, a shelf will have a rim created by framework reef-building organisms such as corals or the shelf edge may be marked by shoals that may create a barrier to circulation. The shelf edge is a declivity that drops steeply into deeper water and can be formed by the growth of a shelf-edge reef and/or have a structural underpinning caused by basin-margin faults. The shelf margin has narrow facies belts such as the sub-environments of a reef. Depending on the steepness of the slope, a slope apron or base-of slope debris apron will contain sediment derived from the carbonate platform and/or eroded from the slope and transported by sediment gravity flows (i.e., turbidity currents, debris flows and slumps).

A carbonate ramp is more similar to a clastic shelf, having a gradual slope from the shoreline or shoals into progressively deeper water. A homoclinal ramp has a relatively constant slope on the order of one to a few meters per kilometer and lacks significant slumps, slope breccias, and turbidites (Read, 1982). Carbonate ramps can be divided into: 1) a shallow-water, nearshore, inner ramp with ooid, skeletal, or pellet sand shoal belts, or 2) an offshore, outer ramp having deeper-water skeletal limestones followed seaward by pelagic and hemipelagic basinal deposits (Ahr, 1973;

Read, 1982). Carbonate ramps build away from positive areas down gentle regional paleoslopes, and lithofacies belts tend to be wide and irregular (Wilson, 1975). A homoclinal ramp lacks a break in slope, whereas a distally steepened ramp has a break in slope in deep-water environments that are seaward of areas of shallow-marine carbonate production. Facies belts on a carbonate ramp are very broad and show gradual facies changes from high-energy shoal deposits, to moderate-energy grainy carbonates deposited above wave base, to low-energy muddy carbonates that formed below wave base, and finally, deeper-water argillaceous mud that accumulated outboard of zones of maximum carbonate production. The shoals may form a fringe connected to land or they can develop as offshore barriers separated from the land by a lagoon (Read et al., 1985). Depending on its size and amount of the water circulation, the area behind the shoals can be an open platform with normal-marine conditions or a restricted platform (lagoon) having poor water circulation and inhospitable conditions (e.g. abnormal salinity).

In Carboniferous time, a lack of frame-building organisms prevented the formation of wave-resistant reefs, so most carbonate platforms of this age have a ramp geometry (James, 1983). Thus, most of the Lisburne Group formed on a south-facing carbonate ramp. Three phases in the evolution of the Lisburne carbonate platform are outlined below.

UPPER KAYAK AND LOWER ALAPAH—RAMP TO IRREGULAR SHELF(?)

Overall, the transition from terrigenous sediments of the upper Kayak Shale into carbonates of the lower Alapah Limestone member represents part of a large-scale, transgressive systems tract. In northern ANWR, the geometry of the carbonate platform most resembles a southward-sloping homoclinal ramp (Fig. 1-15b). Facies relationships within well-developed parasequences in the lower Alapah and upper Kayak are interpreted to represent intertidal and restricted-platform environments bounded by landward marginal marine siliciclastic environments and a seaward carbonate shoal complex. The shoal deposits occupy a wide belt and pass southward into extensive open-marine limestones. Variations in nature of the basal Alapah carbonates indicate that paleotopography along the sub-Mississippian unconformity were an important control on depositional patterns. In southern ANWR, the Kayak to Alapah transition alternates between limestone and shale that indicate earlier onlap and establishment of open-marine carbonates on the outer part of the ramp.

With continued transgression, the cross-bedded, skeletal grainstone shoals migrated northward, and open-marine deposits of bryozoan-pelmatozoan limestones of the middle Alapah Limestone member formed on an irregular depositional paleotopography lying mostly below wave base, with some localized shallow areas above wave base (Fig. 1-15b). A gradational transition into restricted-platform deposits of the upper Alapah indicates that a moderately effective circulation barrier developed, resulting in partially restricted-platform deposits in the upper part of the middle Alapah member (see below). Thickness variations in the middle and lower Alapah suggest that pre-existing paleotopography and

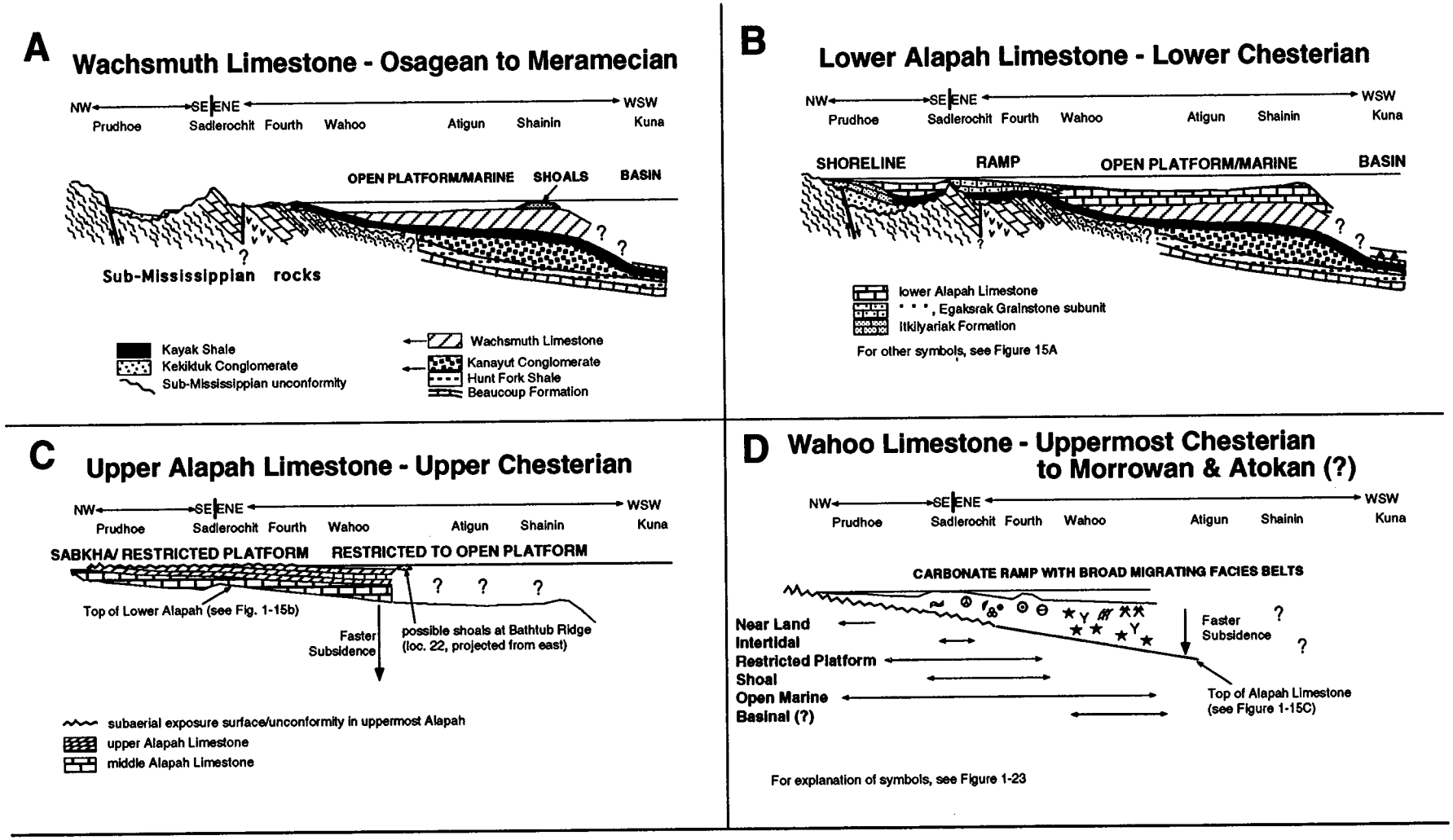


Figure 1-15. Generalized evolution of carbonate platform geometries of the Lisburne Group:
A - Initial onlap of the Lisburne Group onto an irregular paleotopography.
B - Infilling of irregularities and expansion to become a very broad carbonate platfrom with a shoal-dominated carbonate ramp in the north.
C - Exposure of the northern part of the Alapah Limestone platform with the development of an unconformity at Prudhoe, widespread subaerial exposure surfaces in northern ANWR, and a partially restricted platform in southern ANWR.
D - The Wahoo Limestone carbonate ramp developed above the pre-existing Alapah platform that continued to subside more rapidly to the south.

differential subsidence (associated with tectonic movements?) may have influenced depositional patterns (Fig. 1-15a & b).

UPPER ALAPAH LIMESTONE—EXTENSIVE RAMP OR SHELF (?)

During the deposition of the upper Alapah Limestone member, a broad, very shallow low-relief carbonate platform extended across much of northern Alaska (Fig. 1-15c). In the north, restricted-platform to intertidal conditions indicate very shallow conditions on the landward side of this platform. The intertidal deposits and four subaerial exposure surfaces indicate that the upper Alapah formed during the maximum regression within the Lisburne Group. Farther south, slightly deeper water and better water circulation on this broad platform allowed a more normal-marine fauna (bryozoans and pelmatozoans) to develop in muddy carbonates of the transitional unit of the upper Alapah. This represents the time of maximum development of the Lisburne carbonate platform that expanded to cover a previously more irregular paleotopography. This extensive carbonate platform with restricted-platform and intertidal deposits in the north could represent either: 1) a ramp with an extensive inner ramp in the north or 2) an extensive shallow-marine carbonate shelf with an extensive inner shelf in the north.

The progressive restriction of water circulation in the upper middle and upper Alapah may have resulted from the damping effect accompanying the expansion and aggradation of the carbonate platform. Alternatively or additionally, a barrier to water circulation, such as a shallow shoal or sill could have formed in the south. An uplifted sill on the outer part of the platform could have formed due to differential subsidence or tectonic uplift (e.g., block faulting). However, no shelf-edge shoals or evidence of steep carbonate slopes have yet been recognized in the upper Alapah, so the shelf interpretation is based on the inferred circulation barrier and on the expansiveness of muddy shallow-marine carbonates in the upper Alapah. In either case, the expansion of restricted-platform and intertidal environments across northern ANWR appears to be a consequence of a relative lowstand of sea level, associated with a sequence boundary in the upper Mississippian (upper Chesterian, see below).

WAHOO LIMESTONE—HOMOCLINAL RAMP

The more limited distribution of the Wahoo Limestone suggests that it formed a much smaller carbonate platform than the Alapah with a gently south-sloping homoclinal ramp geometry. The broad distribution of facies belts, particularly ooid shoal deposits, indicate deposition on a homoclinal ramp. Gradational vertical and lateral facies changes in parasequences of the Wahoo indicate deposition on a carbonate ramp having gradual changes in sediment characteristics, particularly in outer ramp deposits. Inner ramp deposits are more variable depending on position relative to ooid shoals. The absence of redeposited slope carbonates (turbidites, debris flow and slump deposits) indicates that the carbonate platform lacked a shelf edge and slope; it sloped gently (< 1°) into relatively deep water (Watts et al., 1989). The thickness of the Wahoo Limestone

generally increases to the south (Fig. 1-15d). This seaward increase in thickness means greater accommodation space was available and that carbonate sedimentation kept pace with increased subsidence toward the outer ramp, similar to other ancient, carbonate ramp successions (Wright, 1986; Calvet and Tucker, 1988). The abundance of grainstone and the general lack of carbonate mud in the Wahoo indicates that it formed on a high-energy carbonate ramp where wave agitation had a major effect on facies distribution (c.f. Osleger and Read, 1991).

MICROFACIES ASSEMBLAGES—DEPOSITIONAL ENVIRONMENTS

Carbonate sediments are created primarily through the growth of calcareous organisms and, to a lesser extent, by inorganic precipitation as ooids (Scoffin, 1987, Flügel, 1982). Unlike siliciclastic sediments that are transported into a sedimentary basin, carbonates are formed *in situ* on shallow-water carbonate platforms (James, 1984a). Carbonate sedimentation is favored in areas of warm, clear, shallow-marine waters (Wilson, 1975). The distribution of carbonate-producing organisms is controlled strongly by environmental parameters such as light, hydraulic energy, temperature, salinity, water depth, and depositional topography (Wilson, 1975; Jones and Desrochers, 1992). Because most carbonate sediments are deposited near their site of origin, their composition and texture hold clues that allow interpretation of depositional environments. Petrographic examination of limestones aimed at interpreting depositional environments is a widely used technique and is termed carbonate microfacies analysis (Wilson, 1975; Flügel, 1982). By understanding the vertical and lateral distribution of microfacies and their paleoenvironmental associations, the geometry and evolution of the Lisburne carbonate platform and its response to relative sea-level fluctuations can be interpreted.

Shallow-marine carbonates are sensitive indicators of relative sea-level fluctuations. Water depth is perhaps the most important single factor controlling the nature of carbonate sediments; it has a direct influence on hydraulic energy and penetration of light. Organic carbonate production is controlled largely by water depth and has been shown to be greatest in very shallow water with significant decreases at depths greater than 15 meters (Schlager, 1981). Shallow, warm water favors the precipitation of carbonate, and light is essential for calcareous algae, the base of the food chain and a major producer of carbonate sediment. Modern carbonate sediment production rates are highest in ooid shoal or reef environments (Enos, 1977; Schlager, 1981). In deeper and/or cooler water, fewer carbonate-producing organisms can thrive, so rates of carbonate production are much slower (Kendall and Schlager, 1981). The carbonate platform system has been likened to a "carbonate factory," where calcareous organisms are able to produce huge amounts of sediment and to maintain their position near sea level (James, 1984a; Jones and Desrochers, 1992). However, carbonate-producing organisms are sensitive to inhospitable environmental conditions which can result in reduced sedimentation rates. For example, if carbonate production is unable to keep up with a relative rise in sea level, carbonate production rates drop and platforms might be drowned in

relatively deep water. Alternatively, if carbonate platforms are subaerially exposed due to a relative drop in sea level, carbonate production will generally cease and fresh-water diagenesis can lead to cementation and/or dissolution of previously deposited carbonates. Following shut-down of the carbonate factory, re-establishment of carbonate sedimentation can be difficult, requiring time to "start-up" and "catch up" with a relative sea level rise (Read et al, 1986).

The texture of carbonate sediments is their primary basis for classification (Dunham, 1962). The amount of mud may be related to the hydraulic energy of the environment, the types of organisms in the environment, and/or the affects of bioturbation. Because carbonates form within or near their site of deposition, the texture of carbonate sediments is most strongly affected by currents of removal rather than transport, particularly in shallow water affected by wave agitation (James, 1984a; Scoffin, 1987). Where waves or currents winnow away the lime mud, relatively well-sorted grainy sediments are termed grainstones. The amount of mud and degree of abrasion and sorting can be a measures of hydraulic energy. Very well-sorted grainstones also may show the effects of grain abrasion and rounding, particularly in high-energy shoal environments. Limestones having intergranular lime mud were deposited in moderate- to low-energy environments and include packstone, wackestone, and mudstone. Packstone contains intergranular mud and may grade into poorly sorted grainstone; both are grain-supported limestones. Preservation of delicate fossils such as fenestrate bryozoans characterize low-energy environments. Fenestrate bryozoans and some algae that remain intact and in growth position are termed bafflestones and helped to stabilize muddy carbonates (Embry and Klovan, 1971). Other limestones held together by fossils in growth position include cryptalgalaminate (bindstone) and rare coralline boundstone.

The composition of carbonate sediments derives from the types of carbonate material that formed within or were transported into a depositional environment. Most carbonate grains are the skeletal hard parts of organisms, peloids, ooids, or intraclasts (or limeclasts). The composition of skeletal grains is determined by the paleoecology of the organisms. Some organisms, such as pelmatozoans (crinoids and other similar echinoderms) require normal-marine conditions, and are major carbonate producers that dominate certain lithologies. Other organisms, such a spicular sponges, are most abundant in harsh paleoenvironments (e.g., restricted-platform or deep-marine conditions) that exclude less adaptable organisms, perhaps due to abnormal salinity or reduced availability of oxygen (Armstrong, 1974). The evolution and interaction of organisms with their environment also can play a role in the distribution of calcareous organisms. Peloids include fecal pellets and other micritic grains and are most abundant in restricted-platform conditions (Enos, 1983). Ooids are concentrically laminated, inorganically precipitated grains that form in high-energy wave- or current-agitated shoals. Intraclasts are typically rip-up clasts derived from erosion of early lithified contemporaneously deposited carbonate sediment, whereas the term limeclast indicates that it is uncertain if grains are reworked from the coeval carbonate platform or if they were eroded from older limestones. Lime mud (micrite) is derived mostly from calcareous organisms such

as algae. Cement (spar) is a later diagenetic component. Microfacies analysis involves understanding the paleoecology of calcareous organisms and their paleoenvironmental significance. In addition, sedimentological evidence must be used to determine if the carbonate sediment formed within a depositional environment or if it was redeposited by currents (such as storm deposits).

In summary, carbonate microfacies analysis permits the interpretation of depositional environments (James, 1984b). The criteria used in our interpretations of depositional environments are based on several widely accepted models (Wilson, 1975; Flügel, 1982; Scholle et al., 1983; James, 1984a&b; Jones and Desrochers, 1992). The Lisburne Group of ANWR formed in a variety of primarily shallow-marine carbonate platform environments including intertidal, restricted-platform, shoal, open-marine, open-platform, and possibly basinal conditions as indicated by characteristic microfacies and sedimentary structures summarized below.

TERRIGENOUS CLASTIC TO CARBONATE TRANSITION

The nature of transition between terrigenous clastic sedimentation and biogenic carbonate sedimentation can be quite variable depending on depositional setting, climate, and other factors. Influx of terrigenous sediments, particularly suspended mud, can inhibit carbonate production because turbidity reduces the light penetration necessary for algal growth and it can clog filter-feeding organisms (James, 1984a). Supply of terrigenous sediment also can overwhelm organic carbonate production. Rates of carbonate production also play an important role; a carbonate platform can produce huge volumes of sediment if it remains in shallow water where calcareous organisms can thrive. However, if the platform is unable to keep pace with subsidence and falls into deep water, condensed intervals of argillaceous limestone and shale may accumulate slowly.

A major clastic-carbonate transition occurs between sandstones and shales of the Endicott Group and carbonates of the Lisburne Group. The northward younging of the contact between these units indicates regional passive-margin subsidence and progressive onlap of a large-scale depositional sequence (Fig. 1-5). Paleotopography along the sub-Mississippian unconformity played a major role in controlling the nature of sedimentation in both the Endicott and the Lisburne Groups. On paleotopographic highs, the Lisburne Group either directly overlies sub-Mississippian rocks or localized sandy limestone of the Itkilyariak Formation interbedded with normal-marine limestone. In paleotopographic lows, black shale and argillaceous limestone of the Kayak Shale apparently formed in marginal-marine environments (Figs. 1-15 & 1-16). The influx of large amounts of mud and terrestrial organic matter derived from humid vegetated flood plains apparently resulted in anaerobic to dysaerobic conditions hostile for calcareous organisms (LePain, 1993). Argillaceous limestones interbedded with black shale record the pioneering attempts of calcareous organisms to become established in areas polluted by terrigenous mud and organic matter. In some areas (locs. 10 & 11, Figs. 1-2 & 1-7), associated spiculitic limestone indicates restricted-platform (lagoonal?) conditions

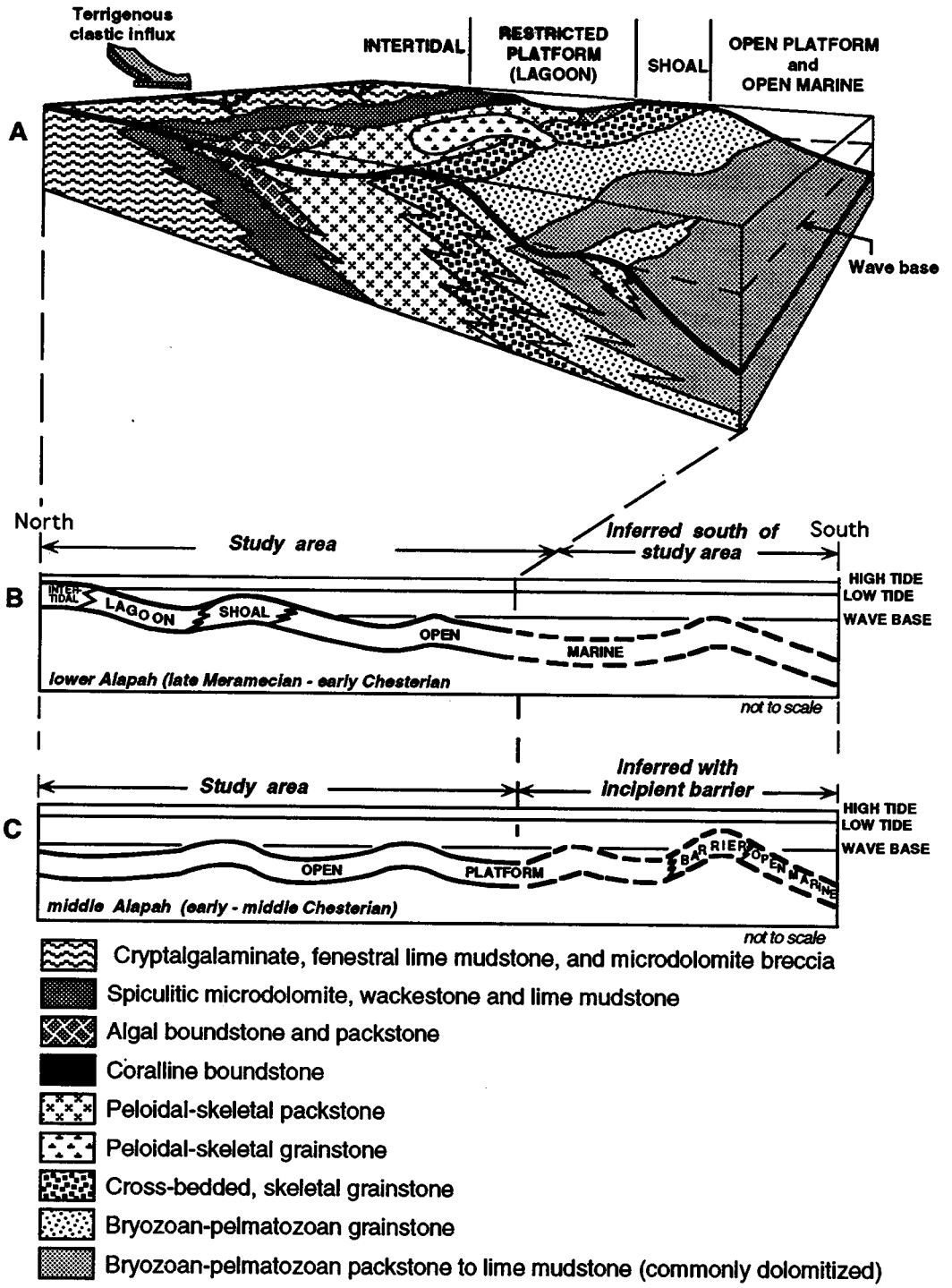


Figure 1-16. A - Facies model for the lower Alapah Limestone and upper Kayak Shale (modified from Gruzlovic, 1991).
B - Regional view of the general ramp geometry without any barriers to circulation.
C - Development of a broader platform geometry in the middle Alapah with a postulated incipient barrier to circulation beginning to develop.

and cryptalgalaminate indicates intertidal conditions (Gruzlovic, 1991). These restricted-platform (lagoonal) and intertidal environments were located landward of bioclastic shoals of the Egaksrak grainstone unit. Elsewhere (loc. 26, Fig. 1-2), siliceous shale and spiculite at the Kayak-Alapah transition may have formed in deeper-water (basinal?) environments. In other areas, normal marine conditions are indicated by argillaceous limestones containing a normal-marine fauna including pelmatozoans, bryozoans and corals. These limestones are laterally discontinuous and appear to represent local bioherms that built up into shallower oxygenated water. The alternation with black shales may have resulted from periodic reductions in terrigenous influx. Alternatively, relative sea-level fluctuations may have caused the limestones to form during shallowing events that brought the seafloor up into the aerobic zone and the black shales formed in deeper anoxic waters after flooding events.

The presence of the diverse fauna in argillaceous limestone implies that abnormal salinity was not a major limiting factor, although the occurrence of pseudomorphs after gypsum associated within associated restricted-platform deposits may indicate local hypersaline areas and possibly herald a change in climate (see below). A more arid climate would have resulted in the reduced production of both terrigenous clay and organic matter, perhaps contributing to the establishment of carbonate sedimentation in ANWR. In the subsurface, the Itkilyariak Formation contains red sandstone, siltstone, and shale (Mull and Mangus, 1972; Armstrong and Mamet, 1974), which may support this notion of climate change.

In ANWR, the Lisburne Group is dominated by carbonates and contains only rare intervals of shale in the upper Wahoo. Most of these shales occur in thin beds (<10 to 20 centimeters thick) at the base of parasequences (see below) and represent relatively deep-water condensed deposits that accumulated during intervals of incipient platform drowning. Some siltier beds may represent terrigenous influx, possibly during lowstands of sea level. For example, quartz silt and fine sand in limestones of the lower upper Wahoo seem to indicate a sea-level lowstand and clastic influx. Alternatively, the terrigenous quartz could have been wind blown, indicating an arid climate.

In contrast, the Lisburne Group at Prudhoe Bay contains significant intervals of green, brown, and red shale and siltstone and lesser thin beds of sandstone, particularly in the lower Alapah Limestone and in rocks equivalent to the lower part of our upper Wahoo (the "Lower sandy limestone interval" of the Alapah and the "Sandy carbonate interval" of the Wahoo of Jamison et al., 1980; see below). Sandstones in the upper part of the Lisburne are locally more abundant to the north (e.g., the Milne Pt. well; Bird and Jordan, 1977) indicating proximity to a source of terrigenous sediment. Widespread intervals of terrigenous shale in the upper Wahoo Limestone at the Lisburne oil field provide a basis for subdividing the unit into a number of different levels or zones (Okland et al., 1987). Their widespread nature indicates they are marine deposits that blanketed the platform and probably formed during incipient platform drowning events (Jameson, in revision).

However, silty and sandy limestones at Prudhoe Bay may have formed during lowstands, representing mixed sediments in carbonate platform environments adjacent to the paleoshoreline (see Chapter 5).

CRYPTALGALAMINATE & MICRODOLOMITE—INTERTIDAL TO SUPRATIDAL

The intertidal environment is subaerially exposed and subjected to desiccation during low tide. During high tide, the intertidal area is submerged and may support an impoverished fauna adapted to variations in salinity and temperature. In arid environments, hypersaline conditions may cause evaporites (gypsum and anhydrite) to be precipitated in tidal flat sediments. The intertidal environment typically is cut by tidal channels that form conduits for terrigenous sediment transported from an adjacent land area into the carbonate system. Intertidal sediments are characterized by three distinctive features: cyanobacterial mats (also called stromatolite or cryptalgalaminate); fenestral fabric; and indications of subaerial exposure such as desiccation cracks (James, 1984b). Microdolomite also may form in this environment due to early diagenesis. Early cemented intertidal sediments may be ripped up by storm currents and redeposited as intraclasts in edgewise conglomerate (Shinn, 1983).

Local intertidal deposits occur at the transition between the upper Kayak Shale and the lower Alapah Limestone and are distinguished by cryptalgal microdolomite and fenestral fabric in microdolomite and lime mudstone (locs. 10, 11, & 27, Figs. 1-2, 1-7, 1-8c & d, and 1-10). Laminations of silty quartz in microdolomite indicate proximity to a source of terrigenous sediment and paleoshoreline. Locally, orange- to red-weathering (oxidized), ferroan dolomites and mudstones with desiccation features indicate subaerial exposure (Gruzlovic, 1991). Microdolomite breccias may represent collapse breccias. Edgewise conglomerates formed in tidal channels or in intertidal to supratidal(?) flat areas as storm-generated rip-up clasts (at loc. 10, Fig. 1-2 & 1-7).

Intertidal conditions in the upper Alapah Limestone member (Fig. 1-13) also are characterized by thin intervals of microdolomite with cryptalgal laminations, fenestral fabric, and microdolomite breccias. These intertidal deposits have been recognized over a wide area (locs. 4, 8-12, 16, 25 & 27, Figs. 1-2, 1-7, 1-9, & 1-17).

Evidence of intertidal conditions in the Wahoo Limestone is sparse and localized. In the eastern Sadlerochit Mountains (locs. 7 & 8, Figs. 1-2, 1-11, & 1-18), cryptalgalaminate is replaced by microdolomite in the basal upper Wahoo (Fig. 19a). It appears to form discontinuous patches at different levels within an interval of orange-weathering dolomite containing quartz silt. These possible intertidal deposits support the interpretation that this interval represents a lowstand and sequence boundary within the Wahoo.

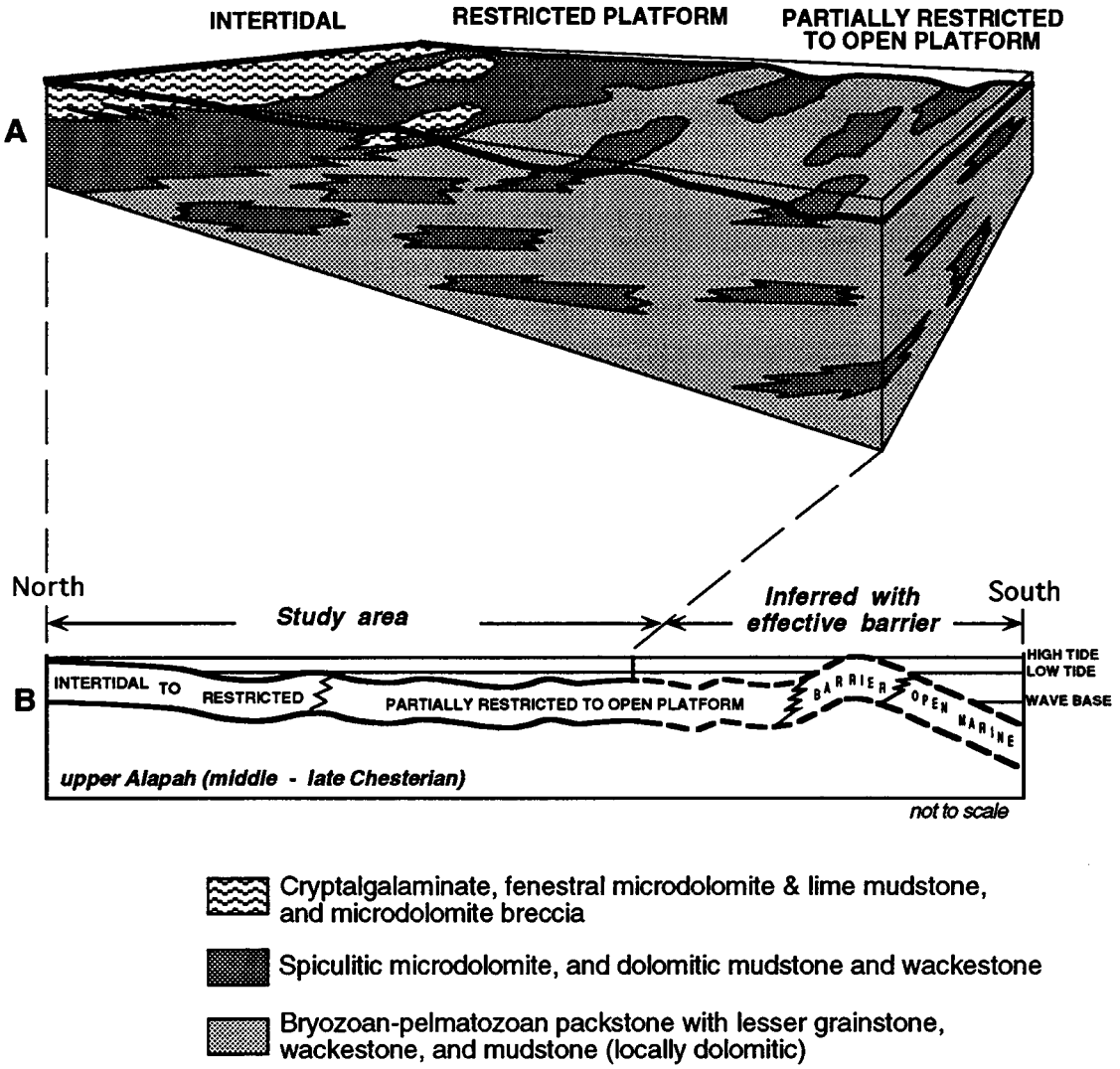


Figure 1-17. A - Facies model for the upper part of the Alapah Limestone (modified from Gruzlovic, 1991).
B - Regional view of the general platform geometry with a postulated barrier to circulation located somewhere to the south. Note that restricted circulation could have resulted from the expansiveness of the Lisburne carbonate platform/shelf at this time.

SUBAERIAL EXPOSURE SURFACES

The Lisburne Group is punctuated by a number of subaerial exposure surfaces that can be used for correlation and for providing insights on the depositional history of the Lisburne Group. Subaerial exposure surfaces provide important constraints for understanding the history of sea-level fluctuations and they have a major effect on the diagenetic history and reservoir potential of carbonates. A detailed discussion of subaerial exposure surfaces and their diagenetic effects is given in Chapter 3. However, subaerial exposure surfaces that are particularly important for understanding the regional stratigraphic framework of the Lisburne Group will be briefly considered here.

Two to seven subaerial exposure surfaces occur in the lower part of the Alapah Limestone and represent lowstands in parasequences superimposed on an overall transgressive systems tract. Several of these are associated with localized intertidal deposits that preceded the onlap of carbonates farther to the north (loc. 11 vs. loc. 8, Fig. 1-2, see Chapter 3).

A group of four subaerial exposure surfaces in intertidal sediments of the upper Alapah Limestone member appear to be a widespread correlatable surface in the northern part of ANWR (locs. 4, 6, 8- 11, 15, 16, & 27, Fig. 1-2) and at Prudhoe Bay (Armstrong and Mamet, 1974). Thus, the northern part of the Lisburne platform was exposed repeatedly and may be marked locally by an unconformity (Schoennagel, 1977), indicating a relative lowstand of sea level and a possible sequence boundary.

Subaerial exposure surfaces in the Wahoo are not easily explained in a sequence stratigraphic framework, mostly occurring in what are interpreted as highstand deposits. However, two localized subaerial exposure surfaces associated with intertidal deposits in northern ANWR mark a lowstand and sequence boundary (Loc. 6-8, Fig. 1-2; see Chapter 3).

The top of the Lisburne Group is truncated by the major sub-Permian unconformity and shows evidence of extensive subaerial exposure. Variable amounts of erosion of the Wahoo Limestone mark this ravinement surface. Local karst breccias at one locality (loc. 10, Fig. 1-2; see Chapter 3) may be related to biostratigraphic problems (possible stratigraphic leak, see Chapters 2 & 6). Moldic porosity in oolitic grainstones in the upper Wahoo may have resulted from dissolution beneath this subaerial exposure surface.

REPLACED EVAPORITES—HYPERSALINE ENVIRONMENT

Calcitized and silicified evaporite nodules are common throughout most of the upper Alapah Limestone member and extend down into the upper part of the middle Alapah member (Fig. 1-10b; Gruzlovic, 1991). They occur in all lithologies but are most abundant in intertidal deposits. The evaporite nodules within bryozoan-pelmatozoan limestone or spiculitic microdolomite are not

syndepositional because their fauna could not survive hypersaline conditions. Instead, the evaporites in these lithologies resulted from the downward migration of brines from hypersaline environments associated with later intertidal sediments and subaerial exposure surfaces. The evaporite brines probably formed during a short time interval, but penetrated into the underlying sediments to a considerable depth. This is supported by the observation that the evaporite nodules are noticeably absent in the uppermost 19 meters of the upper Alapah in the Fourth Range and are very rare in the uppermost 43 meters of the upper Alapah at Plunge Creek (locs. 11 & 12, Figs. 1-2 & 1-7; Gruzlovic, 1991), both above the intertidal deposits and exposure surfaces.

PELOIDAL AND SPICULITIC LIMESTONE—RESTRICTED PLATFORM

The restricted-platform environment forms in low-energy water bodies having restricted circulation resulting in abnormal (not typical marine) salinity, oxygen-content, and/or temperature. Restricted platforms always are submerged, but water depths are generally shallow (5 to 25 meters deep; Scoffin, 1987). Restricted circulation can result from a physical barrier (i.e., a shoal or a reef) or from the damping effect of large expanses of shallow water, such as are found on extensive carbonate platforms (Scoffin, 1987). Although the terms restricted platform and lagoon are often used interchangeably in the literature, a lagoon is located behind a physical barrier. Restricted platform is a more general term that includes lagoons and extensive carbonate platform (shelf) areas having poor water circulation (restricted shelf is the term used by Enos, 1983). Lagoonal sediments are difficult to distinguish from more expansive restricted-platform or deeper marine deposits (see below), all of which are characterized by depauperate fauna and peloids. Lateral or vertical relationships with more distinctive facies that formed in intertidal, shoal or open-platform environments are the best criteria for refining paleoenvironmental interpretations (Enos, 1983). In this report, the term restricted platform is used throughout, but lagoons are distinguished when an association with barrier shoals can be demonstrated.

The restricted-platform environment is characterized by mostly dark, muddy carbonate sediments containing a low-diversity fauna that was tolerant of harsh environmental conditions. Water circulation in restricted platforms typically was sluggish, allowing muddy carbonates to accumulate without being reworked by marine currents or waves. Because organisms requiring normal-marine conditions are excluded from the restricted-platform environment, an impoverished fauna including spiculitic sponges, ostracods, and gastropods can thrive and may dominate the sediment. Soft-bodied organisms are not preserved but may leave their mark in trace fossils and bioturbation. Abundant fecal pellets also are indicative of restricted-platform environments and can be distinguished from other peloids by their more spherical to elliptical shape and homogeneous texture (in contrast to micritized grains which have more irregular shapes and relict internal features); clotted fabrics resulting from compaction of soft fecal pellets is another distinction. Micritization of grains by endolithic (microboring) organisms may create some peloids, particularly

in the photic zone where endolithic algae exist. Certain types of algae such as calcispheres are common in restricted-platform environments but are easily transported to other environments. Commonly, the restricted-platform sediments are disrupted by bioturbation, but fine laminations and organic matter can be preserved if environmental conditions are sufficiently harsh to totally exclude burrowing organisms (Enos, 1983). An excess of organic matter indicated by dark coloration can result in oxygen deficiencies; resultant anaerobic, dysaerobic, or poikiloaerobic conditions can limit growth of organisms struggling to survive on a restricted platform (Oschmann, 1991).

Because the shoal deposits of the Egaksrak grainstone unit apparently formed an effective barrier, the restricted-platform deposits of the lower Alapah Limestone member formed in a lagoon (Fig. 1-16). Fine-grained, peloidal-skeletal packstone is the dominant lithology with lesser intervals of peloidal-skeletal grainstone. Ostracods and calcispheres are common skeletal components and all skeletal grains are highly micritized. Spiculitic microdolomite and muddy limestone formed under more restricted conditions as indicated by their impoverished fauna. Local (locs. 11 & 16, Figs. 1-2, 1-7, & 1-9) algal limestone (boundstone, bafflestone, and packstone; Fig. 1-8a) formed in very muddy, low-energy algal flats associated with spiculite.

In northern ANWR, the upper Alapah Limestone member is dominated by bioturbated, spiculitic microdolomite that formed in a widespread restricted-platform environment (locs. 1-10 & 27, Figs. 1-2, 1-7, & 1-17). Calcareous and siliceous sponge spicules typically are the only grains present, but admixtures of scattered bioclasts, pelmatozoans, intact fenestrate bryozoans, and brachiopods occur to the south (locs. 11 & 12, Figs. 1-2 & 1-7). Detrital silty quartz is generally either absent or rare (1% to 2%), in contrast to the lagoonal deposits in the lower Alapah. Oil stain commonly occurs in intercrystalline porosity in dolomite and in small vugs after leached sponge spicules. The restricted-platform deposits of the upper Alapah pass southward into the open- to restricted-platform deposits of the transitional unit of the upper Alapah (Fig. 1-17). The Lisburne carbonate platform was at its maximum regional extent during deposition of the upper Alapah, suggesting that restricted conditions developed due to dampening of marine currents in a landward (north-northeast) direction.

Restricted-platform deposits in the upper Wahoo Limestone include peloidal-skeletal packstone and grainstone, and spiculitic limestone and microdolomite (Fig. 1-19b). They are most abundant at the transition between the lower and upper Wahoo and in the uppermost part of the Wahoo. Associated oolitic shoal deposits formed a partial barrier that resulted in areas having restricted circulation, but not in a fully restricted lagoon (Fig. 1-18). Localized muddy carbonates interbedded with oolitic grainstone contain unusual assemblages of sponge spicules, skeletal grains, and ooids, apparently representing heterogeneous storm deposits that formed immediately behind the shoals. More widespread peloidal-skeletal packstone and spiculitic microdolomite and limestone formed in more extensive areas having partially restricted circulation. The peloidal-skeletal packstone and grainstone

Figure 1-18

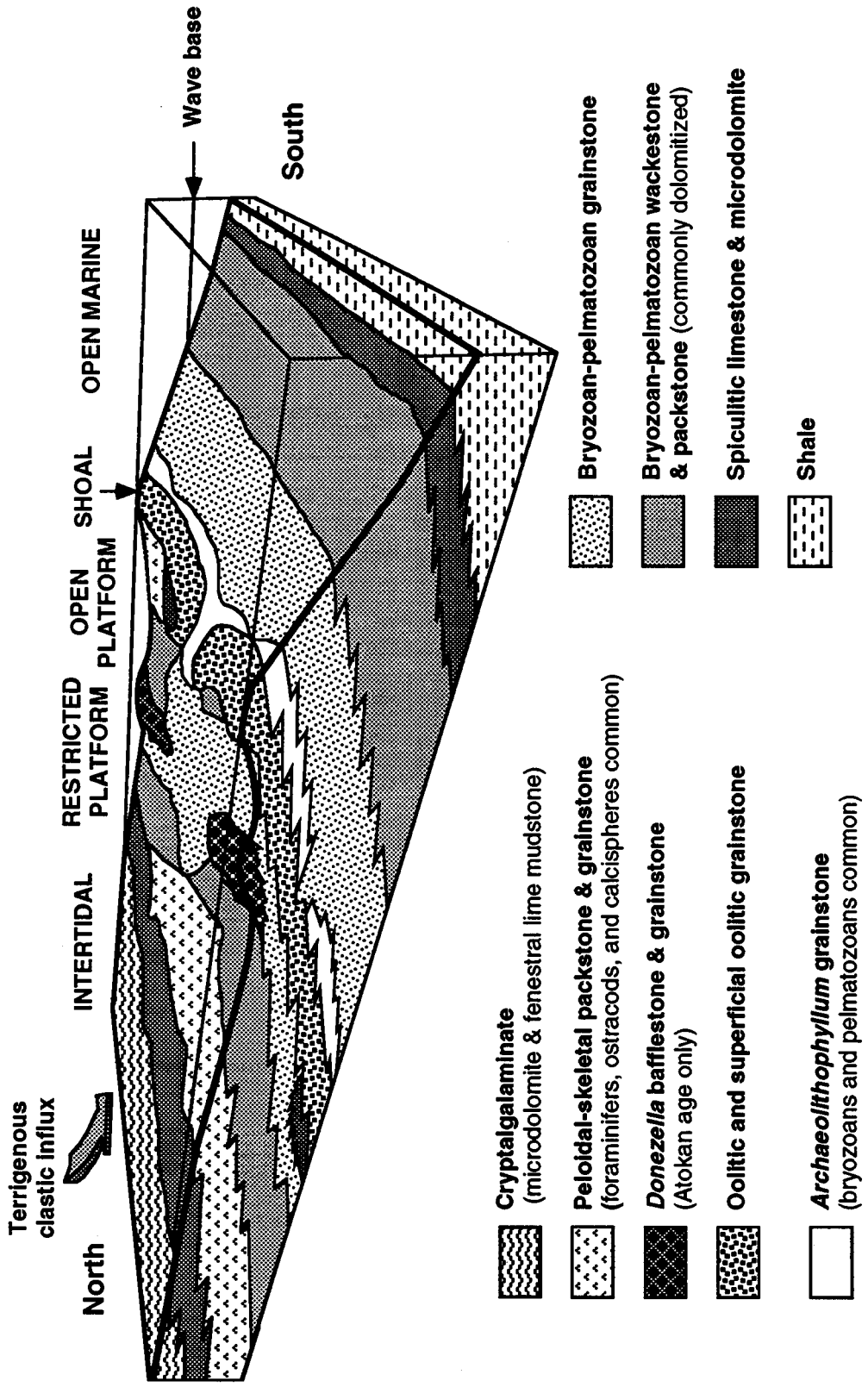
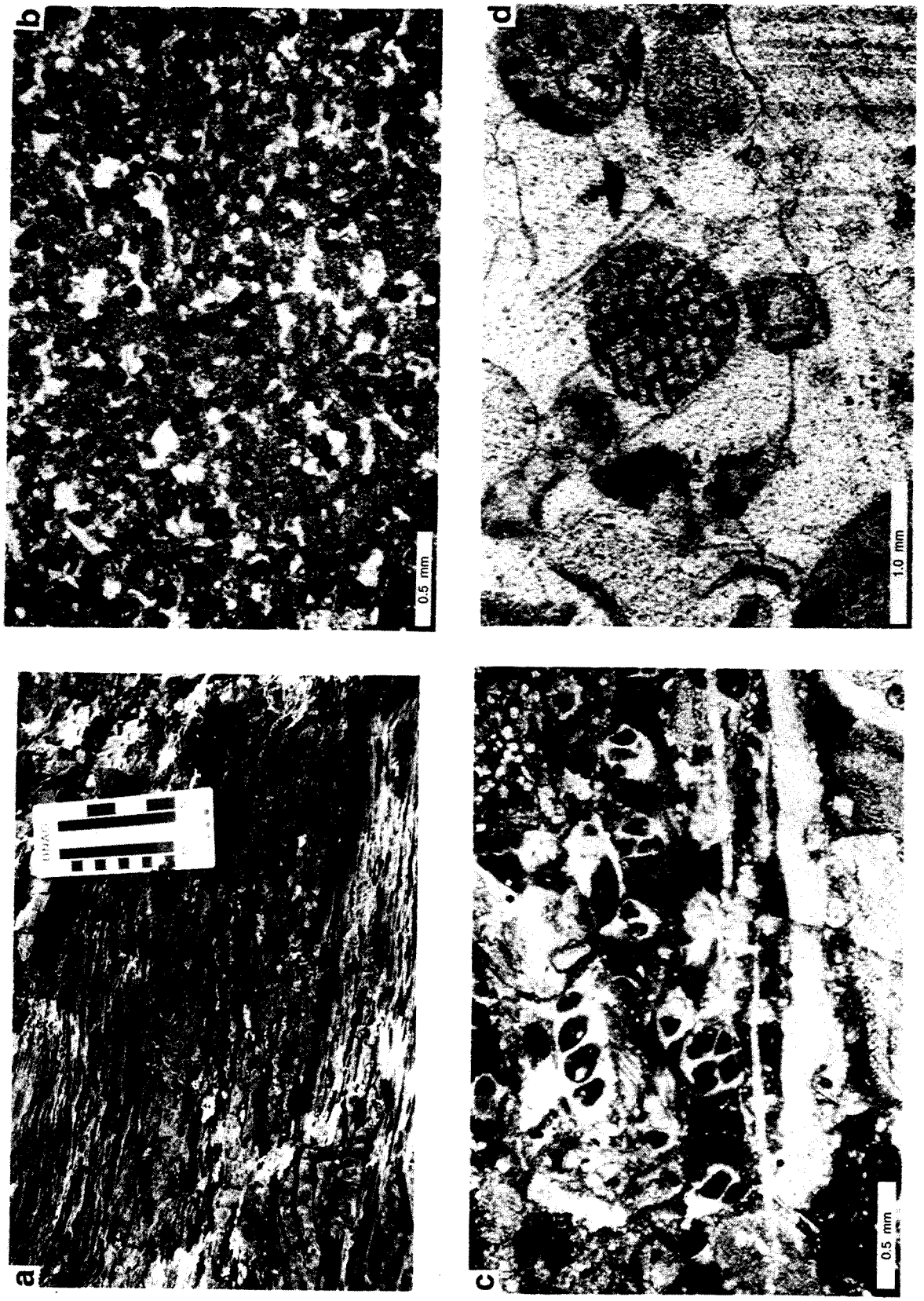


Figure 1-18. Facies model for the Wahoo Limestone has a south-facing carbonate ramp geometry with broad facies belts in the outer ramp and a more complex distribution of carbonate facies on the open to restricted platform (inner ramp) behind ooid shoals.

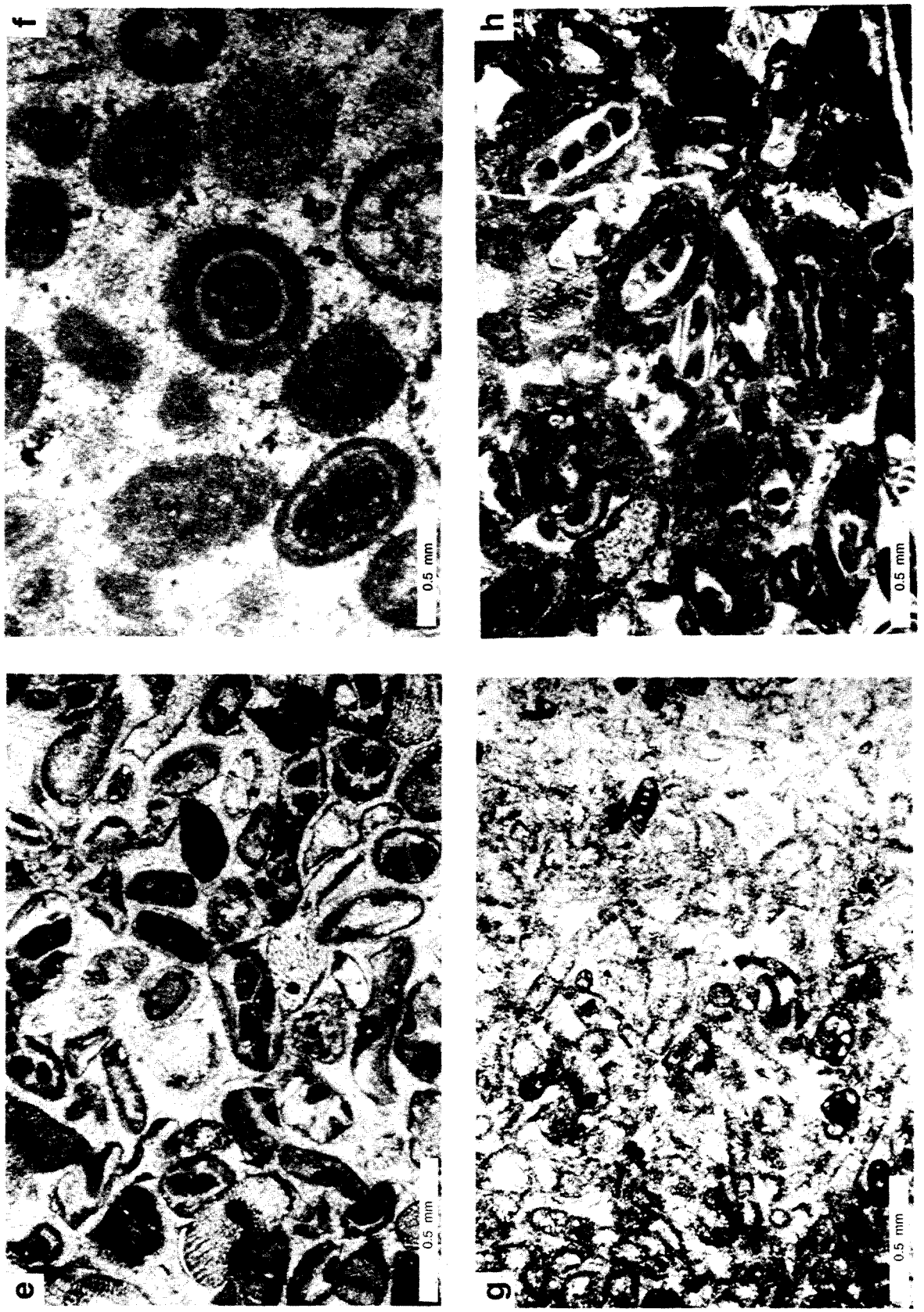
Figure 1-19



b - Peloidal grainstone to packstone.
d- Pelmatozoan-bryozoan grainstone.

Figure 1-19. Microfacies of the upper Wahoo Limestone
a - Cryptalgalaminate in dolomicrite with chert nodules.
c - Bryozoan-pelmatozoan packstone.

Figure 1-19



f - Oolitic grainstone.
h - *"Osagia"* in oncolitic packstone to grainstone.

Figure 1-19. Microfacies of the upper Wahoo Limestone (continued)
e - Grainstone with superficial ooids.
g - *Donezella* algae and simple foraminifers in skeletal grainstone.

mostly consist of highly micritized pelmatozoans, bryozoans, ostracods, foraminifers, and calcispheres. Angular, detrital quartz silt is a minor constituent (1% to 7%) and probably was transported as windblown, terrigenous sediment. Commonly, spiculite and peloidal-skeletal limestone are interbedded and may be mixed by bioturbation, indicating they formed in adjacent environments. The spiculite formed under more restricted conditions and is associated with peloidal packstone and grainstone, particularly in the uppermost Wahoo in the northernmost localities (locs. 6 & 8, Figs. 1-2 & 1-11 and at the Lisburne oil field).

OOLITIC AND CROSS-BEDDED SKELETAL GRAINSTONE—SHOALS

Shoals form in areas subjected to constant wave and current agitation that winnows away lime mud and generates well-sorted, well-rounded grainstone. Small- to medium-scale cross-bedding is a common sedimentary structure in the high-energy shoal environment (Wilson, 1975). Ooids form primarily on high-energy shoals, but carbonate shoal sands also can consist of highly abraded skeletal material (bioclasts). Superficial ooids form along shoal margins and intraclasts can be reworked in shoal deposits. Water depths of the shoal are typically very shallow, ranging from 0 to 5 meters (Scoffin, 1987). Shoals correspond to Wilson's (1975) facies belt 6 (winnowed platform edge sands). The shoal environment is bounded on its seaward side by the open-marine environment and on its landward side by open- or restricted-platform environments, depending on the effectiveness of the shoal barrier.

Shoal deposits in the lower Alapah Limestone member (the "Egaksrak grainstone") primarily consist of highly abraded, well-sorted, cross-bedded, skeletal grainstones (Figs. 1-7, 1-9, & 1-11a). Skeletal grains are highly micritized and are dominated by abraded pelmatozoans and bryozoans (Fig. 1-8b). Ooids and superficial ooids are not a major grain type, but locally are abundant, particularly in northern ANWR (locs. 27 & 28, Fig. 1-20). Cross-bedded bioclastic grainstone occur in distinctive carbonate cycles/parasequences, alternating with restricted-platform deposits in the lower part and open-platform/marine deposits in the upper part of the Egaksrak grainstone. Thus, the shoals were a hydrodynamic buildup of bioclastic sands that formed an effective barrier to marine circulation and created restricted-platform (lagoonal) conditions to the north (Fig. 1-16).

In one of the southern ANWR localities (loc. 22, Figs. 1-2 & 1-9), bioclastic grainstones within the transitional unit at the top of Alapah Limestone may represent shoal deposits. The well-sorted and abraded bioclasts and local cross-beds indicate high-energy shoal conditions. It is possible that these shoals formed a barrier to circulation and helped create the widespread restricted-platform conditions in the upper Alapah farther to the north (Fig. 1-21).

Shoal deposits in the Wahoo Limestone are represented by oolitic grainstones. Ooids having more than three concentric laminae probably formed on the high-energy, current-agitated crests of the shoal (Fig. 1-19f). Superficial ooids, having less than three concentric laminae, are interpreted as having formed in

Figure 1-20

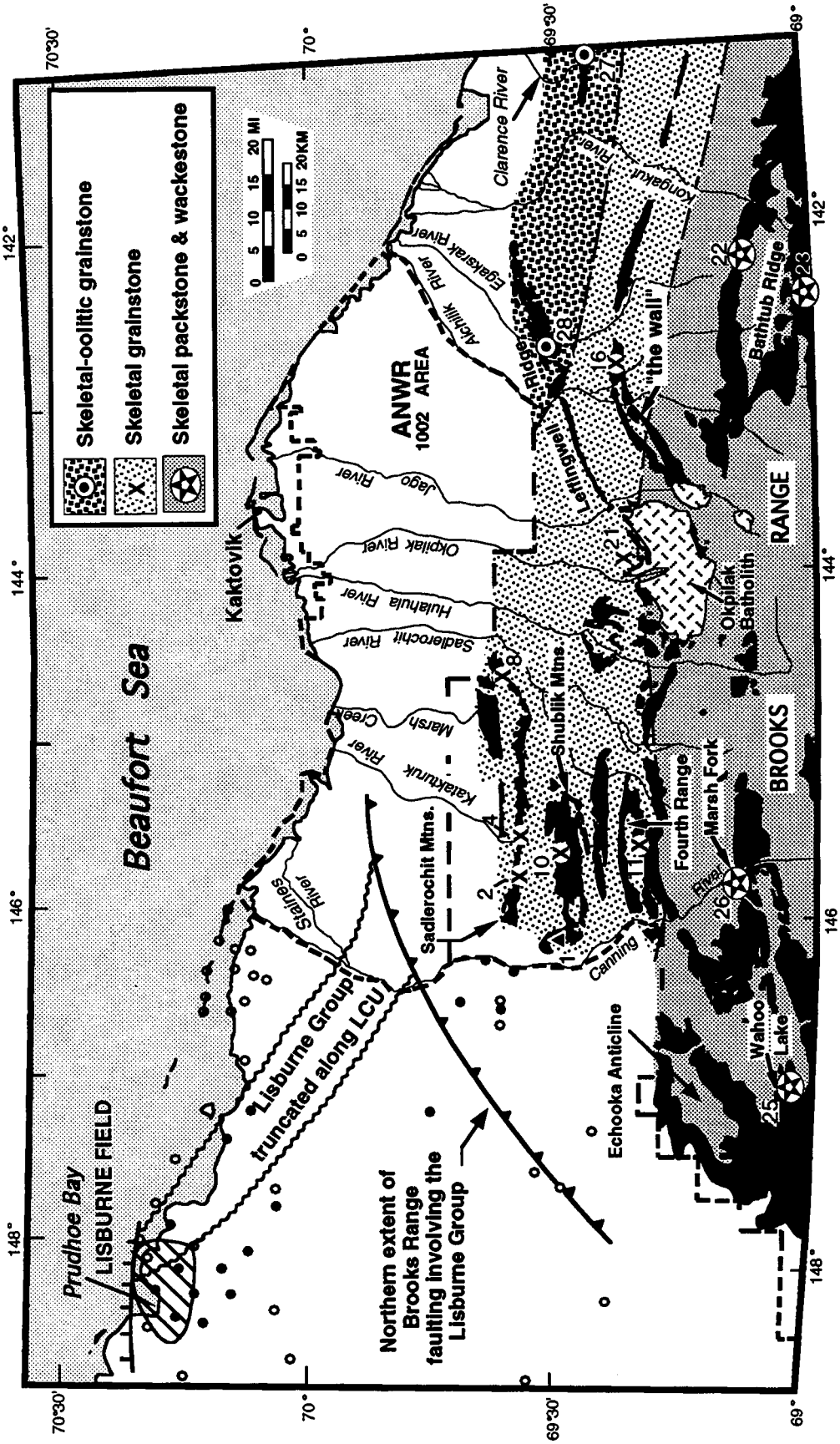


Figure 1-20. Facies map for the lower Alapah Limestone shows distribution of the "Egaksrak grainstone" skeletal (bioclastic) shoals that have an admixture of ooids in the north and a transition into open-marine fossiliferous packstone to the south.

Figure 1-21

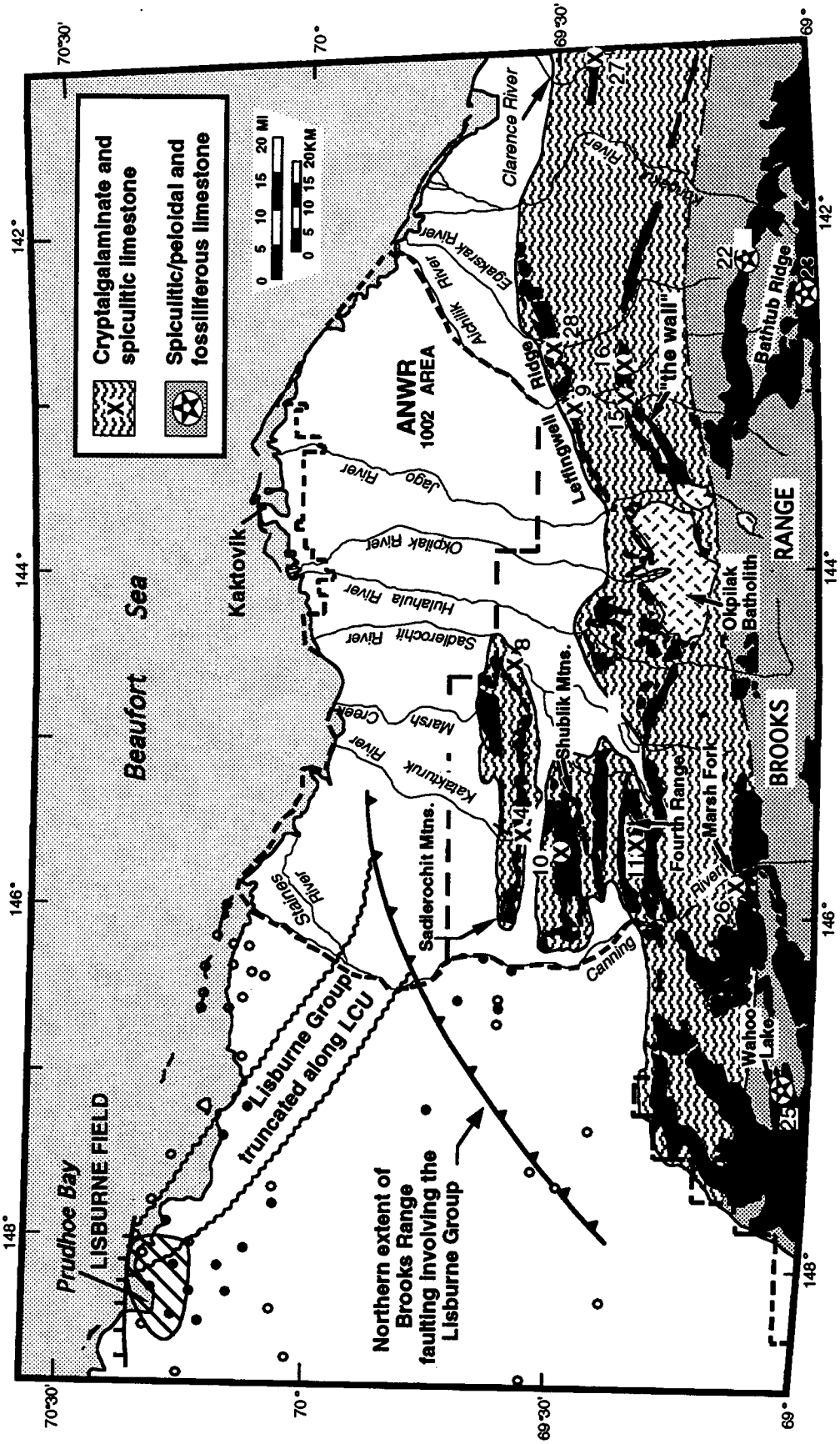


Figure 1-21. Facies map for the upper Alapah Limestone shows area of intertidal to supratidal cryptalgalaminate in northern ANWR and partially restricted platform deposits to the south.

slightly deeper water on the shoal margins where less current agitation existed (Fig. 1-19e). Oolitic and superficial oolitic grainstones are major lithologies in the upper Wahoo, but their distribution is variable depending on paleogeographic position and relative sea-level fluctuations (Figs. 1-18 & 1-22). Migrations of shoals, related to sea-level fluctuations, are evident in both the large-scale transgressive-regressive succession/depositional sequence of the upper Wahoo and in the smaller-scale parasequences. Overall, ooids are best developed in the upper part of the upper Wahoo, suggesting that the shoals in the Wahoo Limestone became more well developed and laterally extensive with time (Figs. 1-7, 1-11, & 1-22).

FOSSILIFEROUS LIMESTONES—OPEN-MARINE VERSUS OPEN-PLATFORM

Most limestones in the Lisburne Group formed on a shallow-marine carbonate platform in subtidal areas having normal-marine salinity conducive for the development of a diverse normal-marine fauna. Bryozoans and pelmatozoans are the dominant grain types, both indicating normal-marine salinity. Algae are common and are shallow-water indicators that grew in the photic zone. For normal-marine carbonates deposited on a carbonate ramp, we differentiate **open-marine** environments located on the seaward side of shoals from **open-platform** (inner ramp) environments located behind shoals that were not effective circulation barriers. This distinction is important in interpreting carbonate cycles/parasequences in the Wahoo which developed due to migration of ooid shoals across a carbonate ramp (see below). Discrimination of open-marine from open-platform deposits is based primarily on stratigraphic and paleogeographic context, but also may be distinguished by minor compositional attributes. On large carbonate shelves, the open-platform deposits located behind shelf-edge reefs or shoals can be much more widespread (if shallow marine conditions are more extensive than on a homoclinal ramp) but are difficult to distinguish from open-marine deposits without a paleogeographic or stratigraphic context.

In carbonate ramp successions, differentiation between the open-platform and open-marine deposits is based largely on paleogeographic and stratigraphic context, particularly progradational relationships with other more distinctive lithologies. An open-platform environment is indicated where bryozoan-pelmatozoan limestone is underlain by oolitic and superficial oolitic grainstone (shoal deposits), and overlain by peloidal-skeletal packstone/grainstone and spiculitic wackestone and microdolomite (restricted-marine deposits). In contrast, open-marine limestones typically pass gradationally from bryozoan wackestone and packstone that formed below wave-base, upward into increasingly well-sorted and abraded skeletal grainstone, and finally into ooid shoal deposits. Progradational-facies transitions in open-marine environments are gradational in response to changing water depths and energy conditions, whereas facies changes in open-platform environments may be more random and due to paleoecological changes in the complex of paleoenvironments sheltered behind shoals.

Figure 1-22

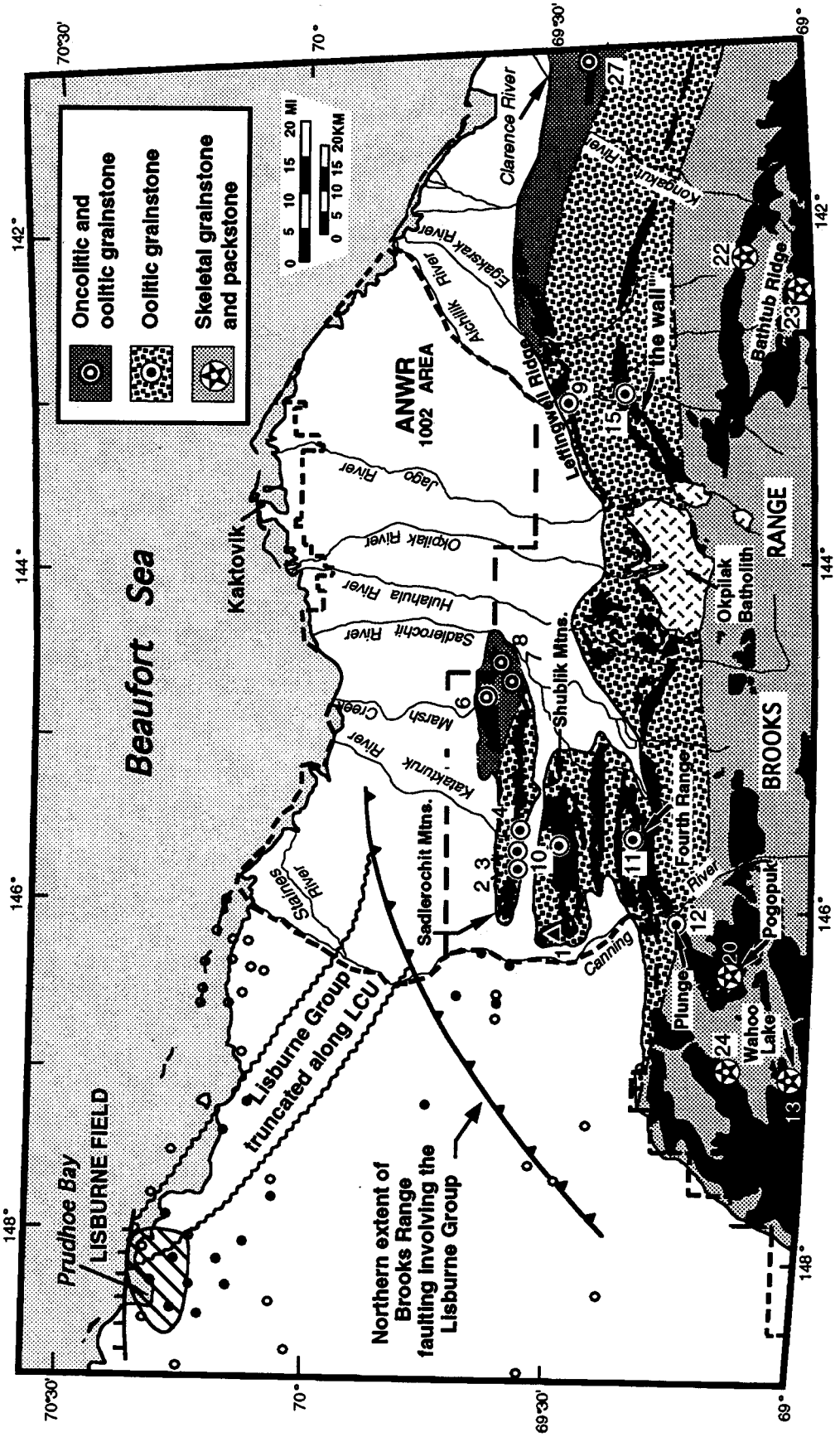


Figure 1-22. Facies map for the Pennsylvanian upper Wahoo Limestone shows the entire breadth of ooid shoal deposits that would have formed a narrower belt at any one time but migrated considerable distances across the Wahoo carbonate ramp in response to relative sea-level fluctuations in the early to mid Pennsylvanian.

At times when no shoals are known to exist on an extensive carbonate platform, the term "open platform" is used in a more general sense. For example, the thick succession of fossiliferous limestones of the middle Alapah Limestone member contains abundant bryozoans and pelmatozoans that formed in an extensive open-platform environment (Fig. 1-16). Bryozoan-pelmatozoan packstone to mudstone with common full-frond (intact) fenestrate bryozoans and articulated crinoid stems formed below wave base. Grainstone composed of moderately abraded and micritized bryozoans and pelmatozoans and lacking cross-stratification formed above wave base. Its stratigraphic position above the retrograding shoal deposits of the Egaksrak grainstone implies open-marine conditions seaward of northward migrating skeletal shoals. However, its gradational upward transition into restricted-platform deposits of the upper Alapah suggests that the middle Alapah formed in open-platform conditions. However, without evidence of shoals migrating southward or developing on some southern paleotopographic high, the interpretation of the change from open-marine to open-platform conditions is uncertain. If restricted-platform conditions developed due poor circulation on an expansive carbonate platform (see above), the adjacent open-platform deposits may form even in the absence of a shoal or reef barrier. Distinguishing open-marine from open-platform deposits is possible for carbonate ramps having well developed shoals, but is more difficult for carbonate shelves with extensive restricted- and open-platform areas but possibly lacking shoals.

Open platform—Inner ramp or middle shelf

The open-platform environment (sensu stricto) is bounded on its seaward side by the shoal environment and on its landward side by the restricted-platform environment (Fig. 1-18). Although the open platform is somewhat sheltered behind the shoal, circulation is adequate enough to maintain normal-marine conditions. Thus, it is similar to the open-marine environment, but water depths of the open-platform environment are generally only a few meters to tens of meters deep (Wilson, 1975).

Bioturbated, fossiliferous limestones are common and are composed of stenohaline organisms similar to those found in the open-marine environment (Scoffin, 1987). Lithologies include bryozoan-pelmatozoan wackestone, packstone, and grainstone. Although bryozoans and pelmatozoans are the dominant grain type, limestones from the open-platform environment generally have a more variable grain content including ooids, foraminifers, gastropods, and algae (*Archaeolithophyllum*, *Stacheoides*, *Asphaltina* and *Donezella*). Ostracods, trilobites, calcispheres, and detrital quartz silt (1% to 4%) are less common components. The grains generally are moderately to highly micritized, probably by endolithic algae in the photic zone. The migration of carbonate facies on the open platform may have patterns different than the progradation succession that typify the open-marine deposits. In the open-platform environment, bryozoan-pelmatozoan grainstone commonly is overlain by full-frond (intact) fenestrate bryozoan-pelmatozoan wackestone and packstone beds that are highly dolomitic

and contain variable amounts of pyrite and detrital quartz silt (Fig. 1-19c & d; Gruzlovic, 1991). The grainstone indicates waves and currents were strong enough to winnow away lime muds in shallow paleoenvironments that migrated laterally to be overlain by muddier carbonates that formed in adjacent deeper-water paleoenvironments.

In the uppermost part of the upper Wahoo Limestone member (Atokan), *Donezella* bafflestone and grainstone formed in the open-platform environment (Figs. 1-8 & 1-19g). Commonly, *Donezella* is associated with calcispheres, foraminifers, and corals. Mamet and DeBatz (1987, 1989) have stated that *Donezella* forms seven consistent levels in the Sadlerochit Mountains that can be used for correlation. This implies that the *Donezella* bafflestones are laterally continuous. However, *Donezella* commonly is associated with corals and the bafflestone intervals are not correlatable between measured sections (Gruzlovic, 1991). This suggests *Donezella* formed in localized buildups and not in widespread, time-equivalent biostromal layers (Fig. 1-18). The *Donezella* buildups formed in shallow enough water to allow the winnowing of mud and to locally form ooid nuclei. This suggests that shoal became established on the pre-existing biohermal(?) paleotopography. Oncolitic grainstone and packstone are another associated lithology in the uppermost Wahoo that formed under slightly higher energy conditions, possibly as algae buildups or shoals in a relatively restricted environment (Fig. 1-19h).

Facies changes into adjacent shoal or restricted-platform environments are probably the best criteria to use in differentiating open-platform from open-marine sediments. Since the open-platform environment is bordered on its seaward side by the shoal environment, grains such as abraded ooids, may be transported onto the open platform by strong, landward-directed storm waves. Similarly, calcispheres from the restricted-platform environment can be transported into the open-platform environment by tidal currents. However, these grains also can be transported farther seaward into the open-marine environment.

Partially restricted to open platform—Inner ramp or shelf

Open-platform deposits may be associated closely with restricted-platform deposits such as peloidal packstone, that help to distinguish them from open-marine limestones. Spiculitic microdolomite interbedded with bryozoan-pelmatozoan packstone to wackestone suggest a close interrelationship between the partially restricted and open-platform environments (Fig. 1-18). Skeletal grains are abraded slightly and full-frond (intact) fenestrate bryozoans are a common grain type, along with lesser brachiopods, ostracods, peloids, foraminifers, intraclasts, and gastropods. Bioturbated mixtures of restricted-platform and open-platform deposits are another indicator of partially restricted conditions (Figs. 1-17 & 1-21).

Open-marine—Outer ramp or shelf

In this report, the open-marine environment is defined as the area bounded by the shoal environment on its landward side and by the deep-water basinal environment on its seaward side. The open-marine environment has excellent water circulation so it is well oxygenated and has normal-marine salinity. Water depths range from approximately 5 to 200 meters, and thus encompass a large range of paleoenvironmental conditions. The open-marine environment is subdivided into two subzones, below and above fair-weather wave base (Scoffin, 1987). In addition, the open-marine environment receives variable amounts of light, being both above and below the photic zone (the photic zone is generally < 100 meters deep; Wilson and Jordan, 1983). It also is possible for shallow well-oxygenated waters of the open-marine environment to be adjacent to dysaerobic or anaerobic (euxinic) bottom waters in deeper-water environments that lack calcareous organisms. The open-marine environment corresponds to Wilson's (1975) facies belt 2 (shelf facies). Many of the lithologic changes evident in a succession of open-marine deposits are related to changes in water depth resulting from relative sea-level fluctuations.

On the seaward margin of a carbonate ramp, the seafloor slopes gently into progressively deeper open-marine environments. A number of broad-facies belts develop in response to paleoenvironmental changes, particularly hydraulic energy conditions resulting from wave-generated currents. Fairweather wave base can be defined as the depth at which normal wave energy intersects the seafloor (Figs. 1-16 & 1-18). The average depth of fairweather wave base is generally accepted as being 10 to 20 meters below sea level (Flügel, 1982). Wave energy above fairweather wave base winnows away lime mud and results in grainstone. Below fairweather wave base, lime mud accumulates resulting in deposition of packstone and wackestone. In this report, wave base refers to fairweather wave base. Storm wave base can be much deeper and can transport coarse-grained sediments to much greater depths than fairweather wave base as indicated by storm deposits (tempestites) within successions of muddy carbonates. Recognizing such redeposited sediments is important in making the proper paleoenvironmental interpretations.

The degree of micritization of grains also appears to be related to water depth in the open-marine environment. Endolithic algae that bore into carbonate grains and create micritic envelopes significantly decrease at depths of more than 18 to 25 meters (Swinchatt, 1969; Perkins and Halsey, 1971). However, micritization can occur at depths below the photic zone (> 100 meters) where it is caused by other organisms such as fungi, bacteria, and heterotrophic algae (Friedman et al., 1971; Wilson and Jordan, 1983). In the Lisburne Group, micritized grains with well developed micritic envelopes probably formed in very shallow water depths (less than 10 meters) based on microfacies analysis and stratigraphic relationships.

The open-marine environment is characterized by bioturbated, highly fossiliferous limestones. A variety of stenohaline organisms such as bryozoans, pelmatozoans, brachiopods, and corals are common. During Mississippian and Early

Pennsylvanian time, pelmatozoans and bryozoans were the dominant organisms living in the open-marine environment (Wilson and Jordan, 1983). The texture and composition of these fossiliferous limestones is related to water depth. Interpreting the different lithologies in terms of position in the open-marine environment is based largely on progradational relationships.

Skeletal packstone & grainstone—Above wave base

The transition between above and below wave-base conditions is gradational and recognized in a stratigraphic succession by a change from muddy carbonates (bryozoan-pelmatozoan wackestone and packstone) to limestones dominated by skeletal grainstone (Figs. 1-16, 1-17, and 1-19c & d). In progressively shallower water depths, bioclastic grains become increasingly abraded and well sorted under higher energy conditions and pass gradationally upward into shoal deposits. Superficial ooids may develop at this transition (adjacent to ooid shoals) and cross-beds and other current-generated structures indicate passage into the shoal environment (Figs. 1-18 & 1-19e). Immediately above wave base, the texture may range between grainstone and packstone with mud remaining beneath large bioclasts and in intergranular spaces such as bryozoan zooecia.

In the upper Wahoo member, beds of bryozoan-pelmatozoan grainstone are gradationally overlain by moderately to highly abraded and micritized, bryozoan-pelmatozoan-*Archaeolithophyllum* grainstone. The abraded and micritized skeletal grains in these grainstone lithologies indicate deposition in progressively shallower water above wave base. *Archaeolithophyllum* appears to have thrived in the high-energy, seaward flank of the ooid shoals (Gruzlovic, 1991; Mamet, 1991; Fig. 1-18).

Skeletal wackestone—Below wave base

Bryozoan-pelmatozoan wackestone and packstone, spiculitic microdolomite and limestone, and calcareous shale all have a lime-mud matrix and are interpreted to have formed in open-marine (below wave base) environments. Typically, the lime mud in wackestone and packstone is preferentially dolomitized because of its fine-grain size and high-surface area exposed to diagenesis. Dolomitized lime mud typically weathers greenish or orangish because of the presence of iron in the ferroan dolomite. Within the upper Wahoo, these lithologies occur in the lower part of parasequences with progradational succession indicating relative position on the carbonate ramp.

Shale and calcareous shale at the base of parasequence is the most seaward and deepest water deposit identified in the Wahoo (Fig. 1-18). The shales grade upward into argillaceous, spiculitic limestone and microdolomite. The spiculites pass upward into bryozoan-pelmatozoan wackestone and packstone. The bryozoan-pelmatozoan wackestone and packstone are slightly argillaceous in the lower part, and full-frond (intact) fenestrate bryozoans and pelmatozoans with articulated stems are relatively unabraded and unmicritized. The presence of mud, and the lack of abrasion and micritization, indicate deposition in an open-marine environment

below wave base. Bryozoan-pelmatozoan wackestone and packstone are gradationally overlain by slightly to moderately abraded and micritized, bryozoan-pelmatozoan grainstone that formed above wave base in a open-marine environment.

Black shale & spiculite—Anaerobic to dysaerobic environment

In deep water, carbonate sedimentation may be slow or nonexistent because of lack of light for calcareous algae, poor circulation for filter feeding organisms, cold temperatures that slow metabolic rates, and possible reduced oxygen contents. Black shale and argillaceous limestone in such deep-water areas may indicate the drowning or the incipient drowning of a carbonate platform. Spicular sponges seem to be well adapted to such hostile deep-water conditions (Flügel, 1982). Peloids (mostly fecal pellets) are another common grain type. Distinguishing spiculite that formed in deep water from spiculite that formed in shallow restricted-platform conditions is difficult; both thrived under harsh environmental conditions that effectively excluded other calcareous organisms. Siliceous spicules may indicate deeper-water conditions (Flügel, 1982). Black shale is typically fissile to laminated and generally lacks biogenic skeletal material, indicating deposition in anaerobic or other hostile environments that are sufficiently harsh enough to totally exclude burrowing organisms (Enos, 1983). Weak bioturbation indicates the presence of dysaerobic or poikiloaerobic conditions that were able to support soft-bodied burrowing organisms. An excess of organic matter indicated by dark coloration indicates oxygen deficiencies; anaerobic, dysaerobic, or poikiloaerobic conditions can limit the growth of organisms struggling to survive on either restricted-platform or deep-water settings that lack sufficient water circulation to supply necessary oxygen (Oschmann, 1991).

For example, black shale and spiculite in the upper Kayak Shale seem to represent shallow-water restricted-platform deposits with associated intertidal cryptalgalaminate (locs. 10 & 11, Figs. 1-2, 1-7, & 1-16). Argillaceous limestone and spiculite at the Wahoo type section (loc. 13, Figs. 1-2, 1-12, & 1-22) appear to have formed in deeper-water outer-ramp conditions as indicated by associated redeposited bioclastic and intraclastic grainstone and its more seaward paleogeographic and stratigraphic context (Watts et al., 1989).

In the upper Wahoo, calcareous shale at the base of some parasequences is interpreted as the most seaward and deepest water deposit (Fig. 1-18). These seem to represent condensed deposits that formed during the incipient drowning of the outer ramp. The shales grade upward into argillaceous, spiculitic limestone and microdolomite. The spiculites pass upward into slightly abraded and slightly micritized, bryozoan-pelmatozoan wackestone and packstone of the open-marine, below wave-base environment.

DEPOSITIONAL SEQUENCES OF THE LISBURNE GROUP OF ANWR

The Lisburne Group has cyclical variations in lithology (and associated depositional environments) that are similar to carbonate cycles comprising most shallow-marine carbonate successions (James, 1984b). Such sequential ordering of beds and changes in lithology occur in most sedimentary successions (Einsele and Ricken, 1991). Cyclical variations in lithology may result from different causal factors including tectonic, eustatic, and climatic factors (allocyclic factors) and modifying autocyclic factors within the depositional environment. These autocyclic factors include local differences in subsidence, sediment supply (or carbonate production), hydrodynamic influences, paleoecology, and the natural migration patterns of sedimentary environments.

The Lisburne carbonate platform apparently subsided continuously, allowing a thick succession of carbonate sediments to form. The interplay between regional subsidence, eustatic sea-level fluctuations, and migration of carbonate environments combined to produce a complex mosaic of carbonate facies. The succession is marked by evidence of periodic subaerial exposure (see Chapter 3), but no major time gaps are apparent (except for a possible unconformity within the Wahoo Limestone at the Fourth Range locality, see Chapter 2). Sequential/cyclical variations in lithology in the Lisburne Group indicate repeated migration of paleoenvironments at two scales. Large-scale transgressive-regressive successions/ depositional sequences (hundreds of meters in thickness) record major long-term fluctuations in relative sea level that formed over periods of 5 to 20 m.y. Smaller scale parasequences are superimposed on the overall transgressive-regressive successions/depositional sequences, and represent high-frequency relative sea-level fluctuations.

Sequence stratigraphy uses unconformities and other stratal discontinuity surfaces to logically subdivide and correlate sedimentary successions (Van Wagoner et al., 1988; Einsele and Ricken, 1991; Vail et al., 1991). Depositional sequence analysis was originally developed for interpretation of seismic data but has been extended to outcrop and well data. Sequence boundaries are marked by unconformities or their correlative conformities. Type 1 sequence boundaries are erosional unconformities whereas Type 2 sequence boundaries show evidence of subaerial exposure but lack significant erosion. Vail and others (1991) explain the latest terminology and concepts used in depositional sequence analysis. Depositional sequences can be further subdivided into the following systems tracts: lowstand, transgressive (retrograding highstand), highstand (prograding highstand) and shelf margin (Posamentier et al. 1988; Posamentier and Vail, 1988; Jervey, 1988; Vail et al., 1991). Systems tracts were developed to link contemporaneous siliciclastic depositional systems, but they also have been applied to carbonates (Sarg et al., 1988). The boundaries between systems tracts are supposedly correlatable surfaces.

Three large-scale transgressive-regressive successions/depositional sequences in the Lisburne Group provide a means of regional correlation, perhaps

representing second- or third-order depositional sequences. These sequences formed in response to regional subsidence patterns, but also may be related to major eustatic fluctuations (Van Wagoner et al., 1988; Einsele and Ricken, 1991; Vail et al., 1991). The lowest transgressive-regressive succession, **Sequence A**, begins above the regional sub-Mississippian unconformity with deposition of the Endicott Group and continues into the Alapah Limestone. A series of subaerial-exposure surfaces in the upper Alapah are associated with intertidal deposits, represent the maximum lowstand/regression, and approximate a Type 2 sequence boundary. The second transgressive-regressive succession, **Sequence B**, includes the uppermost Alapah, lower Wahoo Limestone and lowest upper Wahoo Limestone. An indistinct Type 2 sequence boundary between Sequences B and C is marked by local intertidal and restricted-platform deposits and an influx of quartz silt in the lower upper Wahoo, both indicating an overall lowstand/regression. The last transgressive-regressive succession, **Sequence C** represents most of the upper Wahoo Limestone and is truncated at the top by the regional sub-Permian unconformity beneath the Echooka Formation, a Type 1 sequence boundary.

SEQUENCE A: ENDICOTT GROUP TO UPPER ALAPAH LIMESTONE

Overall, the Endicott Group and lower to middle Alapah Limestone represent a major transgressive systems tract (retrogradational highstand of Vail et al., 1991), passing from fluvial to marginal marine to carbonate-platform depositional systems (Figs. 1-4 & 1-18). The transgression began in southern ANWR in the Tournaisian (Early Mississippian, Osagean) as indicated by marine limestones in the Kayak Shale (locality southwest of Bathtub Ridge; Anderson, 1993). Northern ANWR was not inundated until the late Visean (Late Mississippian, early Chesterian, Mamet Zone 16s) as indicated by marine limestones of the basal Alapah that directly overlie the sub-Mississippian unconformity (locality 8 on Fig. 1-2). Carbonate cycles of the lower Alapah, particularly the Egaksrak grainstone unit, represent small-scale parasequences superimposed on the overall transgressive succession. The parasequences record repeated migration of shoals and adjacent lagoons across a shallow inner ramp located at the northern margin of the Alapah carbonate platform (Figs. 1-7, 1-9, & 1-16). The middle Alapah formed in somewhat deeper open-platform conditions where small-scale fluctuations in sea level had little effect, representing the maximum highstand/transgression in the Alapah and containing the maximum flooding surface in Sequence A. The middle Alapah passes gradationally into the upper Alapah Limestone that formed on a broad restricted platform periodically subjected to intertidal conditions and subaerial exposure (Figs. 1-16 & 1-18). The regressive trend seen in the middle to upper Alapah can be interpreted as a highstand (progradational highstand) systems tract (c.f. Van Wagoner et al., 1988; Vail et al., 1991); the shallowing-upward trend is due to the aggradation and/or progradation of platform carbonates. Up to four intervals of intertidal deposits and subaerial exposure surfaces in the upper Alapah formed during relative lowstands of sea level in parasequences superimposed on this overall lowstand, together representing the maximum lowstand/regression and sequence boundary at the top of Sequence A. Brines generated during this lowstand

percolated through the underlying part of the upper Alapah and into the middle Alapah as indicated by pseudomorphs after evaporites.

The subaerial exposure surfaces (see Chapter 3) and general lack of evidence of an unconformity indicates that the top of Sequence A is a Type 2 sequence boundary. Although aggradation/progradation of carbonates can explain the shallowing to intertidal conditions, evidence of subaerial exposure implies the relative lowering of sea level (possibly glacioeustatic). It is possible that an unconformity exists farther updip near Prudhoe Bay (Schoennagel, 1977; Jameson, in revision). Farther to the south, part of the open- to restricted-platform deposits of the transitional unit of the upper Alapah Limestone may represent a shelf-margin systems tract that formed during the time when the northern part of the Lisburne platform was emergent. The age of sequence boundary is imprecise because of the lack of age-diagnostic fauna in restricted-platform to intertidal carbonates of the upper Alapah, but is Namurian (late Chesterian, Mamet Zone 17-18 to latest Chesterian, Upper *muricatus* conodont zone). This unconformity could correspond to the interregional Kaskaskia-Absaroka sequence boundary of Sloss (1963, 1988). It does not coincide with the Mississippian-Pennsylvanian boundary as is typical on the craton, but instead occurs within upper Chesterian strata (i.e., during latest Mississippian time, Sloss, 1988). This reduced hiatus may be due to greater subsidence rates and more continuous deposition in the passive-margin succession (miogeosynclinal) of northern Alaska than on the craton (Sloss, 1963, 1988).

SEQUENCE B: ~LOWER WAHOO LIMESTONE MEMBER

Sequence B approximates the lower Wahoo Limestone member but also includes the uppermost Alapah Limestone and the lowermost upper Wahoo Limestone member and represents the second large-scale transgressive-regressive succession/depositional sequence in the Lisburne Group(Fig. 1-4). Restricted platform carbonates of the uppermost Alapah pass gradationally up into open-marine carbonates of the lower Wahoo, representing a major flooding surface and a relatively rapid transgression in the lower part of a transgressive (retrograding highstand) systems tract. The lower Wahoo is dominated by open-marine carbonates organized into four or five parasequences representing relative sea-level fluctuations between below and above wave base; the maximum flooding surface falls within this interval. The maximum regression and sequence boundary between Sequence B and C occurs in the lower part of the upper Wahoo member as indicated by the maximum influx of terrigenous quartz and the local occurrence of cryptalgalaminate, signifying local intertidal conditions in northern ANWR (loc. 8, Figs. 1-2 & 1-18). To the south, restricted-platform deposits and more distal ooid shoals also indicate the maximum regression farther down the carbonate ramp (locs. 10-12, Fig. 1-2). Although local evidence of erosion was recognized in northern areas, this appears to represent another Type 2 sequence boundary, with no evidence of a significant hiatus. This maximum regression probably correlates with a significant influx of terrigenous sediment in the lower sandy limestone of the Wahoo Limestone farther updip at Prudhoe Bay (Jamison et al, 1980; see below).

Within Sequence B in the eastern Sadlerochit Mountains (loc. 8, Fig. 1-2, 1-13 &1-13), the Mississippian-Pennsylvanian boundary may be a subaerial exposure surface with minor paleotopography (see Chapter 3), but it is not a significant unconformity. Strangely, this interval approximates the maximum transgression/flooding surface in Sequence B and no major changes in microfacies or inferred depositional environments occur across the systemic boundary. In the Fourth Range (loc. 10 on Fig. 1-2), an unconformity of considerable magnitude may occur at the Mississippian-Pennsylvanian boundary. Rocks containing conodonts of the Upper *Rhachistognathus muricatus* Subzone of latest Chesterian age are overlain by rocks containing conodonts of late Morrowan or early Atokan age (the *Idiognathodus* Fauna, see Chapter 3). However, this would not represent an unconformity if the unusually low occurrence of *Idiognathodus* is due to stratigraphic leak from higher strata along solution pipes extending down from local karst breccias beneath the sub-Permian unconformity.

If an unconformity does occur at this level, then this calls into question the sequence and parasequence analysis that was completed prior to the conodont study (Gruzlovic, 1991 and summarized below). This would require changes in the correlation of parasequences shown on Figure 1-25 and other figures based on these correlations (Fig. 1-26 to 1-28; see below). For the sake of discussion in this chapter, we ignore the consequences of this possible unconformity and assume that stratigraphic leak is the best explanation. Chapter 6 will consider the importance of this possible unconformity and its repercussions for sequence and parasequence stratigraphy and correlation. If the unconformity in the lower Wahoo really exists, then it stands as a warning against using sequence stratigraphy without adequate biostratigraphic age control.

SEQUENCE C: ~UPPER WAHOO LIMESTONE MEMBER

Sequence C, the transgressive-regressive succession/depositional sequence comprising the rest of the upper Wahoo is superimposed by numerous parasequences and carbonate cycles. The nature of parasequences in a vertical succession shows a general retrogradation followed by a progradation of carbonate-ramp depositional environments, but varies depending on their position of the Wahoo carbonate ramp.

For example, in the central part of the Wahoo ramp (e.g., loc. 10, Figs. 1-2 & 1-7), skeletal-spiculitic parasequences (restricted marine/lagoonal) pass upward into skeletal-oolitic parasequences (shoal), which in turn grade into shale-based parasequences (deeper water); together representing a transgressive (retrograding highstand) systems tract. The deepest water shale-based parasequences correspond to the maximum flooding surface. The upper part of the upper Wahoo shows a progradational/regressive trend from the shale-based parasequences back into skeletal-oolitic parasequences, indicating a transition from deeper-water to shoal conditions and representing a highstand (progradational highstand) systems tract.

In a more landward position (loc. 6-8, Figs. 1-2, 1-11, & 1-18), skeletal-cryptalgal parasequences (intertidal) pass up into oolitic parasequences (shoal) and finally peloidal-oncolitic parasequences (restricted platform-lagoon), indicating the same overall transgressive-regressive succession/depositional sequence. Seaward (loc. 20, Figs. 1-2, 1-12, 1-18, & 1-22), a thick succession of Wahoo Limestone is dominated by open-marine limestones with indistinct parasequences. These mostly Pennsylvanian limestones are lithologically similar to the Mississippian part of the lower Wahoo, showing minor fluctuations of environments above and below wave base. It is unclear if any of the additional thickness resulted from deposition in a shelf-margin systems tract or simply from additional accommodation space associated with greater subsidence rates on the outer part of the Wahoo ramp.

The top of the Wahoo is truncated by a major regional unconformity beneath the Permian Echooka Formation (Figs. 1-4 & 1-5). This Type 1 sequence boundary is marked by a significant ravinement surface incised into the upper Wahoo. The age of the upper Wahoo is youngest (Atokan) in northern ANWR and generally older (Morrowan and Chesterian) to the south and west (Watts et al., 1992). A slightly thicker and younger Atokan-age succession occurs at Prudhoe Bay (Armstrong and Mamet, 1974; Jameson, 1990a, 1990b, in revision). The age of the Echooka is not tightly constrained but ranges from Artinskian to Ufimian (Leonardian) in the south to Kazanian (Guadelupian) in the north (Detterman et al., 1975). This unconformity has been attributed to regional epeirogenic uplift, sometime between Middle Pennsylvanian and Early Permian (Bird et al., 1987).

PARASEQUENCES IN THE WAHOO LIMESTONE

Like other ancient carbonate successions (Wilkinson, 1982; James, 1984b), the Carboniferous Wahoo Limestone is composed of a series of small-scale carbonate cycles. Many of these are shallowing-upward (progradational) cycles that have recently been termed parasequences, defined as relatively conformable successions of genetically related beds bounded by marine-flooding surfaces (Van Wagoner et al., 1988). In the Lisburne Limestone, such parasequences are most evident in the lower Alapah and the upper Wahoo limestones, where distinctive shoal or intertidal deposits occur (Figs. 1-16 & 1-18). Parasequences are difficult to recognize in areas dominated by open-platform or open-marine carbonates that were not significantly influenced by relative sea-level fluctuations. Our most detailed analysis of carbonate cycles has focused on the Wahoo Limestone. Microfacies analyses supplemented by field observations were used to interpret depositional environments. Systematic thin section collections at 0.5-meter intervals allowed us to document progressive changes in carbonate lithology that resulted from relative sea-level fluctuations and the migration of carbonate environments. Abrupt changes in lithology and inferred depositional environments mark parasequence boundaries, and typically indicate rapid transgression and transition to more seaward environments. Iterative analyses of numerous parasequences allowed us to refine our facies models and to

illustrate the interrelationships between different microfacies on the Wahoo carbonate ramp (Fig. 1-18).

Carlson (1987) documented the cyclic stratigraphy of the Wahoo Limestone in three stratigraphic sections in the eastern Sadlerochit Mountains (locs. 6- 8, Figs. 1-2, 1-11, & 1-23). Several paraconformities within the sequence were first recognized by Mamet (pers. comm., 1987; Mamet and DeBatz, 1987, 1989), based on the occurrence of *Palaeomicrocodium* (a perforating algae, associated with emergence and subaerial exposure) and/or abrupt changes in microfacies. Analyses of diagenesis indicate that significant changes in cement stratigraphy also occur across the paraconformities and they indicate that differences in early diagenesis are associated with subaerial exposure (see below). The paraconformities can be used to subdivide the upper Wahoo into different subunits (parasequence sets), each characterized by different types of lithologic cycles; they also serve as a means of correlation within a sequence stratigraphic framework (Figs. 1-11 & 1-23; Carlson, 1987).

COMPOSITE PROGRADATIONAL SUCCESSION OF THE WAHOO LIMESTONE

Gruzlovic (1991) examined three stratigraphic sections of the Lisburne Group representing a downdip profile across the Wahoo carbonate ramp (locs. 10-12, Figs. 1-2 & 1-7). Gradational changes in the composition of parasequences occur between different areas and within individual vertical successions. However, selected diagnostic characteristics of parasequences allowed them to be logically grouped into parasequence sets. The overlapping nature of lithologic changes in three types of parasequence sets were used to construct a model illustrating the progression of microfacies expected to develop from the progradation of different environments across the Wahoo carbonate ramp (Figs. 1-18 & 1-24). Although the entire succession does not occur within a single parasequence, they provide a conceptual basis for interpreting the range of depositional environments represented by the different parasequences and parasequence sets.

In relatively deep-water shale-based parasequences, the progradational succession typically begins with thin intervals of shale, argillaceous spiculitic limestone and microdolomite that formed in deep-water outer-ramp conditions. A few parasequences begin with thin, basal beds containing highly abraded, skeletal-intraclastic grainstone representing transgressive lag deposits that formed under shallow high-energy conditions during the initial rise in sea level. The spiculitic limestone is overlain by a thick interval of dolomitic bryozoan-pelmatozoan wackestone and packstone containing full-frond (intact) fenestrate bryozoans that are locally argillaceous at the base, indicating the establishment of normal-marine fauna under open-marine below wave-base conditions. The packstone passes gradationally upward into a thick interval of bryozoan-pelmatozoan grainstone, indicating progressively shallower open-marine conditions that passed above wave-base. Grain abrasion and micritization increase in intensity from the argillaceous, skeletal wackestone and packstone upward into superficial and oolitic grainstone (Fig. 1-24). Full-frond (intact) fenestrate bryozoans and pelmatozoans with

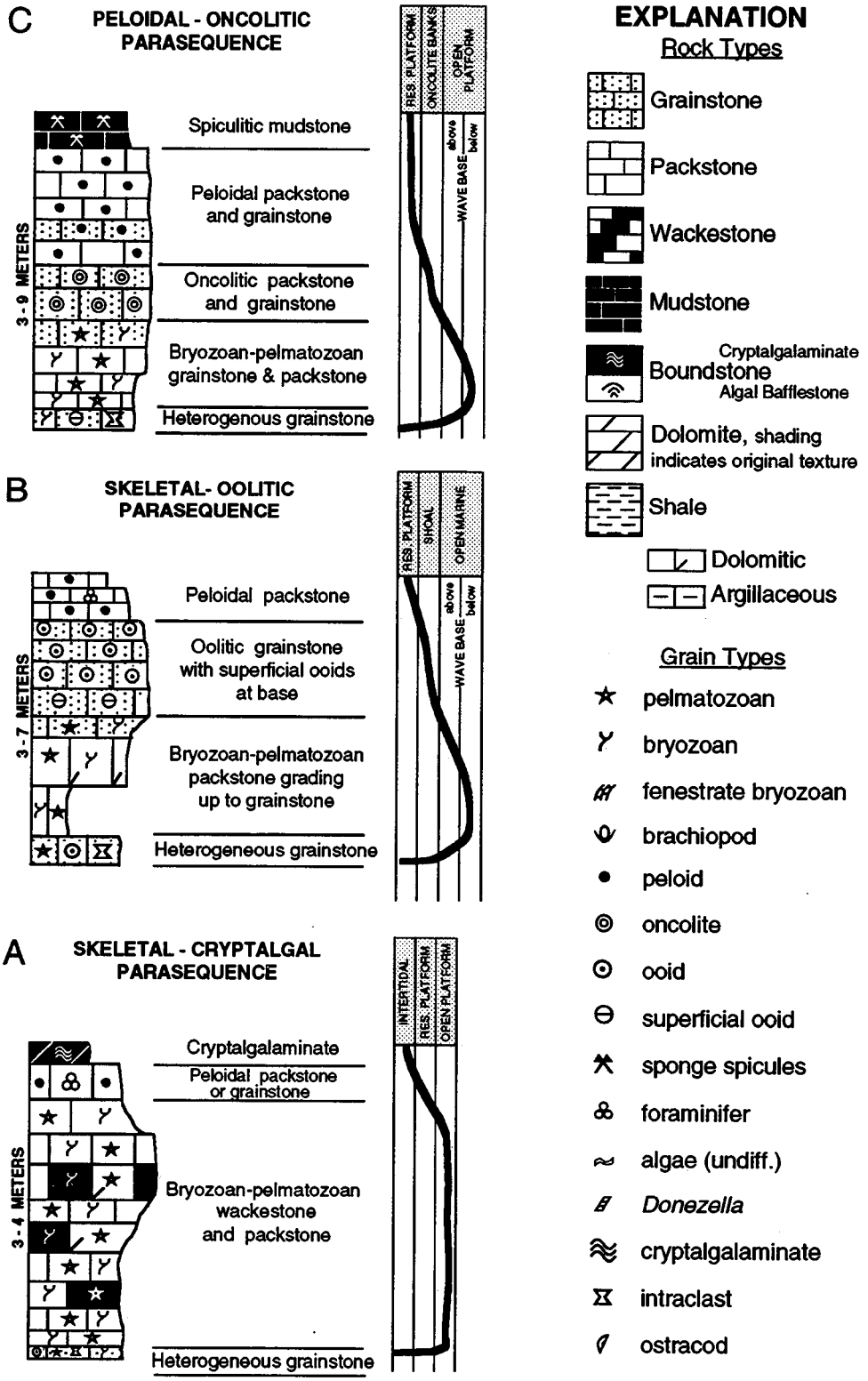


Figure 1-23. Parasequences (shallowing-upward cycles) of the Pennsylvanian upper Wahoo Limestone of northern ANWR (modified from Carlson, 1987).
A - Peloidal-oncolitic parasequences of the upper upper Wahoo Limestone.
B - Skeletal-oolitic parasequences of the middle upper Wahoo Limestone.
C - Skeletal-cryptalgal parasequences of the lower upper Wahoo Limestone

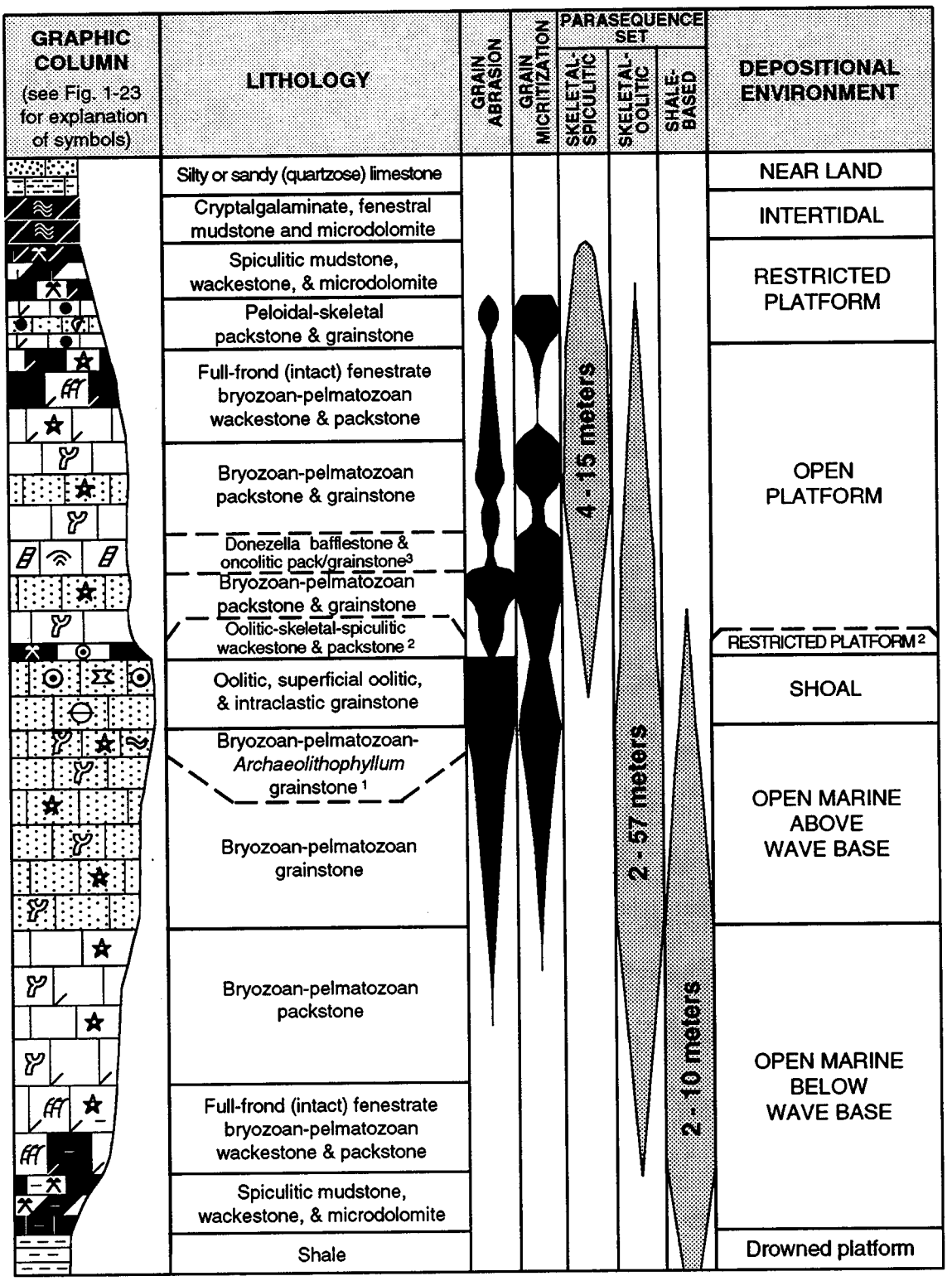


Figure 1-24. Idealized progradational succession of carbonate microfacies recognized in the Wahoo Limestone (modified from Gruzlovic, 1991). This diagram synthesizes the vertical facies changes seen in the numerous parasequences that comprise the Wahoo. Lithologies that are not always present are indicated with footnotes: 1)restricted to the upper Wahoo; 2) occurs infrequently in the Wahoo; and 3) restricted to the Atokan part of the Wahoo (as indicated by foraminiferan biostratigraphy).

articulated stems are common in slightly abraded and micritized, skeletal wackestone and packstone, whereas highly abraded skeletal grains form the nuclei of extensively micritized ooids and superficial ooids in oolitic and superficial oolitic grainstones.

The Wahoo Limestone is dominated by skeletal-oolitic parasequences containing principally skeletal (bryozoans and pelmatozoans) and oolitic limestone. The basal beds of skeletal-oolitic parasequences commonly are slightly abraded and micritized, bryozoan-pelmatozoan wackestone and packstone that are overlain by slightly to moderately abraded and micritized, bryozoan-pelmatozoan grainstone, indicating deposition in below and above wave-base open-marine conditions, respectively. In skeletal-oolitic parasequences in the lower Wahoo member (Sequence B), most parasequences alternate between skeletal packstone and grainstone. Less commonly, bryozoan-pelmatozoan grainstone is overlain by cross-bedded, superficial oolitic and oolitic grainstone, indicating progressive shallowing into the high-energy shoal environment. Oolitic grainstone is more common in the upper Wahoo member. In the upper Wahoo member (Sequence C), bryozoan-pelmatozoan limestones typically pass upward into a thin interval of moderately to highly abraded and micritized, bryozoan-pelmatozoan-*Archaeolithophyllum* grainstone overlain by a thicker interval of cross-bedded, superficial oolitic and oolitic grainstone (Figs. 1-18 & 1-24). The lithologies that overlie oolitic and superficial oolitic grainstone are less predictable in grain assemblage and texture (Fig. 1-24). The most common lithologies are a variably abraded and mostly moderately to highly micritized, bryozoan-pelmatozoan packstone and grainstone that formed under open-platform conditions. In Atokan-age rocks from the central Shublik Mountains and the Fourth Range, skeletal packstone and grainstone are interbedded with *Donezella* bafflestone and grainstone that formed small bioherms in moderate-energy, open-platform conditions. Less commonly, oolitic grainstone is directly overlain by a thin interval of skeletal-oolitic-spiculitic or peloidal-skeletal wackestone and packstone that formed in protected areas behind the shoal. Some skeletal-oolitic parasequences that do not contain superficial oolitic and oolitic grainstone are capped by a thick interval of variably abraded and mostly moderately to highly micritized, bryozoan-pelmatozoan packstone and grainstone that locally contain ooids and *Archaeolithophyllum*. In northern areas (locs. 6-8, Fig. 1-2), oolitic grainstone is directly overlain by a thin interval of peloidal-skeletal packstone and grainstone or skeletal-oolitic-spiculitic wackestone and packstone (Fig. 1-23).

In the upper part of the composite progradational succession (Fig. 1-24), skeletal-spiculitic parasequences begin with slightly abraded and dolomitic, full-frond (intact) fenestrate bryozoan-pelmatozoan wackestone and packstone beds containing minor (1% to 4%) detrital quartz silt. Near the top, peloidal-skeletal packstone and grainstone is overlain by spiculitic limestone and microdolomite, and generally contains a greater amount (1% to 7%) of detrital quartz silt. In the Wahoo Limestone of northern ANWR, dolomitic cryptalgalaminate that formed in intertidal conditions represents the most landward depositional environment in the composite progradational succession (Fig. 1-18 & 1-24). In the Prudhoe Bay area,

terrigenous siltstone and sandstone punctuating some cycles could represent relatively shallow marine terrigenous sediments that formed adjacent to the paleoshoreline, but most terrigenous shales are thought to be deeper marine deposits that indicate incipient platform drowning events bounding parasequences in the upper Wahoo (Sequence C).

The majority of the parasequences in the Wahoo Limestone in the study area formed entirely in subtidal conditions as indicated by shallow-marine, skeletal and non-skeletal (oolitic and intraclastic) limestones. Parasequences in the Wahoo Limestone are mostly progradational and represent transitions from open-marine, shoal, open-platform, and restricted-platform depositional environments (Figs. 1-19 & 1-20). Intertidal deposits in the Wahoo Limestone were recognized only in the northern part of ANWR in lowstand deposits marking the boundary between sequences B and C (locs. 7 & 8, Fig. 1-2). Subaerial exposure surfaces occur at several levels as a diagenetic overprint on mostly subtidal deposits (see Chapter 3). However, most of the parasequences did not shallow to above sea level (supratidal environments), where carbonate sedimentation would have been inhibited due to subaerial exposure (an autocyclic mechanism for the development of carbonate cycles). Thus, an allocyclic mechanism, such as glacioeustatic fluctuation, is more likely to have induced the development of carbonate cycles and parasequences in the Wahoo.

One of the ultimate goals of the work was to test whether parasequences could be used as a means of correlation and to model sea-level fluctuations. However, without having an independent means of correlation, correlating such small-scale parasequences generally is a subjective exercise in pattern matching. Unfortunately, many age-diagnostic conodonts (e.g. Baesemann and Lane, 1985; see Chapter 2) have not been found in northern Alaska and we discovered inconsistencies in Mamet's microfossil zonation, so high-resolution biostratigraphic control is unavailable. Correlation by lithostratigraphy and sequence stratigraphy also lack sufficient resolution and could be disrupted by paraconformities and small unconformities. Thus, it is difficult to make high-resolution correlations of individual parasequences with any degree of confidence. However, grouping similar parasequences into parasequence sets may help define trends in depositional history and paleogeography, particularly within the sequence-stratigraphic framework discussed above.

PARASEQUENCE SETS IN THE WAHOO LIMESTONE

The parasequences in the Wahoo Limestone can be grouped into shale-based, skeletal-oolitic, and skeletal-spiculitic parasequence sets (Fig. 1-25). Parasequence sets are composed of 4 to 8 vertically stacked parasequences that are genetically related as indicated by similar ranges of lithologies. Shale-based parasequences formed in relatively deep-water, open-marine outer-ramp environments. The skeletal-oolitic parasequences formed in open-marine, shoal, and open-platform depositional environments under a range of water depths. Skeletal-spiculitic parasequences

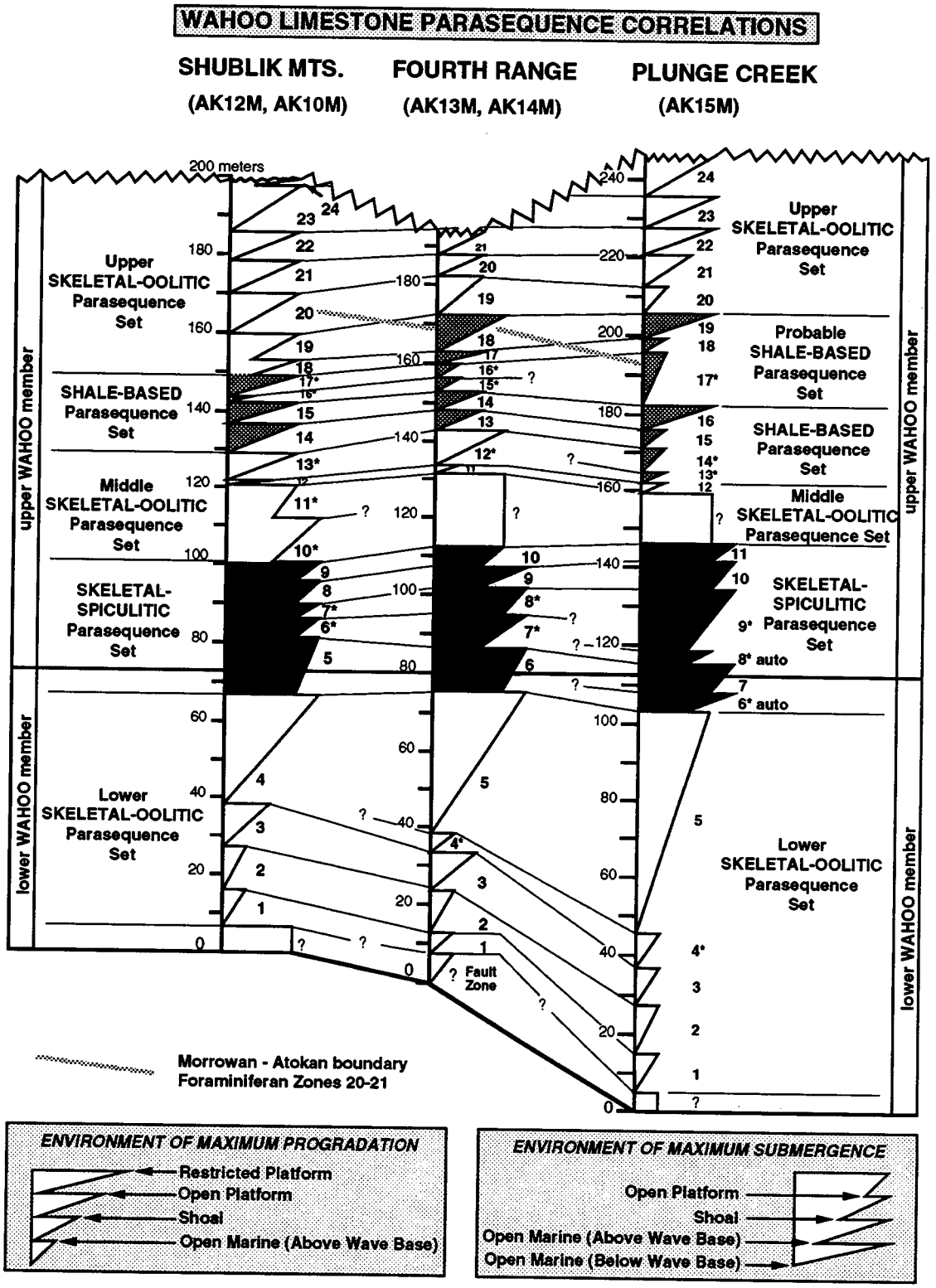


Figure 1-25. Preliminary correlation of parasequences and parasequence sets in the Wahoo Limestone (from Gruzlovic, 1991). The zigzag lines show the environments of maximum submergence and progradation of each parasequence. Numbers refer to parasequences in ascending order from the base of the Wahoo; asterisks indicate a lack of obvious correlation. This diagram does not account for new conodont data that indicate a possible intraformational unconformity within the lower Wahoo at the Fourth Range section (see Fig. 1-7, Chapters 2 and 6, compare with Fig. 6-3)).

formed in relatively shallow water in open-platform to restricted-platform depositional environments behind coeval shoals. The vertical succession of parasequence sets defines two large-scale cycles or transgressive-regressive successions (Sequences B and C) in the Wahoo Limestone.

Parasequences, parasequence sets, and transgressive-regressive successions/ depositional sequences can be used, with varying success, for detailed correlation in the Wahoo Limestone. The thickness and the lithologies of the parasequences and parasequence sets vary in a predictable pattern from north to south in the study area. The Wahoo Limestone thickens toward the south reflecting increased subsidence rates in a basinward direction (Fig. 1-2). Variations in lithology and associated variations in sedimentation rates apparently influenced the thickness of individual parasequences and parasequence sets in the Wahoo Limestone.

Skeletal-oolitic parasequences are the dominant part of the Wahoo Limestone in ANWR and are assigned to three separate skeletal-oolitic parasequence sets (Fig. 1-25). The lower skeletal-oolitic parasequence set comprises the bulk of the lower Wahoo member (Sequence B). The middle skeletal-oolitic parasequence set occurs in a transgressive (highstand retrogradational) systems tract of Sequence C between the skeletal-spiculitic set below and the shale-based parasequence set above. The upper skeletal-oolitic parasequence set forms the upper part of the upper Wahoo member and represents the highstand (highstand progradational) systems tract of Sequence C truncated at the top by the sub-Permian unconformity (Fig. 1-25). The widespread distribution of repeated intervals of oolitic grainstone that define these parasequences indicate that ooid shoals migrated repeatedly across the Wahoo ramp (Fig. 1-22). Ooids are not as abundant in the lower Wahoo (Sequence B) as in the upper Wahoo (Sequence C).

In northern ANWR (locs. 6-8, Figs. 1-2 & 1-11), a skeletal-cryptalgal parasequence set in the lower part of the upper Wahoo (Sequence C) correlates with the skeletal-spiculitic parasequence set farther to the south. Most of the upper Wahoo (Sequence C) is represented by a single skeletal-oolitic parasequence set that brackets the maximum transgression (maximum flooding surface) without the intervening shale-based parasequence set recognized farther to the south (loc. 6-8, Fig. 1-11 vs. loc. 10-12, Fig. 1-25). The upper part of the unit consists of peloidal-oncolitic parasequences that represents a progradational highstand systems tract and correlates (in part) with the upper skeletal-oolitic parasequence set farther to the south.

LOWER WAHOO—SEQUENCE B

Lower skeletal-oolitic parasequence set

Above the non-cyclic, basal part of the lower Wahoo Limestone member, four to five skeletal-oolitic parasequences are among the thickest parasequences in the Wahoo Limestone (Fig. 1-25). The lower part of each parasequence is bryozoan-pelmatozoan wackestone and packstone deposited in open-marine (below wave

base) conditions. The parasequences pass upward into bryozoan-pelmatozoan grainstone that formed in an open-marine (above wave base) setting. Some of the parasequences (3 out of 14 parasequence analyzed in 3 sections) contain thin, oolitic grainstone capping beds deposited in a shoal environment (Fig. 1-25). An upward increase of bryozoan-pelmatozoan wackestone and packstone reflect a gradual overall rise in relative sea level to a maximum transgression (maximum flooding surface) in the middle part of the lower Wahoo member (Figs. 1-4 & 1-25). The skeletal-oolitic parasequence set and its component parasequences in the lower Wahoo member both thicken southward, due to increased subsidence and accommodation space (Fig. 1-25). Above a maximum flooding surface, just below the Mississippian-Pennsylvanian boundary, the lower Wahoo Limestone member begins to shallow-upward and the highest skeletal-oolitic parasequence is capped by open- and restricted-platform deposits (Fig. 1-25).

LOWER UPPER WAHOO —LOWSTAND AT SEQUENCE B TO C TRANSITION

The maximum regression/lowstand in the Wahoo occurs in the lower part of the upper Wahoo Limestone member, approximating the sequence boundary between Sequences B and C (Figs. 1-4 & 1-25). Lateral facies changes result in changes in the nature of parasequences from skeletal-cryptalgal in the north to skeletal-spiculitic in the south. This represents a transition from intertidal conditions across a restricted platform (lagoon) to shoals in the south (over a present distance of 73 km / 46 miles; locs. 8, 10-12, Figs. 1-2 & 1-18).

Skeletal-cryptalgal parasequence set

In the eastern Sadlerochit Mountains (locs. 7-8, Fig. 1-2 & 1-11), the lowest parasequences in the upper Wahoo Limestone culminate in cryptalgalaminate (Fig. 1-23; Carlson, 1987). The cryptalgalaminate is poorly developed. laterally discontinuous and is particularly questionable in the upper part of the interval. The skeletal-cryptalgal parasequence set may be up to 47 m thick if the upper parasequences really contain cryptalgalaminate. In the lower part of the set, irregular cryptalgalaminate within a thick interval of dolomicrite contain abundant quartz sand and silt (35-50%) and are the best developed intertidal deposits. This interval of dolomite is barren of age-diagnostic foraminifers and algae and contains a mixture of redeposited conodonts (Mamet, pers. comm. 1987; see Chapter 2). In the lower part of each parasequence, wackestone and packstone pass up into grainstone, all containing abundant bryozoans and pelmatozoans that indicate open-platform conditions. In the upper part of the parasequences, rippled peloidal bioclastic grainstone with minor ooids pass up into thin-bedded sandy dolomitic cryptalgalaminate, representing restricted-platform and intertidal deposits.

Two possible paraconformities occur in the skeletal-cryptalgal parasequence set (Carlson, 1987). The lower paraconformity occurs at the base of the upper Wahoo Limestone (approximating the boundary between Sequences B and C) and is marked by an abrupt facies change from bryozoan-pelmatozoan packstone to cryptalgalaminate and local channels filled by peloidal-bioclastic grainstone

(Carlson, 1987). Another localized paraconformity (5 to 15 meters above the base of upper Wahoo) is marked by a transition between bryozoan-pelmatozoan packstone and quartz-rich, calcisphere packstone. *Palaeomicrocodium*, a perforating algae associated with subaerial exposure occurs above each paraconformity (Mamet, pers. comm., 1987). Carlson also found diagenetic evidence of two subaerial exposure surfaces within the skeletal-cryptalgal parasequence set (Fig. 1-11; see Chapter 3, subaerial exposure surfaces xiv and xv). These paraconformities and/or subaerial exposure surfaces indicate that the skeletal-cryptalgal parasequence set formed during a maximum regression and approximates a sequence boundary.

Skeletal-spiculitic parasequence set

To the south (loc. 10, Fig. 1-2), the lower part of the upper Wahoo Limestone lacks cryptalgalaminate but is represented by the skeletal-spiculitic parasequence set. These parasequences contain skeletal (mostly bryozoan and pelmatozoan) limestone that passes upward into peloidal-skeletal and spiculitic limestone and microdolomite (Figs. 1-15 & 1-18). Lime mud increases upward in skeletal-spiculitic parasequences and commonly is partially replaced by ferroan dolomite (Figs. 1-15 & 1-18). Detrital quartz silt generally increases from the base of the skeletal-spiculitic parasequences (1% to 2%) to the top (3% to 7%). Skeletal-spiculitic parasequences range from 4 to 15 meters in thickness and form the uppermost part of the lower Wahoo member and the lower part of the upper Wahoo member (Fig. 1-25). Thus, the lithostratigraphic boundary between the informal members is gradational and defined at the top of the mappable cliff formed by the lower Wahoo. Each parasequence represents a transition from partially restricted into restricted-platform environments. Correlative parasequences farther to the south (loc. 12, Figs. 1-2, 1-7, & 1-25) contain oolitic grainstones at the base that pass up into peloidal skeletal packstone, indicating a slightly more seaward position in a lagoon immediately behind ooid shoals on a carbonate ramp (Fig. 1-18; Gruzlovic, 1991).

The proportional thickness of open-platform, bryozoan-pelmatozoan limestone beds remains constant in the skeletal-spiculitic parasequence set throughout the study area (Fig. 1-26). However, restricted-platform, spiculitic and peloidal-skeletal limestone and microdolomite lithologies decrease in abundance toward the south, with a concomitant increase in oolitic-intraclastic grainstone, shoal deposits (Fig. 1-26). Carbonate productivity in modern restricted-platform (lagoonal) environments is less than in ooid shoal or open-marine depositional environments (Enos, 1977), which possibly explains the thickness variations in the skeletal-spiculitic parasequence set. The relatively thin parasequences in the Shublik Mountains (loc. 10, Fig. 1-2 & 1-25) could have resulted from the abundance of restricted-platform facies. At Plunge Creek, the skeletal-spiculitic parasequences are thicker because of less restricted-platform lithologies coupled with thick (2-7 meters) basal beds of oolitic grainstone that have high sedimentation rates (Fig. 1-27).

The number of parasequences in the skeletal-spiculitic parasequence set is similar in all sections (Fig. 1-25). Therefore, the southward-thickening trend of the

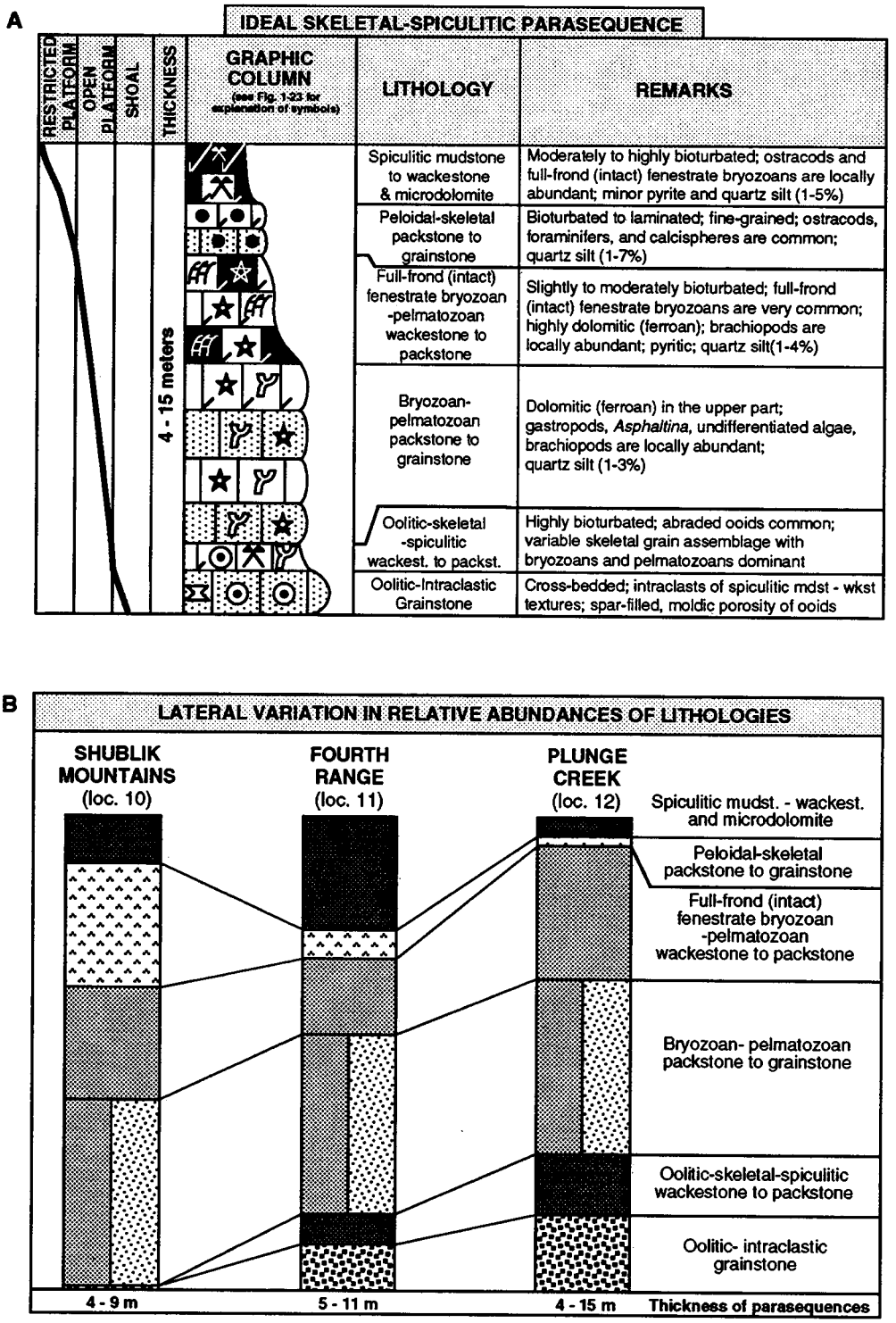


Figure 1-26. Facies relationships in the skeletal-spiculitic parasequence set of the Wahoo Limestone (from Gruzlovic, 1991).
A - Idealized detailed stratigraphic column illustrates the progradational succession of lithologies and paleoenvironmental interpretations.
B - Variations in the relative proportion of different lithologies indicates downdip lateral facies change from restricted platform in the north to shoals in the south. Does not account for age problems mentioned in Fig. 1-25 caption (see Fig. 1-7, Chapters 2 and 6).

Figure 1-27

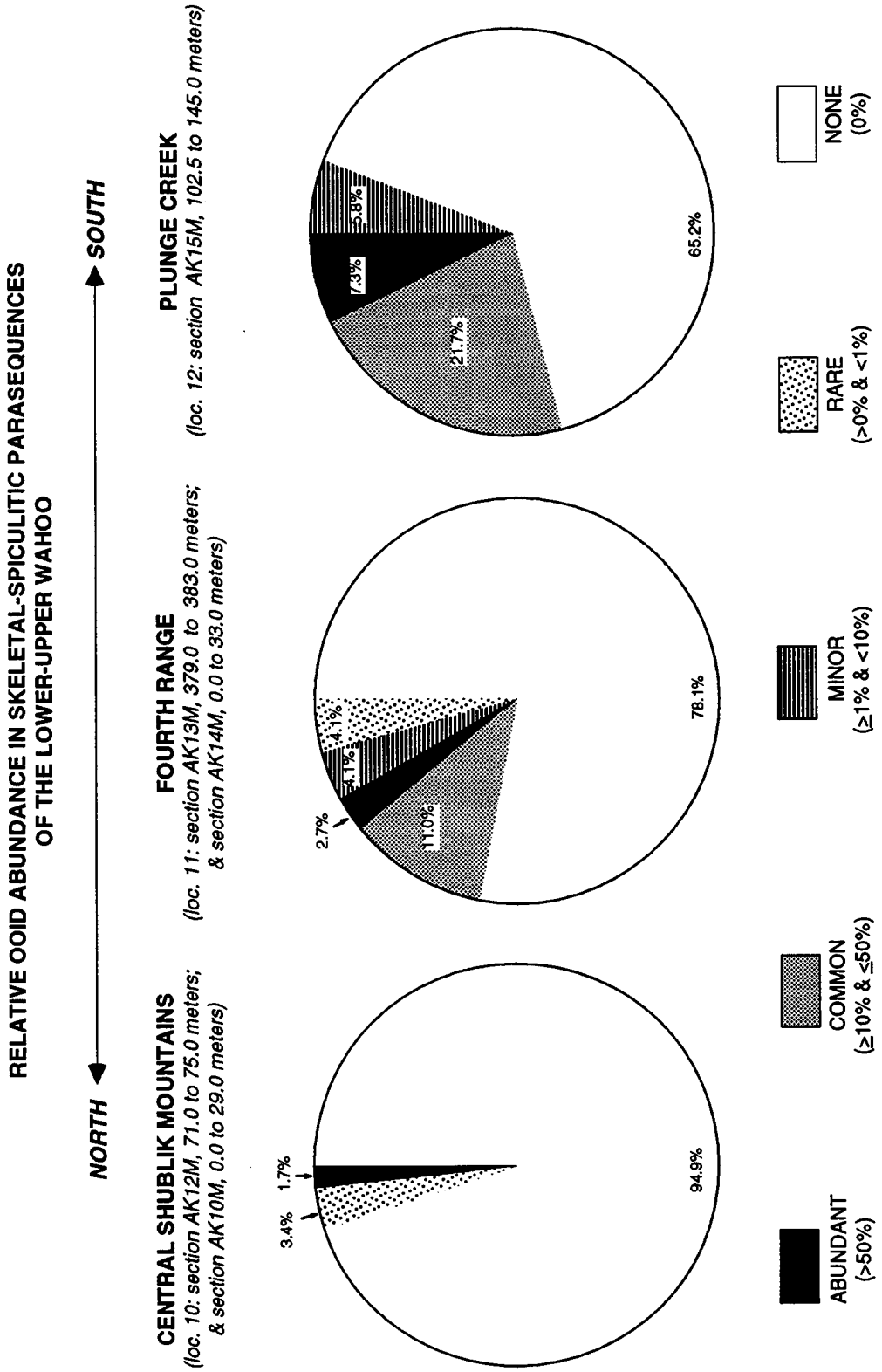


Figure 1-27. Relative abundance of oolitic grainstone (shoals) in skeletal-spiculitic parasequence set of the lower upper Wahoo along a downdip transect (locs. 10-12, Figs. 1-2, 1-12, 1-25 & 1-26). The increased abundance of ooids to the south indicates proximity to shoals during the maximum regression (lowstand, near sequence boundary) in the Wahoo. Diagram was generated using semi-quantitative data in the Wahoo database (see Chapter 5; from Gruzlovic, 1991). Does not account for age problems mentioned in Fig. 1-25 caption.

skeletal-spiculitic parasequence set is not caused by additional parasequences in the south, but instead is caused by lithologic variations and associated changes in sedimentation rates in the skeletal-spiculitic parasequences. Thus, the paleogeography during the maximum regression involved southward migration of ooid shoals and the establishment of a restricted platform (lagoon) in the north that was bounded by tidal flats adjacent to the present coastal plain of ANWR (Figs. 1-22 & 1-27).

MIDDLE UPPER WAHOO—RETROGRADATION & HIGHSTAND OF SEQUENCE C

In northern ANWR (locs. 6-8, Figs. 1-2 & 1-7), a single thick skeletal-oolitic parasequence set comprises the middle part of the upper Wahoo. Farther to the south (locs. 10-12, Fig. 1-2, 1-22 & 1-25), the middle and upper oolitic parasequence sets can be distinguished, separated by the southward-thickening shale-based parasequence set that formed in deeper water where carbonate sedimentation was more difficult to initiate.

Middle skeletal-oolitic parasequence set

In the north (locs. 6-8, Figs. 1-2 & 1-11), skeletal-oolitic parasequences overlie a possible paraconformity at the top of the skeletal-cryptalgalaminate parasequence set. Oolitic grainstone becomes increasingly common upsection, occurring in most of the parasequences in the middle part of the upper Wahoo Limestone. A typical skeletal oolitic parasequence may begin with a basal heterogeneous transgressive lag deposit (Fig. 1-23). The majority of a parasequence is progradational (regressive) with bryozoan-pelmatozoan packstone passing gradationally upward into oolitic grainstone. Some are capped by peloidal packstone. The gradational transition between skeletal limestones and oolitic grainstone is evident in increasing amounts of grain abrasion and rounding in skeletal grains, in the increase in micritization (probably by endolithic algae), and in the progressive development of superficial ooids and multiple-layered ooids. These transitions resulted from the progradation of ooid shoals over open-marine facies on the Wahoo ramp (Figs. 1-22 & 1-23). The peloidal packstones formed in restricted-platform (lagoonal) conditions immediately behind the ooid shoals. Oolitic grainstones are best developed in northernmost ANWR, farthest up the ramp (loc. 6, Figs. 1-2, 1-11, & 1-28).

In the eastern Sadlerochit Mountains (locs. 6-8, Fig. 1-2 & 1-11), a possible paraconformity within the interval containing oolitic parasequences coincides with the Morrowan/Atokan boundary (as defined by foraminiferan biostratigraphy) and is overlain by *Donezella* algal bafflestone with *Palaeomicrocodium* (Carlson, 1987; Mamet, pers. comm., 1987). Evidence of subaerial exposure occurs near this boundary (Fig. 1-11; see Chapter 3, subaerial exposure surface xvii). The introduction of *Donezella* coincides with the advance of open-platform conditions associated with ooid shoals and the progradational highstand systems of Sequence C. Thus, a single thick oolitic parasequence set occurs in northern areas where ooid shoals formed during the maximum transgression (maximum flooding surface) in

Figure 1-28

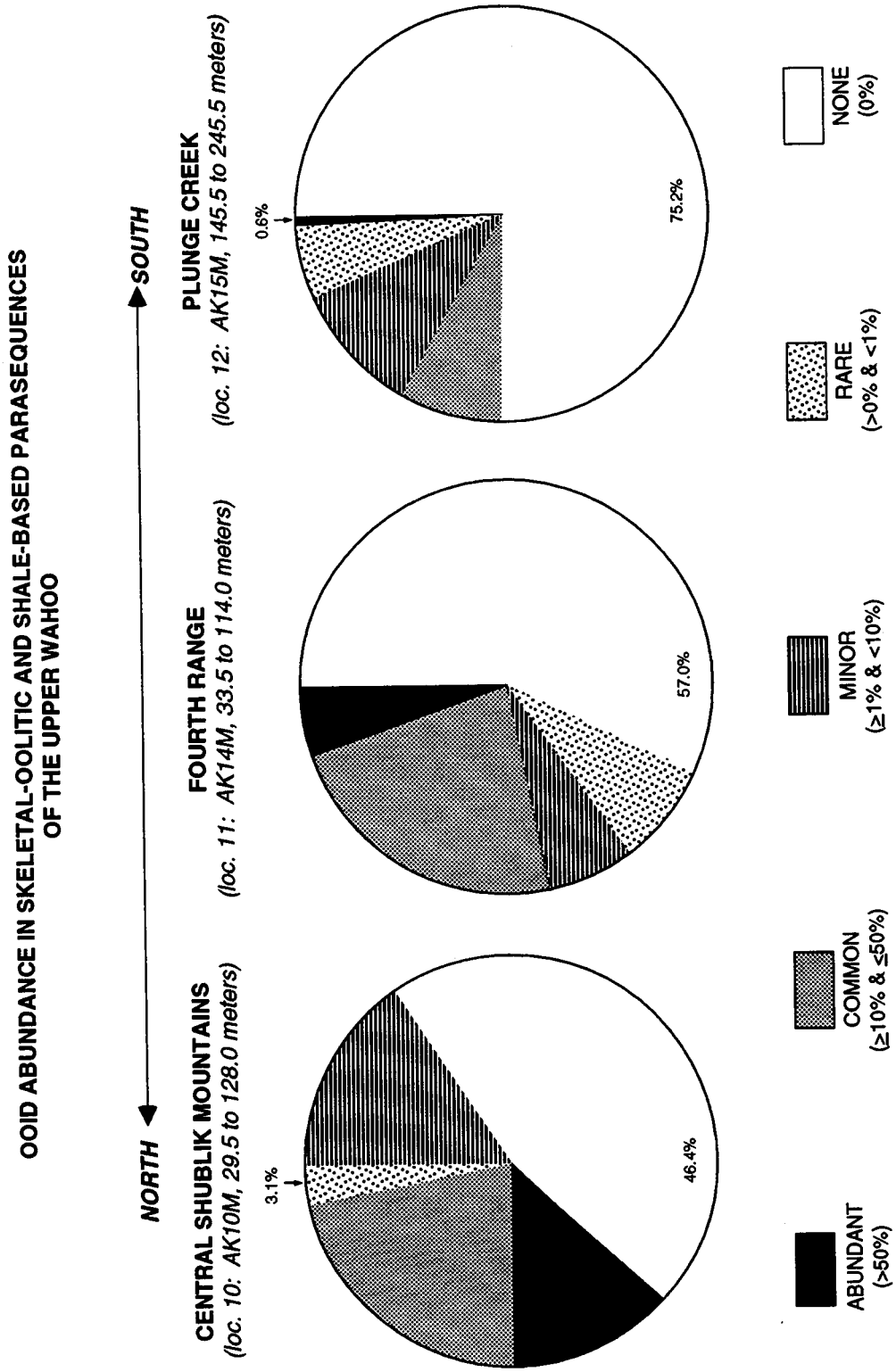


Figure 1-28. Relative abundance of oolitic grainstone (shoals) in skeletal-oolitic and shale-based parasequences of the upper Wahoo along a downdip transect (locs. 10-12, Figs. 1-2, 1-12, & 1-25). The decreased abundance of ooids to the south indicates position on outer part of Wahoo ramp, distal from shoals during the maximum transgression (highstand, both retrogradational and progradational highstand) in the Wahoo. Diagram was generated using semi-quantitative data in the Wahoo database (see Chapter 5; from Gruzlovic, 1991). Does not account for age problems mentioned in Fig. 1-25 caption.

addition to within the adjacent transgressive and progradational highstand systems tracts of Sequence C.

To the south (loc. 10-11, Fig. 1-25), this maximum flooding surface occurs within a southward thickening shale-based parasequence set. The middle skeletal-oolitic parasequence set in the south is part of a transgressive (highstand retrogradational) systems tract along with parts of the spiculitic and shale-based parasequence sets that bracket it. The middle skeletal-oolitic parasequence set thins rapidly southward (Fig. 1-25) where parasequences become less distinct and of deeper-water affinity (Gruzlovic, 1991). In the Fourth Range, a thick interval (19 meters) of bryozoan-pelmatozoan-*Archaeolithophyllum* grainstone interbedded with only minor oolitic grainstone could represent a laterally extensive algal mound(?) structure along the south flank of the ooid shoals (Figs. 1-22 & 1-25).

Shale-based parasequence set

In the Shublik Mountains, Fourth Range and Plunge Creek sections (locs. 11 & 12, Figs. 1-2 & 1-7), the shale-based parasequence set overlies the middle skeletal-oolitic parasequence set and represents the maximum transgression in the Wahoo Limestone. The shale-based parasequence set is dominated by open-marine deposits. Ideally, shale-based parasequences begin with poorly exposed beds of shale that are overlain by argillaceous, spiculitic limestone or microdolomite. However, the basal part typically is covered and the first exposed bed of the shale-based parasequences is slightly abraded and micritized, argillaceous, bryozoan-pelmatozoan wackestone and packstone. The skeletal wackestone and packstone beds are overlain by bryozoan-pelmatozoan grainstone that becomes more abraded and micritized upsection. Some of the shale-based parasequences pass upward into, and are capped by, moderately to highly abraded and micritized, bryozoan-pelmatozoan-*Archaeolithophyllum* grainstone (Figs. 1-24 & 1-25). Less commonly, the shale-based parasequences shallow upward into, and are capped by, superficial oolitic and oolitic grainstone.

Shale and argillaceous to silty limestone are particularly well developed in the lower part of parasequences in southern areas, farther down the Wahoo ramp. Shale-based parasequences form many of the thinnest (1.5 to 3 meters) parasequences (Fig. 1-25). The basal beds of shale formed during incipient drowning of the carbonate ramp as the relative sea-level rise outpaced carbonate production. Shale, along with the overlying thin beds of argillaceous, spiculitic, and skeletal (bryozoans and pelmatozoans), dolomitic limestone, and microdolomite represent a relatively condensed interval with very slow sedimentation rates (Kendall and Schlager, 1981). A northward-thickening trend of individual shale-based parasequences can be attributed to variations in lithologies that directly influenced sedimentation rate. Shale-based parasequences in the north commonly contain thick beds (3-4 meters) of oolitic grainstone , whereas farther to the south, the parasequences generally lack oolitic grainstone (Figs. 1-25 & 1-28) and are primarily composed of open-marine, bryozoan-pelmatozoan packstone and grainstone. Oolitic grainstones have relatively high sedimentation rates compared to other carbonate

lithologies (Enos, 1977; Schlager, 1981). Shale and associated argillaceous limestone and microdolomite represent condensed intervals characterized by very low sedimentation rates and are most abundant in the south. The greater number of shale-based parasequences and the southward-thickening of the entire shale-based parasequence set is a function of increasing water depth on the south-dipping carbonate ramp (Figs. 1-18, 1-22, & 1-25). As water depth increases, the likelihood of drowning the carbonate platform also increases, thus, more parasequences have basal condensed intervals of shale, argillaceous limestone, and microdolomite.

UPPERMOST WAHOO LIMESTONE—PROGRADATION OF SEQUENCE C

Peloidal-oncolitic parasequence set

In northern ANWR (locs. 6-8, Figs. 1-2, 1-11, & 1-23), the upper part of the upper Wahoo Limestone has parasequences containing abundant peloids and *Osagia* oncolites (Carlson, 1987). Similar oncolitic parasequences occur in the subsurface near Prudhoe Bay and are reservoir rocks in the Lisburne oil field (see Chapter 4, Jamison et al., 1980; Jameson, in revision). In the lower part of a typical parasequence, bryozoan-pelmatozoan grainstone and packstone pass upward into oncolitic (*Osagia*) packstone and grainstone that formed in open to partially restricted-platform environments (Fig. 1-23c). The upper part of a parasequence contains abundant peloidal packstone and grainstone and lesser spiculitic mudstone that formed in restricted-platform (lagoonal) conditions. Thus, the peloidal-oncolitic parasequences formed in lagoonal conditions behind the ooids shoal complex that migrated south (Fig. 1-18). The transition from skeletal-oolitic parasequences to peloidal-oncolitic parasequences indicates a continuing overall regression and represents a highstand (highstand progradational) systems tract. Elsewhere in ANWR, age-equivalent parasequences probably were removed by erosion beneath the sub-Permian unconformity or possibly are represented by the upper skeletal-oolitic parasequence set that formed farther down the Wahoo carbonate ramp.

Upper skeletal-oolitic parasequence set

To the south (locs. 10-12, Figs. 1-2 & 1-7), the uppermost Wahoo Limestone consists of the upper skeletal-oolitic parasequence set that overlies the shale-based parasequence set, indicating an overall regression and a highstand (highstand progradational) systems tract. The Morrowan-Atokan boundary is within the upper skeletal-oolitic parasequence set or in the upper part of the shale-based parasequence set, above the maximum flooding surface. Similar age rocks to the north show an appearance of *Donezella* algae that may indicate the advance of open-platform conditions and associated ooid shoals in a highstand (progradational) systems tract (locs. 6-8, Fig. 1-11) . The thickness of the upper skeletal-oolitic parasequence set depends on depths of erosion beneath the sub-Permian unconformity and on the timing of the transition from the deeper-water shale-based parasequences (Figs. 1-7, 1-12, & 1-25).

The lower part of a typical skeletal-oolitic parasequence is composed of open-marine, bryozoan-pelmatozoan packstone and grainstone (Fig. 1-24). However, in the north (loc. 10, Figs. 1-2, 1-7, & 1-25), the majority of the parasequences are dominated by ooid grainstones that pass upward into bryozoan-pelmatozoan packstone and grainstone interbedded with *Donezella* bafflestone and grainstone, indicating a progradational transition from ooid shoals to open-platform. To the south (loc. 11, Figs. 1-7 & 1-25), skeletal-oolitic parasequences are capped by thick beds of oolitic grainstone with *Donezella* skeletal grains forming the nuclei for the ooids. Farther south (loc. 12, Fig. 1-2), the majority of the skeletal-oolitic parasequences are dominated by open-marine, bryozoan-pelmatozoan packstone and grainstone with a few (2 of 5) parasequences containing very minor beds of oolitic grainstone (Figs. 1-25 & 1-28). The highest parasequences at this southern locality have beds of oolitic grainstone overlain by minor bryozoan-pelmatozoan packstone and grainstone (but lacking *Donezella*), indicating progradation of open-platform over shoal deposits.

A northward-thickening trend in the upper skeletal-oolitic parasequence set can be attributed to higher sedimentation rates resulting from the abundance of oolitic grainstone and *Donezella* and coralline boundstone bioherms (Fig. 1-25; c.f. Enos, 1977; Schlager, 1981).

Overall, ooid shoals migrated southward overall but shifted back and forth across a broad area (Fig. 1-22). Behind the shoals, *Donezella* bafflestone and grainstone and other skeletal limestones formed in an open-platform environment behind the shoals (Fig. 1-18). To the south, a paucity of ooids and lack of *Donezella* algae indicates an open-marine environment. Although the peloidal-oncolitic parasequence set in the north appears to be younger (due to less sub-Permian erosion), it is likely that such restricted-platform environments existed on more landward part of the broad lagoon behind the shoals (Figs. 1-22 & 1-23).

SUB-PERMIAN UNCONFORMITY AND THE ECHOOKA FORMATION

The Echooka Formation, the basal part of the Sadlerochit Group, lies unconformably above the Lisburne Group along a sharp easily mapped contact. In most places, the Echooka consists of siltstone, glauconitic sandstone, shale, conglomerate, chert and pyrite nodules, with lesser amounts of calcareous sandstone and siltstone (to sandy limestone). *Zoophycos* trace fossils are one of the most characteristic features, indicating a shelf environment. Marine fossils are not abundant but include brachiopods, crinoids, bryozoans, gastropods, foraminifers, corals, and lesser trilobites and bivalves (Detterman et al., 1975). Most commonly, brachiopods occur as basal lag deposits along with chert pebbles, representing shelf-storm deposits (Crowder, 1990). The age of the Echooka is possibly as old as Early Permian (Wolfcampian/early Sakmarian) in the south but is Leonardian to early Guadalupian (Artkinskian to Ufimian) in the north; the youngest documented age is Guadalupian (Kazanian) (Detterman et al., 1975). Locally, conglomerates apparently fill channels cut into the Lisburne (Crowder, 1990). Clasts are predominantly chert, but lesser limestone clasts were clearly derived from the

underlying Lisburne. Locally, karst features and moldic porosity occur in the uppermost Lisburne (see Chapter 3).

The sub-Permian unconformity is a major break in the stratigraphic record, a hiatus of approximately 38 m.y., beneath which erosion removed variable amounts of the Lisburne Group strata. Based on foraminiferan biostratigraphy, the youngest Wahoo Limestone beneath the unconformity is Atokan (Mamet Zone 21) and the thickest known exposed Atokan succession is in northernmost ANWR (loc. 6, Figs. 1-2 & 1-11) and is thicker still in the subsurface at Prudhoe Bay. Significant erosional topography developed on the emergent Lisburne platform with depths of erosion generally increasing to the south and west. In the western Shublik Mountains (loc. 1, Fig. 1-2), the upper Wahoo is only 38 meters thick beneath a thick basal conglomerate in the Echooka Formation, which is much thinner than the 235 meters of upper Wahoo to the northeast (loc. 6, Fig. 1-2; 35 miles/55 km ENE). Although some thickness differences are due to variations in depositional thickness, sub-Permian erosion may have removed approximately 200 meters from the top of the Wahoo. Crowder (1990) describes conglomerates in the basal Echooka that appear to fill broad erosional gullies cut into the top of the Lisburne. Farther to the south, the top of the Wahoo has been reported to be Late Mississippian (late Chesterian) in age. At their Kongakut River section (south Bathtub Ridge, loc. 23, Fig. 1-2), Armstrong and Mamet (1975) reported a Chesterian (Zone 18) age for the top of the Lisburne. Our conodont samples from this section indicate an imprecise age no older than late Chesterian (*R. muricatus* Zone) but no younger than early Atokan (highest sample is 28 m below the top of the section and 322 m above the base of the Wahoo). However, the top of this section is a long dip slope that prevented collection of samples immediately beneath the Echooka contact.

To the north at Prudhoe Bay, the Atokan "oncolitic" interval at the top of the Wahoo Limestone (Jamison et al., 1980, Jameson, in revision) is correlative to, but thicker than, the peloidal-oncolitic parasequence set comprising the uppermost Wahoo of northern ANWR (locs. 6-8, Fig. 1-2). In the subsurface of the National Petroleum Reserve of Alaska (west of Prudhoe Bay), interbedded Permian limestones and shales have been assigned to the Lisburne Group but their relationship to the older Pennsylvanian (Morrowan to Atokan) Lisburne at Prudhoe Bay and in the Brooks Range has not been determined (Dutro and Silberling, 1988; Kirschner and Rycerski, 1988).

The top of the Wahoo Limestone at the Mt. Doonerak fenster (supposedly parautochthonous, but southwest of parautochthonous rocks in ANWR) is Morrowan in age (Armstrong et al., 1976). In the Endicott Mountains allochthon (southwest of ANWR, Fig. 1-1), much of the Pennsylvanian part of the Lisburne Group is missing beneath the pre-Permian unconformity as indicated by foraminiferan biostratigraphy (Armstrong and Mamet, 1977, 1978). Near the Trans-Alaska Pipeline at Atigun Gorge, conodonts from the top of the Wahoo indicate a very thin (< 20 meters) Morrowan interval above Chesterian rocks. West of the pipeline at Itikmalak Creek (~15 mile/25 km west of the Atigun locality), conodonts

indicate the top of the Wahoo is Chesterian. Thus, depths of erosion appear to increase to the south and west in a seaward direction on the emergent Wahoo ramp. However, unpublished conodont analyses of numerous samples from the upper Lisburne Group in the Endicott Mountains allochthon have yielded Pennsylvanian (Morrowan) ages (A. G. Harris, pers. comm.). In the central Brooks Range (Endicott Mountains), a reworked assemblage containing both Pennsylvanian (Morrowan to Atokan) and Mississippian conodonts occurs in the upper part of the Lisburne Group below the Siksikpuk Formation (Siok and Harris, 1992). Farther to the west, Pennsylvanian limestones of the Lisburne do not occur and may have never been deposited, particularly where the Etivluk Group includes deeper-water chert of Pennsylvanian age, implying that the Lisburne platform was drown in this area (Mull et al., 1982; Dumoulin and Harris, 1992; Dumoulin et al., in press). Thus, the original thickness of Pennsylvanian limestones of the Lisburne Group was probably variable, so the amount of section lost to sub-Permian erosion is uncertain.

The unequal depths of erosion beneath the sub-Permian unconformity in ANWR may indicate differential uplift and erosion of the Lisburne Group carbonate platform. Greater depths of erosion to the south and west suggest greater amounts of uplift in this direction because the maximum erosion would be expected in areas having the most uplift and the greatest duration of exposure (Fig. 1-29, model A). Alternatively, if a relative sea-level drop occurred sometime in the Late Pennsylvanian and/or Early Permian, an emergent plateau of Lisburne carbonate would have been subjected to regional erosion. One would expect the amount of erosion to be proportional to elevation and/or duration of uplift; both would be greatest in the north and east (the opposite of the observed trend). However, if this emergent platform was eroded to base level along a shoreline located to the southwest, then the plateau farthest from the shoreline (i.e., in the northeast) may have been in equilibrium with relatively young rocks preserved below erosional base level (Fig. 1-29, model B; c.f., Posamentier and Vail, 1988). For example, the different depths of erosion could represent erosional terraces on an emergent plateau of Lisburne carbonates with erosion stepping downward toward the paleoshoreline some distance to the southwest. However, the local erosional topography evident in northern ANWR indicates ravinement with relatively deep levels of erosion (tens of meters?), indicating incision and non-equilibrium conditions. This argues for the regional tectonic uplift model. Although more information is needed to determine the nature and causes of this differential uplift and/or erosion, this certainly is an important event in the geologic history of the region (Hubbard et al., 1987). The sequence boundary may be similar to coeval unconformities throughout the circumarctic region, suggesting a major plate tectonic reorganization (Beauchamp, 1992).

Clearly, subaerial exposure of the Lisburne platform led to its demise, and subsequent carbonate sedimentation in the Permian Echooka Formation was relatively limited (Crowder, 1990). The Lisburne Group carbonates formed in a temperate to semi-arid climate (not tropical) as indicated by evaporites in the upper part of the Alapah Limestone. Abundant oolitic grainstone in the upper Wahoo

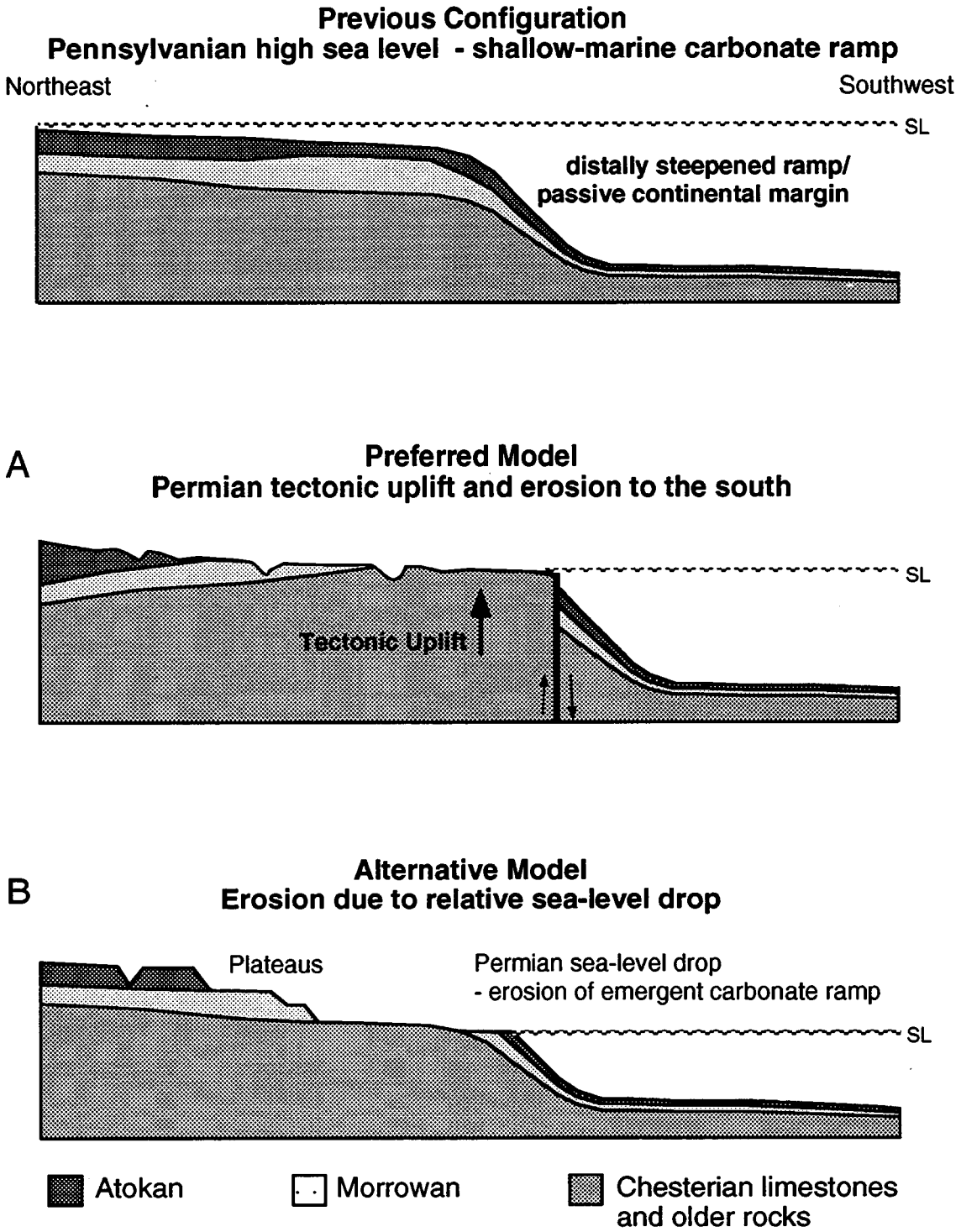


Figure 1-29. Models showing possible causes of differential erosion of the Lisburne beneath the sub-Permian unconformity, being deeper to the south and west (as shown in Fig. 1-5). :
A - Preferred model—Uplift of the southern part of the Lisburne platform led to deeper levels of erosion in this area.
B - Alternative model—this model requires the Lisburne Group to have a distally steepened ramp geometry along the southern passive continental margin of the Arctic Alaska terrane. With a relative sea-level drop and lowering of base level, areas closest to the shoreline were eroded down to sea-level (base level) whereas northern areas formed uplifted plateaus that were in quasi-equilibrium at local base levels, and so were not eroded as deeply (as in model of Posamentier and Vail, 1988, p. 141).

Limestone indicate a warm climate (c.f. Flügel, 1982). The composition of foraminiferan assemblages and the general lack of calcareous algae indicate a temperate climate compared to more tropical conditions in the midcontinent region (Armstrong, 1972; Armstrong and Mamet, 1975, 1977). Although the original position of the North Slope terrane is uncertain, Ross and Ross (1985) show a position near 30°N latitude during the Pennsylvanian. Depending on the original location of the North Slope terrane, it is possible that by Permian time the region had a more northerly paleolatitude with paleoenvironmental conditions too harsh for calcareous organisms to gain an adequate foothold following the onlap of the Echooka Formation. Impure carbonates in the Echooka contain a depauperate fauna, including pelmatozoans, bryozoans and brachiopods, which were able to exist in temperate conditions. By Triassic time, radiolarians in the Otuk Formation indicate that northern Alaska was at boreal latitudes (Blome, pers. comm. 1991). The only Triassic carbonates are bioclastic limestones composed of thin-shelled, pelagic(?) bivalves such as *Halobia* and *Monotis* in the Shublik Formation (Parrish, 1987). A similar transition to colder conditions is recognized in the Permian of the Canadian Arctic islands (Beauchamp et al., 1989).

LISBURNE GROUP AT PRUDHOE BAY

The Lisburne Group at Prudhoe Bay is similar to the Lisburne Group of northern ANWR in many respects, but contains much more terrigenous sand, silt and clay, particularly in the northernmost wells (Fig. 1-30; Armstrong and Mamet, 1974; Bird and Jordan, 1977, Jamison et al., 1980; Jameson, in revision). The Lisburne Group in the Prudhoe discovery well was initially subdivided into the Mississippian Alapah Limestone and the Pennsylvanian Wahoo Limestone, extending terminology from the Brooks Range (Armstrong and Mamet, 1974). However, because these formations are difficult to distinguish in the subsurface, Bird and Jordan (1977) recognized a lower limestone unit, a middle dolomite unit, and an upper limestone unit. Jamison et al. (1980) informally subdivided the Mississippian Alapah into a "lower sandy carbonate interval," a middle "dolomite" interval and an upper "grainstone-packstone" interval; and they informally subdivided the Pennsylvanian Wahoo Limestone into a lower "sandy carbonate" interval, a middle "oolite" interval, and an upper "oncolite" interval (Fig. 1-30).

The general stratigraphic organization at Prudhoe Bay is similar to that in ANWR but some differences seem to represent deposition closer to a source of terrigenous sediments (i.e., the Colville high or Barrow Arch; Bird and Jordan, 1977). As noted previously, our definition of the Alapah-Wahoo boundary is based on lithostratigraphic criteria and is located well below the formation contact placed at the Mississippian-Pennsylvanian boundary by Armstrong and Mamet (1974). However, our Wahoo Limestone corresponds to the upper limestone unit of Bird and Jordan (1977) and our Alapah represents their middle dolomite and lower limestone units of the Lisburne. Although Jamison et al. (1980) also use the Mississippian-Pennsylvanian boundary to define the Wahoo-Alapah boundary, we

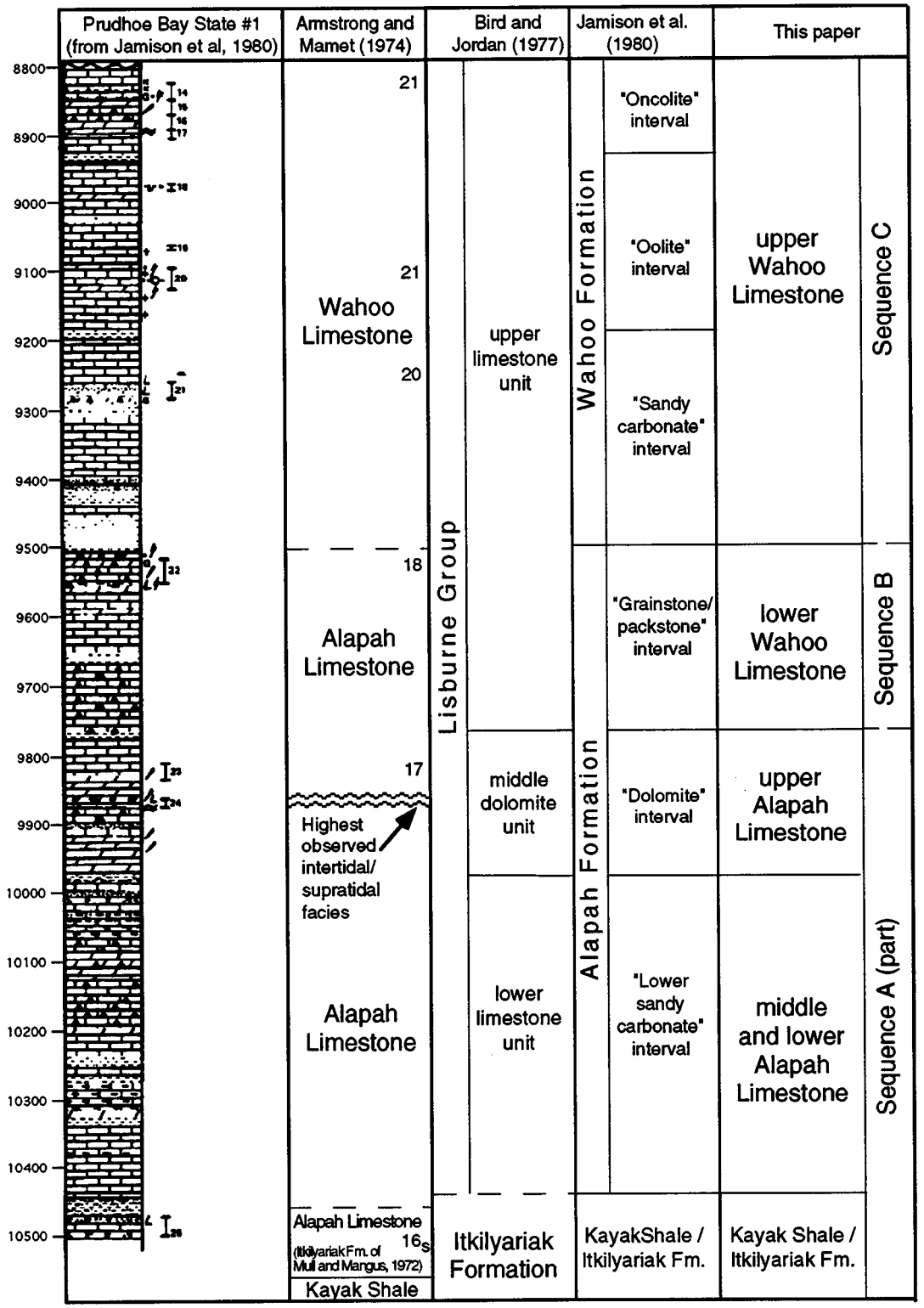


Figure 1-30. Diagram shows the stratigraphic nomenclature used in previous publications on Prudhoe Bay and our terminology extended from the Lisburne Group of ANWR. The nomenclature we use in this paper is consistent with the original definition of the Wahoo Limestone. The depositional sequences shown on the diagram correspond to the sequence stratigraphy of the Lisburne Group in ANWR, but the sequence boundaries at Prudhoe Bay are marked by unconformities, rather than the correlative conformities (or paraconformities) located farther down dip in ANWR.

are able to correlate their three subdivisions of the Wahoo with the three subdivisions of our upper Wahoo member. Their upper "grainstone-packstone" interval of the Alapah closely resembles our lower Wahoo. The "dolomite" interval again corresponds to our upper Alapah. The "lower sandy carbonate" interval is equivalent to our lower and middle Alapah but contains more terrigenous sand.

Cryptalgalaminate (stromatolite) and replaced evaporites in our upper Alapah Limestone apparently represent an extensive correlatable marker horizon, indicating widespread deposition in intertidal to supratidal (sabkha) environments (middle part of Alapah of Armstrong and Mamet, 1974; i.e., a maximum regression/ lowstand). Intercrystalline and vuggy porosity is common in the dolomite, making the unit the most promising reservoir rock in the Lisburne Group (Jamison et al., 1980; Bird et al., 1987). Bird and Jordan (1977) trace this widespread interval of relatively porous dolomite across much of the North Slope. East of the Lisburne field at Prudhoe Bay, a small but very permeable hydrocarbon reservoir in the unit is chiefly below the oil-water contact (J. Jameson, pers. comm. 1987). Schoennagel (1977) interpret a northwestward thinning of the dolomite interval to be attributable to erosion along an unconformity (Late Mississippian, at the top of Mamet Zone 17, Chesterian). We interpret this surface to represent a sequence boundary, similar in many respects to that indicated by maximum regression and subaerial exposure at the top of Sequence A in ANWR.

Our sequence stratigraphic framework for the Lisburne Group correlates well with interpretation of the Prudhoe Bay succession (Fig. 1-30). The sequence boundary in the upper Alapah Limestone (boundary between Sequence A and Sequence B) corresponds to the possible unconformity of Schoennagel (1977) and Jameson (in revision) and is near the stromatolitic interval noted by Armstrong and Mamet (1974). The sequence boundary in the lowest upper Wahoo Limestone (between Sequence B and Sequence C) corresponds to the "sandy carbonate" interval above the Mississippian-Pennsylvanian boundary (Fig. 1-30). This interval of terrigenous influx at Prudhoe Bay could be related to the drop in base level associated with the sequence boundary. A similar influx of terrigenous quartz in northern ANWR also marks this sequence boundary. Thus, the Lisburne Group at Prudhoe Bay can be subdivided into three major transgressive-regressive successions (deposition sequences) that are similar to the three depositional sequences of ANWR. More abundant quartz and other associated facies suggest closer proximity of Prudhoe Bay to the shoreline and a source of terrigenous sediment.

PARAUTOCHTHONOUS VERSUS ALLOCHTHONOUS LISBURNE

The Wachsmuth and Alapah limestones were originally described near Shainin Lake (Bowsher and Dutro, 1957) in what has become recognized as part of the Endicott Mountains allochthon (Fig. 1-1; Mull et. al, 1987b). These formation names were then extended to parautochthonous rocks of the northeastern Brooks Range (Brosgé et al., 1962; Armstrong, 1972; Mamet and Armstrong, 1972;

Armstrong and Mamet, 1975, 1977; Wood and Armstrong, 1975). The present distance between the Shainin Lake section and the nearest measured section of parautochthonous rocks in the northeastern Brooks Range is 115 km (71 miles) to the northeast (Wahoo Lake section, loc. 13, Fig. 1-3). At least an additional 88 km (55 miles) of separation is required to account for the northward tectonic transport of the Endicott Mountains allochthon (Mull et al., 1987a). In order to determine whether this stratigraphic nomenclature was overextended between these widely separated areas and for comparison with our work on correlative(?) rocks in ANWR, we measured and sampled the type sections of the Alapah and Wachsmuth limestones.

Figure 1-31 summarizes the stratigraphy of the type section of the Wachsmuth and Alapah limestones and shows our paleoenvironmental interpretation. Interestingly, the Wachsmuth Limestone has several intervals of massive, coarse-crystalline dolostone with considerable intercrystalline, moldic and vuggy porosity which contain possible bitumen. Many of the molds are after crinoid ossicles suggesting that these calcitic grains were later dissolved from the dolomite matrix. These porous carbonates were one of the original targets of North Slope hydrocarbon exploration (Mull, pers. comm., 1990). These, thick-bedded, light-colored dolostones have relict textures suggestive of pelmatozoan packstone/grainstone and occur in several thick intervals which cyclically alternate with dark-colored argillaceous muddy limestone and dolomite with chert nodules. Cross stratification in the coarse dolostone intervals indicates deposition in high-energy shoal conditions, not unlike the Chesterian "Egaksrak grainstone" unit of the lower Alapah in ANWR. However, its Osagean age is older indicating earlier onlap on a more seaward part of the Lisburne carbonate platform. Thin intervals of limestone in the underlying Kayak Shale (the "argillaceous limestone" and "red limestone" members of Bowsher and Dutro, 1957) yield Kinderhookian ages and indicate earlier failed attempts at carbonate sedimentation during breaks in relatively anoxic conditions. The upper part of the Wachsmuth and most of the Alapah are late Meramecian in age; the Alapah could range into the Chesterian in the uppermost part. Thus, their age generally is older than the Alapah of ANWR. The type Alapah is dominated by bryozoan-pelmatozoan grainstone that formed in open-marine above wave-base conditions on an extensive carbonate platform. Coralline boundstone is common in the lower part of the unit and was deposited in slightly deeper open-marine (or open-platform) conditions. An interval of bryozoan-pelmatozoan grainstone and packstone containing peloids and with interbeds of black shale in the upper part may indicate slightly deeper and restricted conditions. The top of the Alapah is not exposed at the type section, so younger and possibly more correlative part of the Lisburne Group is missing. However, the stratigraphic organization of the Alapah Limestone is considerably different than what has been called Alapah in ANWR (upper Meramecian to Chesterian carbonates). These differences probably resulted from the more seaward position of the type Alapah on the Lisburne carbonate platform than the rocks in ANWR that formed closer to the northern margin of the carbonate platform where onlap was later. Elsewhere in the central Brooks Range, the sub-Permian unconformity cuts

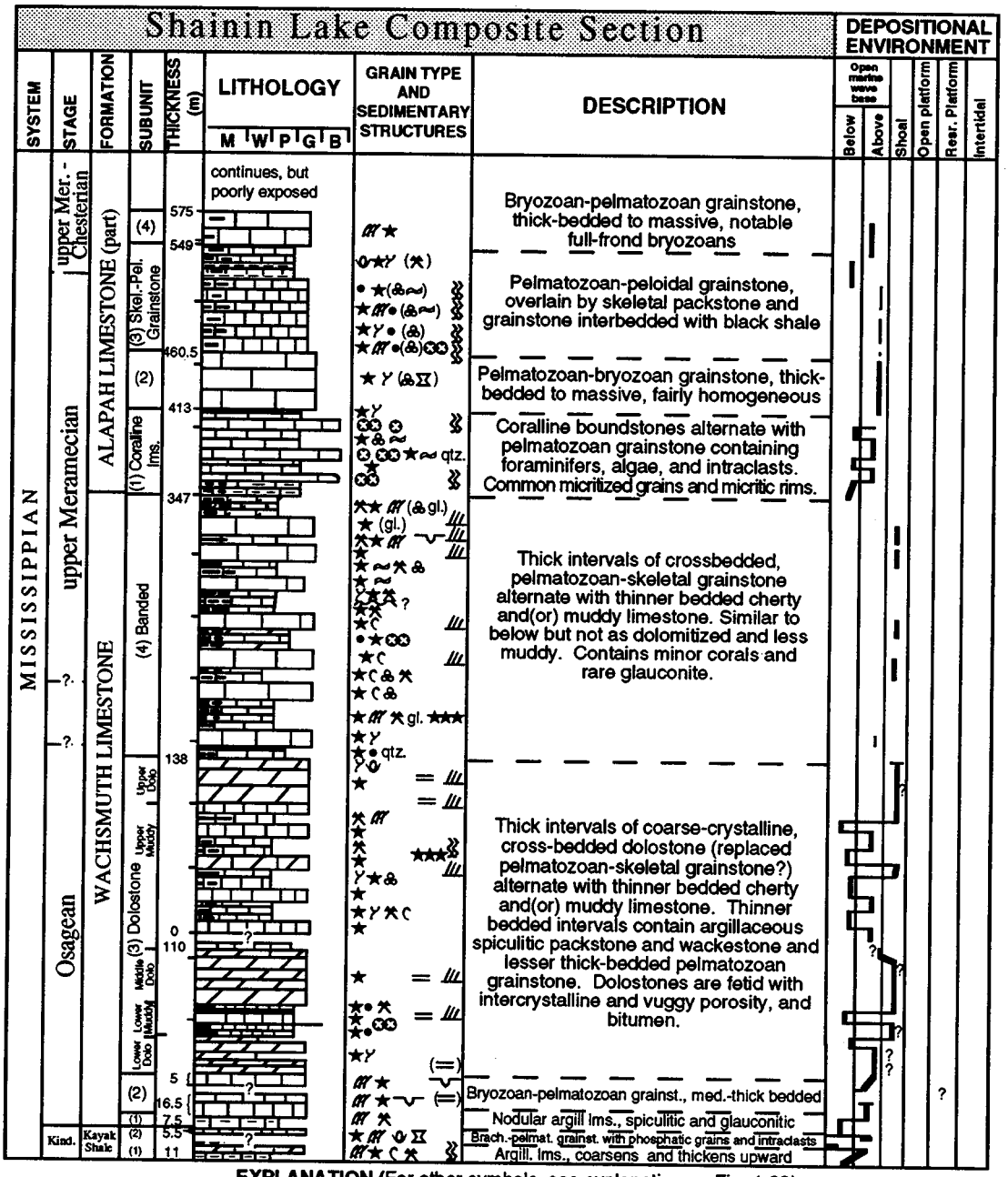


Figure 1-31. Stratigraphic column for the type localities of the Wachsmuth and Alapah limestones at Shainin Lake in the central Brooks Range. Note the similarity between the cyclic cross-stratified shoal deposits (dolomitized) in the lower Wachsmuth to those in the younger Alapah (Egaksrak grainstone) in ANWR (Fig. 1-9). The shoal complex apparently developed in response to the initial onlap of carbonate shoals in a transgressive (retrogradational highstand) systems tract. The organization of the Alapah here does not correspond well with that in ANWR.

into Chesterian rocks (Armstrong and Mamet, 1978; Siok and Harris, 1992), and farther to the west, the Lisburne platform may have been drowned during the Pennsylvanian.

COMPARISON WITH EUSTATIC SEA-LEVEL CURVES

The lack of adequate age control for the Lisburne Group inhibits developing high-resolution regional sea-level curves for correlation with available eustatic curves for the Carboniferous (Ross and Ross, 1978; Ramsbottom, 1979). However, local sea-level curves based on interpretation of carbonate microfacies have been completed for several stratigraphic sections in ANWR (Gruzlovic, 1991; Carlson, 1987). As pointed out in previous discussions, small-scale parasequences cannot be correlated on an individual basis, particularly with the possibility of missing record along unconformities and subaerial exposure surfaces and autocyclic controls on the migration of carbonate environments.

However, general comparisons of our sequence and parasequence stratigraphy with available eustatic curves provide some insights. The major sequence boundary between Sequences A and B of the Lisburne Group, generally coinciding with the transition between the Alapah and Wahoo limestones, is latest Chesterian (latest Mississippian) in age based on conodont biostratigraphy (Upper *muricatus* Subzone - foraminiferan-based age determinations may be slightly older in Mamet Zone 18), corresponding to the Kaskaskia-Absaroka sequence boundary (Sloss, 1963, 1988). This sequence boundary is a major hiatus in most of the North American midcontinent that spans the Mississippian-Pennsylvanian boundary. It is shown as a major sea-level fall on the generalized sea-level curve of Vail and others (1977), but is not a major drop on Hallam's (1984) curve (Fig. 1-32). Ross and Ross (1988) show the maximum sea-level drop to coincide with the Mississippian-Pennsylvanian boundary, later than the sequence boundary in ANWR. The Mississippian-Pennsylvanian boundary in ANWR is marked by a subaerial exposure surface, but no hiatus is evident based on conodont biostratigraphy and no significant change in carbonate facies and inferred depositional environments is apparent (besides the diagenetic evidence of subaerial exposure). The boundary between Sequences B and C in ANWR is early Morrowan in age and could coincide with lowstands at this time (Vail et al., 1977; Ross and Ross, 1988). The duration of depositional sequences A, B, and C of the Lisburne are longer than and do not seem to correspond to the transgressive-regressive depositional sequences of Ross and Ross (1988). The numerous parasequence of the Wahoo Limestone have a higher frequency than these transgressive-regressive sequences. The major sub-Permian unconformity at the top of the Wahoo does not appear to correspond to any indicated eustatic lowstand (Fig. 1-32), except for the Early Permian lowstand of Vail et al. (1977)

In summary, available sea-level curves for the Carboniferous are rather contradictory and generally do not match the sea-level fluctuations apparent in the Lisburne Group. However, the most dramatic change in depositional conditions

Figure 1-32

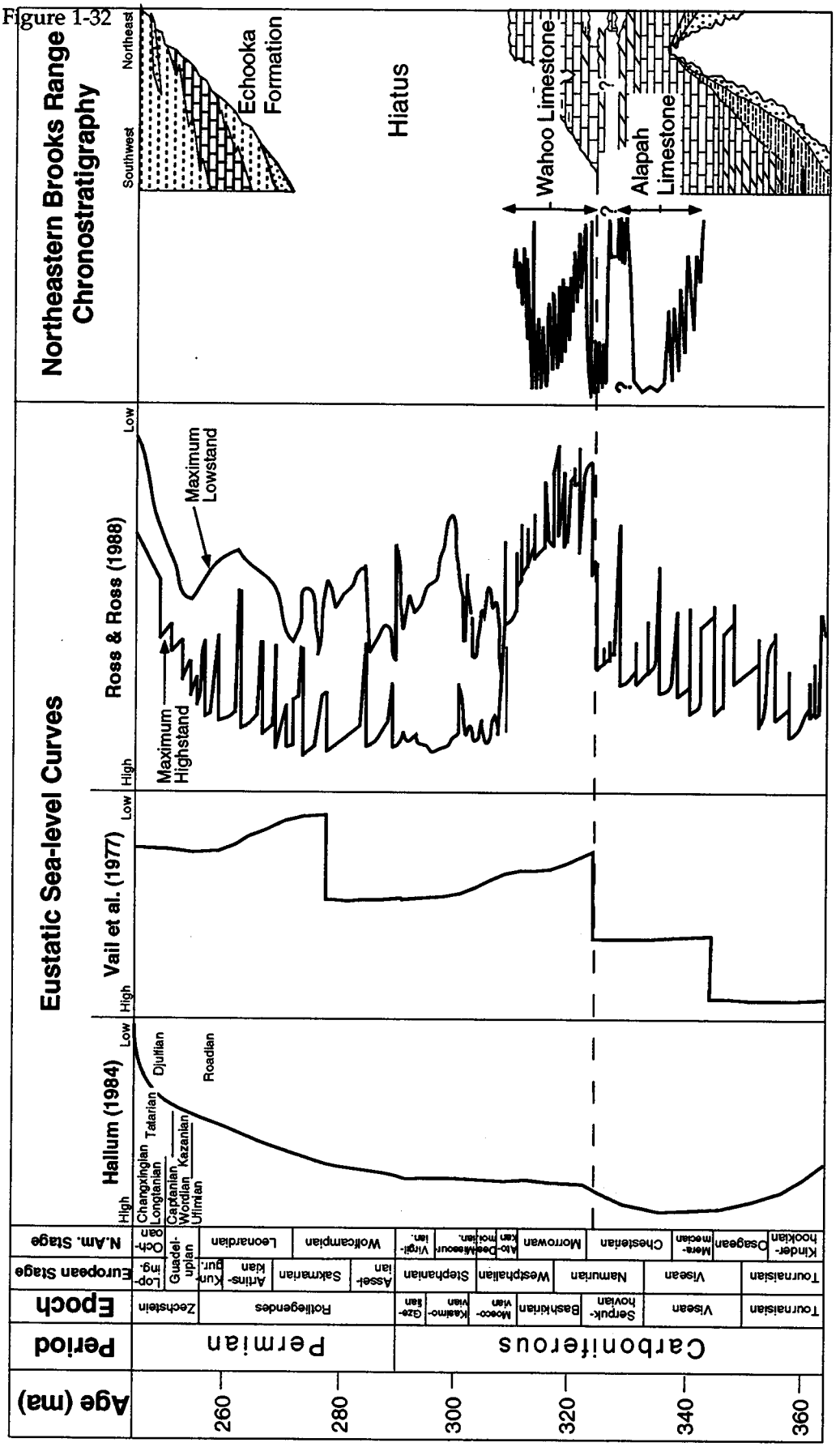


Figure 1-32. Comparison of the chronostratigraphy of the Lisburne Group with different sea-level curves that have been proposed for the upper Paleozoic. Note the lowstand which approximates the boundary between the Alapah and Wahoo limestones in the latest Mississippian (Vail et. al., 1977 and Ross and Ross, 1988), corresponding to the Kaskaskia-Absaroka sequence boundary of Sloss (1963, 1988). Vail et al. (1977) show a sea-level drop in the middle Permian that could be related to the sub-Echooka unconformity, but neither of the other sea-level curves show a drop of sufficient magnitude to explain the deep ravinement into the upper Lisburne. Chronostatigraphy from Harland et al. (1989) and Fig. 1-5.

occurs in the latest Mississippian and may coincide with the Kaskaskia-Absaroka sequence boundary (Sloss, 1963, 1988). The depositional sequences and parasequence of the Lisburne Group are at lower and higher frequencies than shown on available eustatic curves (e.g., Ross and Ross, 1988).

COMPARISON WITH OTHER UPPER PALEOZOIC ROCKS OF THE CIRCUMARCTIC REGION

The Ellesmerian Sequence has been correlated with rocks at its namesake, Ellesmere Island of the Canadian Arctic Islands (Lerand, 1973; Grantz and May, 1983), but may be more similar to correlative rocks in the Yukon Territory. On Figure 33, the age and nature of the depositional sequence comprising the lower part of the Ellesmerian Sequence (Endicott and Lisburne Groups), the sub-Permian unconformity, and Permian sedimentary rocks in northern Alaska are compared with upper Paleozoic successions in the Sverdrup Basin (Ellesmere Island; Beauchamp et al., 1989) and the Ogilvie Mountains (Yukon Territory; Bamber and Waterhouse, 1972; Bamber et al., 1989).

The age of onlap of carbonate sedimentation in the Lisburne Group ranges from Osagean to Chesterian, generally earlier than the Late Mississippian to Pennsylvanian inception of carbonate sedimentation in the Sverdrup basin (Fig. 1-33). The deeper-water limestones in Yukon Territory are more similar in age to the Lisburne, but appear to prograde basinward to the southwest. The Ogilvie Mountains is thought to represent the northeastern part of the North American plate, inboard of the terranes comprising most of Alaska. Both the Lisburne Group and Yukon Territory carbonates are widespread and may represent passive margin successions whereas the Sverdrup Basin carbonates are more localized on the flank of a failed rift basin.

The top of the Lisburne Group is truncated by a major regional unconformity beneath the Permian Echooka Formation. This Type 1 sequence boundary is marked by an irregular ravinement surface incised into the upper Wahoo. The age of the top of the Wahoo is youngest (Atokan) in northern ANWR and generally older (Morrowan and Chesterian) to the south and west. The age of the Echooka is not tightly constrained but ranges from Artinskian to Ufimian (Leonardian) in the south to Kazanian (Guadelupian) in the north. This unconformity has been attributed to regional epeirogenic uplift, sometime between the Middle Pennsylvanian and Early Permian (Bird and Molenaar, 1987). It generally correlates with a sub-Permian unconformity in the Yukon Territory of Canada that also has been attributed to tectonic movements (Bamber and Waterhouse, 1972; Bamber et al.,). Carbonate sedimentation along the flanks of the Sverdrup Basin continued through the Early Permian. Beauchamp (1992) stated that the "Melvillian Disturbance" of the Canadian Arctic Islands may correspond to the sub-Permian unconformity in Alaska and that tectonic events of similar age affecting the circumarctic region possibly resulted from major plate reorganization at this time (Fig. 1-33). However, the precise timing of deformation may vary between areas.

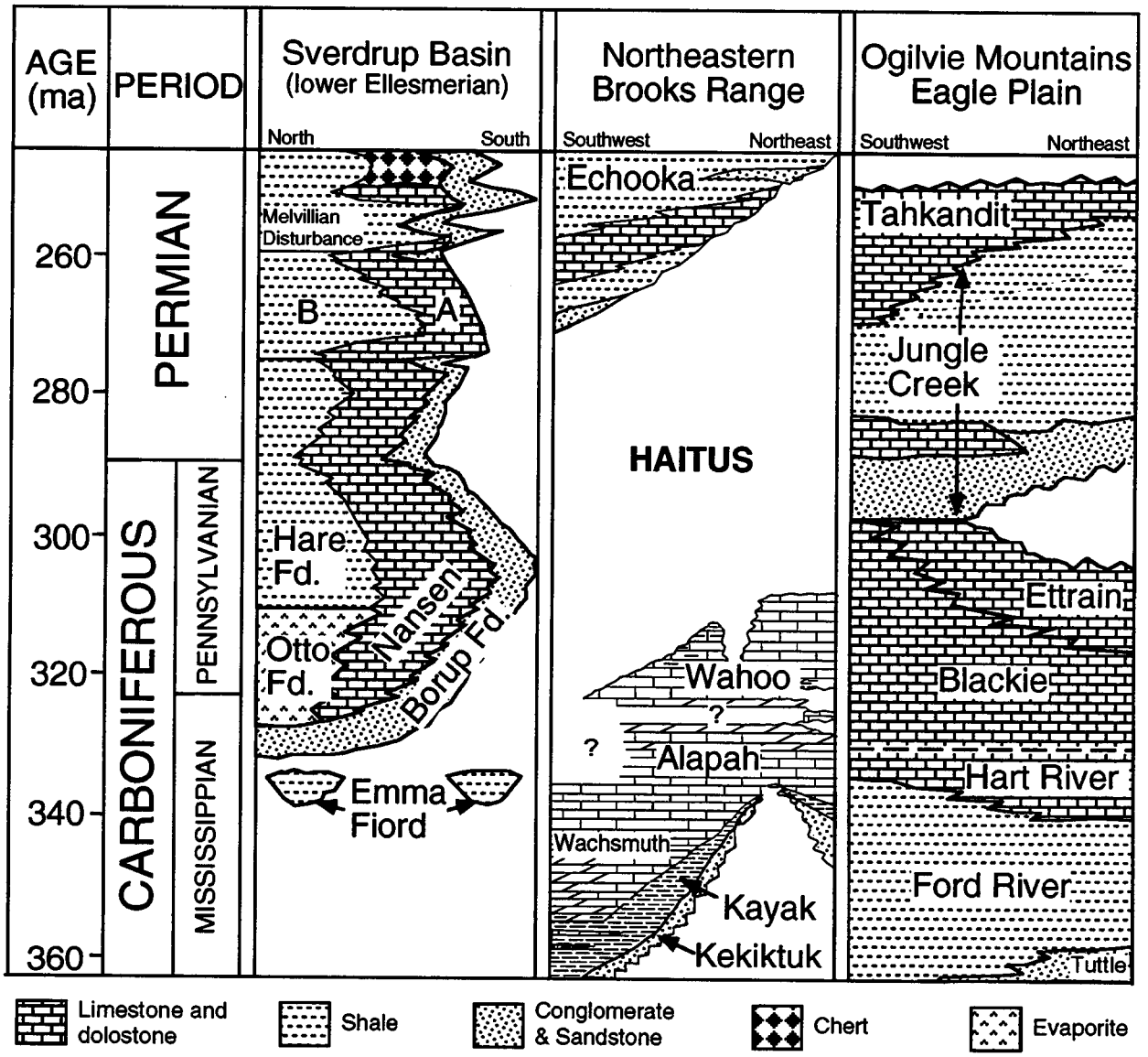


Figure 1-33. Chronostratigraphic diagram compares the upper Paleozoic succession of the Brooks Range (ANWR and the Endicott allochthon) with that in the Canadian Arctic Islands (Beauchamp et al., 1989; the type Ellesmerian sequence of the Sverdrup basin) and the Ogilvie Mountains (Bamber et al., 1989; the northeasternmost part of North American plate, inboard of the terranes comprising most of Alaska). The Carboniferous succession and age of the sub-Permian unconformity of ANWR is most similar to that in the Ogilvie Mountains, although Beauchamp (1992) related this unconformity to the Melvillian Disturbance on Ellesmere Island.

SUMMARY AND CONCLUSIONS

The Lisburne Group, together with the underlying terrigenous sediments of the Endicott Group, can be subdivided into three major depositional sequences (transgressive-regressive successions). These sequences are useful for correlation across ANWR and to Prudhoe Bay.

The lowest sequence begins with the progressive onlap of terrigenous (Endicott) and carbonate sediments over the regional sub-Mississippian unconformity in ANWR. The widespread deposition of the Alapah Limestone represents the most extensive carbonate platform in the Lisburne Group. In northern ANWR, a belt of shoals is represented by repeated intervals of cross-stratified skeletal grainstone of the informal Egaksrak grainstone unit. Progradation of intertidal carbonates and associated subaerial exposure surfaces mark the sequence boundary in the uppermost Mississippian. This sequence boundary may correspond to the Kaskaskia-Absaroka cratonal sequence boundary of Sloss (1963, 1988).

The second sequence begins with rapid establishment of a high-energy carbonate ramp in the lower Wahoo Limestone. Most of the sequence formed in open-marine carbonate ramp conditions fluctuating between below and above wave base. The Mississippian-Pennsylvanian boundary coincides with a short-duration subaerial exposure surface and approximate the beginning of an overall regressive trend. The rest of the sequence represents a progradational highstand systems tract with a maximum regression and sequence boundary indicated by local cryptalgalaminate and an increase in terrigenous quartz in the lowest upper Wahoo Limestone. Redeposited Mississippian conodonts above the Mississippian-Pennsylvanian boundary could have been derived from erosion along tidal channels (possibly up to 15m deep) or from along a correlative unconformity located farther to the north.

The third sequence, representing most of the upper Wahoo Limestone, begins with local intertidal and more widespread restricted-platform limestones. The sequence boundary and an associated influx of terrigenous quartz can be correlated with an unconformity and thick interval of terrigenous sediment at Prudhoe Bay. Numerous parasequences in the unit can be grouped into parasequence sets that help define the evolution and paleogeography of the Wahoo carbonate ramp. However, individual parasequences cannot be correlated with a high degree of confidence because of the effects of unconformities and autocyclic migration of carbonate facies and a lack of an independent means of high-resolution correlation.

A regional unconformity beneath the Echooka Formation has considerable erosional relief and represents a hiatus of approximately 38 m.y. Widespread subaerial exposure associated with this unconformity essentially killed the Lisburne carbonate platform (i.e., its calcareous organisms). Major carbonate production was

never reestablished, possibly because of paleoclimatic changes associated with the northward plate tectonic drift of northern Alaska. This unconformity apparently indicates regional uplift of the Lisburne platform and may be related to correlative unconformities throughout the circumarctic region (Beauchamp, 1992).

Conodont biostratigraphy has allowed us to precisely define the position of the Mississippian-Pennsylvanian boundary within the lower Wahoo member (Sequence B) at an important reference section (see Chapter 2). Previous biostratigraphic studies using foraminifers were inconsistent in defining the position of the biostratigraphic and lithostratigraphic boundaries. However, most of the middle to late Morrowan North American conodont zonation is not applicable to northern Alaska so we lack high-resolution age control.

Subaerial exposure surfaces provide another means of correlation, and are particularly useful for recognizing sequence boundaries (see Chapter 3). The numerous subaerial exposure surfaces at the boundary between Sequences A and B represent a regionally correlatable surface that signifies emergence of the Alapah carbonate platform prior to the formation of the Wahoo carbonate ramp. However, in the Wahoo Limestone, enigmatic subaerial exposure surfaces occur in highstand deposits near surfaces of maximum flooding in Sequences B and C.

CHAPTER 2

CONODONT BIOSTRATIGRAPHY AND BIOFACIES OF THE LISBURNE GROUP

By A. G. Harris, A. P. Krumhardt, and K. F. Watts

ABSTRACT

Conodont data from the Lisburne Group are presented in three parts. Part 1 summarizes the thesis work of Andrea P. Krumhardt on the conodont biostratigraphy and biofacies of the Wahoo Limestone in the eastern Sadlerochit Mountains (Krumhardt, 1992). This is virtually the same report as Krumhardt and others (in press). A more detailed report on the Wahoo Limestone is in the final stages of preparation as a U.S. Geological Survey Professional Paper (Krumhardt and others, in review). The major results of this study include the precise determination of the Mississippian-Pennsylvanian boundary within the lower member of the Wahoo Limestone and establishment of a conodont biostratigraphy for the Pennsylvanian part of the Wahoo that is applicable to northern Alaska. Conodont biofacies are related to depositional environments and compared with carbonate microfacies analyses; both indicate high-energy, chiefly normal-marine conditions in the northern part ANWR.

Part 2 describes the conodont zonation used for the middle Carboniferous in northern Alaska and the criteria used for assigning ages. A series of chronostratigraphic diagrams illustrates age variations and correlation of the Lisburne Group in ANWR, at two localities in the central Brooks Range, and in wells in the National Petroleum Reserve in Alaska.

Part 3 includes a map showing conodont color alteration indices. Variations in the thermal history of different parts of ANWR are related to the tectonics of the northeastern Brooks Range.

PART 1—CONODONT BIOSTRATIGRAPHY AND BIOFACIES OF THE WAHOO LIMESTONE (CARBONIFEROUS), EASTERN SADLEROCHIT MOUNTAINS, BROOKS RANGE, ALASKA

ABSTRACT

The Wahoo Limestone is the youngest formation of the Lisburne Group (chiefly Carboniferous) in northeasternmost Alaska. Systematic sampling for microlithofacies and conodont analysis at a relatively continuous section (~262-meter thick) in the eastern Sadlerochit Mountains shows that existing Carboniferous conodont zonations are not readily applicable because most zonal indicators are absent. The following zones and faunal intervals were recognized: Upper *Rhachistognathus muricatus* Subzone (latest Chesterian); *Declinognathodus noduliferus-Rhachistognathus primus* Zone (earliest Morrowan); *Rhachistognathus minutus* Fauna (Morrowan); and an *Idiognathodus* Fauna (late Morrowan and (or) early Atokan). The Mississippian-Pennsylvanian boundary is at 55 meters above the base of the Wahoo. Established foraminiferal biostratigraphy is inconsistent with respect to conodont-based time-rock boundaries in the study section.

The Mississippian part of the Wahoo Limestone was deposited under near restricted to normal-marine conditions in a chiefly open-platform to open-marine setting; it produces a chiefly cavusgnathid biofacies. The Pennsylvanian part of the Wahoo was deposited under predominantly normal-marine, high-energy conditions characterized by migrating ooid shoals; it produces a chiefly rhachistognathid biofacies. Abraded conodonts and bioclasts and mixed assemblages indicate considerable postmortem hydraulic mixing across the Pennsylvanian carbonate platform.

INTRODUCTION

A section of the Wahoo Limestone in the eastern Sadlerochit Mountains (Fig. 2-1; Fig. 1-2, loc. 8) was studied to: (1) establish a conodont biostratigraphic framework for the formation in the Arctic National Wildlife Refuge (ANWR); (2) determine the position of the Mississippian-Pennsylvanian boundary; (3) integrate conodont biofacies with microlithofacies studies; and, (4) compare conodont and foraminiferal biostratigraphic data.

LISBURNE GROUP, NORTHEAST BROOKS RANGE

The Lisburne Group, a sequence of chiefly platform carbonate rocks more than 500 meters in thickness, is exposed across the Brooks Range (Fig.1-1). In most of the northeast Brooks Range, the Lisburne Group gradationally overlies fluvial to marginal-marine deposits of the Endicott Group (Lower Mississippian in northern

ANWR, extending into the Upper Devonian in allochthonous rocks to the southwest). In the eastern Sadlerochit Mountains, however, the Endicott Group is thin or absent because older rocks formed a paleotopographic high so that the Lisburne rests with angular discordance on chiefly Proterozoic rocks (Watts et al., 1988).

In the northeast Brooks Range, the Lisburne Group consists of the Alapah Limestone and the overlying Wahoo Limestone. The Wahoo is subdivided into lower and upper members (Watts et al., 1989). The contact between the members appears to be planar, but, locally, in the eastern Sadlerochit Mountains, it may have erosional relief (Carlson, 1987).

WAHOO LIMESTONE, EASTERN SADLEROCHIT MOUNTAINS

At the study section (Fig. 2-1), the lower member of the Wahoo Limestone is 70 meters thick and consists primarily of bryozoan-pelmatozoan packstone to grainstone that formed in a chiefly open-marine environment. A peloidal-skeletal wackestone partly replaced by nodular chert occurs 55 meters above the base of the lower member. The bed is <0.5-1-m thick, has sharp contacts, and appears to have been deposited on a surface of relief developed on rocks that were subaerially exposed (Carlson, 1990). The chert-bearing bed is 0.5 meter above the highest Mississippian conodonts and immediately below a bed containing the lowest Pennsylvanian conodonts.

A few redeposited, latest Mississippian conodonts occur sporadically in the Pennsylvanian part of the lower member of the Wahoo Limestone and increase in abundance 1 meter below the boundary between the lower and upper members. The redeposited conodonts indicate intermittent reworking of slightly older Wahoo deposits. Quartz sand increases slightly in the upper 1 meter of the lower member and then abruptly increases to an average of 12% in the lower 20 meters of the upper member. This sudden increase suggests considerable regression and some exposure of the Wahoo platform. Exposure surfaces have been reported in the lower member at the study section and in outcrops 1 km to the west (Carlson, 1990).

The upper member of the Wahoo Limestone is 192-meters thick at the study section and consists chiefly of packstone and grainstone deposited in a variety of open-platform to open-marine environments. A disconformity of considerable magnitude separates the Wahoo from the overlying Echooka Formation of Permian age (Crowder, 1990).

CONODONT BIOSTRATIGRAPHY

The conodont zonation (Baesemann and Lane, 1985) for uppermost Mississippian and Pennsylvanian (Morrowan) rocks in North America can only be recognized in the lower 84 meters of the Wahoo Limestone (Fig. 2-2). The Upper *muricatus* Subzone (latest Mississippian) occurs from at least 82 meters below to 55

Figure 2-1

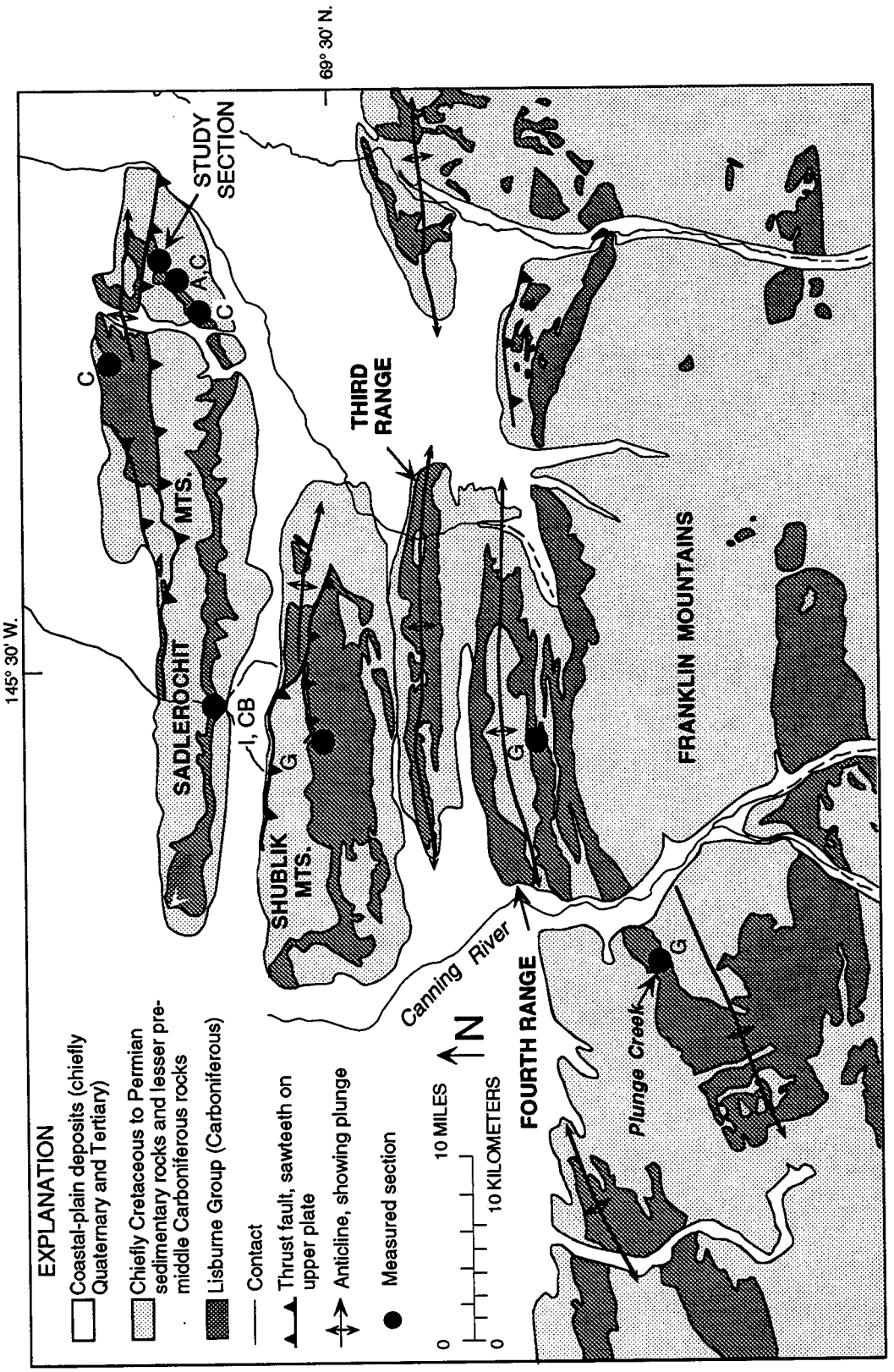


Figure 2-1. Map showing Lisburne Group outcrop belt, major structural features, and location of the study section (modified from Gruzlovic, 1991 and Krumhardt, 1992). Other stratigraphic sections were described by: C = Carlson (1987); G = Gruzlovic (1991); A = Armstrong (see Fig. 2-3); CB = Clough and Blodgett (1986); and I = Imm (1986).

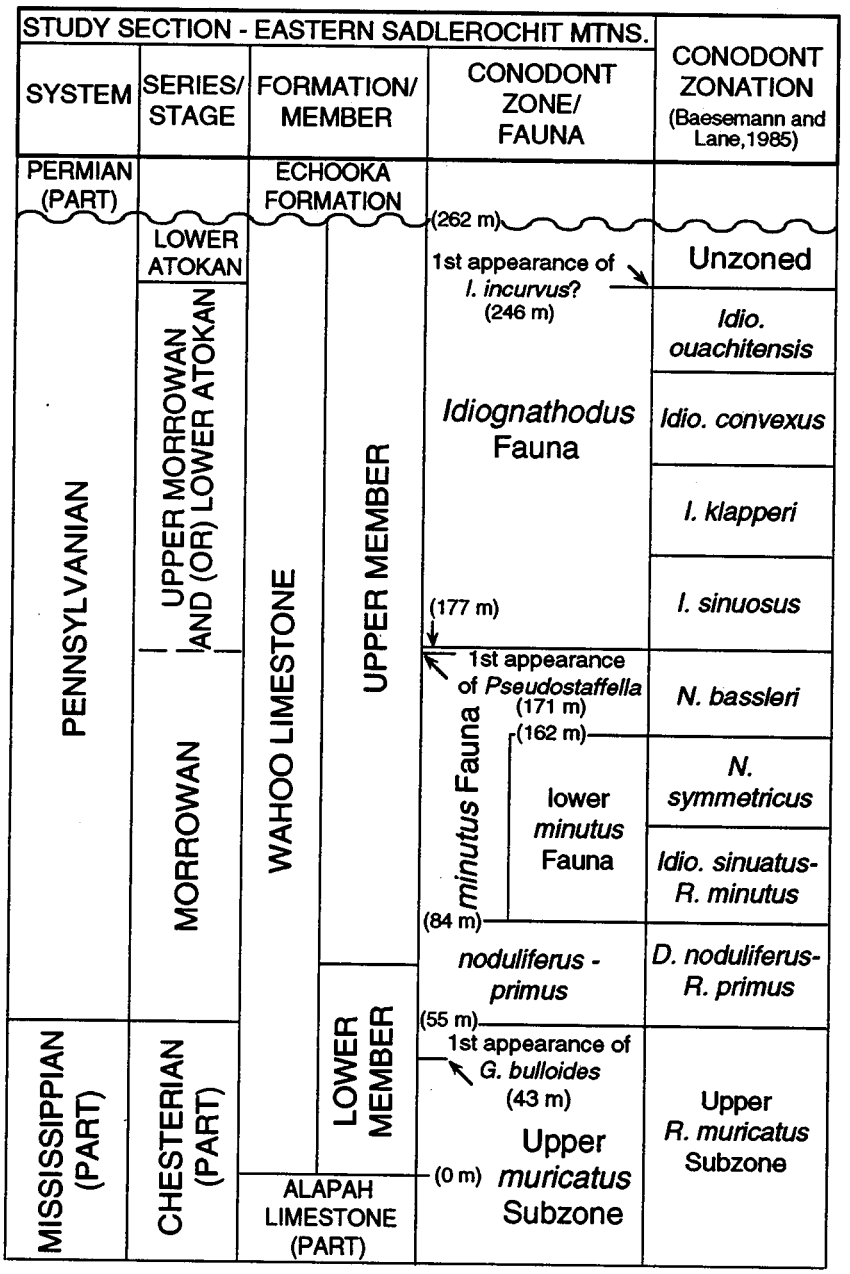


Figure 2-2. Conodont zones and faunas recognized in the Wahoo Limestone at the study section compared to the North American middle Carboniferous conodont zonation of Baesemann and Lane (1985). Numbers in parentheses indicate stratigraphic position above the base of Wahoo Limestone in the study section. Foraminiferal data from P.L. Brenckle, Amoco Production Co. (written commun., 1991). Generic abbreviations for conodonts are: *D., Declinognathodus; I., Idiognathodus; Idio., Idiognathoides; N., Neognathodus; R., Rhachistognathus.* Foraminifers are *Globivalvulina bulloides* and *Pseudostaffella.*

meters above the base of the Wahoo; the *noduliferus-primus* Zone (earliest Pennsylvanian) is present from 55 to 84 meters above the base of the Wahoo. The remaining Pennsylvanian strata could not be precisely dated because most zonal indicators are absent. Consequently, we used an informal conodont succession based on local ranges of some rhachistognathids and the first appearance of *Idiognathodus* (Fig. 2-2). The informal *minutus* Fauna represents the local range of *Rhachistognathus minutus* below the first appearance of *Idiognathodus* (Fig. 2-2). A lower subdivision of the *minutus* Fauna is defined by the overlapping ranges of *R. minutus* subspp. and *R. websteri*. The lower *minutus* Fauna is considered Morrowan because the foraminiferan guides to the base of the Atokan occur in the uppermost part of the *minutus* Fauna (Fig. 2-2). At the study section, the *minutus* Fauna occurs from 84 to 177 meters above the base of the Wahoo; the basal 78 meters are assigned to the lower *minutus* Fauna.

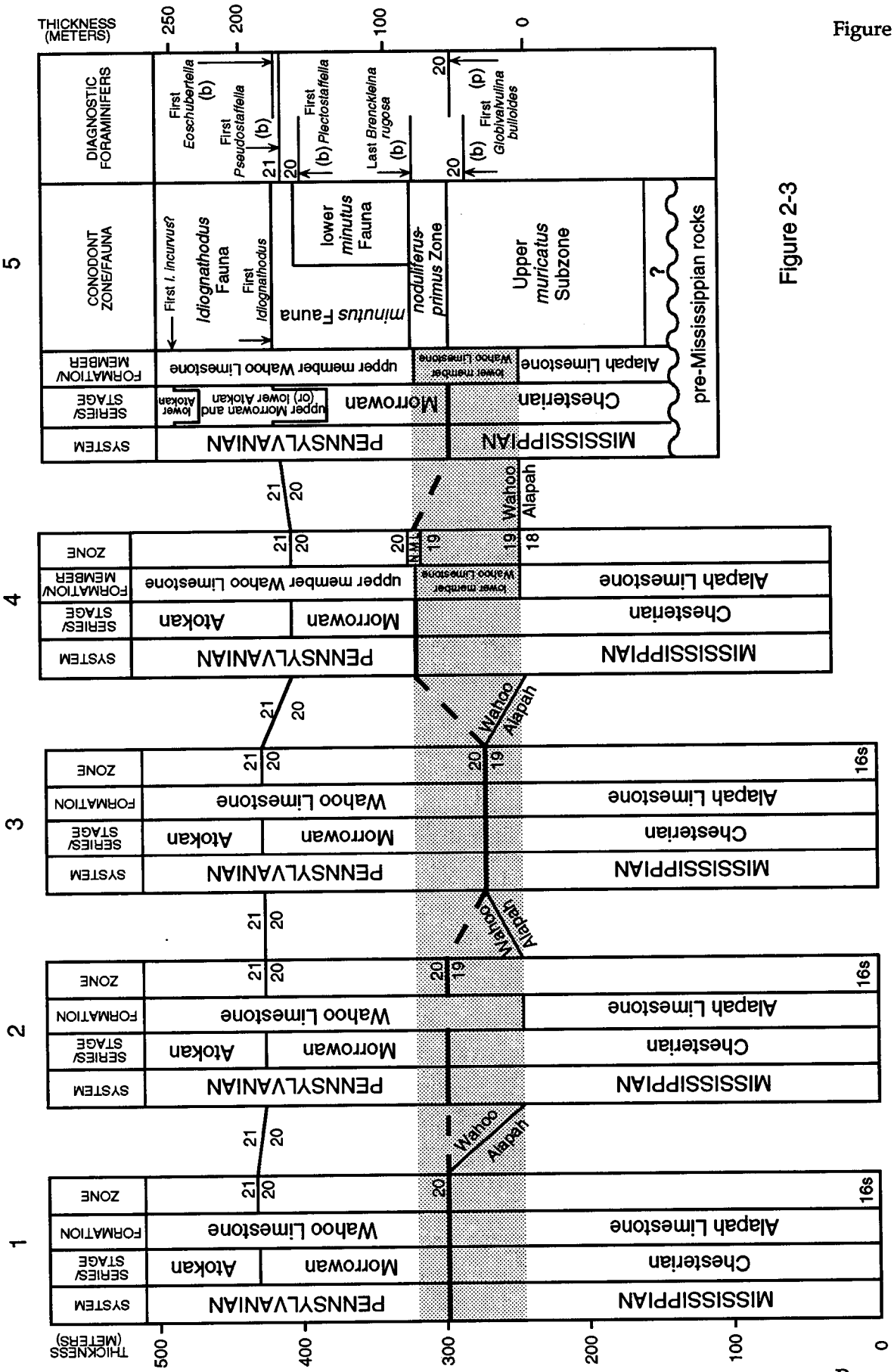
The *Idiognathodus* Fauna is characterized by the association of *Idiognathodus* spp., *Rhachistognathus minutus*, and *Adetognathus lautus*. The first appearance of *Idiognathodus* in the Wahoo Limestone marks the lower boundary of the fauna; the fauna extends to the top of the formation (Fig. 2-2). The lower boundary of the *Idiognathodus* Fauna could be as old as middle Morrowan, or as young as early Atokan. Many of the idiognathodids in our collections are specifically indeterminate. Representatives of *Idiognathodus*, a genus that ranges from the middle Morrowan through at least the Pennsylvanian, occur in the upper 75 meters of the Wahoo and 6 meters above the lowest occurrence of *Pseudostaffella*, a foraminifer which is used to approximate the base of the Atokan in much of North America (Groves, 1986). If *Pseudostaffella* approximates the base of the Atokan in Alaska, then the entry of *Idiognathodus* above it occurs in the early Atokan and, thus, considerably later than its debut in the type Morrowan. One specimen of *I. incurvus*? was found 16 meters below the top of the Wahoo. This species is restricted to the Atokan and lower Desmoinesian so that the upper 16 meters of the *Idiognathodus* Fauna in the study section is no older than Atokan. In addition, *I. incurvus*? occurs within the range of *Rhachistognathus minutus*, further suggesting that the top of the *Idiognathodus* Fauna here is no younger than early Atokan.

MISSISSIPPIAN-PENNSYLVANIAN BOUNDARY: FORAMINIFERS VERSUS CONODONTS

Because foraminifers have chiefly been used to correlate the Lisburne Group (Armstrong et al., 1970; Armstrong and Mamet, 1975), we were eager to tie conodont biostratigraphy to Mamet's foraminiferal zonation. Unfortunately, the foraminiferal zonation appears to have been used inconsistently in the eastern Sadlerochit Mountains (Fig. 2-3). Microfossil analyses of the same thin sections taken from the Sunset Pass section (about 1 km west of our study section) were reported by B.L. Mamet at least three times with conflicting results; the Sunset Pass section was resampled by Carlson (1987) and also analyzed by Mamet. Conodonts indicate that the Mississippian-Pennsylvanian boundary (on the basis of the first occurrence of *Declinognathodus noduliferus* above forms transitional from *Gnathodus girtyi*

Figure 2-3. Comparison of lithostratigraphic, biostratigraphic, and time-rock boundaries between the study section and the nearby Sunset Pass section analyzed in previous reports shows inconsistencies in stratigraphic nomenclature and age determinations for the Wahoo Limestone. Prior to Carlson (1987; column 4), all interpretations for the Sunset Pass section were based on one composite section (Armstrong et al., 1970, sections 68A-4A, 4B); Carlson's section is along the same traverse. The Alapah Limestone-Wahoo Limestone boundary is at the same stratigraphic level in columns 2, 4, and 5 but differs from columns 1 and 3. Foraminiferan zonal boundaries in columns 1 through 4 were determined by B.L. Mamet; foraminiferan data for column 5 are from P.L. Brenckle (b) and Sylvie Pinard (p). In column 5, the first occurrence of the diagnostic foraminifer that approximates the base of the Pennsylvanian, *Globivalvulina bulloides* , is at least 12 meters below the first *Declinognathodus noduliferus*. P.L. Brenckle also noted the last occurrence of *Brenckleina rugosa* well above its known range in the conterminous United States (at or very slightly above the base of the Pennsylvanian). The Morrowan-Atokan boundary is poorly constrained by conodonts. *Pseudostaffella* sp. is used to approximate this boundary in the Midcontinent and Cordillera of the conterminous United States (Lane and Manger, 1985; Groves, 1986). In the study section it appears 14 meters above the lowest occurrence of its plectostaffellid ancestor and 75 meters below the first definitive Atokan conodont. Column 1 is from Armstrong and others (1970) and Armstrong and Mamet (1977); column 2 from Armstrong (1972; 1974) and Wood and Armstrong (1975); column 3 from Armstrong and Mamet (1975) and Mamet and Armstrong (1984); column 4 from Carlson (1987); column 5 from this report--thickness measured from base of Wahoo Limestone. Heavy dashed line shows relative position of Mississippian-Pennsylvanian boundary for the various studies. NML, "No Man's Land" as used by B.L. Mamet in Carlson (1987) and Gruzlovic (1991).

Figure 2-3


THICKNESS (METERS)
DIAGNOSTIC FORAMINIFERS
CONODONT ZONE/FAUNA
SYSTEM
SERIES/ STAGE
FORMATION/ MEMBER
ZONE
PENNSYLVANIAN
MISSISSIPPIAN
Morrowan
Atokan
Chesterian
Wahoo Limestone
Alapah Limestone
upper member Wahoo Limestone
lower member Wahoo Limestone
upper Morrowan and (or) lower Atokan
lower Atokan
Idiognathodus Fauna
minutus Fauna
lower minutus Fauna
nodulifer-primus Zone
Upper muricatus Subzone
pre-Mississippian rocks
Wahoo
Alapah
16s
Figure 2-3

simplex) is at about the same stratigraphic level shown in Armstrong et al. (1970) and Armstrong (1974), but about 25 meters higher than in Armstrong and Mamet (1975), and about 17 meters lower than in Carlson (1987) for the Sunset Pass section (Fig. 2-3). If the first appearance of the foraminifer *Globivalvulina bulloides* is used as a guide to the base of the Pennsylvanian in our section (Fig. 2-2), the systemic boundary would be 12 meters lower than indicated by conodonts, but would still not coincide with any position determined by Mamet. The Subcommission on Carboniferous Stratigraphy (SCCS), however, has recommended that the first appearance of the conodont *Declinognathodus noduliferus* be used as the primary micropaleontologic guide for the base of the Pennsylvanian (Lane and Manger, 1985). We followed the biostratigraphic recommendation of the SCCS in our study.

CONODONT BIOFACIES

All conodont morphotypes identifiable to genus were used for biofacies analysis. Samples containing <20 generically identifiable elements and genera represented by <5 elements were not used for analysis. Following Ziegler and Sandberg (1990), conodont biofacies are named for the one or two genera that make up ~70% of a sample. If the two most abundant genera make up <70% of the conodont fauna, the assemblage is, with some exceptions, considered the result of postmortem mixing. Although most of our samples indicate some mixing, samples dominated by two genera are interpreted as *in situ* assemblages or assemblages derived from laterally adjacent environments. The data set for conodont biofacies described below is given in Krumhardt (1992).

Paleoenvironments were interpreted from regional and local, and vertical and lateral stratigraphic relationships; carbonate lithology and grain types (including skeletal grains), and fossil assemblages. Some lithologies, representing environments considered unfavorable for conodonts, were rarely sampled (e.g., intertidal and restricted-marine lithofacies).

Mississippian biofacies

Regional relationships suggest that the Mississippian part of the lower member of the Wahoo Limestone was deposited on an open-marine carbonate platform. The eastern Sadlerochit Mountains probably lay along the inner part of this platform (Krumhardt, 1992; Watts, 1992). The base of the Wahoo coincides with the beginning of a major transgressive-regressive cycle; the Mississippian part of the lower member formed during the transgressive phase of this cycle. The major environments sampled for conodonts and conodont biofacies are shown in Fig. 2-4*A*.

Samples that yielded a cavusgnathid biofacies represent a near-restricted to open-platform environment. Conodonts are rare to common (11/kg), but only 43% are generically determinate reflecting a relatively high-energy regime. *Cavusgnathus* makes up about 85% of the identifiable conodonts in this environment.

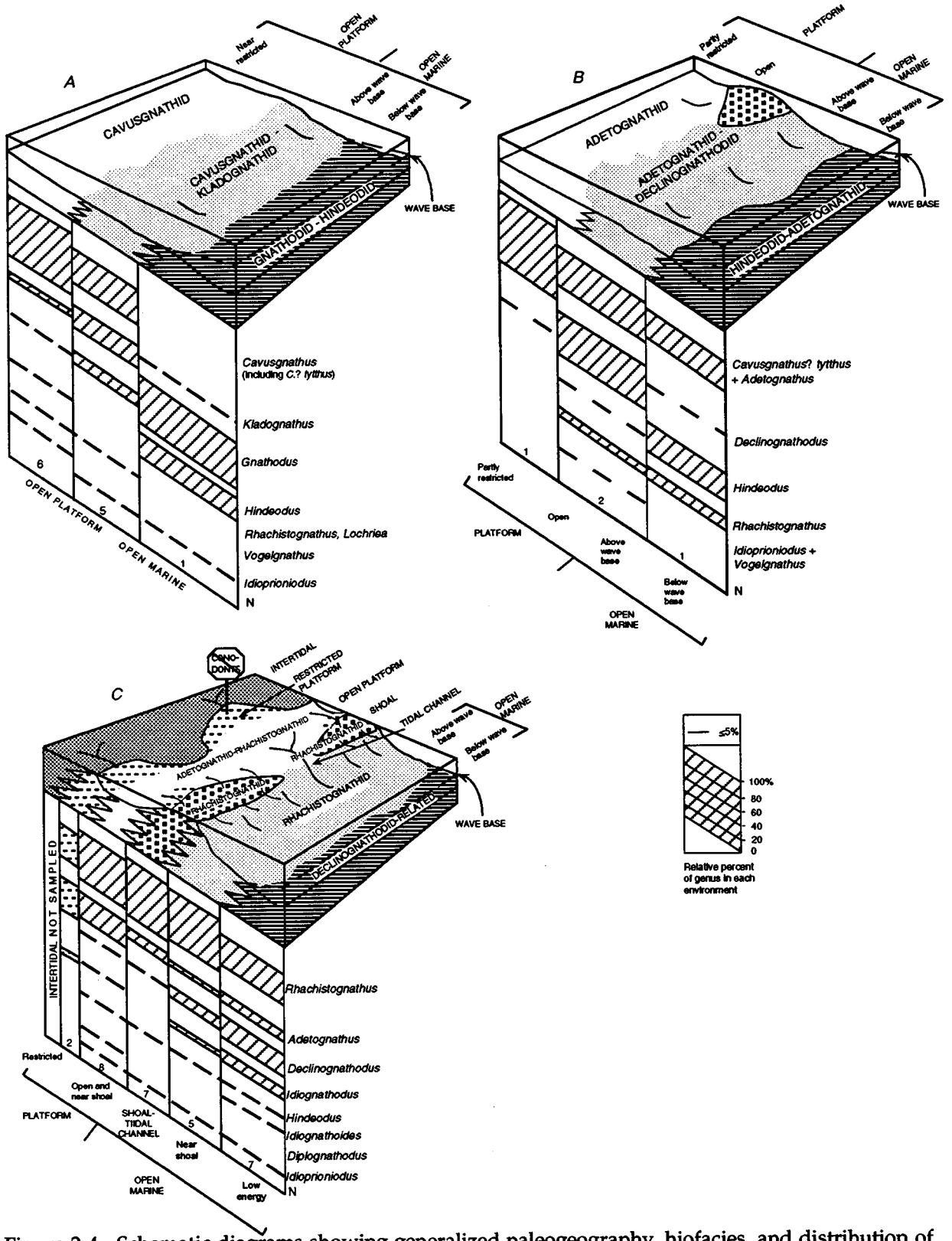


Figure 2-4. Schematic diagrams showing generalized paleogeography, biofacies, and distribution of conodont genera for the Wahoo Limestone in the eastern Sadlerochit Mountains. *A*, Mississippian part of lower member; *B*, Pennsylvanian part of lower member; C, upper member (Pennsylvanian). N, number of samples qualifying for biofacies analysis in each environment.

Samples that produced a cavusgnathid-kladognathid biofacies represent an open-platform to open-marine environment. These samples contain relatively abundant conodonts (26/kg), but ~60% are indeterminate fragments. Many conodonts, however, are complete, so that postmortem transport was probably local and relatively short lived.

The gnathodid-hindeodid biofacies was recorded in one sample representing a low-energy (below wave base), open-marine environment. *Gnathodus* and *Hindeodus* probably lived in and seaward of the site represented by the study section as these forms are rare in contemporaneous shoreward facies.

Pennsylvanian biofacies

Pennsylvanian depositional patterns are less complex in the lower member of the Wahoo Limestone than in the upper member (compare Figs. 2-4*B* and *C*). Ooid shoal facies make up 20% of the upper member. This high-energy regime caused many conodonts to be transported beyond their habitat, substantially disrupting and even obliterating original biofacies patterns.

The adetognathid biofacies was found in one sample from the Pennsylvanian part of the lower member of the Wahoo Limestone (Fig. 2-4*B*). *Cavusgnathus? tytthus* (included here in the adetognathids) is virtually the only conodont present. It is characteristic of nearshore, possibly intermittently restricted environments. Two other samples from this part of the lower member represent an adetognathid-declinognathodid biofacies. Microlithofacies suggest a moderate-energy, open-platform to open-marine setting. Adetognathids and *Cavusgnathus? tytthus,* together, account for 35-58% of the conodonts in this biofacies. These occur with declinognathodids, a cosmopolitan group. Rhachistognathids are few in the Pennsylvanian part of the lower member because their principal habitat, the shoal-water environment, was also rare (Fig. 2-4*B*). A fourth sample from this stratigraphic interval produced a hindeodid-adetognathid biofacies. The microlithofacies indicate a low-energy, open-marine environment. Although the sample qualifies for biofacies analysis, the species association suggests a mixed assemblage. It is likely that *Hindeodus minutus* is *in situ* as all elements of its apparatus are present. This species is long ranging and consistently appears in rocks representing the relatively deeper parts of the Wahoo Limestone (compare Figs. 2-4*A-C*). This biofacies may represent the outer limit of the *Cavusgnathus? tytthus* and adetognathid habitats. More likely, these forms are hydraulic admixtures, so that the adetognathid part of the "biofacies" is unnatural. In addition, rhachistognathids (18%) were probably carried here from their shallow-water, high-energy habitat.

Two samples from the upper member of the Wahoo Limestone representing the restricted-platform environment qualified for biofacies analysis (Fig. 2-4C). These samples yielded nearly equal numbers of adetognathids and rhachistognathids. The

collections represent either the outer limit of the adetognathid-rhachistognathid biofacies or, more likely, storm-tossed skeletons or stranded voyagers.

The most prevalent and sampled environment in the upper member of the Wahoo Limestone is the open-platform to near-shoal environment; eight qualified for biofacies analysis. Although conodonts are relatively rare (8/kg), 60% are generically determinate. Many conodonts were undoubtedly transported from the adjacent, higher energy, shoal environment. Rhachistognathids make up 67% and adetognathids 33% of collections from this environment.

The rhachistognathid biofacies was identified in 5 of 7 samples from massive-bedded, well-sorted oolitic to bioclastic grainstone inferred to represent shoal and (or) tidal-channel environments (Fig. 2-4C). Conodonts are common (20/kg) and well preserved; 57% are generically determinate suggesting the conodonts lived in and (or) adjacent to these environments. Rhachistognathids make up 79% of the collections. Adetognathids, the only other group common in this depositional setting, represent 17% of the collections and are probably migrants or postmortem additions from the open platform.

Five samples from the near-shoal, open-marine environment (Fig. 2-4C) were eligible for biofacies analysis and represent the rhachistognathid biofacies. Conodonts are slightly more abundant (22/kg) than in other environments identified in the upper member of the Wahoo Limestone. Nearly 55% are generically determinate and include 69% rhachistognathids, 16% declinognathodids, and 7% each of adetognathids and idiognathodids (Fig. 2-4C). The relative abundance of adetognathids and declinognathodids is inversely related in different samples suggesting separate sources of postmortem admixture and (or) migrants. The adetognathids were probably derived from the shallower waters of the inner platform, and the declinognathodids probably came from other nearby open-marine environments or lived in small numbers within this environment.

Seven samples collected from the low-energy, open-marine environment produced a mix of biofacies, but all contain predominant to substantial numbers of declinognathodids, thus the declinognathodid-related biofacies. Conodonts are common to rare, but only 40% are generically determinate. The conodonts are a mix of platform, shoal, and open-marine forms (29% adetognathids, 40% rhachistognathids, and 27% declinognathodids). On the basis of microlithofacies, we assume the adetognathids and rhachistognathids are postmortem additions to a low-population declinognathodid biofacies.

The Wahoo Limestone formed in a range of chiefly open-platform, near-shoal, and open-marine environments on the shallow, inner part of a high-energy carbonate ramp. In the uppermost Mississippian and lowermost Pennsylvanian part of the Wahoo, shoal facies were uncommon so that open-platform and open-marine microlithofacies and conodont biofacies were not clearly separated. Grain types and, to a lesser extent, conodonts were hydraulically spread beyond their natural environments making some environmental interpretations equivocal. The

use of conodont biofacies and microlithofacies in concert, clarifies some of these environmental ambiguities. In the Pennsylvanian part of the Wahoo, extensive ooid- and skeletal-shoal tracts separated open-marine and open-platform environments producing more distinct biofacies and diagnostic microlithofacies. Rhachistognathids thrived in and adjacent to the barrier facies. After death, many of their skeletal elements remained *in situ*, however, a substantial number were washed into surrounding environments, masking natural species associations. Similarly, mixing of carbonate grains obscures microlithofacies interpretations.

CONCLUSIONS

Foraminifers have been the primary biostratigraphic indices for the Lisburne Group in ANWR. Some studies, however, indicate inconsistent assignment of foraminiferal zones and lithologic boundaries within our study area. Conodonts seem to provide better biostratigraphic resolution than foraminifers for the Lower Pennsylvanian part of the Lisburne Group. Neither group, however, adequately constrains the Morrowan-Atokan boundary.

It is apparent that taxonomic interpretations, biostratigraphic models, and paleobiogeography, in addition to spacing and selection of foraminiferal and conodont samples, control time-rock boundary placement. As taxonomic interpretations stabilize and global biostratigraphic data increase for both foraminifers and conodonts, correlations should improve. Data from other fossil groups may be needed to distinguish evolutionary from migratory patterns in foraminifers and conodonts.

Although conodont biofacies analysis of Carboniferous rocks in northern Alaska is just beginning, the use of conodonts to augment environmental interpretations based on microlithofacies is promising, particularly for rocks in which primary carbonate textures have been obscured by diagenesis and metamorphism.

PART 2—REGIONAL CONODONT BIOSTRATIGRAPHY

Conodont biostratigraphy has provided valuable age control that allows correlation of stratigraphic sections and an understanding of the depositional framework of the Lisburne Group and its equivalents. As noted in the previous section, detailed systematic conodont sampling of the Wahoo Limestone precisely positioned the Mississippian-Pennsylvanian boundary in the lower member of the Wahoo. However, many of the zonal indicators for Lower and Middle Pennsylvanian conodont zones used elsewhere in North America are absent in the Lisburne thereby necessitating the use of local faunal assemblages for biostratigraphic correlation.

We have not yet systematically sampled and analyzed conodonts from the Alapah Limestone. Many of the indices for Mississippian conodont zones in North America also appear to be lacking so that age determinations are based on the overlapping ranges of several conodont species. In this section, we discuss the criteria used for conodont-based age determinations in the Carboniferous of northeastern Alaska (Fig. 2-5). The conodont data are summarized in correlation diagrams that illustrate age variations in the Kayak Shale, Alapah Limestone, and Wahoo Limestone (Figs. 2-6 to 2-9). We will briefly consider the bearing of these on the understanding of the evolution of the Lisburne carbonate platform.

CONODONT-BASED AGE DETERMINATIONS

KINDERHOOKIAN

The Kayak Shale is poorly productive of conodonts. Those that have been recovered indicate that the Kayak Shale of the central Brooks Range is of Kinderhookian age (Fig. 2-6, columns for Shainin Lake and Atigun Gorge). Conodont faunas from the Kayak contain chiefly bispathodids and polygnathids indicating predominantly shelfal depositional environments. Species include *Bispathodus aculeatus aculeatus, Bi. ac. anteposicornis, Bi. ac. plumulus, Bi. stabilis, Branmehlia* sp., *Polygnathus communis communis, Po. inornatus, Po. longiposticus,* and digyrate apparatuses and, more rarely, *Hindeodus crassidentatus* and siphonodellids. Nearly all of these species range throughout the Kinderhookian and many of the bispathodids range into the late Famennian. Locally, middle and late Kinderhookian faunas have been identified by the presence of biostratigraphically diagnostic species of *Siphonodella* and, to a lesser extent, *Hindeodus*.

OSAGEAN

Conodont faunas of Osagean age occur in the lower part of the Wachsmuth Limestone in the Shainin Lake section (Fig. 2-6). At Atigun Gorge, conodonts in the

Figure 2-5

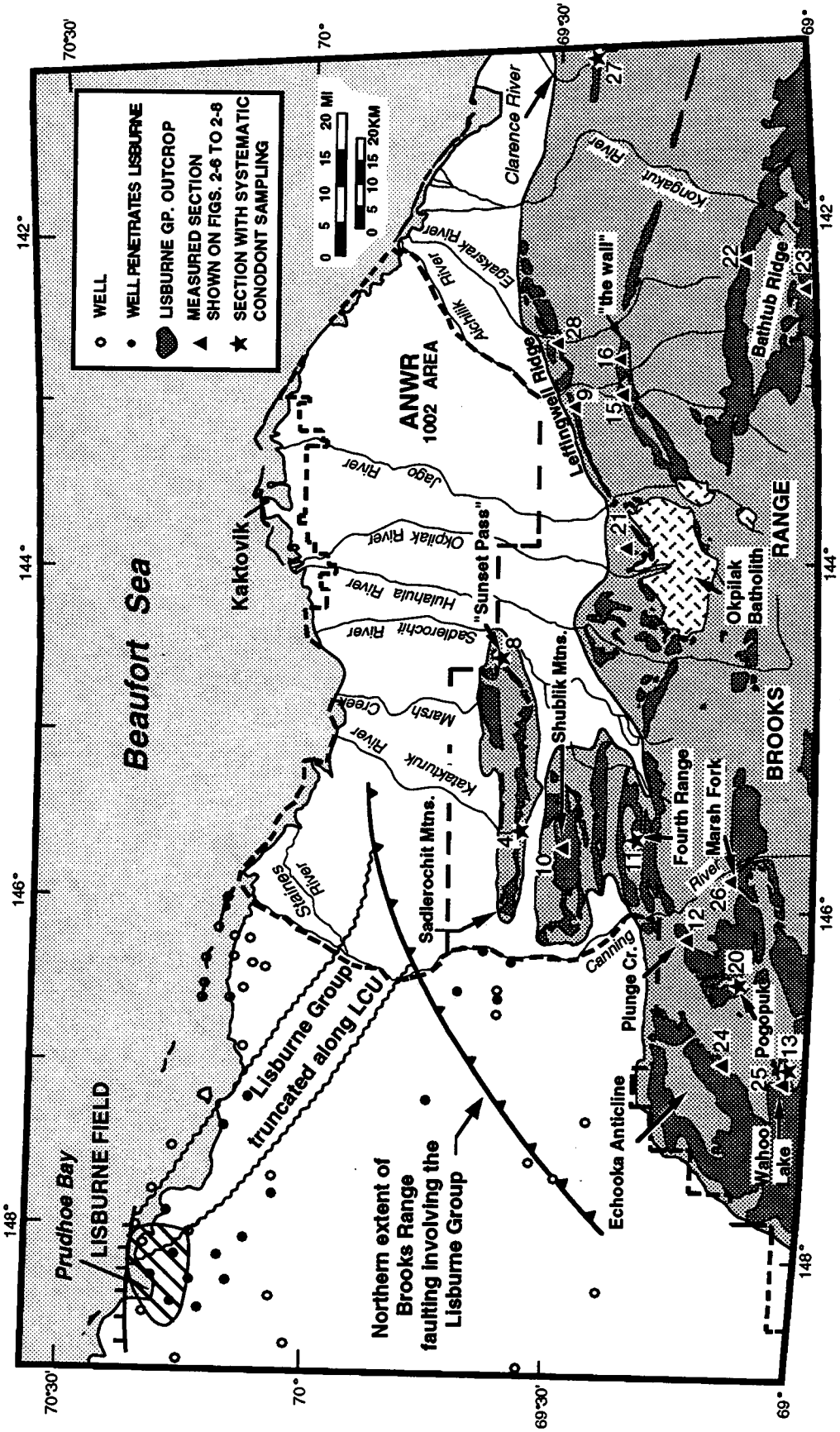


Figure 2-5. Map showing the distribution of exposures of the Lisburne Group in ANWR and locations of measured sections having conodont samples. The general location of the truncation of the Lisburne Group beneath the Lower Cretaceous unconformity (LCU) is also shown extending southeastward from Prudhoe Bay (modified after Bird et al., 1987).

lower part of the Wachsmuth(?) are longer ranging and merely indicate an Early Mississippian age, no older that late Kinderhookian. In the southern Romanzof Mountains, the upper part of the Kayak Shale and an interval transitional between the Kayak and overlying Lisburne Group also contain conodonts of Osagean age. Osagean conodont faunas from these areas are of relatively low diversity, yielding chiefly bispathodids, hindeodids, and kladognathids that indicate relatively shallow-water depositional regimes. Osagean conodont faunas from the Lisburne Group and Kayak Shale include representatives of *Bispathodus utahensis, Branmehlia* sp., *Gnathodus cuneiformis, Hindeodus crassidentatus, Kladognathus* spp., and *Synclydognathus geminus*. Most of these species are long ranging within the Osagean and Meramecian, but *Hi. crassidentatus* is not known above the Osagean and *Gn. cuneiformis* is limited to the *Gn. typicus* and *Sc. anchoralis-D. latus* Zones of the Osagean. Osagean conodont faunas from deeper water deposits that occur farther south and west in the Brooks Range are of relatively high diversity (Dumoulin and others, 1993 and in press).

EARLY MERAMECIAN

Conodonts of definitive early Meramecian age have not yet been identified from shallow-water deposits of the Lisburne Group in the northeast Brooks Range. Rocks of early Meramecian age may well be represented in the thick succession of shallow-water platform carbonate deposits represented by the upper part of the Wachsmuth Limestone in the central Brooks Range, but index fossils of this age have not yet been recovered. On the other hand, the early Meramecian was a time of relatively low sea level so that rocks of this age may well be unrepresented in shallow-water platform sequences.

LATE MERAMECIAN

Conodont faunas of late Meramecian and younger Mississippian age are common in the shallow-water carbonate rocks of the Lisburne Group. The late Meramecian is represented in the upper part of the Wachsmuth Limestone and lower part of the Alapah Limestone in the Shainin Lake section (Fig. 2-6). The first appearance of representatives of *Cavusgnathus*, a long-ranging late Meramecian and Chesterian genus, marks the beginning of the late Meramecian. Late Meramecian conodonts from the shallow-water deposits of the Alapah are predominantly bispathodids, cavusgnathids, kladognathids, and synclydognathids. Species include *Bispathodus utahensis, Cavusgnathus unicornis, Idioprioniodus* sp., *Kladognathus* spp., *Synclydognathus geminus,* and *Sy. pinnatus*. Once again, the species listed above are relatively long-ranging within the Mississippian, but the occurrence of *Bi. utahensis*, a species not known above the Meramecian, with *Cavusgnathus*, a genus that first appears in the late Meramecian, restricts several samples to the late Meramecian.

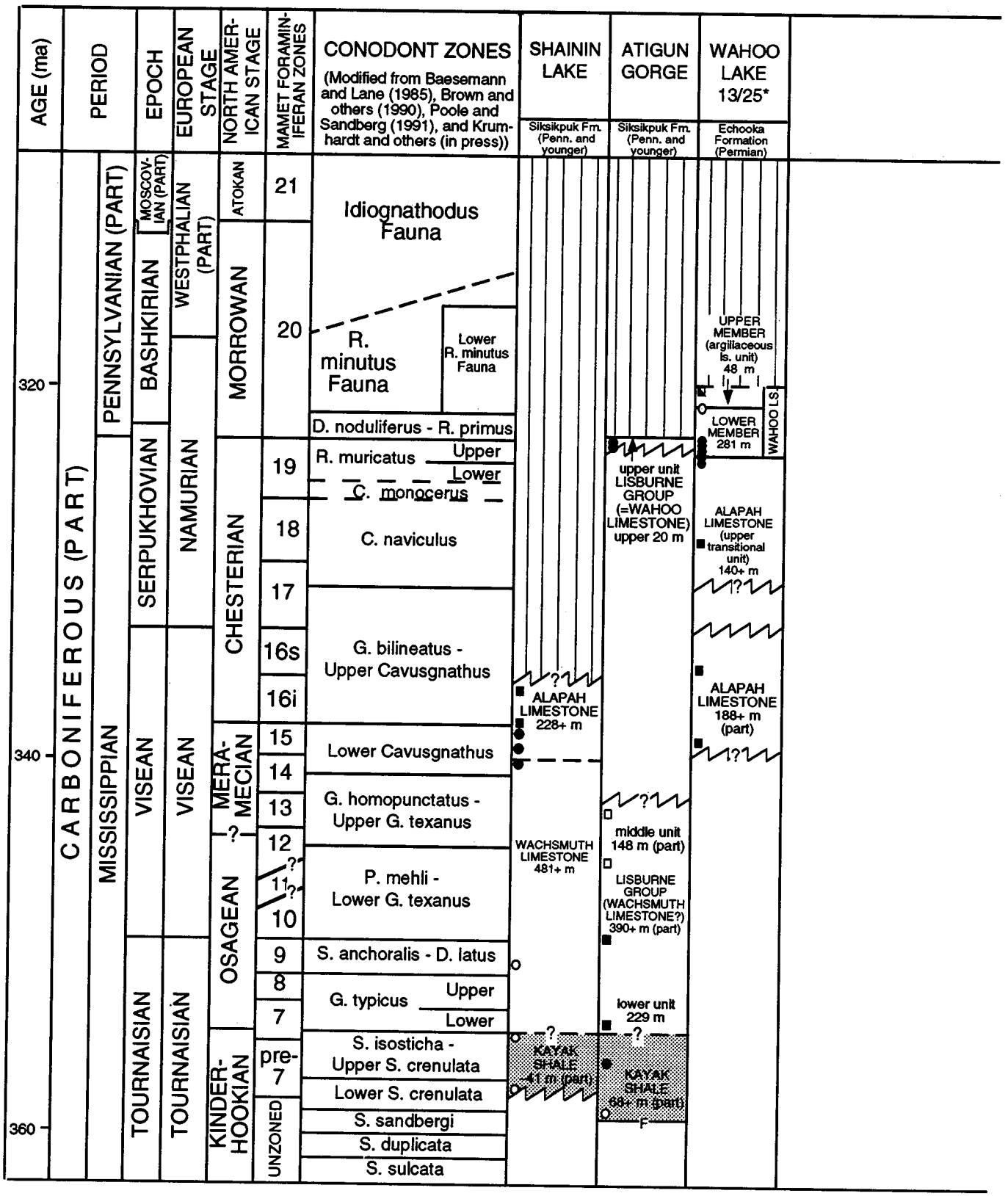


Figure 2-6. Chronostratigraphic diagram showing stratigraphic sections of the Lisburne Group from Shainin Lake (central Brooks Range) in the west to Clarence River (near Canadian border) in the east. *, indicates systematic samping for conodonts.

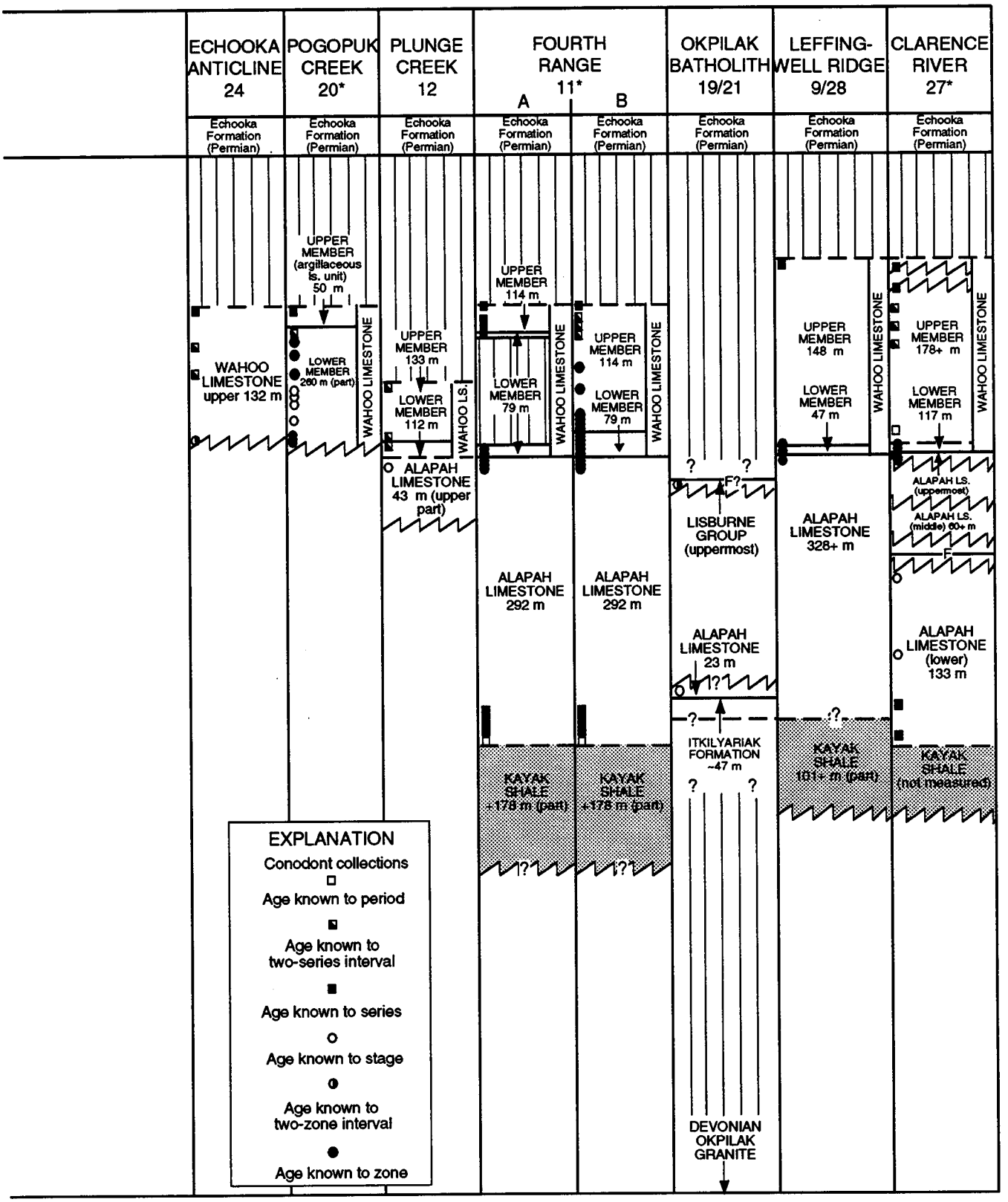


Figure 2-6 (continued).

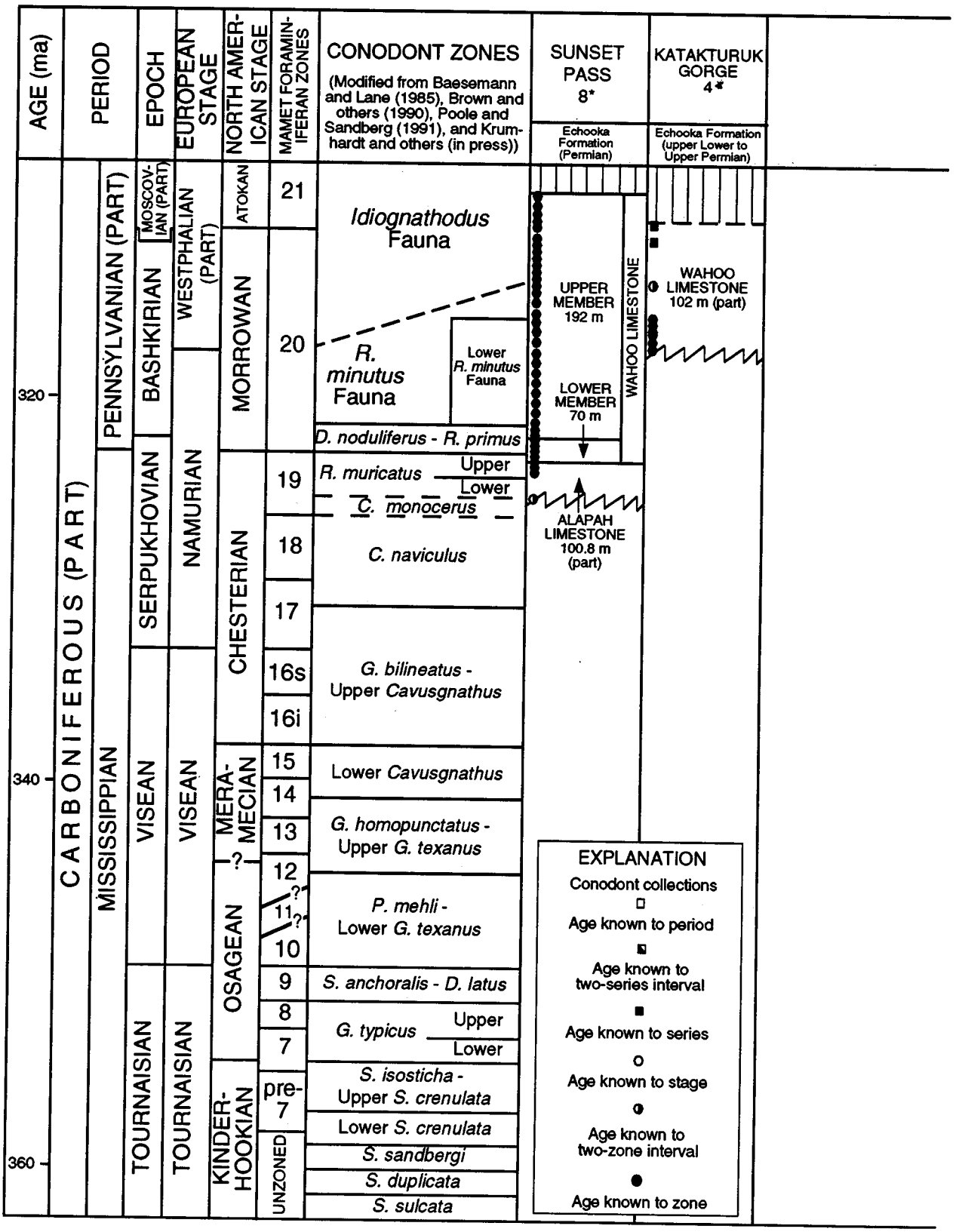


Figure 2-7. Chronostratigraphic diagram showing stratigraphic sections of the Lisburne Group along the Canning River transect. *, indicates systematic samping for conodonts.

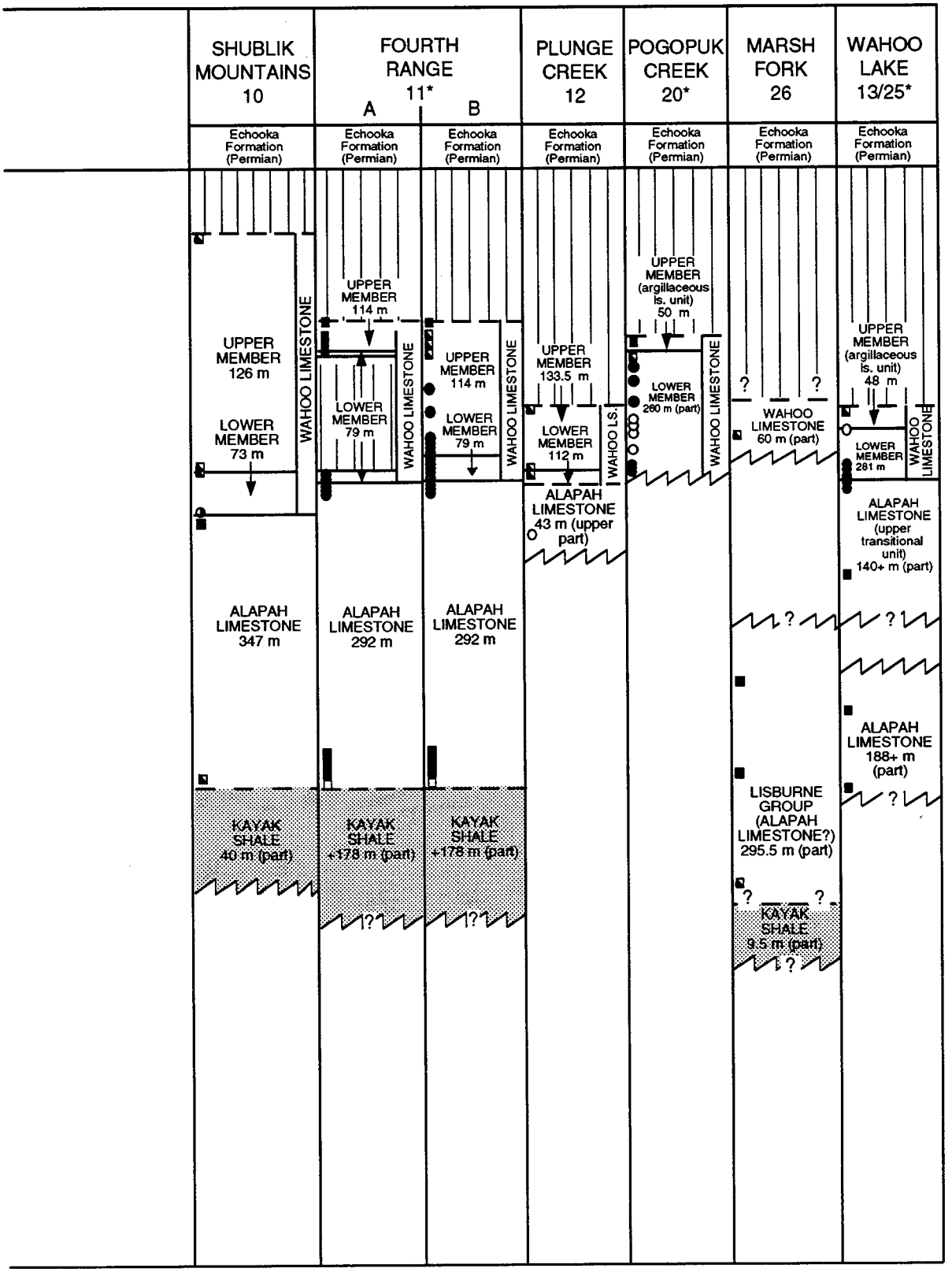


Figure 2-7 (continued).

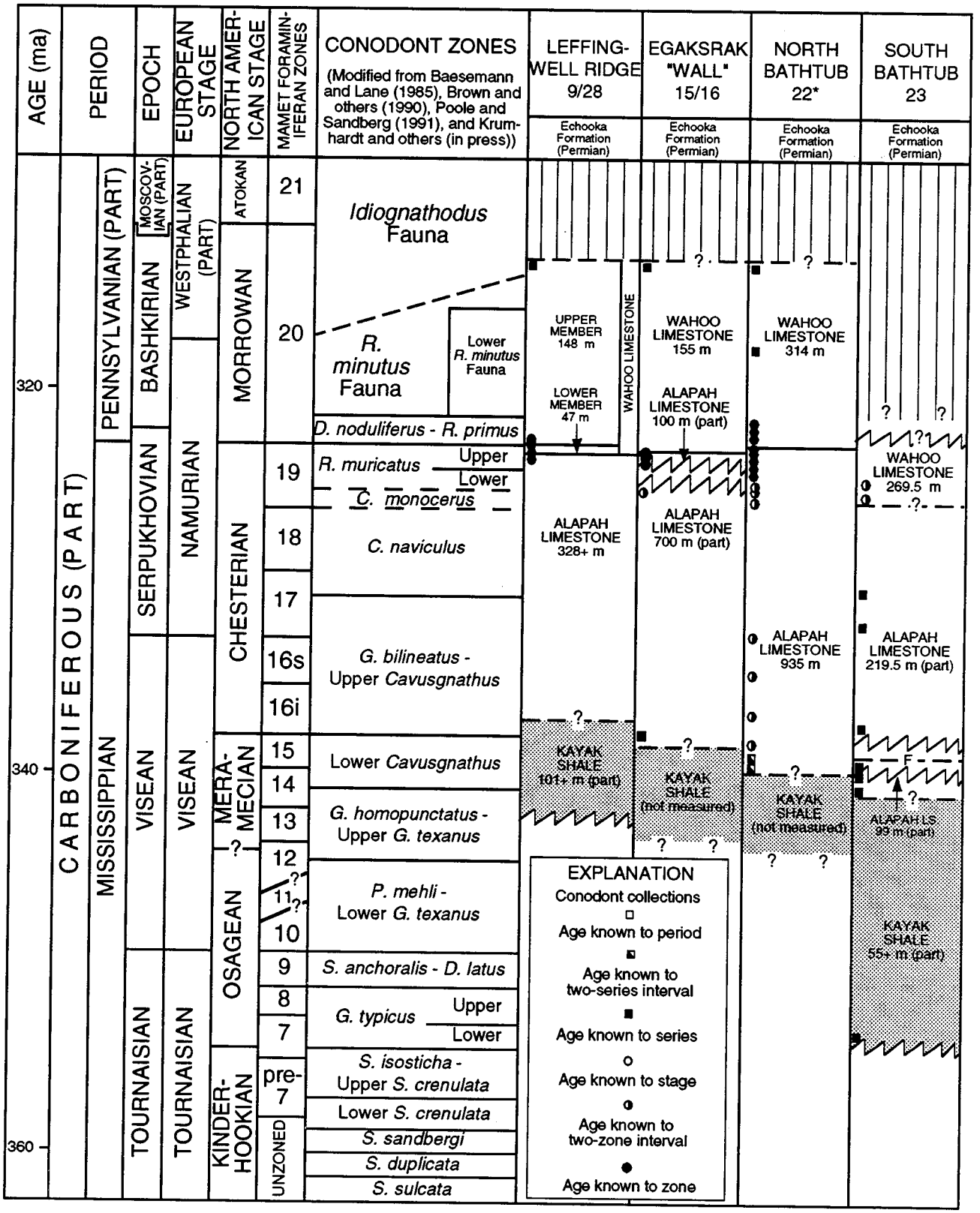


Figure 2-8. Chronostratigraphic diagram showing stratigraphic sections of the Lisburne Group along the Aichilik River transect. *, indicates systematic samping for conodonts.

LATE MERAMECIAN-EARLY CHESTERIAN

The shallow-water deposits of the lower part of the Alapah Limestone in the northeast Brooks Range and at Shainin Lake in the central Brooks Range (Figs. 2-6 and 2-7) commonly yield low numbers of *Cavusgnathus unicornis* and *Synclydognathus* spp. and thus are assigned a late Meramecian to early Chesterian age. Rocks of this age produce cavusgnathids, idioprioniodids, kladognathids, and synclydognathids. Even though the absence of *Bispathodus utahensis* suggests a Chesterian rather than late Meramecian age, the lack of gnathodids in these rocks prevents a definitive early Chesterian age designation.

LATE CHESTERIAN

Rocks of late Chesterian age are abundantly represented in the Lisburne Group, in the upper part of the Alapah and lower part of the Wahoo limestones in the northeast Brooks Range and in the Inigok Test Well in NPRA (Figs. 2-6 to 2-9). The *Cavusgnathus naviculus* and *C. monocerus* Zones have not been recognized; the interval of the *C. monocerus* and *R. muricatus* Zones, however, is readily diagnosed and widespread. This interval produces *Adetognathus lautus, Cavusgnathus altus, Ca. unicornis, Ca.? tytthus, Gnathodus bilineatus, Gn. girtyi girtyi, Gn. gr. simplex, Hindeodus minutus, Idioprioniodus conjunctus, Kladognathus* spp., *Lochriea commutata, Rhachistognathus prolixus,* and *Vogelgnathus postcampbelli.* The occurrence of *Hi. minutus* with *Cavusgnathus* spp. (exclusive of *C.? tytthus*) in the absence of *Rhachistognathus muricatus,* indicates the *C. monocerus* or *R. muricatus* Zone. The interval of the *Ca. monocerus-R. muricatus* Zones is at least 257 m thick in the Fourth Range section (loc. 10, Fig. 2-7).

The *Rhachistognathus muricatus* Zone occupies a substantial thickness of rock in the upper part of the Alapah Limestone and lower part of the Wahoo Limestone in the northeast Brooks Range. The Zone is at least 250 m thick in the North Bathtub section Fig. 2-8). The upper part of the zone is at least 138 m thick in the Sunset Pass section, at least 109 m thick in the Fourth Range section, and at least 140 m thick at the Wahoo Lake section (Figs. 2-6 and 2-7). The *Rh. muricatus* Zone is defined by the first appearance of *Rh. muricatus* below the occurrence of either *Declinognathodus noduliferus* or *Rh. primus.* The Lower *Rh. muricatus* Subzone is defined by the first appearance of the zonal indicator below the occurrence of *Adetognathus lautus.* This subzone is nearly impossible to recognize. Virtually all common associations of this subzone from shallow-water deposits extend or likely extend into the Upper *Rh. muricatus* Subzone, with the possible exception of *Hindeodus cristulus.* The Upper *Rh. muricatus* Subzone is recognized by the overlapping ranges of the zonal indicator and *Ad. lautus* below the appearance of *Declinognathodus noduliferus* or *Rh. primus.*

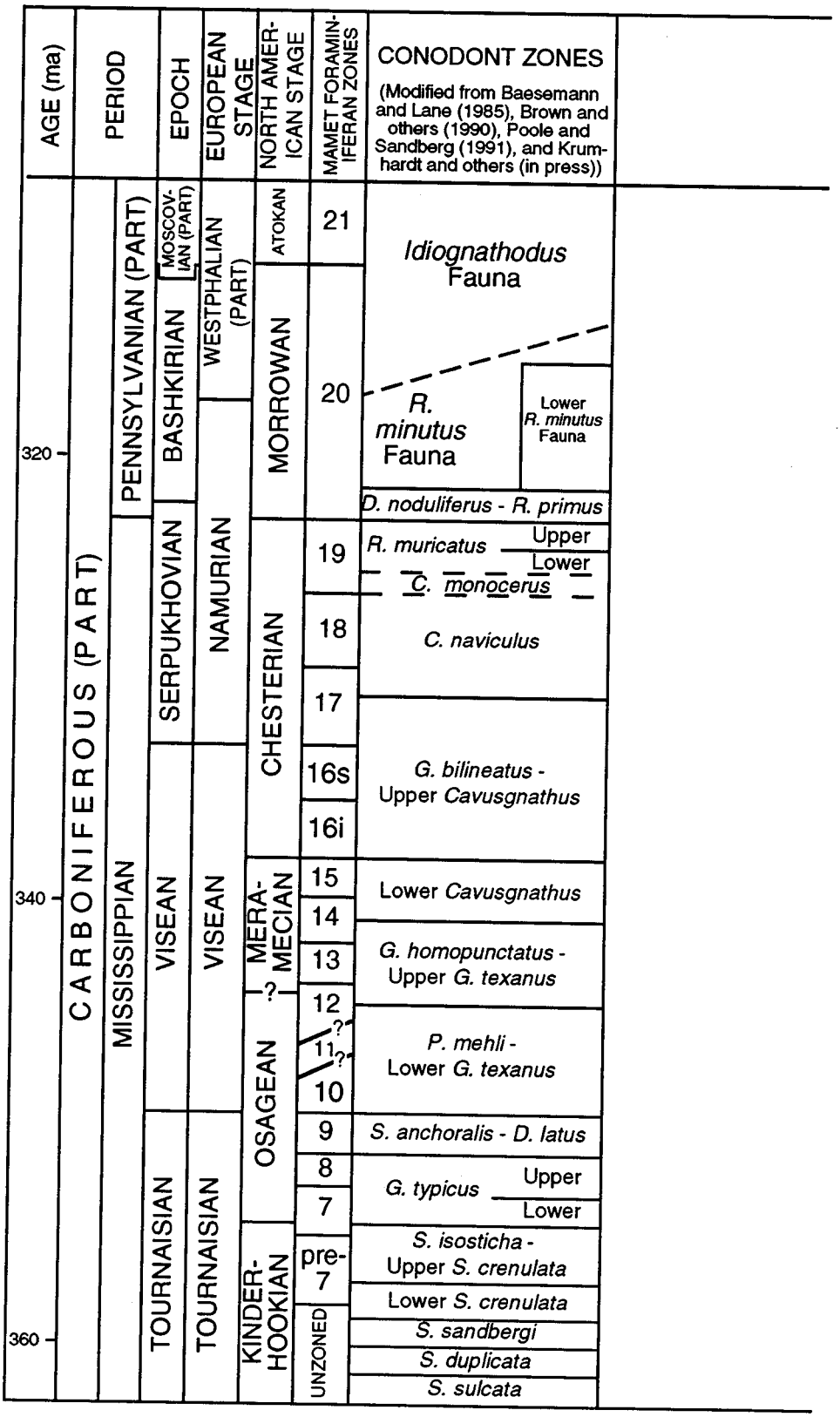
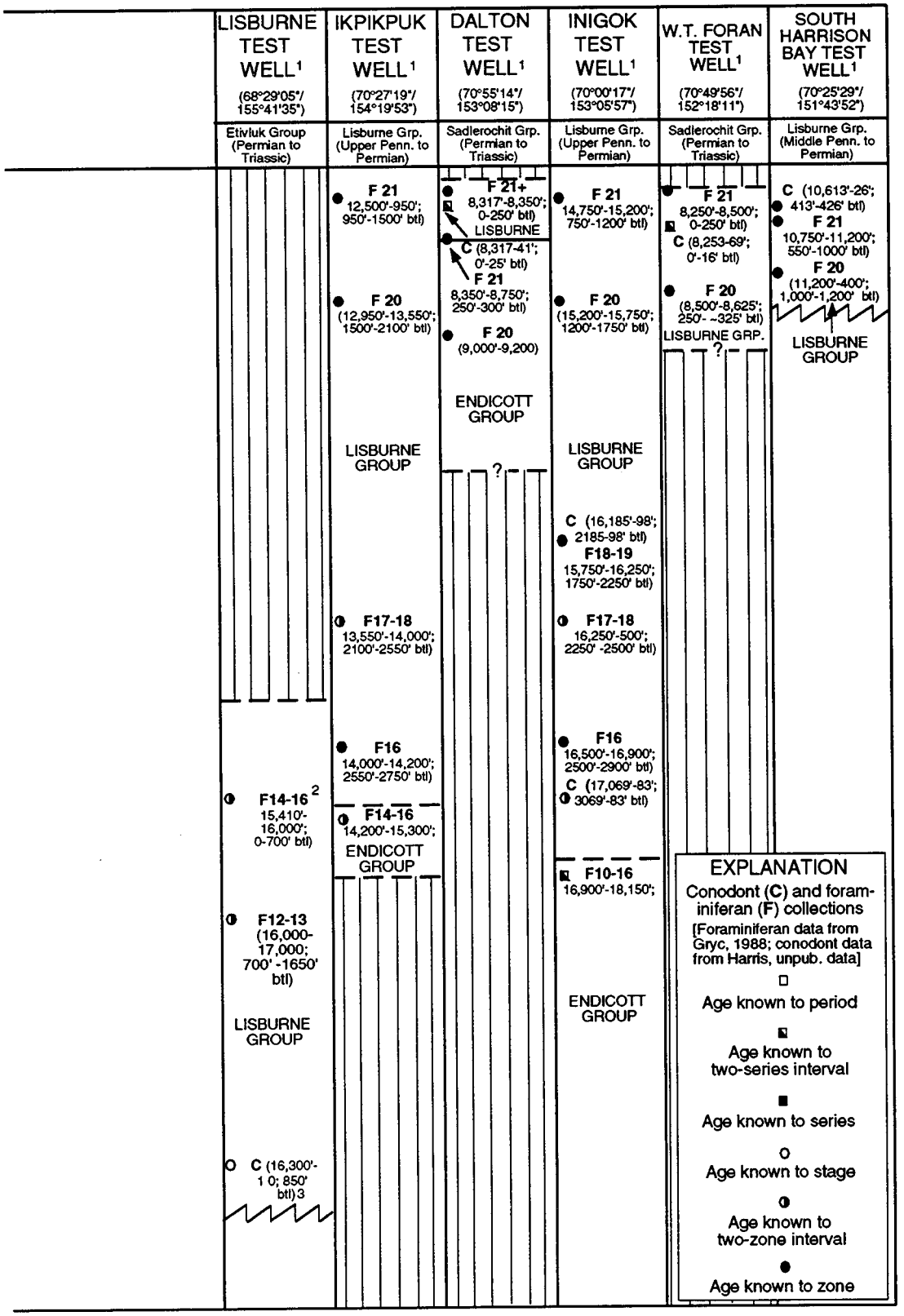


Figure 2-9. Chronostratigraphic diagram showing stratigraphic sections of the Lisburne Group in the National Petroleum Reserve in Alaska (NPRA).



[1] Lithostratigraphic and foraminiferan biostratigraphic data from Gryc (1988).
[2] btl, footage below top of Lisburne Group.
[3] Conodonts possibly reworked or from a fault slice of older carbonate rocks.

Figure 2-9 (continued).

EARLY MORROWAN

Declinognathodus noduliferus-Rhachistognathus primus Zone

The *Declinognathodus noduliferus-Rhachistognathus primus* Zone is recognized by the occurrence of either *De. noduliferus* or *Rh. primus* below the appearance of *Rh. minutus* or *Idiognathoides sinuatus.* The zone occurs in the upper part of the lower member and lower part of the upper member of the Wahoo Limestone or in the lower part of the formation where members have not been distinguished. The zone has been recognized in the Wahoo Lake, Pogopuk Creek, North Bathtub, Sunset Pass, and Leffingwell Ridge sections (Figs. 2-6 to 2-8). The zone was not recognized at some of our other sections that include at least 70 m of the lower part of the Wahoo because rocks of this age were not sampled (Bathtub South and Plunge Creek). The zone may be represented by at least 11 m of the lower member and 38 m of the upper member of the Wahoo at the Fourth Range section (Fig. 2-7). In this section, *Declinognathodus noduliferus japonicus* first appears 11 m below the top of the lower member, marking the base of the Pennsylvanian. A single specimen of *Idiognathodus* sp. occurs at the same level, however, suggesting an age no older than late Morrowan as well as a disconformity of considerable magnitude within the lower member of the Wahoo in the Fourth Range section (Figs. 2-6 and 2-7, column 11A). No other idiognathodids appear in the Wahoo until 26 m higher in the section where three specimens were recovered. The only other occurrence of idiognathodids is in a sample from the top of the Wahoo, 90 m higher in the section, where they are abundant. The conodont succession in the Pennsylvanian part of the Wahoo in the Fourth Range section is similar to that found in our other sections in the northeast Brooks Range, except for the stratigraphically low appearance of idiognathodids. In addition, a greater number of reworked Mississippian conodonts occur through a thicker interval of the Pennsylvanian part of the Wahoo here than elsewhere. It is possible that the two occurrences of a few idiognathodids low in the section represent stratigraphic leak, that is, the idiognathodids were transported to lower stratigraphic levels along fractures and solution surfaces after deposition of the Wahoo. Both interpretations, a disconformity of considerable magnitude within the Wahoo versus stratigraphic leak, are shown in Figures 2-6 and 2-7, columns 11A and B. Conodont species that occur in the *De. noduliferus-Rh. primus* Zone include *Adetognathus lautus, Cavusgnathus? tytthus, Declinognathodus noduliferus japonicus, De. nod. noduliferus, Hindeodus minutus, Idioprioniodus conjunctus, Rhachistognathus muricatus, Rh. primus, Rh. websteri,* and *Vogelgnathus postcampbelli*

EARLY AND LATE MORROWAN

Rhachistognathus minutus Fauna

The *Rhachistognathus minutus* Fauna is characterized by the local range of *Rhachistognathus minutus* subspp. below the range of *Idiognathodus* spp. This fauna is characterized by a high diversity of rhachistognathids. The appearance of

the *Rh. minutus* Fauna is coincident with the onset of well-developed shoal facies in the Pennsylvanian part of the Lisburne Group, the preferred habitat for rhachistognathids. Conodont species that occur in the *Rh. minutus* Fauna include *Adetognathus lautus, Ad. spathus, Declinognathodus noduliferus japonicus, De. nod. noduliferus, Hindeodus minutus, Idioprioniodus conjunctus, Rh. minutus declinatus, Rh. m. havlenai, Rh. m. minutus, Rh. muricatus, Rh. prolixus,* and *Rh. websteri.* The fauna occurs in the middle part of the Wahoo Limestone in the Katakturuk gorge, Pogopuk Creek, Sunset Pass, and North Bathtub sections (Figs. 2-7 and 2-8).

A lower subdivision of the *Rh. minutus* Fauna is distinguished by the local overlapping ranges of *Rh. muricatus, Rh. primus, Rh. websteri,* and *Rh. minutus* subsp. below the range of *Idiognathodus* spp.

LATE MORROWAN AND EARLY ATOKAN

Idiognathodus Fauna

The *Idiognathodus* Fauna is characterized chiefly by the association of *Idiognathodus* spp., *Rhachistognathus minutus* subspp., and *Adetognathus lautus.* The first appearance of *Idiognathodus* in the Wahoo Limestone marks the lower boundary of the fauna. The upper boundary is at the unconformity that separates the Wahoo from the overlying Sadlerochit Group of Permian age. The lower boundary of the fauna could be as old as the *Idiognathodus sinuosus* Zone of Baesemann and Lane (1985) or as young as early Atokan. The *Idiognathodus* Fauna occurs in the upper part of the Wahoo Limestone or Lisburne Group. Conodont species that occur in the *Idiognathodus* Fauna include *Adetognathus lautus, Ad. spathus, Declinognathodus noduliferus japonicus, De. nod. noduliferus, Diplognathodus ellesmerensis?, Hindeodus minutus, Idiognathodus incurvus?, Id. sinuosus, Idiognathoides pacificus, Id. sinuatus, Idioprioniodus conjunctus, Rh. minutus* subspp, and *Rh. muricatus.* The *Idiognathodus* Fauna has been recognized in the Echooka anticline, Pogopuk Creek, Fourth Range, Leffingwell Ridge, Clarence River, Sunset Pass, Katakturuk gorge, Egaksrak "wall", and North Bathtub sections, in the Harrison Bay test well, and in the southern Romanzof Mountains (Figs. 2-6 to 2-9). It is possible that the fauna occurs through the upper 117.5 m of the Wahoo in the Fourth Range section (Figs. 2-6 and 2-7, column 11A), but the presence of a few idiognathodids in the lower 26 m of the Pennsylvanian part of the Wahoo may be the result of stratigraphic leak (see under *Declinognathodus noduliferus-Rhachistognathus primus* Zone). The only other occurrence of idiognathodids in the Fourth Range section is at the top of the Wahoo so that the Idiognathodus Fauna may be restricted to the uppermost meter of the section.

AGE OF THE BASE OF THE LISBURNE GROUP

The base of the Lisburne Group is not exposed at many of our sections (Figs. 2-6 to 2-8). At some others, the basal beds of the Lisburne are exposed but their age is not well constrained by fossils. In the central part of the Brooks Range, at Shainin

Lake, Atigun Gorge, and possibly in the Lisburne test well, the base of the Lisburne Group is Osagean in age (Figs. 2-6 and 2-9). At the Fourth Range, Egaksrak wall, South Bathtub, and Clarence River sections, the basal beds of the Lisburne are Late Mississippian in age and no older than late Meramecian at the Fourth Range, South Bathtub and Clarence River sections (Figs. 2-6 to 2-8). The base of the exposed Lisburne is youngest at the Sunset Pass section (late Chesterian) and even younger in the subsurface in the W. T. Foran and Dalton test wells (Morrowan and Atokan, respectively). The onset of relatively shallow-water carbonate deposition during the Mississippian in the northeast Brooks Range appears to be time transgressive from southwest to northeast, beginning in the Osagean at Shainin Lake, late Meramecian or early Chesterian at the Fourth Range and Clarence River sections, late Chesterian at the Sunset Pass section, and well within the Pennsylvanian in the W. T. Foran and Dalton test wells (Figs. 2-6 and 2-9).

MID-CARBONIFEROUS BOUNDARY

The mid-Carboniferous boundary approximates the Mississippian-Pennsylvanian boundary in North America. The boundary is within the Wahoo Limestone in the northeast Brooks Range. Where the Wahoo is subdivided into members, the boundary lies within the lower member of the formation at the Pogopuk, Fourth Range, Shublik Mountains, and Sunset Pass sections, and may be within the lower member at the Wahoo Lake, Plunge Creek and Clarence River sections (Figs. 2-6 and 2-7);. At the Fourth Range section, the mid-Carboniferous boundary may coincide with an unconformity of considerable magnitude within the lower member of the Wahoo. Here, rocks representing the Upper *Rhachistognathus muricatus* Subzone of the latest Chesterian are disconformably overlain by rocks of possible late Morrowan or early Atokan age. An alternative interpretation for this section is given above in the section on the *Declinognathodus noduliferus-Rhachistognathus primus* Zone.

AGE OF THE TOP OF THE LISBURNE GROUP

The age of the top of the exposed Lisburne Group in the northeast Brooks Range is Pennsylvanian but is not well constrained within the Period. The uppermost beds of the Lisburne generally yield an *Idiognathodus* Fauna of post-early Morrowan age. At several sections, *Rhachistognathus minutus* occurs in this fauna restricting the age of the uppermost Lisburne to the late Morrowan or early Atokan (e.g., Pogopuk Creek, Fourth Range, and Clarence River sections). At Sunset pass, our best dated section, the top of the Lisburne is within the early Atokan. The Echooka Formation of Permian age disconformably overlies the Lisburne. Conodonts from the base of the Echooka near the Katakturuk gorge section indicate a late Early to Late Permian age. Thus the unconformity between the Lisburne and Echooka ranges from the Early (Wahoo Lake) or Middle (Sunset Pass) Pennsylvanian to at least late Early Permian. To the northeast, in the Lisburne test well, Permian rocks of the Etivluk Group disconformably overlie Lisburne strata of early Chesterian age. Still farther north in the Ikpikpuk and Inigok test wells (Gryc,

1988), the Lisburne extends into the Permian so that the Lisburne may be conformable with overlying Permian rocks.

PART 3—CONODONT COLOR ALTERATION

In addition to providing valuable biostratigraphic control, conodonts also provide information on the thermal history of rocks in ANWR. Epstein and others (1977) and Rejebian and others (1987) have shown that color and textural alteration of conodonts can be used to estimate the thermal history of the host rock. These authors established a conodont color alteration index (CAI) ranging from 1 to 8 with corresponding temperatures of <50°C to >600°C. CAI values are a useful indicator of the thermal maturation of hydrocarbons; CAI values of 1.5 to 2 indicate the host rock reached temperatures within the oil generation window (80°C to 140°C). Variable CAI values within a single sample and textural alteration of conodonts indicate hydrothermal alteration of the host rock.

Unaltered conodont elements are pale yellow, have a smooth glassy luster, and are composed of hydroxy-apatite and trace amounts of organic matter. With heating and time, conodonts visibly change color from pale yellow, to amber, light brown, dark brown, and black in the range of 60°C to 300°C as a result of carbonization of the trace amount or organic matter sealed within these transparent skeletal elements. Above 300°C, conodonts change from black to gray, opaque white, and finally to crystal clear as a result of carbon loss, release of water of crystallization, and recrystallization. These color changes have been assigned CAI values ranging between 1 and 8, with 1 being pale yellow, and 8 crystal clear. The color alteration is irreversible and time and temperature dependent, thus recording the maximum temperature reached by the host rock during long-term burial metamorphism.

SUMMARY OF ANWR DATA

The CAI values of conodonts in the eastern Sadlerochit Mountains (Fig. 1-2, loc. 8, section AK22M) range from 2.5 to 6. No conodonts have a value of 5 (black) and the majority of conodonts in most samples have a CAI of 4 (brown). In addition, most conodonts have a sugary and (or) corroded texture. The wide range of CAI values with single samples along with the altered surface texture are indicative of hydrothermal alteration. Some samples from the uppermost Alapah Limestone are much more bleached and corroded than those from the lowest part of the Wahoo Limestone, suggesting increased hydrothermal activity at this level. The presence of cavernous porosity at the Alapah-Wahoo boundary, now filled by coarse spar, may have promoted the flow of hydrothermal fluids through the relatively porous dolostones of the uppermost Alapah, whereas the more tightly cemented limestones of the Wahoo were a barrier to hydrothermal fluids.

Figure 2-10 shows the CAI values for the numerous conodont samples collected from the Lisburne and Endicott groups throughout ANWR between 1985

Figure 2-10

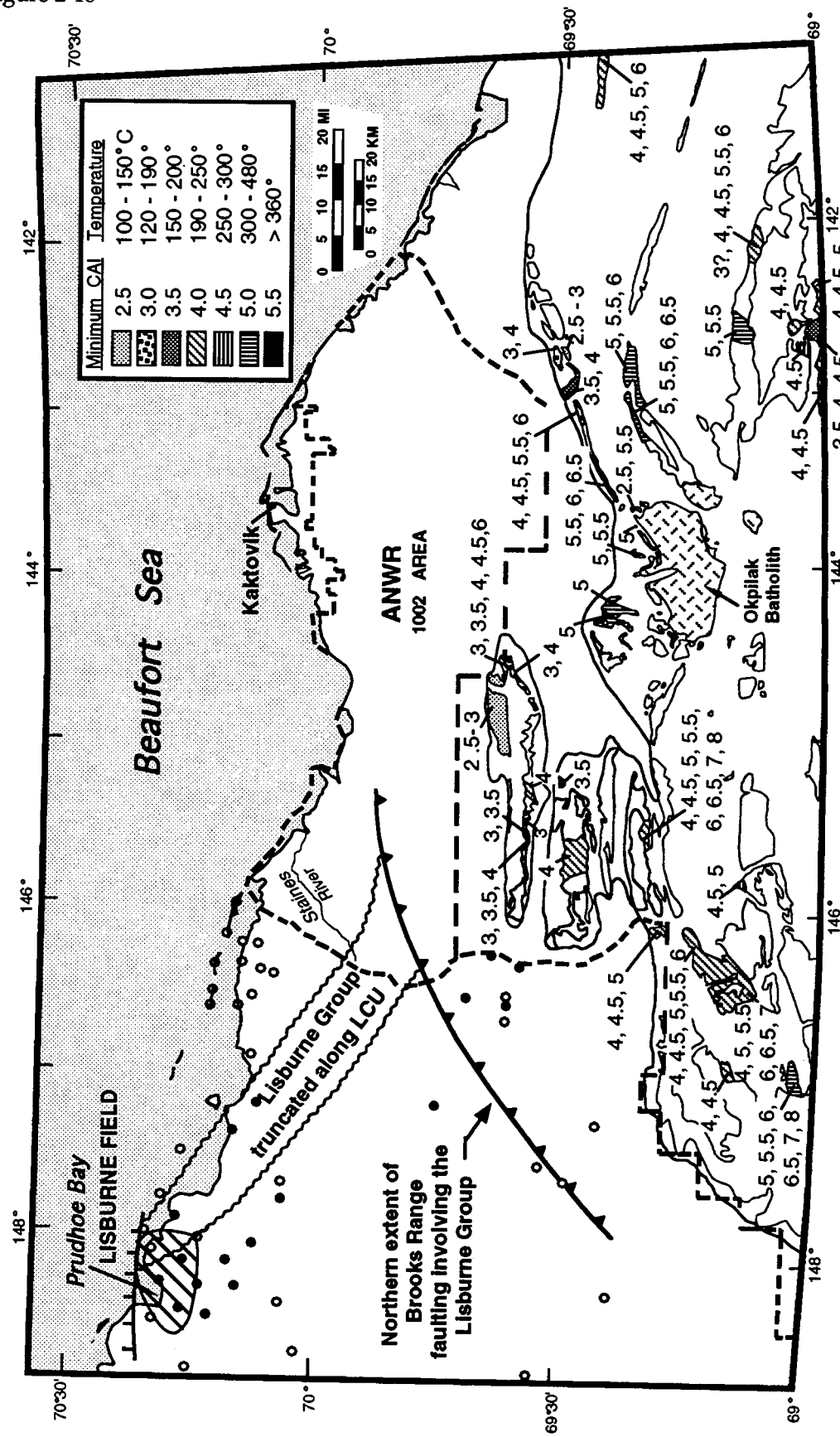


Figure 2-10. Map showing conodont color alteration indices (CAI) in ANWR. Conodonts from some localities have a wide range in CAI values and textural alteration that indicate hydrothermal alteration. Areal variations in minimum CAI values are probably related to differences in geothermal gradient and depth (chiefly tectonic) and duration of burial. The temperature ranges for CAI values were determined from the Ahrrenius plot of the experimental data of Epstein and others (1977, Fig. 3). These ranges cover durations of <1 million (high value) to 500 million years (low value). See Fig. 1-2 for names of geographic features and localities.

and 1992 by the University of Alaska Fairbanks researchers and analyzed by Harris and Krumhardt. Harris also analyzed the data from samples collected by personnel of the U.S. Geological Survey and the Alaska Division of Geological and Geophysical Surveys. Certain trends are evident on the CAI map:

CAI values within the Brooks Range in ANWR are chiefly between 2.5 and 6.5 indicating thermal levels beyond the oil generation window.

Almost all samples contain conodonts showing textural alteration and having a range in CAI values, indicating hydrothermal alteration.

The lowest CAI values are in the north, adjacent to the ANWR coastal plain, being as low as 2.5 in the northeastern Sadlerochit Mountains. The rest of the Sadlerochit Mountains has slightly higher minimum CAI of 3. Leffingwell Ridge yielded values as low as 2.5-3.5, but shows a progressive westward increase toward the Okpilak batholith.

A progressive southward increase in CAI values is evident along the Canning River transect. Minimum CAI values in the Shublik Mountains are 3.5-4 increasing to 4 farther to the south. CAI values of 5 and above (>300°C) occur near Wahoo Lake.

A similar southward increase in minimum CAI values is evident long the Aichilik transect, increasing from 2.5-3 at Leffingwell Ridge to 5 at "the wall" near the Aichilik River and north of Bathtub Ridge.

The south flank of Bathtub Ridge shows a possible southward decrease in minimum CAI values from 4-4.5 to 3.5, possibly indicating less tectonic burial of higher thrust sheets to the south.

Generally high CAI values near the Okpilak batholith of 5-5.5 may be related to proximity to this major structural high.

Outside of ANWR, CAI values in the Endicott allochthon at Shainin Lake and Atigun Gorge are relatively low (2 to 2.5, within the oil window), indicating less tectonic burial.

The color alteration index (CAI) of conodonts from the Lisburne Group generally increases southward in the northeast Brooks Range from values as low as 2.5 and 3 in the Sadlerochit Mountains to values as high as 5, 5.5, and 6 to the south in the Franklin Mountains (Fig. 2-10). The regional increase in CAI values southward is probably related to increasing depth of tectonic burial. At virtually all localities sampled, conodonts have a range of CAI values within a small area, section, and even within a single sample. In addition, many conodonts have a sugary to corroded texture. Taken together, the range in CAI values within a section and even within a sample and the textural alteration indicate hydrothermal alteration. This hydrothermal alteration occurred after the early Atokan, mostly

likely after the Permian (probably related to Brookian orogenesis) and after maximum burial metamorphism that elevated CAI values in Carboniferous and Permian rocks to their regional levels.

CHAPTER 3

DIAGENESIS OF THE LISBURNE GROUP, NORTHEASTERN BROOKS RANGE, ALASKA

By R.C. Carlson, R.H. Goldstein, Paul Enos, and K.F. Watts

ABSTRACT

Petrographic cathodoluminescence studies of the cement stratigraphy of the Lisburne Group yield insights on its diagenetic history. Crosscutting relationships between features of subaerial exposure and calcite cements show that early generations of nonferroan, nonluminescent and multibanded-luminescent calcites are synchronous with or postdated by subaerial exposure surfaces within the Lisburne. Surfaces of subaerial exposure occur at 18 horizons within the Lisburne and are distinguished by features as laminated crusts, rhizoliths, autoclastic breccia, fissure fills, mud cracks, and erosional surfaces.

Crosscutting relationships also occur between calcite cements and clasts in karst breccias and conglomerates that formed along the sub-Permian unconformity at the top of the Lisburne. In addition to postdating early nonluminescent and multibanded calcites, the sub-Permian unconformity postdates later generations of calcite cement. These cements formed in the following sequence: nonferroan to low-ferroan, dully luminescent calcite; ferroan, very-dully luminescent calcite; and second generation of nonferroan, multibanded calcite. The crosscutting relationships not only constrain the timing of cement precipitation, but also suggest that the cements probably were precipitated from meteoric groundwaters introduced during subaerial exposure of the Lisburne platform.

Late cements in the Lisburne postdate the Permian Echooka Formation. These cements are low-ferroan, moderately-bright to dully luminescent calcite, followed by a second generation of ferroan, very-dully luminescent calcite. Features of compaction and pressure solution are coincident with the precipitation of the late ferroan calcite and further constrain its timing to deep burial of the Lisburne.

The youngest phase of calcite cement precipitated in the Lisburne Group is nonferroan, very-dully luminescent calcite. It commonly fills tectonically-induced shear fractures, indicating precipitation after the onset of Cretaceous (and/or Cenozoic) tectonism in the northeastern Brooks Range.

INTRODUCTION

This study attempts to expand our present understanding of cementation in carbonate rocks by describing the diagenetic history of the Lisburne Group, a thick succession of Carboniferous carbonate rocks in northern Alaska. The framework for the diagenetic study is a description of the cement stratigraphy of the Lisburne Group along a 45 km, northeast-southwest transect from the Sadlerochit Mountains to the Fourth Range in the northeastern Brooks Range (Fig. 3-1).

REGIONAL GEOLOGIC SETTING OF THE LISBURNE GROUP

Three tectono-sedimentary sequences, the Franklinian, Ellesmerian, and Brookian, make up the sedimentary rocks in northern Alaska (Grantz and May, 1983; Bird and Molenaar, 1987). The sequences were first recognized in the Canadian Arctic (Lerand, 1973) and are bounded by regional unconformities that mark significant reconfiguration of the tectonic setting of the Arctic during the late Precambrian to the Recent. The Franklinian sequence is a Precambrian to Devonian assemblage of mostly sedimentary rocks that are strongly deformed and weakly metamorphosed. The` sub-Mississippian, angular unconformity truncates the top of Franklinian rocks with significant erosional relief (Watts et al., 1988). The Ellesmerian sequence including the Lisburne Group is a thick succession of Mississippian to lower Cretaceous strata that lies above this unconformity. These rocks are predominately marine carbonates and siliciclastic sediments that were deposited along a south-facing, passive, continental margin (Armstrong and Mamet, 1977; Bird and Jordan, 1977). Inboard rifting of a new north-facing passive margin during the Early Cretaceous led to the formation of the Arctic Ocean (Grantz and May, 1983; Hubbard et al., 1987) and incorporated the Ellesmerian and Franklinian sequences into the northward-facing margin of present-day Alaska. Continental collision of the southern margin of northern Alaska with northward moving terranes beginning in the Cretaceous (Mull, 1982) formed the central and western Brooks Range. Resultant subsidence from continental loading formed a north-facing, foreland basin in which terrigenous siliciclastic sediments of the Brookian sequence buried the Ellesmerian and Franklinian strata. The area of this study, the Sadlerochit, Shublik and Fourth Range mountains of the northeastern Brooks Range, was uplifted as recently as the Oligocene due to continued compressional tectonics in the Cenozoic(Wallace and Hanks, 1990).

STRATIGRAPHIC SETTING OF THE LISBURNE GROUP

The Carboniferous Lisburne Group (500 to 700 meters thick) is a succession of marine carbonates. The Lisburne carbonate platform formed along the south-facing passive continental margin and the basin deepened to the southwest (relative to present day coordinates; Armstrong and Mamet, 1977). In the northeastern Brooks Range, the Lisburne Group is divided into two formations (Watts et al., 1990). The lower unit is the Upper Mississippian Alapah Limestone (180 to 340 meters thick) and the upper unit is

Figure 3-1.

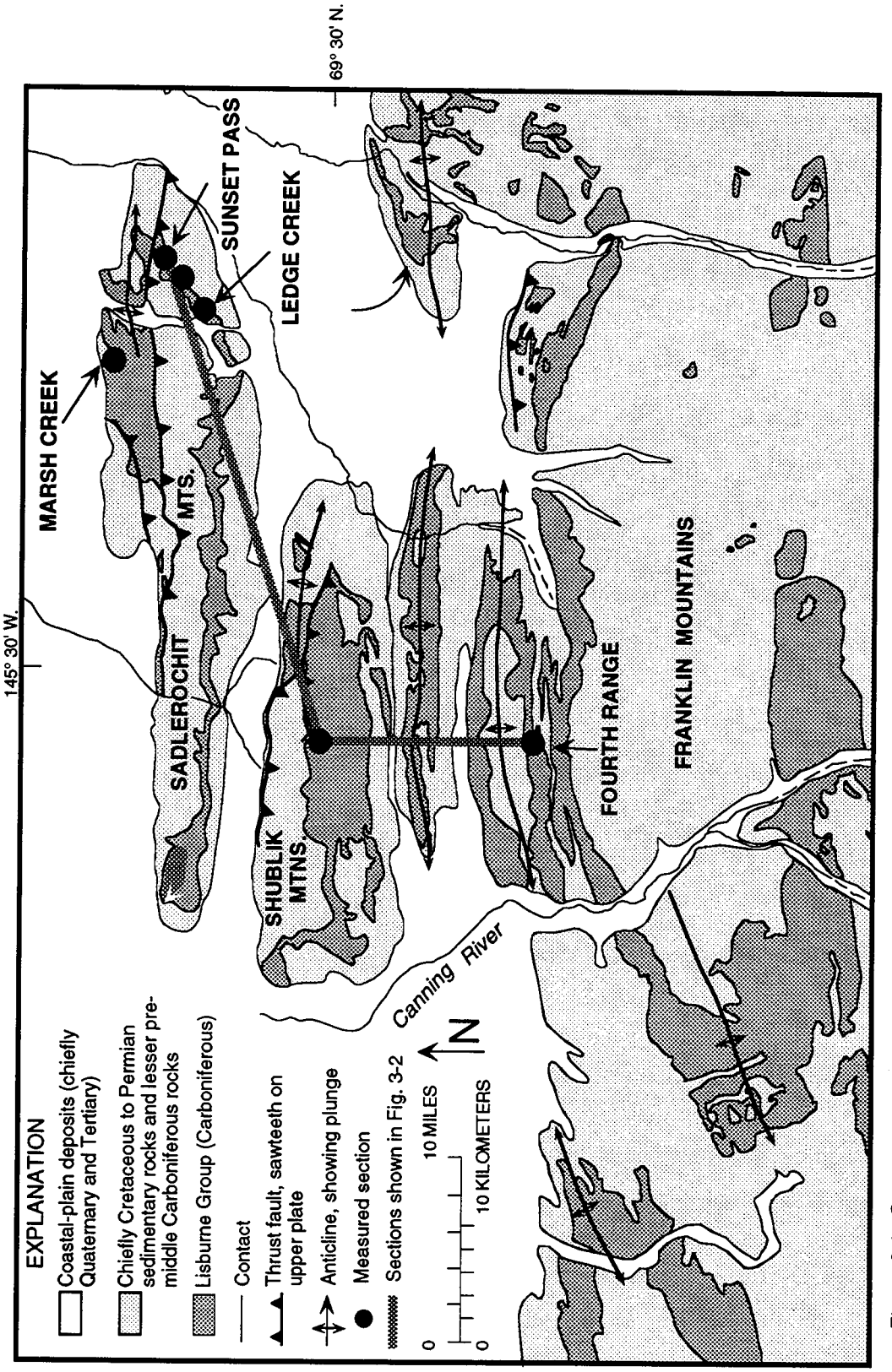


Figure 3-1. Outcrop map of the Lisburne Group in the northeastern Brooks Range showing location of stratigraphic sections used for the study of diagenesis of the Lisburne Group (modified from Gruzlovic, 1991). Regional setting of these sections shown on Figs. 1-1 and 1-2.

the Wahoo Limestone (200 to 300 meters thick), which ranges in age from uppermost Chesterian to Atokan.

SURFACES OF SUBAERIAL EXPOSURE IN THE LISBURNE GROUP

The major goal of the study was to locate surfaces of subaerial exposure to find crosscutting relationships that would date separate generations of calcite cement. A cross section from the Sadlerochit Mountains to the Fourth Range traverses the Lisburne carbonate platform across depositional strike, from shallow platform (north) to deeper platform (south) environments (Figs. 3-1 & 3-2). Study of this cross section was undertaken to assess the relationship of diagenesis to paleogeographic setting on the Lisburne carbonate platform.

Several subaerial exposure surfaces were identified in the Lisburne Group during our field studies and are numbered i through xviii (Fig. 3-2). The sub-Permian unconformity at the top of the Lisburne is designated as surface xix.

Subaerial exposure surfaces i to vii—lower Alapah Limestone

Subaerial exposure surface i occurs near the base of the Alapah Limestone (Fig. 3-2). At the Fourth Range section, surface i lies at the top of a shallowing-upward cycle composed of dark-gray, algal bafflestone overlain by cryptalgal-laminated dolostone. Autoclastic breccia is present in the algal bafflestone and fenestral (rhizolith?) pores riddle the cryptalgal-laminated dolostone. Above surface i, algal bafflestone passes upward into dark-gray, bioturbated, finely-crystalline dolostone with a sparse molluscan fauna. The dark dolostone then grades upward into light-gray, finely-crystalline, fenestral and algal-laminated dolostone. This succession defines a second shallowing-upward cycle. The top of this cycle has fine-scale autoclastic breccia and is designated as surface ii. Four more shallowing-upward cycles, consisting of dark-gray, molluscan dolostone overlain by light-gray, fenestral dolostone, are present and are capped by horizons with fine-scale autoclastic breccia, rhizoliths and early cracks (exposure surfaces iii, iv, v, and vi). Studies of foraminiferan zones in the northeastern Brooks Range (B.L. Mamet; cited in Carlson, 1987 and Gruzlovic 1991) indicate that the lower part of the Alapah is older in the Shublik Mountains and Fourth Range than it is in the Sadlerochit Mountains. Therefore, these surfaces appear to lap out northward before the Sadlerochit section is reached. Above surface vi in the Fourth Range section is 15 meters of peloidal packstone that is capped by fenestral dolomite that has early cracks and rhizoliths filled with calcite spar. This horizon, surface vii, appears to correlate with the lowermost exposure surface in the Alapah in the Sadlerochit Mountains. In the Sadlerochit Mountains, the horizon is marked by either a black, laminated crust and rhizoliths or solution pipes filled with chert breccia. Surface vii in the central Shublik Mountains also has a laminated crust and laterally extensive autoclastic breccia beneath it.

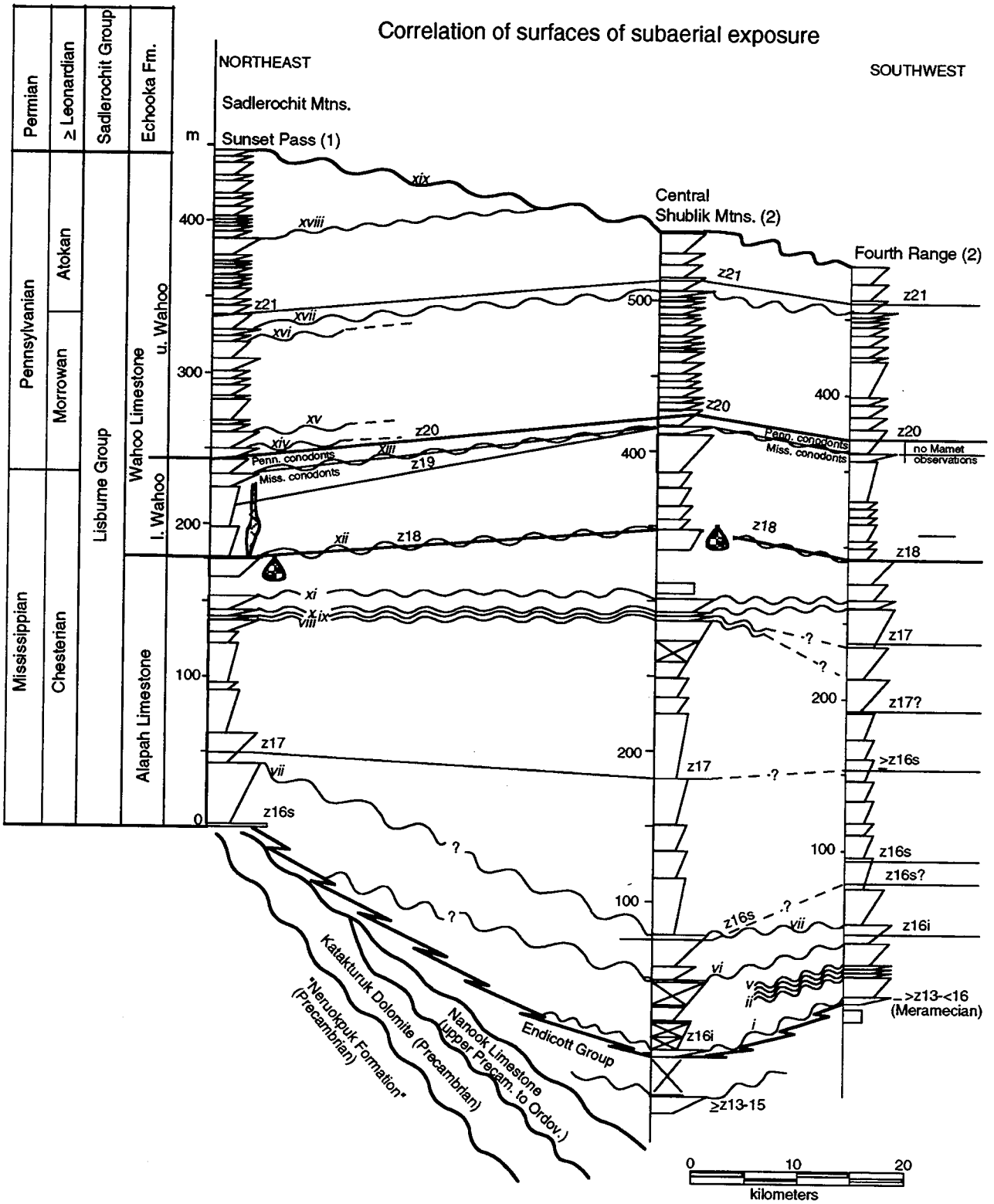


Figure 3-2. Cyclic stratigraphy and correlation of surfaces of subaerial exposure in the northeastern Brooks Range, Alaska. Interpretation of carbonate cyclicity is based on descriptions of stratigraphic sections measured by Krumhardt, 1989 (AK22M; Sunset Pass) and Gruzlovic, 1991 (AK-10 to 12-M, Shublik Mountains; and AK13 to 14-M, Fourth Range). Does not account for the possible unconformity indicated by conodont data from the Fourth Range section discussed in Chapters 2 & 6. (2 pages).

EXPLANATION

	Correlation line of surface of subaerial exposure
i - xix	Surfaces of subaerial exposure
	Unconformity of several m.y.
	Lithologic contact
	Shallowing-upward sequence, reaches subaerial exposure.
	Shallowing-upward sequence, reaches shoal depths
	Shallowing-upward sequence, reaches wave base
	Not Exposed
	Vertical dissolution pipes up to 1 meter wide, filled with very coarse calcite spar
	Cavernous porosity
z13 - z21	Foraminiferan biostratigraphic zones, (Bernard Mamet, pers. comm., 1986, 1989, 1990; and Gruzlovic, 1991)
Miss. & Penn. conodonts	Conodont biostratographic zones (Krumhardt, 1992, and pers. comm. 1991, 1992)
(1)	Modified from Carlson, 1987
(2)	Modified from Gruzlovic, 1991

Fig. 3-2 (continued)

Subaerial exposure surfaces viii to xi—upper Alapah Limestone

The middle part of the Alapah strata between surfaces vii and viii consist of 100 to 200 meters of echinoderm-bryozoan packstone and grainstone that form several subtidal, shallowing-upward parasequences. This package of carbonates is capped by four shallowing-upward cycles composed of dark-gray, burrowed, peloidal packstone capped by creamy-white lime mudstone that commonly displays fine-scale, autoclastic breccia, rhizoliths and minor pisolites. These subaerial exposure surfaces are numbered viii to xi. Two of these surfaces (viii and ix?) were not found in the Fourth Range section. The upper Alapah appears to represent a peritidal environment that was the culmination of a long period of open-marine, subtidal deposition. Exposure surfaces viii through xi in the Sadlerochit and Shublik mountains show the same close spacing, indicating that there was little relief on the platform between these two areas during deposition of the upper Alapah. These surfaces can be used in a geologic cross section as a reasonably true horizontal datum for viewing the development of the Lisburne platform (Fig. 3-2).

The middle part of the Alapah Limestone between surface vii and surface viii is 100 meters thick in the Sadlerochit Mountains, but is 200 meters thick in the Shublik Mountains. If the position surface vii is compared with line of correlation of surface viii between the Sadlerochit and Shublik mountains sections (assuming this is reasonably horizontal datum), then the change in thickness between the measured sections suggests that there was 100 meters of topography, and that a 100-meter relative fall in sea level occurred during the development of exposure surface vii. However, differential subsidence and sedimentation above surface vii but before exposure along surface viii could account for some of the difference in thickness. The middle part of the Alapah in the Fourth Range (55 m versus 105m) is thinner than in the Shublik Mountains to the north, indicating differential subsidence or other complexities in platform geometry.

Subaerial exposure surface xii—top of the Alapah Limestone

The uppermost beds of the Alapah Limestone in all three sections have interbedded stromatolites and finely crystalline dolostone. Stromatolites are most abundant in the Sadlerochit and Shublik mountains sections and less well developed in the Fourth Range section. Early cracks and disruption of algal textures in the stromatolitic beds indicate supratidal to subaerial conditions for deposition of upper Alapah sediments. The uppermost Alapah in the Shublik Mountains section has dark laminations that coat skeletal grains and extend from one grain to the next. The laminations occur both below and above the grains and indicate that they may be rhizolaminae that developed during subaerial exposure. Hence, the top of the Alapah Limestone is designated as surface xii.

In the Sadlerochit Mountains at the top of the Alapah Limestone, large solution pockets up to one meter in diameter are filled by chert breccia and very coarse crystalline calcite. These solution pockets are limited to the top of the Alapah

Limestone, but vertical solution pipes extend downward through the overlying lower Wahoo Limestone to the solution pockets. The pipes vary abruptly from a few centimeters up to a meter, and have irregularly sculpted sides formed by dissolution of the wall rock. Such pipes can be traced about 40 meters upward in the lower Wahoo Limestone until covered by talus as the ridge trends away from the vertical pipes.

The Alapah-Wahoo Limestone boundary in the Shublik Mountains has cavernous porosity filled by calcite cement. At the top of Gruzlovic's (1991) measured section of the Alapah Limestone (AK11M, see Chapter 1, Fig. 1-7), a large calcite-filled cave is an irregular body exposed in three dimensions (15 meters wide, 40 meters long and at least 20 meters high). The cave contains meter-sized, down-dropped blocks of Wahoo Limestone, very coarse crystalline calcite spar, and minor amounts of silicified sediment. The blocks appear to have been well lithified at the time they fell from the roof of the cave. Because the lowermost beds of the Wahoo Limestone collapsed into the cave, it does not appear related to development of subaerial exposure surface xii at the top of the Alapah but instead resulted from later dissolution. Two other large spar-filled caves were found by following the Alapah-Wahoo contact along the spur ridge between section AK11M and Gruzlovic's (1991) lower Wahoo measured section (AK10M). These caves occur entirely in the upper Alapah Limestone and are two-dimensional exposures. The first cave along this traverse measures 21 meters wide and at least 6 meters high (the base of the cave was not exposed) and is filled by very-coarsely crystalline calcite. A black calcite cement occurs as a lining next to the wall rock of the cave and most of the remainder is filled by white calcite. The third cave is 21 meters high and has a funnel shape, being 6 meters wide at the base and 13.5 meters wide at the top. It is floored by about 1 meter of layered cave sediment and 10 to 20 cm long, down-dropped blocks of limestone. White calcite overlies the cave sediment and fills the cave to the top. The top of the cave is overlain by the basal beds of the Wahoo Limestone that show no sign of collapse.

Although large porosity does not occur at the top of the Alapah at the Fourth Range section, cave formation at this stratigraphic level is regional in extent. At Wahoo Lake, 60 km south of the Fourth Range (Loc. 10 & 13, Fig. 1-2), cavernous porosity in the upper Alapah is filled by cave sediment and speleothem cements (K.F. Watts, pers. comm., 1990). Cave features also occur in the upper Alapah at Clarence River near the Canadian border (110 miles east (loc. 27., Fig. 1-2; A.P. Krumhardt, pers. comm., 1992)

Subaerial exposure surface xiii—Mississippian-Pennsylvanian boundary

The next subaerial exposure surface upsection, surface xiii, occurs at the Mississippian-Pennsylvanian boundary. In the Sadlerochit Mountains, surface xiii is about 50 to 60 meters above the base of the Wahoo Limestone and has erosional topography ranging from a meter to a few centimeters above thick-bedded, echinoderm packstone. This surface is overlain by a distinctive, thin interval of limestone containing abundant reddish replacement chert, which is immediately beneath the lowest definitive Pennsylvanian conodonts recognized in the Lisburne Group at this reference section (Krumhardt and others, in press; see Chapter 2). In the Shublik Mountains

section, samples collected from beneath the Mississippian-Pennsylvanian boundary have ribbon spar that fills fine fractures that meander around grains. Ribbon spar and early cracks are associated with meteoric-vadose conditions.

In the Fourth Range, autoclastic breccia occurs near the transition from Mississippian to Pennsylvanian rocks at about 360 meters above the base of the Lisburne Group. The lowest Pennsylvanian conodonts include forms of late Morrowan to Atokan age that may be the result of stratigraphic leak from higher strata beneath the sub-Permian exposure surface (xix) that infiltrated down to subaerial surface xiii (see Chapters 2 & 6). Reworked Mississippian conodonts occur throughout the Wahoo Limestone above the Mississippian-Pennsylvanian boundary (A. P. Krumhardt, pers. comm., 1992).

Subaerial exposure surfaces xiv and xv—lower upper Wahoo Limestone

Surfaces xiv and xv occur locally at the tops of the first two shallowing-upward cycles in the upper Wahoo Limestone at Sunset Pass. The cycles consist of skeletal wackestone and packstone that is overlain by finely crystalline dolostone with cryptalgal laminae. Subaerial exposure is recorded by solution fissures that extend downward into the dolostone from the tops of the cycles. The solution fissures are one to two centimeters in diameter and up to a meter in length. They are filled with chalcedony, minor calcite cement and laminated clay. The chalcedony and calcite cement predate the laminated clay, and the clay lines the sides of the fissures.

Evidence of exposure was not found at the top of the second shallowing-upward cycle at the central Shublik Mountains and Fourth Range sections. Hence, surface xv may pass into a conformable succession as it is traced southward from the Sadlerochit Mountains.

Subaerial exposure surface xvi—middle upper Wahoo Limestone

Subaerial exposure surface xvi occurs at approximately 140 meters above the base of the Wahoo Limestone at Sunset Pass. Surface xvi is marked by mud cracks at the top of a green dolostone that caps the sixth shallowing-upward cycle in the upper Wahoo. This surface also was not found at the Shublik Mountains and Fourth Range sections and may become conformable southward.

Subaerial exposure surface xvii—middle upper Wahoo Limestone

At Sunset Pass (Krumhardt, 1992; section AK-88-A), mud-cracked dolostone occurs at 157 meters above the base of the Wahoo and this surface is designated surface xvii. The first Atokan foraminifers occur in the middle of the next shallowing-upward parasequence above surface xvii. At other locations at Sunset Pass (section A, Carlson, 1987), karst breccia, consisting of limestone clasts surrounded by green dolostone, is believed to mark surface xvii. Ribbon spar occurs beneath the Morrowan-Atokan boundary at the Shublik Mountains section, and reworked *Palaeomicrocodium* occurs slightly above this boundary (Gruzlovic, 1991). In the Fourth Range, black shale

infiltrated into partially cemented oolitic grainstone along early developed fractures beneath surface xvii. However, if the presence of conodonts of late Morrowan to Atokan age within the lower Wahoo Limestone in the Fourth Range is due to an unconformity (see Chapter 2 and 6, see Fig. 6-4b), the surface may instead correspond to surface xiii. The correlations of subaerial exposure surfaces shown on Figure 3-2 assume that these conodonts are the result of stratigraphic leak, being derived from higher in the section and transported downward by fluid migration during karstification beneath the sub-Permian unconformity.

Subaerial exposure surface xviii—middle upper Wahoo Limestone

Surface xviii is expressed by small solution pockets cut into an oolitic grainstone. The pockets are filled with dolomitic, skeletal, lime mud. This surface occurs about 210 meters above the base of the Wahoo Limestone at Sunset Pass, but was not identified at the Shublik or Fourth Range sections.

Subaerial exposure surface xix—top of the Wahoo Limestone

A major unconformity surface truncates the top of the Lisburne Group at each of the sections studied. In the Sadlerochit Mountains (north of the Sunset Pass section, Fig. 3-1), the basal Echooka Formation (Permian) above the Lisburne Group has conglomerate with well rounded clasts of Lisburne limestone. In the Shublik Mountains, a red ferroan soil horizon with root casts overlies the Lisburne. At the Fourth Range section, extensive karst breccia occurs at the top of the Lisburne Group. Comparison of the stratigraphic sections along this transect shows that sub-Permian erosion cut down to the south, possibly removing 60 meters of Lisburne strata between the Sadlerochit Mountains and the Fourth Range (assuming the anomalously low conodonts of late Morrowan to Atokan age in the Fourth Range are due to stratigraphic leak).

CEMENT STRATIGRAPHY OF THE LISBURNE GROUP

INTRODUCTION

Cement stratigraphy is a description of the stratigraphic distribution and sequential occurrence of cement phases in sedimentary rocks and is directed toward the correlation of cement phases and toward determining the timing of their precipitation (Meyers, 1974). Just as the description of lithostratigraphy provides a basis for interpreting depositional history, cement stratigraphy provides a descriptive framework for the interpretation of diagenetic history. Like lithostratigraphy, cement stratigraphy is based on superposition. The oldest cements are those adjacent to the substrate and younger cements overlie them. A stratigraphic description of the cement zone distribution can be constructed by studying closely spaced samples in measured sections. The descriptive cement stratigraphy then serves as the evidence for interpretation of diagenetic history. The usefulness of a stratigraphic approach to studying diagenesis is apparent. Through such an approach , the stratigraphic

distribution, diagenetic condition, and time equivalence of the cement zones can be determined.

A simple cement stratigraphy can be based on changes in mineralogy of cements, such as calcite followed by dolomite followed by quartz. Ancient limestones, however, are commonly cemented entirely by calcite. For such limestones, cement phases may be differentiated by zonation of trace elements that substitute for Ca^{2+}. The trace elements most commonly involved in this substitution are Mg, Mn, and Fe, which are abundant in many pore waters and have the same charge and similar ionic radii to Ca^{2+} (Krauskopf, 1979). Zonation may be studied by using chemical stains that mark the presence of trace elements or by using fluorescence microscopy to identify zones rich in elements which fluoresce. Cathodoluminescence (CL) microscopy is a powerful technique for studying variations in trace-element compositions in modern diagenetic studies (Sipple and Glover, 1965; Goldstein, 1991). What appears as a single generation of calcite cement under transmitted light often appears to be the result of many generations of cementation when viewed under cathodoluminescence. The zonation of Mn and Fe is well suited for study in calcite cements because Mn luminesces under an electron beam, whereas Fe acts as a quencher of luminescence (Carpenter and Oglesby, 1976). Other elements, such as Pb and some rare earth elements, are reported to exhibit similar luminescent behavior to Mn (Machel, 1985), although these are relatively uncommon in natural calcites. $FeCO_3$ in the calcite lattice also can be identified by treatment with potassium ferricyanide that reacts with Fe to form a blue stain.

Compositional zonation occurs in two ways: as sector zonation and as concentric zonation; the latter is of interest in cement stratigraphy. Sector zonation does not reflect variations in pore-water chemistry. It occurs due to the attributes of crystal structure that allow for differential concentration of trace elements within separate crystal faces. Sector zonation is minor within Lisburne Group cements. On the other hand, concentric compositional zones occur in all crystal faces and, thus, directly reflect changes in the chemistry of the pore waters. Therefore, concentric zones are important clues in interpreting the nature and sequence of diagenetic events.

TIMING OF CEMENT PRECIPITATION—KEY TO DIAGENETIC INTERPRETATION

Determining the timing of precipitation of cement phases relative to diagenetic events can be accomplished in different ways. Unique mineralogies or morphologies may be associated with a particular depositional or diagenetic environment. For example, the presence of evaporite minerals in shallow marine carbonates may indicate hypersaline conditions associated with a sabkha (arid peritidal) environment. Likewise, pendant cements clearly are interpreted as the result of cementation in the vadose zone. However, such readily interpreted clues commonly are not found in the cement of most limestones. In transmitted light, calcite cements of the Lisburne Group appear uniform throughout the section and appear to be mostly a function of grain type. Syntaxial overgrowths of calcite commonly are found on echinoderm grains and equant calcite cements fill the pore space where echinoderm grains are few or absent. In these

circumstances, one can turn to crosscutting relationships between cements and features imposed by diagenetic events. Crosscutting relationships prove to be a most convincing means of dating cement phases. For example, if grain fracturing resulting from burial cuts a cement phase then the cement must have formed prior to burial or at least prior to the fractures. Similarly, if features along a subaerial exposure surface, such as reworked pebbles, postdate a cement phase then the cements in the pebbles probably formed prior to the exposure event. The timing of cement precipitation can be refined further if a feature of subaerial exposure, such as early shrinkage cracks, both predates and postdates the cement phase, thus limiting precipitation of the cement phase to the exposure event. Once crosscutting relationships are established for a cement zone and particular diagenetic features, cement zones can more readily correlated within and between stratigraphic sections.

METHODS

Field studies of Lisburne outcrops in the Sadlerochit, Shublik, and Fourth Range Mountains were conducted during a four-week period in the summer of 1990. Surfaces of subaerial exposure were identified and representative samples of the affected strata were collected for later petrographic studies.

Rocks from four localities were utilized to characterize the entire section of the Lisburne Group in the Sadlerochit Mountains. Cements in the lower 60 meters of the Alapah Limestone were studied utilizing 15 samples taken from outcrops on the western side of the Sunset Pass locality (Fig. 3-1). Cements in the upper part of the Alapah Limestone were studied from 36 samples taken from the eastern side of Sunset Pass (below section AK22M of Krumhardt, 1992). Outcrop studies of the Wahoo Limestone also were conducted at Sunset Pass and briefly at Ledge Creek. Systematic petrographic studies of calcite cements in the Wahoo Limestone at the Sadlerochit Mountains are from two sections: 331 samples from Marsh Creek (section D, Carlson, 1987) and 124 samples from Ledge Creek (section B, Carlson, 1987). In the central Shublik Mountains, calcite cements in 231 thin sections were studied from the prior collection of sections AK10M, AK11M, and AK12M (Gruzlovic, 1991) and additional samples collected during outcrop studies. In the Fourth Range, calcite cements in 176 thin sections were studied from the prior collection of sections AK13M and AK14M (Gruzlovic, 1991) and additional samples collected during outcrop studies.

A cement stratigraphy for the Lisburne Group was erected through transmitted light and cathodoluminescence (CL) petrographic studies of thin sections from samples from the measured sections. Samples typically are spaced at 5- to 10-meter intervals in the Alapah Limestone and 0.5- to 2-meter spacing in the Wahoo Limestone. The percent of the cement phases relative to the total cement in a sample was determined either by visual estimates, point counts of 200 to 300 points of the entire thin section, or point counts of 200 points on cement-filled pores. Thin sections of samples collected during field work were examined for crosscutting relationships between the cement phases and diagenetic features.

CEMENT ZONE NOMENCLATURE

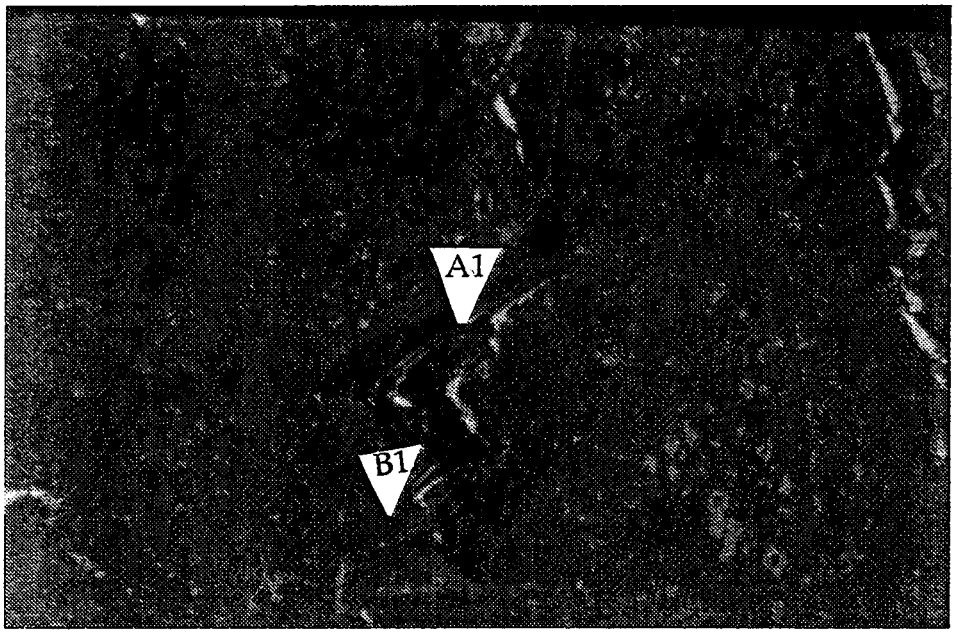
Four general types of CL zones occur in the Lisburne Group: 1) multibanded calcites that are nonferroan and have a subzonation of one to several sets of nonluminescent-bright-dull or nonluminescent-bright zones, 2) nonluminescent, nonferroan calcite, 3) nonferroan to low-ferroan, dully-luminescent calcite, and 4) ferroan, very-dully luminescent calcite (Figure 3-3). The dully luminescent low-ferroan calcites typically have less than 0.1 wt.% $FeCO_3$, while the very-dully luminescent, ferroan calcites have greater than 0.1 wt.% $FeCO_3$.

An alphanumeric labeling system was developed to record both the luminescent character and the relative ages of the cement zones and is utilized in discussions of cement stratigraphy (see below). The letters A, B, and C are used to designate the luminescent character of different cement zones: type A cements are multibanded-nonferroan calcite and nonluminescent-nonferroan calcite; type B cements are dully luminescent, nonferroan to low ferroan calcite; and type C cements are very-dully luminescent, ferroan calcite. These letters could be used alone to describe the sequential occurrence of zones in an individual sample (e.g., A-B-C-B-C...). To add a relative timing dimension to the labeling system, similar cement types within an individual sample are given sequential numbers (e.g., A1-B1-A2-B2...). This designation allows cement zones that have the same luminescent character but differ in relative age to be tracked through a stratigraphic succession.

One cement type that does not fit into this nomenclature scheme is microcrystalline calcite. This cement was found in only one sample in this study. The microcrystalline calcite is ferroan and very-dully luminescent, and precedes A1 calcite. Quartz cements within the Lisburne Group limestones are also not given an alphanumeric designation.

A drawback to the alphanumeric labeling system is that cement zones discovered through subsequent analyses of adjacent samples may require re-labeling of cements that have similar luminescent character in previously analyzed samples. For example, consider three samples collected in stratigraphic order: the lowest sample has an A1-B1-C1-B2 cement sequence; the middle sample has an A1-B1-C1-A2-B2 cement sequence; and the highest sample has an A1-B1-C1-B2-A2-B3 cement sequence. In the uppermost sample, superposition of B3 calcite over A2 calcite makes it evident that the sequence of zones in the middle sample should be designated as A1-B1-C1-A2-B3. Hence, discovery of a new zone requires modification of labeling of previously designated zones. In addition, given that A2 calcite does not occur in the lowermost sample, B2 calcite in the lower sample could be either or both the B2 and B3 cements recognized in the uppermost sample.

Thus, the alphanumeric labeling system presents a simplistic picture of the stratigraphic distribution of cement zones and should not be looked at as an implicit correlation of time equivalence for cements in different samples. Instead, it provides a tracking system that serves as an aid in making correlations between samples and in interpreting the timing of cement precipitation relative to diagenetic events.



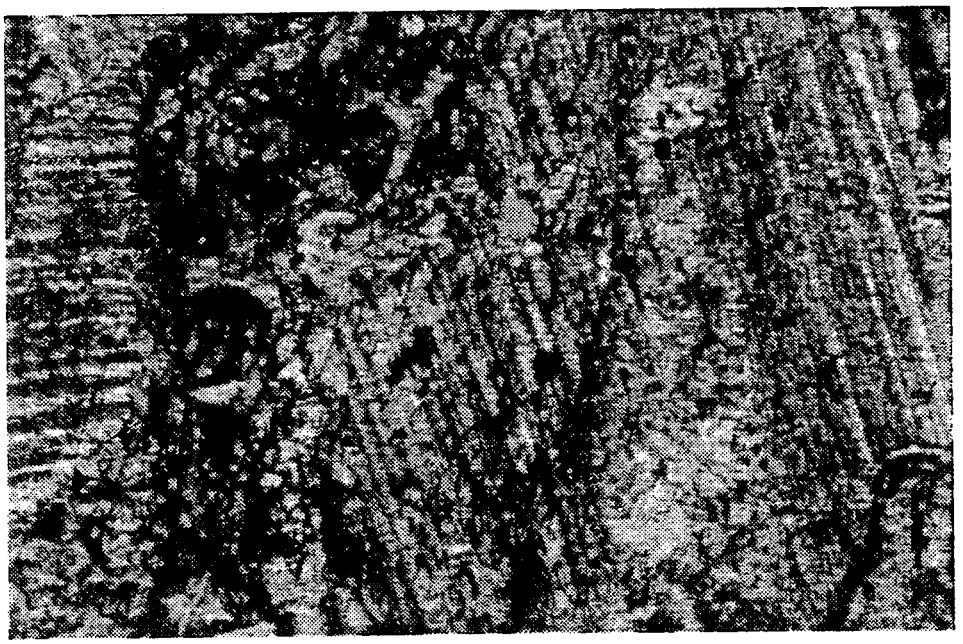


Figure 3-3. Compositional zones in calcite cement of the Lisburne Group. Cement zones A1 multibanded calcite, B1, C1, B2, and C2 calcite in an echinoderm-bryozoan grainstone. Location 145.5 meters above the base of the Wahoo Limestone, Marsh Creek section.

RESULTS

Figures 3-4 to 3-7 show the cement stratigraphy for each measured section. For each sample the cement proportions are graphed to total 100 percent cement, with the oldest cements on the left and succeeding younger cements added to the right. Where crosscutting features are present, the cement type is linked to the exposure surface in the figures by the number assigned to the subaerial exposure surface.

Microcrystalline calcite cement

Microcrystalline calcite cement was found in only one sample in this study. It occurs beneath surface xvii at Sunset Pass in the Sadlerochit Mountains. Microcrystalline calcite is the initial cement in an oolitic grainstone and precedes A1 multibanded calcite that is also found in the pore space of the sample. The microcrystalline calcite has a meniscus distribution relative to the grains; the cement is ferroan and very dully luminescent. Microcrystalline calcite is crosscut by infiltrated sediment in fissure fills developed beneath surface xvii.

A1 multibanded and A1 nonluminescent calcites

At the west Sunset Pass section (Fig. 3-4), the lower 40 meters of the Alapah Limestone contain A1 multibanded calcite comprised of two to three sets of nonluminescent bands and thinner, bright bands. This phase accounts for 20 to 100 percent of the cement showing first an increase in volume, followed by a decrease, upsection toward surface vii. A1 multibanded calcite is crosscut by early fractures filled with clay at surface vii (Fig. 3-8). A1 nonluminescent calcite, with a pendant distribution, also occurs in the strata beneath surface vii.

In the Shublik Mountains (Fig. 3-6), A1 nonluminescent calcite is the first cement phase present in the strata beneath surface vii. An upward trend of increasing abundance is present, just as was found for A1 multibanded calcite in the Sadlerochit Mountains. A1 nonluminescent calcite increases upsection from 5 percent of total cement to nearly 80 percent, toward surface vii, and then is crosscut by infiltrated sediment in the autoclastic breccia beneath surface vii.

Just beneath surface vii in the Fourth Range (Fig. 3-7), A1 calcite is absent, and C1 calcite is the first cement in the pore space. A1 nonluminescent calcite is present, however, lower in the section in the Fourth Range. Six surfaces of subaerial exposure occur between surface vii and the base of the Alapah. A1 nonluminescent calcite fills all of the pore space beneath surfaces i and ii, and is very abundant in some samples beneath surface vi.

This part of the Alapah is poorly exposed at the Shublik section (Fig. 3-6); surfaces ii through v, if present here, are covered. The few available samples have B1 calcite as the first cement phase.

Figure 3-4.

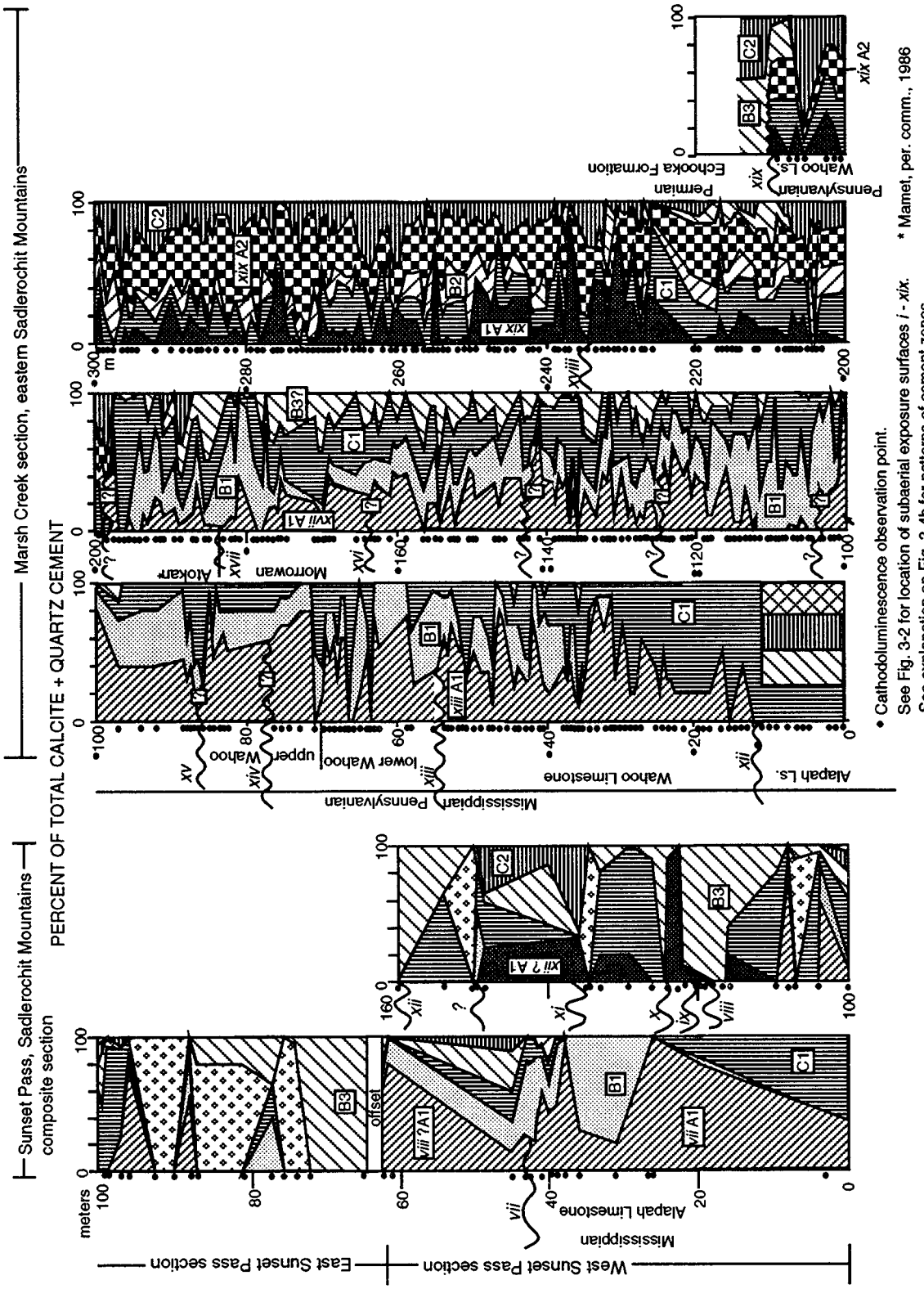


Figure 3-4. Cement stratigraphy of the Lisburne Group, Sadlerochit Mountains. A composite of sections from Sunset Pass and Marsh Creek shows the relative distribution of zoned calcite cements in the Lisburne Group. Oldest to youngest cement phases are depicted left to right. Stratigraphic section D (Carlson, 1987).

EXPLANATION

CEMENTS & CALCITE CATHODOLUMINESCENCE

- A1 calcite - nonferroan, nonluminescent and dull bands and bright hairlines
- A1 calcite - nonferroan, nonluminescent calcite
- B1 calcite - nonferroan, dull luminescent calcite
- C1 calcite - ferroan, very dull luminescent calcite
- B2 calcite - lowferroan, dull luminescent
- A2 calcite - nonferroan, nonluminescent band and bright hairline zoned calcite
- quartz cement
- B3 calcite - nonferroan, dull to moderately bright luminescent calcite
- C2 calcite - ferroan, very dull luminescent calcite
- B4 calcite - nonferroan, dull luminescent

Figure 3-4b. Expalantion of symbols used in Figures 3-4 to 3-7.

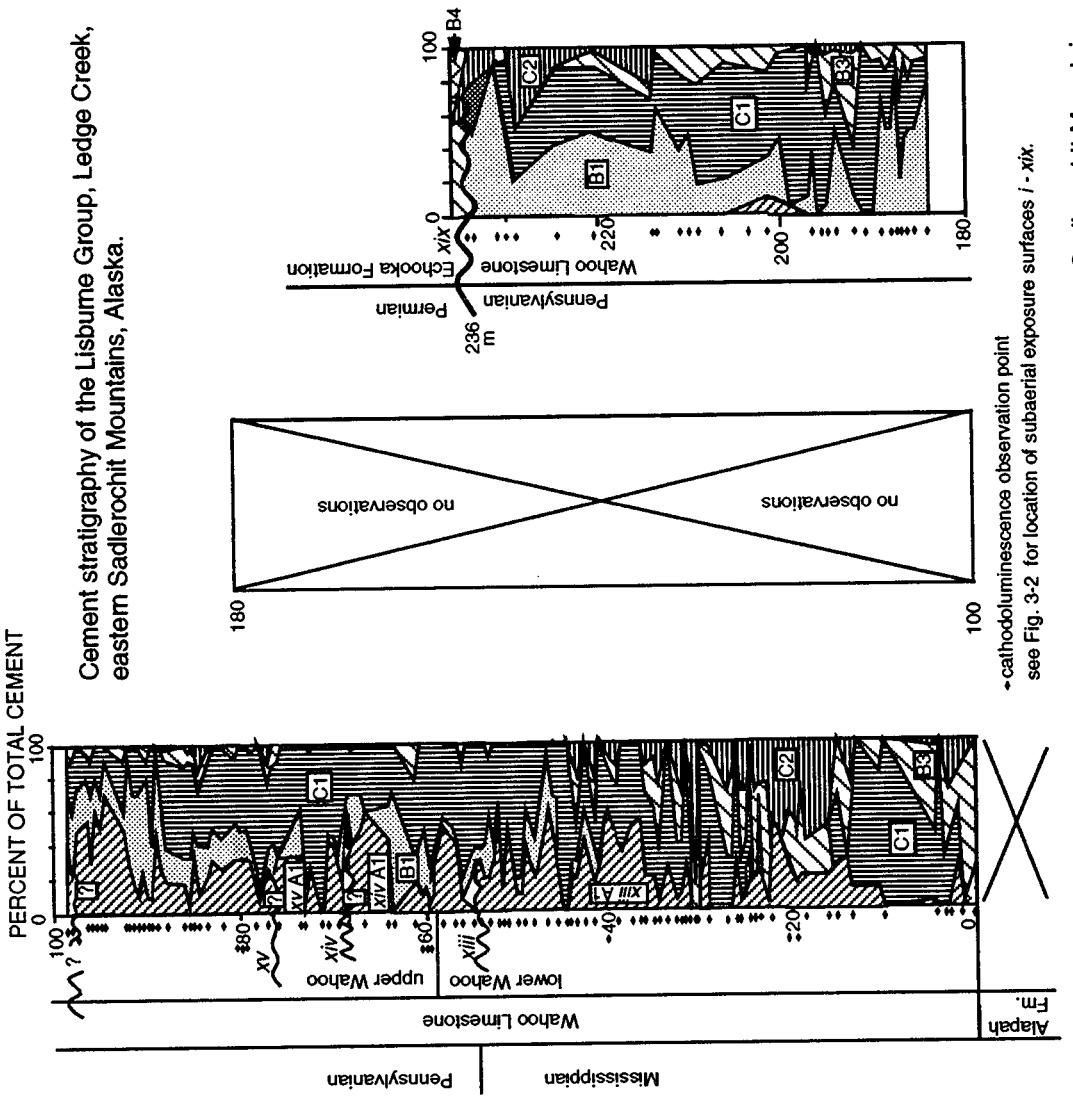


Figure 3-5. Cement stratigraphy of the Lisburne Group, Ledge Creek section, eastern Sadlerochit Mountains. Oldest to youngest cement phases are depicted left to right. Stratigraphic section B (Carlson, 1987). See Fig. 3-4b for explanation.

Figure 3-6.

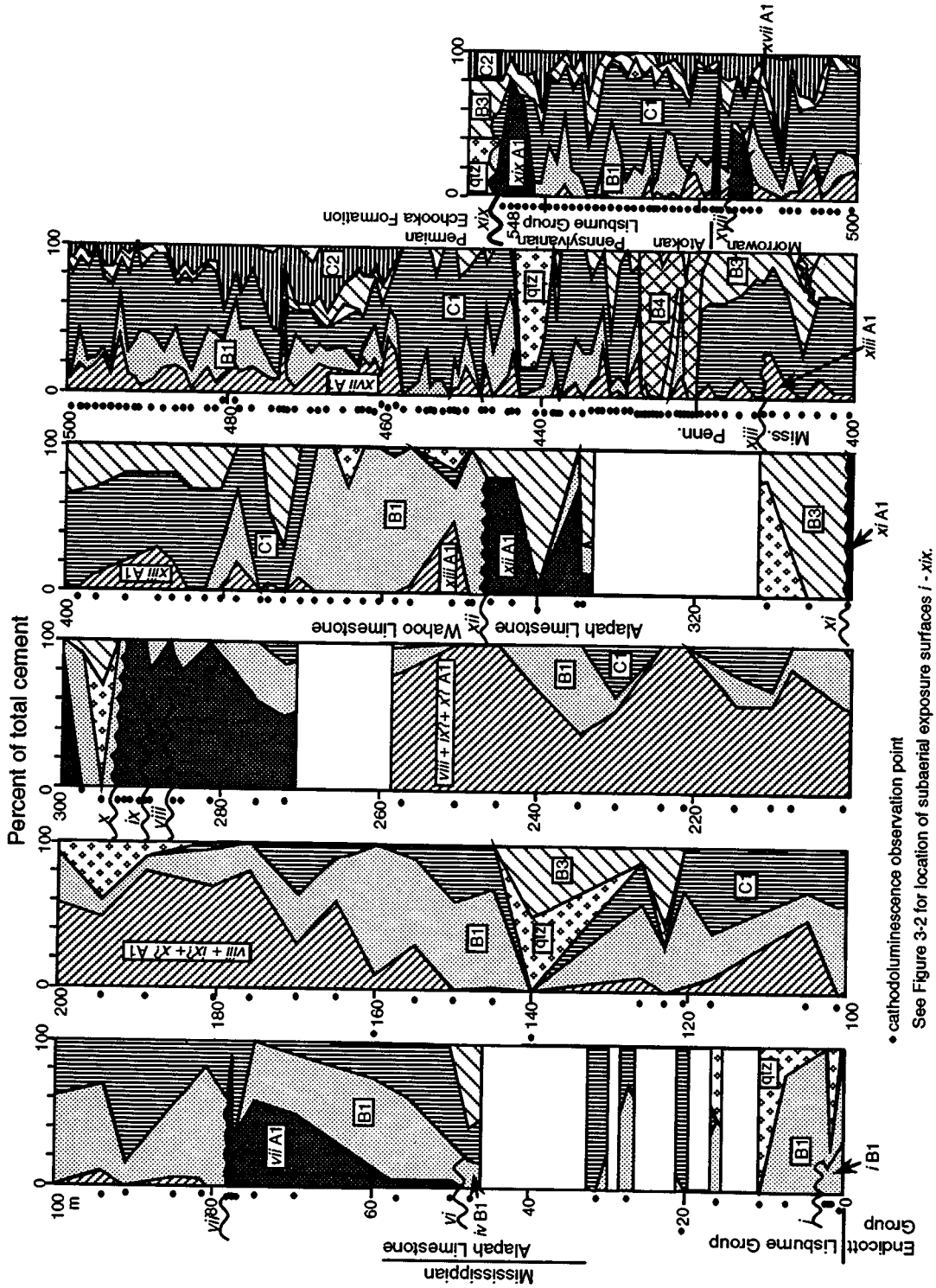


Figure 3-6. Cement stratigraphy of the Lisburne Group, central Shublik Mountains section. Oldest to youngest cement phases are depicted left to right. Stratigraphic sections AK-10, 11, and 12-M (Gruzlovic, 1991). See Fig. 3-4b for explanation.

Figure 3-7.

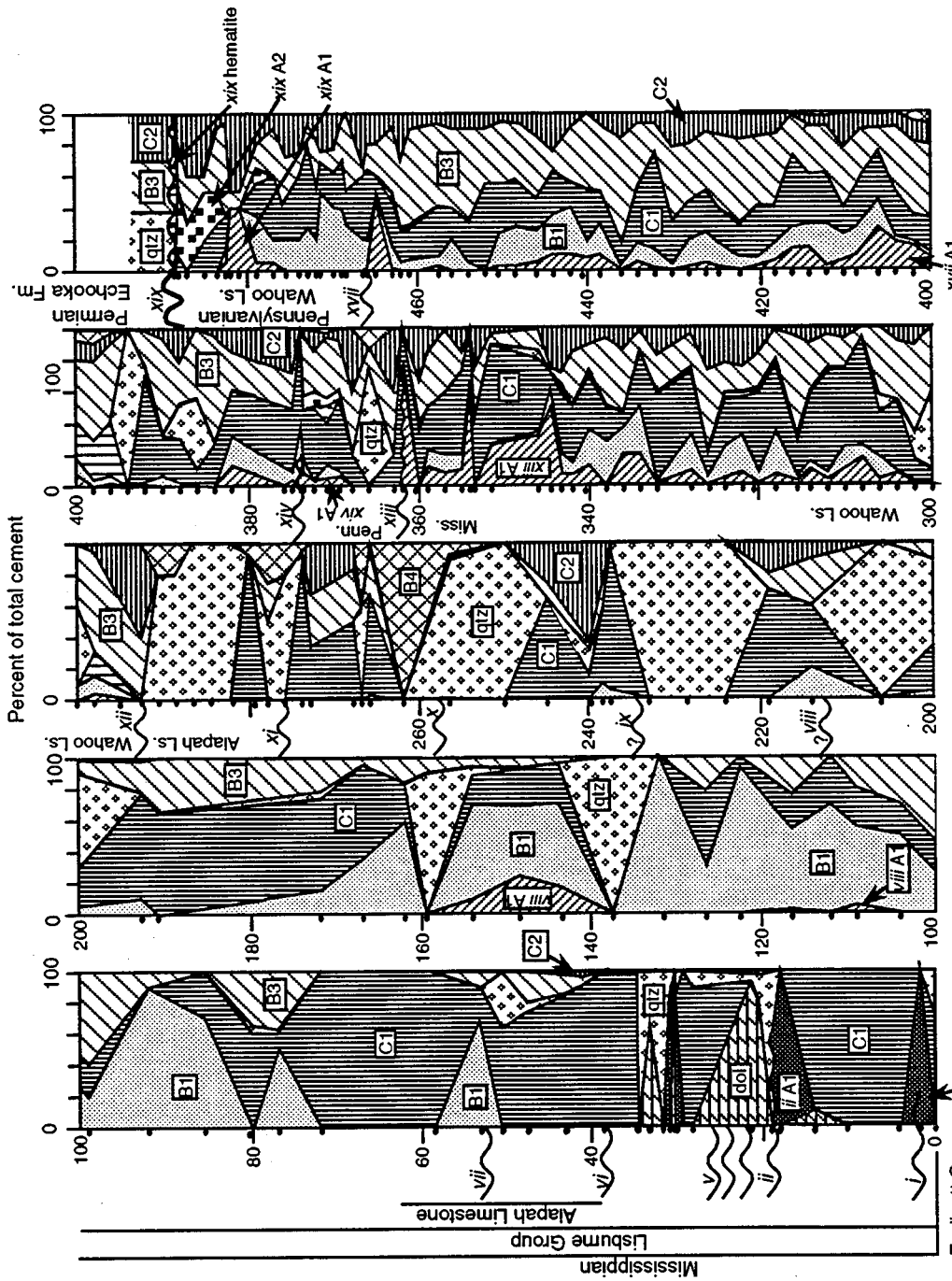


Figure 3-7. Cement stratigraphy of the Lisburne Group, Fourth Range Mountains. Oldest to youngest cement phases are depicted left to right. Stratigraphic sections AK-13 and 14-M (Gruzlovic, 1991). See Figures 3-2 and 3-4b for explanation.

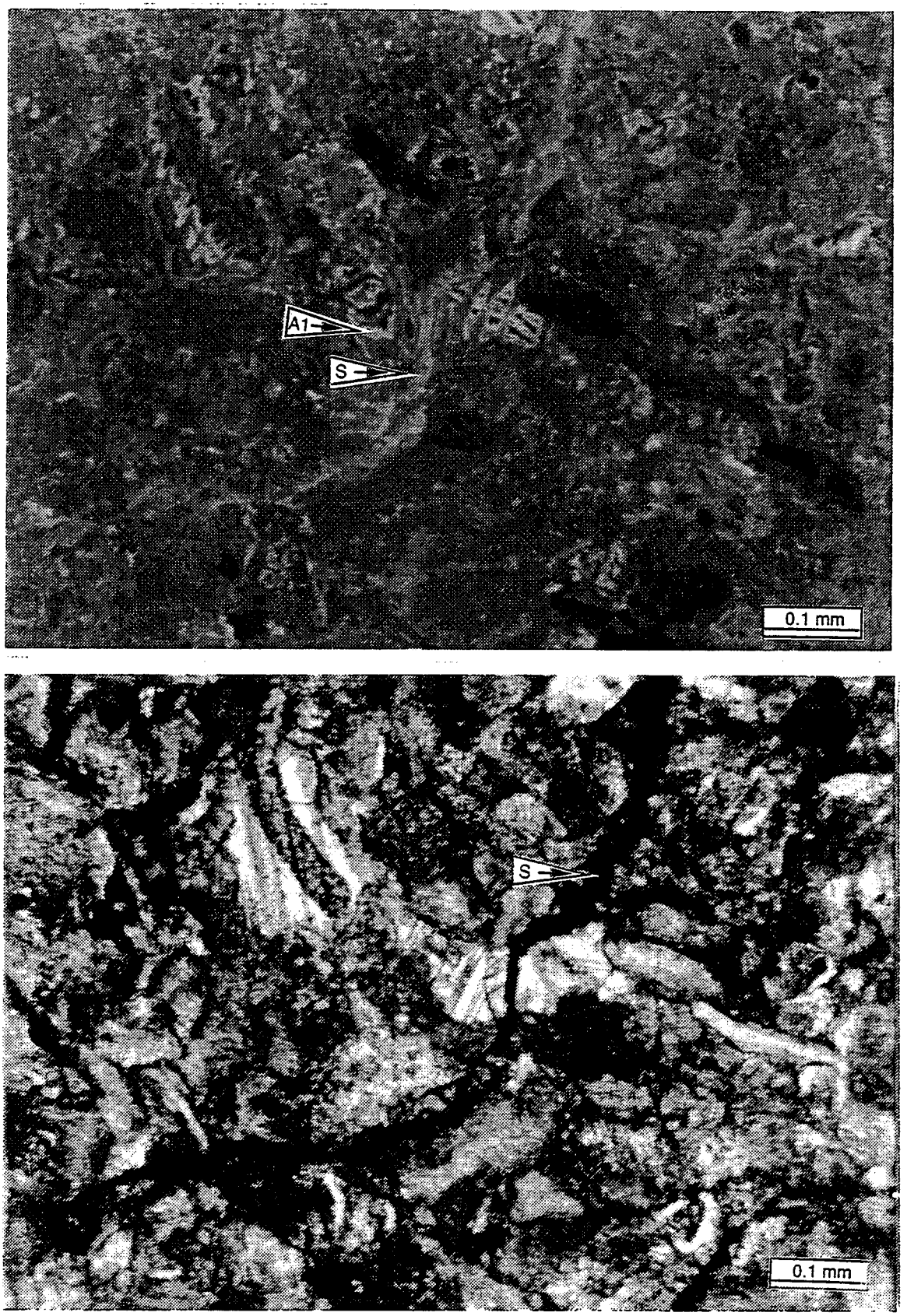


Figure 3-8. Early cracks filled by dark sediment (S) below surface vii crosscut multibanded calcite cement (A1).

The lower part of the Alapah Limestone at the Shublik Mountains and Fourth Range contains foraminifers of biozones 16i (Mamet, pers. comm., in Gruzlovic, 1991), whereas in the Sadlerochit Mountains, the lower Alapah foraminifers are of biozone 16s (Mamet, in Carlson, 1987). This indicates that the lower part of the Alapah in the Fourth Range and Shublik Mountains laps out northward before reaching the Sadlerochit Mountains (Fig. 3-2).

Above surface vii in the Sadlerochit Mountains (Fig. 3-4), A1 multibanded calcite is present and shows the same trend in abundance upsection for 20 meters, as was noted below surface vii. The interval consists of cross-bedded, peloidal grainstone at the base, peloidal-skeletal packstone/grainstone in the middle, and cross-bedded skeletal grainstone at the top. Evidence of subaerial exposure was not apparent, however, at the top of the grainstone. Offsetting to the east Sunset Pass section, A1 multibanded calcite occurs sporadically within the skeletal packstone and grainstone upsection to 110 meters above the base of the Alapah Limestone, and then disappears about 20 meters below surface viii. In place of A1 multibanded calcite, A1 nonluminescent calcite occurs in the fenestral and skelmoldic porosity in the dolostones of the upper Alapah. A1 nonluminescent calcite generally accounts for 20 to 30 percent of the total cement in the upper Alapah, although in some samples it is the only cement present. A1 nonluminescent calcite is not present, however, in the uppermost beds of the Alapah Limestone in the Sadlerochit Mountains.

In the Shublik Mountains (Fig. 3-6), minor amounts of A1 multibanded calcite occur immediately above surface vi. Here, throughout the middle part of the Alapah Limestone, the abundance of A1 multibanded calcite increases upsection toward the overlying subaerial exposure surfaces. A1 multibanded calcite comprises less than 10 percent of the cement in most of the samples between 80 and 150 meters above the base of the section, and then increases to 80 to 100 percent of the cement upsection to 265 meters above the base of the Lisburne Group. Then, as in the Sadlerochit Mountains, A1 multibanded calcite abruptly disappears about 20 meters below exposure surface viii, and in its place, A1 nonluminescent calcite occurs. At exposure surface viii, as well as surfaces ix, x and xi, A1 nonluminescent calcite occurs within and between breccia grains and is crosscut by infiltrated sediment within the breccia. A1 nonluminescent calcite is not present in the first few samples above surface xi, and its next appearance is about 10 meters below surface xii at the top of the Alapah Limestone. A1 nonluminescent calcite does not continue upward in the lower part of the Wahoo Limestone.

In the Alapah Limestone at the Fourth Range section (Fig. 3-7), A1 multibanded calcite occurs in only four samples of echinoderm-bryozoan grainstone from near the middle of the Alapah. The cements disappear 100 meters below the next obvious exposure surface upsection, surface x.

The boundary between the Alapah Limestone and the Wahoo Limestone marks a significant change in the character of the early calcite cements, from nonluminescent in the upper Alapah Limestone to multibanded in the lower Wahoo. At the base of the

Wahoo at Marsh Creek, A1 multibanded calcite comprises 10 to 20 percent of the cement and then increases in abundance upsection, accounting for up to 80 percent of the cement, toward surface xiii. A1 multibanded calcite is crosscut by early fractures filled with sediment at surface xiii, the Mississippian-Pennsylvanian boundary (Fig. 3-9).

Cements in the lower 100 meters of the Wahoo Limestone at Ledge Creek in the Sadlerochit Mountains are similar to those at Marsh Creek (Fig. 3-4 & 3-5). A1 multibanded calcite cements are present in the lower 58 meters of the Wahoo and increase upsection from 0 to 50 percent toward surface xiii.

Near the base of the Wahoo Limestone at the Shublik Mountains section (Fig. 3-6), A1 multibanded calcite can account for up to 50 percent of the cement and then varies in abundance upsection from zero to nearly 40 percent of the cement upwards toward surface xiii.

In the Wahoo Limestone at the Fourth Range (Fig. 3-7), A1 multibanded calcite shows a general increase upsection, from less than 5 percent at the base of the Wahoo up to nearly 80 percent of the total cement at surface xiii. A1 multibanded calcite is crosscut by early cracks filled with sediment at surface xiii.

Above surface xiii at Marsh Creek (Fig. 3-4), A1 multibanded calcite is present in the Pennsylvanian strata, although at a much lower volume than in upper Mississippian rocks. Within a few meters upsection, however, A1 multibanded calcite increases to 60 to 80 percent of the total cement. At surfaces xiv and xv, the number of nonluminescent and bright bands in A1 multibanded calcite decreases from below the exposure surface to above the exposure surface. A1 multibanded calcite is crosscut by dissolution pipes at exposure surface xiv at Sunset Pass. At Marsh Creek, above surface xv, decreases in the number of subzones and in the percent of A1 multibanded calcite also coincide with transitions from the top of one shallowing-upward cycle to the base of the next shallowing-upward cycle. Such changes in cement character and volume also occur at exposure surfaces xiii and xiv, hence, such changes may be an indication of subaerial exposure.

At the Ledge Creek section above surface xiii (Fig. 3-5), A1 multibanded calcite increases in abundance upsection toward surfaces xiv, xv, and a questionable surface at about 100 meters above the base of the Wahoo Limestone . This echoes a similar trend in A1 multibanded calcite above surface xiii at Marsh Creek (Fig. 3-4).
At surface xvii at Sunset Pass, A1 multibanded calcite is crosscut by early fractures filled with sediment composed of clay, quartz silt, and lime mud. At Marsh Creek, A1 multibanded calcite is present above surface xvii upsection, but stops abruptly at surface xviii (Fig. 3-4).

At the Shublik Mountains section (Fig. 3-6), A1 multibanded calcite forms 5 to 30 percent of the total cement above surface xiii, until a few meters below surface xvii. In its place, A1 nonluminescent calcite occurs as the first cement phase and then is crosscut by early, clay-filled fractures at surface xvii.

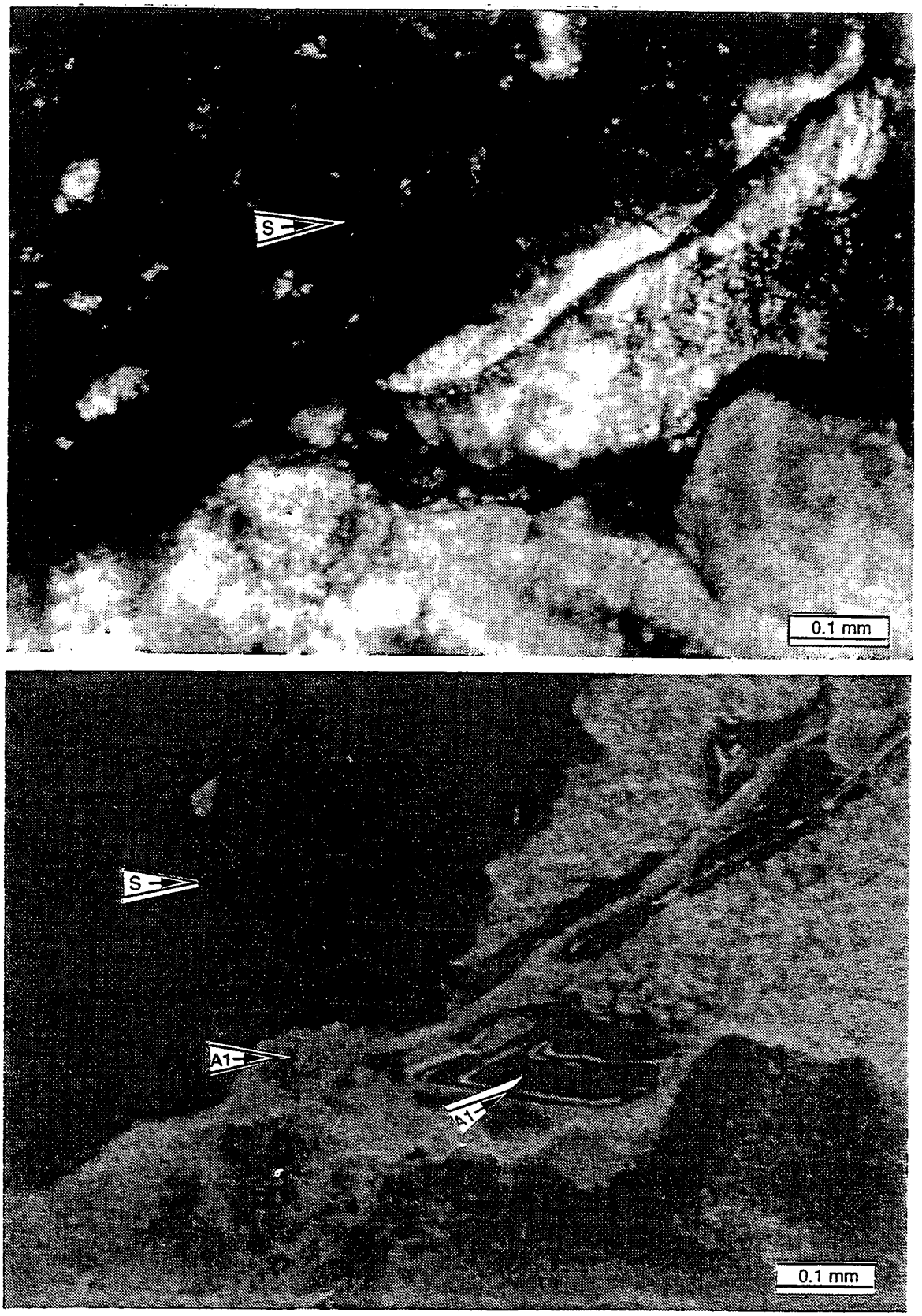


Figure 3-9. Early fractures and infilled sediment (S) below surface xiii crosscut multibanded calcite cement (A1).

In strata immediately above surface xiii in the Fourth Range (Fig. 3-7), A1 multibanded calcite is absent and then appears again below surface xiv, where it is then crosscut by early cracks and infilled clay-carbonate sediment. A1 multibanded calcite is present as 5 to 30 percent of the cement over the next 100 meters of strata in the Fourth Range and then is crosscut by solution channels beneath surface xvii.

A change occurs in the zonation of the calcite cements about 35 meters below surface xviii at Marsh Creek (Fig. 3-4). Here, the upper 100 meters of the Wahoo Limestone have A1 nonluminescent calcite as the first cement, rather than A1 multibanded calcite, and an A2 multibanded calcite, described below, occurs as a prevalent cement phase. The A1 nonluminescent calcite varies from 10 to 80 percent of the cement and does not show any apparent trend in abundance with stratigraphic position. Unconformably above the Lisburne, the basal conglomerate of the Echooka Formation contains clasts with A1 nonluminescent calcite that is crosscut by sand matrix at the clast margins.

Above surface xvii in the Shublik Mountains (Fig. 3-6), A1 multibanded calcite commonly occurs as 5 to 20 percent of the cement. It decreases in abundance upward and then disappears about 5 meters below the top of the Lisburne Group, and in its place, A1 nonluminescent calcite is present. Echooka conglomerate unconformably above the Lisburne in the Shublik Mountains has limestone clasts derived from the Lisburne that are cemented by A1 nonluminescent calcite crosscut at the clast margins.

At the Fourth Range section (Fig. 3-7), A1 multibanded calcite is absent for 10 meters above surface xvii. It then occurs over a short interval, comprising up to 40 percent of the cement, but disappears in the upper 5 meters of grainstone at the top of the Fourth Range section. Following the top contact of the Lisburne Group westward down the slope of the spur ridge from the Fourth Range section, rubble exposures of the top of the Lisburne occur that are composed of karst breccia infiltrated by black clay. The infiltrated clay crosscuts A1 multibanded calcite as well as later cement phases.

B1 calcite cements

B1 calcite accounts for 20 to 80 percent of the cement in the lower 80 meters of the Alapah Limestone at Sunset Pass (Fig. 3-4), and then is rarely present in the remainder of the Alapah. B1 calcite makes a more significant contribution to cements in the Alapah Limestone at the Shublik Mountains section. Unlike other sections, the oldest cement at the Shublik Mountains section is B1 calcite, equant, nonferroan and dully luminescent. Furthermore, B1 calcite is crosscut at the edges of clasts of autoclastic breccia beneath surface i. Additional B1-type calcite postdates the formation of the clasts. Talus covers much of the section for approximately 45 meters above surface i, and in the few samples available, B1 calcite comprises 0 to 70 percent of the cement. At surface vi, B1 calcite is crosscut at the edges of autoclastic breccia. B1 calcite is present above surface vi, and increases in abundance upsection until just below surface vii, where it is abruptly absent in the autoclastic breccia beneath that exposure surface. Above surface vii and over the next 210 meters of section up to surface x, B1 calcite is present as the second cement phase and accounts for 20 to 80 percent of the total cement. Above surface x, B1 calcite

varies from absent up to 90 percent of the cement. It last occurs in the Alapah about 20 meters beneath surface xii, the top of the formation.

At the Fourth Range section (Fig. 3-7), B1 calcite first occurs as about 70 percent of the total cement just above surface vii, and then constitutes 40 to 80 percent of total cement through most of the middle Alapah Limestone. B1 calcite decreases upsection toward upper Alapah strata. Its last occurrences in the Alapah are just above surfaces viii and ix, where it comprises less than 20 percent of the total cement.

B1 calcite occurs consistently, beginning at about 15 meters below surface xiii, in the lower 200 meters of the Wahoo Limestone at Marsh Creek (Fig. 3-4). Here, B1 calcite ranges from 5 to 40 percent of the total cement. B1 calcite fills dissolution reentrants in A1 multibanded calcite in the lower Wahoo Limestone. B1 calcite disappears about 35 meters below surface xviii at Marsh Creek and is not present in the remainder of the section.

At Ledge Creek (Fig. 3-5), B1 calcite is absent in the lowermost Wahoo Limestone. It first appears about 10 meters below surface xiii, and then accounts for 10 to 20 percent of the total cement over the next 40 meters. In the upper part of the Wahoo at Ledge Creek, the first generation of cements are B1 calcites rather than an A1 calcite phase. Here, B1 calcite constitutes 10 to 80 percent of total cement.

B1 calcite is also an abundant phase in the lower 25 meters of the Wahoo Limestone at the Shublik Mountains section (Fig. 3-6), but then disappears upsection and does not occur again until about 15 meters above surface xiii. From there upward, B1 calcite is present as 10 to 30 percent of the cement in most of the remainder of the Wahoo. Notable exceptions to this are the lower abundance of B1 calcite beneath exposure surfaces xvii and xix.

B1 calcite is persistent throughout the Wahoo Limestone in the Fourth Range section and averages about 20 percent of the total cement (Fig. 3-7). In the lower 50 meters of the Wahoo Limestone, the abundance of B1 calcite increases upward, from 5 to 30 percent. However, B1 calcite decreases to zero towards surface xiii. B1 calcite is absent for 12 meters above surface xiii, but reappears, following A1 multibanded calcite beneath surface xiv. Early cracks filled with clay appear to crosscut B1 calcite at surface xvii, however, isotopic data, presented below, do not support the apparent petrographic relationship. B1 calcite accounts for up to 50 percent of the total cement above surface xvii but disappears about 10 meters below the top of the Lisburne Group. B1 is cross-cut by infiltrated sediment in the karst breccia at the top of the Lisburne Group in the Fourth Range, dating the B1 calcite in the upper part of the Lisburne as pre-Leonardian. Other B1 calcites, lower in the section, are crosscut at surfaces of subaerial exposure within the Lisburne Group and can be dated relative to the age of the different subaerial exposure surfaces (Chesterian to Atokan).

C1 calcite cements

C1 calcite accounts for 60 percent of the cement at the base of the Alapah Limestone at the west Sunset Pass section (Fig. 3-4), but is present in only minor amounts (2 to 5 percent) as surface vii is approached. C1 calcite continues to be present above surface vii, accounting for 10 to 20 percent of the cement. At the east Sunset Pass section, C1 calcite occurs in some abundance again in the upper 60 meters of the Alapah, where it is locally the first cement phase in the pores and sometimes accounts for up to 80 percent of the cement. The uppermost beds of the Alapah Limestone at Marsh Creek are cemented by alternating bands of ferroan and nonferroan calcite that fill the interparticle porosity.

At the Shublik Mountains section (Fig. 3-6), 20 meters above the base of the Alapah Limestone, C1 calcite comprises 100 percent of the total cement and then decreases upsection toward surface vi. C1 calcite becomes more abundant immediately above surface vi, and then decreases upsection toward surface vii. The same trend in abundance is evident, but over a much greater range of section, between surfaces vii and viii; C1 calcite comprises 40 to 80 percent of the cement in the 40 meters of strata above surface vii and then decreases over the next 150 meters upsection until it disappears about 15 meters below surface viii. C1 calcite is absent in the remaining 70 meters of the Alapah Limestone.

In the lower 80 meters of the Alapah Limestone at the Fourth Range section (Fig. 3-7), C1 calcite commonly makes up 100 percent of the total cement. From 80 to 160 meters in the section, C1 calcite decreases to 5 to 30 percent, as B1 calcite increases. Above 160 meters, C1 calcite increases up to 60 percent of the total cement as B1 calcite decreases. In the upper Alapah, from 200 to 280 meters, C1 calcite is typically the first calcite cement in the pore space and can account for 50 to nearly 100 percent of the cement.

In the lowermost Wahoo Limestone at Marsh Creek (Fig. 3-4), C1 calcite makes up 50 to 100 percent of the cement and then decreases in abundance upsection toward surface xiii, where it is limited to about 10 percent of the cement. Continuing upsection toward surfaces xiv, xv, and a questionable exposure surface about 100 meters above the base of the Wahoo, C1 calcite makes up 20 to 60 percent of the cement and is most abundant in rocks that lack earlier cement phases. Up to about 110 meters above the base of the Wahoo Limestone, C1 calcite is typically the last cement phase present. From 110 to about 200 meters, C1 calcite averages about 40 percent of the total cement and the remainder of the pore space is filled by B3 calcite. About 35 meters below surface xviii, C1 calcite is the first or second phase of cement present in the rocks. In the upper 110 meters of the Lisburne Group, C1 calcite is present as 30 to 20 percent of the cement. C1 calcite is truncated along the margins of Lisburne-derived limestone clasts in the basal conglomerate of the Permian Echooka Formation.

C1 calcite forms 20 to 60 percent of the cement in the two parts of the section studied at Ledge Creek (Fig. 3-5). One notable exception is a 10-meter interval in the lower Wahoo Limestone where C1 calcite is absent.

C1 calcite is present in minor amounts in the lower part of the Wahoo Limestone at the Shublik Mountains section and then is abundant over most of the remaining section (Fig. 3-6). One exception occurs at 420 to 428 meters above the base of the section where there is a change in lithology from skeletal limestone to finely crystalline dolostone. There also are decreases in the abundance of C1 calcite at surface xvii and beneath the unconformity at the top of the Lisburne, surface xix.

In the lower 100 meters of the Wahoo Limestone at the Fourth Range section (Fig. 3-7), C1 calcite commonly accounts for 40 percent or more of the cement. In the remainder of the formation, C1 calcite is slightly less abundant, comprising 20 to 30 percent of the total cement. At the very top of the Lisburne Group at the Fourth Range section, C1 calcite is the first cement in the pores. C1 calcite cements at the karstic top of the Lisburne are crosscut by infiltrated sediment , dating C1 calcite as pre-Permian in age.

B2 calcite cement

B2 calcite is a dully luminescent, nonferroan to low ferroan calcite that follows C1 calcite, and precedes A2 calcite and quartz cement. B2 calcite cannot be differentiated from B3 calcite if A2 calcite and quartz cement are not present, hence a B2 calcite phase was recognized only at the Marsh Creek section in the upper 100 meters of the Wahoo Limestone (Fig. 3-4). There, B2 calcite occupies 5 to 20 percent of the cement in the upper Wahoo.

A2 calcite cement

A2 calcite occurs in the upper 110 meters of the Wahoo Limestone at Marsh Creek (Fig. 3-4). This cement appears about 35 meters below surface xviii and forms a significant portion of the cement in the remainder of the Lisburne Group. A2 calcite increases in abundance upsection; beginning at 30 percent, it increases to as much as 80 percent of the cement over the next 100 meters of the Wahoo, before decreasing to 30 percent in the upper 10 meters of the formation.

None of the other stratigraphic sections examined in this study contained any significant amount of A2 calcite. It occurs in trace amounts in only a few samples from the upper part of the Wahoo Limestone at the Ledge Creek and Shublik Mountains sections. In the Fourth Range (Fig. 3-7), A2 calcite first appears in trace amounts at surface xiii and then, sporadically, in trace amounts through the remainder of the Lisburne Group. Exceptions to this are occurrences just below surface xiv, where A2 calcite accounts for 10 percent of the total cement, and at the very top of the Wahoo, where A2 calcite contributes up to 30 percent.

Samples of the basal conglomerate of the Echooka Formation at Sunset Pass did not yield Lisburne pebbles that were cemented by A2 calcite. At the Fourth Range section (Fig. 3-7), however, A2 calcite is present and is crosscut by infiltrated sediment that was deposited on the karstic surface of the Lisburne during the sub-Permian unconformity, and is dated as pre-Permian in age.

Quartz cement

Quartz occurs as a late stage cement. Its precipitation follows C1 calcite and precedes B3 calcite. Its occurrence is mostly limited to mud-rich rocks that have little macroporosity. Quartz is much more common in the Alapah Limestone than in the Wahoo Limestone. At Sunset Pass (Fig. 3-4), it forms 70 to 100 percent of the total cement in the mid-Alapah and accounts for 100 percent of the cement in a few samples in the upper Alapah. Even so, the small volume of pore space in these rocks limits the quartz to a small fraction of the total.

The same is true of quartz cement at the Shublik Mountains section (Fig. 3-6). It makes up 20 to 100 percent of the cement in the lower 18 meters of the Alapah, but then occurs sporadically in the remainder of the Alapah.

Quartz cement is more common in the Alapah Limestone at the Fourth Range section (Fig. 3-7). In the lower Alapah, quartz cement fills fractures in autoclastic breccia below surface i, and fills interparticle porosity, as well as late fractures, in the lower 50 meters of the Alapah. In some samples of skeletal wackestone from the middle Alapah, quartz fills most of the interparticle pore space. The most abundant occurrence of quartz is in the upper 90 meters of the Alapah Limestone at the Fourth Range section. There, in spiculitic lime mudstone and skeletal wackestone, quartz commonly comprises 100 percent of the cement.

Quartz cement is rare in the Wahoo Limestone. It is largely absent in the sections examined in the Sadlerochit Mountains (Fig. 3-4 & 3-5). At the Shublik Mountains section (Fig. 3-6), quartz occurs as 20 percent of the cement in some grainstones in the lower Wahoo and also as 80 percent of the cement at one interval in the mid-Wahoo. At the Fourth Range section (Fig. 3-7), quartz is present in dolostone just above surface xiii, and again about 20 meters above surface xiv in a skeletal wackestone.

Quartz is a common cement in fractures throughout the Lisburne Group and is commonly found in shear fractures. Cements in the fractures, however, rarely amount to more than trace amounts of the total volume of cement. Quartz cement postdates infiltrated sediment at the sub-Permian unconformity at the top of the Lisburne Group, and is the common cement in the overlying Echooka Formation.

B3 calcite cement

At Sunset Pass (Fig. 3-4), B3 calcite follows precipitation of quartz in the Alapah Limestone. The lowermost occurrence of B3 calcite is in root-moldic porosity at surface vii, where it accounts for 10 percent of the cement. Above surface vii, and on through most of the remainder of the Alapah, B3 calcite makes up a significant portion of the cement. In the lower part of the middle Alapah strata, B3 calcite averages about 30 percent of the cement, but in some samples is the only cement present. In the upper Alapah, below surfaces viii, ix, and x, B3 calcite constitutes 80 to 100 percent of the cement. At the west Sunset Pass section, the top of the Alapah is completely cemented by B3 calcite.

In the Shublik Mountains section (Fig. 3-6), B3 calcite occurs in the autoclastic breccia below surface vi as 50 percent of the cement. It is also present in the middle Alapah Limestone, following quartz cement, and then is most abundant in the upper 45 meters of the Alapah, where it ranges from 20 to 100 percent of the cement.

At the Fourth Range section (Fig. 3-7), B3 calcite is much more common than in the more northerly sections. It is present as 10 to 40 percent of the total cement in most of the middle Alapah Limestone, and then is less abundant in the upper Alapah.

B3 calcite does not occur in the lower 110 meters of the Wahoo Limestone at Marsh Creek (Fig. 3-4). From 110 meters above the base of the Wahoo up to surface xviii, B3 calcite is the final phase of cement in the pore spaces and averages about 20 percent of the total. Above surface xviii, B3 calcite occurs as 5 to 10 percent of the cement following A2 calcite for the next 40 meters upward, and then is largely absent in the remainder of the Wahoo.

B3 calcite forms 100 percent of the total cement at the base of the Wahoo Limestone at the Ledge Creek section and then averages 20 percent of the total for the next 40 meters of section (Fig. 3-5). It continues to be present, although in lesser amounts, in the next 60 meters of the Wahoo. In the upper 50 meters of the Ledge Creek section, B3 calcite occurs as 10 to 20 percent of the cement.

At the Shublik Mountains section (Fig. 3-6), B3 calcite is absent in the lower 25 meters of the Wahoo Limestone, but then is present as 20 to 60 percent of the cement over the next 60 meters of section. Its volume then decreases to 5 to 10 percent over the remainder of the Wahoo.

The contribution of B3 calcite increases greatly in the Wahoo Limestone at the Fourth Range section (Fig. 3-7). There, B3 calcite ranges from 10 to 60 percent of the total cement and is consistently present.

B3 calcite postdates infiltrated sediment in the sub-Permian, karstic fabric of the top of the Lisburne Group. Minor calcite cements in the overlying Echooka Formation postdate quartz cement and have a moderately bright luminescence.

C2 calcite cement

C2 calcite is the final cement phase of significant volume in the Lisburne Group in the Sadlerochit Mountains (Fig. 3-4 & 3-5). Its lowermost occurrence is above surface vii, where C2 calcite makes up 10 percent of the cement. C2 calcite occurs in greater abundance in the upper Alapah Limestone above surface xi where it makes up 20 to 60 percent of the cement.

C2 calcite was not recognized in the Alapah Limestone in the Shublik Mountains section (Fig. 3-6). C2 calcite occurs in very minor amounts in the lower 200 meters of the Alapah Limestone at the Fourth Range section (Fig. 3-7). C2 calcite becomes more common in the upper Alapah Limestone above surface viii(?). In the upper Alapah, C2

calcite occurs sporadically, but where present, forms up to 60 percent of the total cement.

In the Wahoo Limestone at Marsh Creek (Fig. 3-4), C2 calcite was not distinguished in the lower 180 meters of the formation. This may be because B3 calcite is not present and C1 and C2 calcite phases appear merged as one ferroan phase. In the remainder of the section, C2 calcite commonly is present, averaging 30 percent of the cement.

At Ledge Creek in the lower 100 meters of the Wahoo Limestone (Fig. 3-5), C2 calcite averages about 50 percent of the total. In the upper part of the Ledge Creek section, C2 calcite contributes as much as 40 percent to the total cement.

At the Shublik Mountains section of the Wahoo Limestone (Fig. 3-6), C2 calcite only is present in the upper 85 meters. There, C2 calcite makes up between 10 to 40 percent to the total cement.

This contrasts with the Fourth Range section where C2 calcite is present throughout the Wahoo Limestone (Fig. 3-7). It is most abundant at the base of the Wahoo, where it makes up 60 percent of the cement. In the remainder of the Wahoo, C2 calcite ranges up to 30 percent of the cement except for the uppermost Wahoo, where it comprises 50 percent of the total cement in some samples.

Near Sunset Pass, C2 calcite is present in fractures in the basal conglomerate of the Echooka Formation. The fractures crosscut clasts derived from the Lisburne Group and the quartz matrix of the conglomerate. At the Fourth Range, C2 calcite postdates infiltrated sediment derived during development of the sub-Permian unconformity.

B4 calcite cement

B4 calcite is a very dully luminescent, nonferroan calcite that comprises the last significant cement phase in the Lisburne Group. B4 calcite mostly occurs in fractures, many of shear origin, and also postdates formation of stylolites. At Sunset Pass (Fig. 3-4), B4 calcite also fills solution pockets at the top of the Alapah Limestone. B4 calcite makes its most striking occurrence where it fills cavernous porosity at the Alapah-Wahoo contact at the Shublik Mountains section (Fig. 3-6). Here, the cement is white and very coarsely crystalline and curving twin planes in the calcite crystals are sometimes evident. At the Fourth Range section (Fig. 3-7), B4 calcite occurs within fractures of autoclastic breccia at surface xi, and commonly fills the remaining pore space in finely crystalline dolostone.

B4 calcite is rare in the Wahoo Limestone. One exception is its occurrence in wide, vertical, solution pipes in the lower Wahoo at Sunset Pass. Another exception at the Shublik Mountains section is an interval of finely crystalline dolostone, 420 to 428 meters above the base of the Lisburne Group, that is laced with fine fractures filled with B4 calcite (Fig. 3-6). B4 calcite occurs in very minor amounts in the Wahoo Limestone at the Fourth Range section (Fig. 3-7).

SUMMARY OF CEMENT ZONATION

Based on the relative age and stratigraphic distribution of CL zones, calcite cements in the Lisburne Group can be divided into the following generations of cement. Three types of early cements occur: A1 nonluminescent, a nonferroan calcite; A1 multibanded, a nonferroan calcite with one to several sets of nonluminescent-bright-dull or nonluminescent-bright subzones; and, a rarely occurring cement, microcrystalline calcite. Earliest calcite cement zones are followed by (from oldest to youngest): B1 calcite, low ferroan and dully luminescent; C1 calcite, ferroan and very-dully luminescent; B2 calcite, ferroan and dully luminescent, and preceding quartz cement; A2 calcite, nonferroan and with 1 or 2 sets of nonluminescent and bright zones; B3 calcite, ferroan and dully luminescent, and postdating quartz cementation; C2 calcite, ferroan and very dully luminescent; and B4 calcite, nonferroan and very dully luminescent.

COMPARISON OF CEMENT STRATIGRAPHY ACROSS DEPOSITIONAL STRIKE

Calcite cements in the Sadlerochit, Shublik, and Fourth Range mountains have a similar sequence of zones, but there are changes in the relative volumes of the zones making up the cements at the different sections. There is a southward decrease in the volume of A1 nonluminescent and A1 multibanded calcites and an increase in the volume of C1 calcites and B3 calcites. A2 calcite cement is most abundant at the most northerly section, Marsh Creek, and greatly decreases southward. It rarely occurs in more than trace amounts in the upper parts of the Ledge Creek, central Shublik, and Fourth Range sections.

DISCUSSION

The general geologic history of Lisburne Group deposition and the sequence of geologic events affecting the rocks of northern Alaska shows the spectrum of diagenetic environments (marine, subaerial, burial, tectonic, and uplift) that might have impacted the fabric of Lisburne rocks during their geologic history. Sometime during one, some, or all of these diagenetic episodes, calcite cements precipitated in the pore spaces of Lisburne rocks. The timing of cement precipitation in the Lisburne Group can be divided as follows:

1. Marine diagenetic phases that formed synchronously with Lisburne deposition (Mississippian to Pennsylvanian);

2. Diagenetic phases that formed during one of the episodes of subaerial exposure that punctuated Lisburne deposition (Mississippian to Pennsylvanian);

3. Diagenetic phases that formed during the sub-Permian unconformity that followed final Lisburne deposition (mid-Pennsylvanian/Atokan to mid-Permian/Leonardian age);

4. Diagenetic phases that postdate the sub-Permian unconformity but predate tectonic fabrics (post-mid Permian to Cretaceous);

5. Diagenetic phases that formed synchronously with tectonism (Cretaceous to pre-Oligocene);

6. Diagenetic phases that postdate compressional tectonic fabrics, and precipitated during uplift of the mountain ranges in northeastern Alaska (Oligocene to present).

DIAGENETIC PHASES SYNCHRONOUS WITH LISBURNE GROUP DEPOSITION

Aragonite and Mg calcite are the predominant carbonate cement phases precipitated in modern, shallow, warm, marine waters (Bathurst, 1975). The morphology of these cements is distinctly different from most calcite cements in the Lisburne Group. Aragonite and Mg calcite occur either as microcrystalline cements, as a mesh of needles or as isopachous crusts of fibrous crystals. The crystal habit of these minerals is very similar, but they can be distinguished because aragonite is orthorhombic and tends to have pinacoidal (flat) terminations, whereas Mg-calcite is hexagonal and typically has scalenohedral (steep) or rhombic terminations (James and Choquette, 1984). Aragonite also occurs as fibrous botryoidal fans (Folk, 1965; Ginsburg and James 1976).

Lisburne Group calcite cements are predominately syntaxial overgrowths on echinoderm grains and equant crystals on other grain types. There are rare occurrences of calcite cements that form fibrous or bladed, isopachous fringes on peloids and ooids in grainstone lithologies. These cements, never more than a small percent of the total cement, are now low-Mg calcite. Their morphology indicates that they may have recrystallized to low-Mg calcite from either aragonite or Mg calcite precursors (Sandberg, 1985). Botryoidal, fibrous calcite occurs in one bed of a peloidal packstone just below surface vii in the Shublik Mountains. Botryoidal calcite overlies, and joins together, clasts in the autoclastic breccia beneath surface vii, thus postdating the exposure event. The botryoids are highly recrystallized and now consist of low-Mg calcite. Because they postdate subaerial exposure, it is likely that the cements formed in marine waters during the next phase of carbonate deposition following subaerial exposure at surface vii.

Given the small volume of marine cements recognized in this study, one may conclude that either marine cementation was insignificant in Lisburne Group lithification or that marine Lisburne cements have the same morphology, and perhaps mineralogy, as cements that formed during one of the periods of subaerial exposure represented by surfaces i through xix.

The upper Alapah Limestone is predominately a finely crystalline dolostone with cryptalgal laminations and fenestral fabrics as common features. These sedimentary structures indicate a peritidal depositional setting. Finely crystalline dolomite forms the matrix of these rocks and may have formed, initially at least, during peritidal

conditions. The dolomite is nonferroan and dully luminescent. Micro-karst breccias composed of dolostone clasts are common features at surfaces viii, ix, x, and xi in the upper Alapah. The pore space in the breccia is filled by calcite and lacks dolomite cement. This indicates that the dolomite began forming prior to development of the breccia textures and supports an interpretation of peritidal conditions during dolomite formation.

The upper Alapah Limestone also has calcite pseudomorphs after gypsum and nodules having a chickenwire fabric filled by calcite, dolomite, and/or quartz that are presumed to be replaced anhydrite nodules. Solitary nodules are present for 40 meters downsection from the dolostone at the top of the Alapah. Gypsum and anhydrite are the common diagenetic minerals of modern sabkhas. Evidence of the former presence of evaporites, together with evidence of peritidal conditions, indicates that the upper Alapah was deposited in a sabkha setting and fluids from that environment penetrated deeper into the underlying strata, depositing evaporite minerals for a significant stratigraphic distance below the sabkha environment.

Chert, early and later

Chert occurs in outcrop as 5-15 cm thick layers and nodules that are more or less parallel to bedding. On a microscopic scale, chert commonly is present as selective grain replacements in limestone and dolostone. Field observations show that replacement chert formed initially as an early diagenetic phase and preceded the precipitation of A1 multibanded calcite. In the lower Alapah Limestone at Sunset Pass, early chert formation is shown by straight fractures through the chert that were filled by nonlithified carbonate sediment. This interval of grainstone later was cemented by A1 multibanded calcite.

However, the boundaries between chert and A1 and B1 calcite have dissolution reentrants or irregular replacement contacts that extend into the calcite cements. The reentrants and replacement textures indicate that chert continued to form following precipitation of A1 and B1 calcites. Chert also formed following the sub-Permian unconformity and deposition of the Echooka Formation. Replacement chert cuts across both Lisburne clasts and sand matrix in basal conglomerates of the Echooka.

Chert commonly occurs as an insoluble residue along stylolite surfaces, therefore, predating deep burial of the Lisburne Group. Significant burial of the Lisburne occurred during Permian to Early Cretaceous deposition of northward-derived siliciclastic sediments. The thickness of the Permian-Triassic Sadlerochit Group, above the Lisburne, is 250 to 300 meters. An additional 700 meters was added by deposition of siliciclastic sediments in the Jurassic and Lower Cretaceous. Studies of deep sea cores show that stylolites begin forming at depths greater than 200 meters (Garrison, 1981). The burial history of the Lisburne Group, taken together with outcrop and petrographic observations, indicate that chert in the Lisburne may have formed at different times ranging from the Mississippian through the Triassic.

Diagenetic phases associated with surfaces of subaerial exposure

Low-Mg calcite is the dominant carbonate cement in meteoric diagenetic environments (Bathurst, 1975; James and Choquette, 1984). Meteoric groundwaters exist in two distinct realms: the vadose zone, the region above the water table where pores contain both air and water, and the phreatic zone, the region below the water table where pores are completely filled by water.

The vadose zone is characterized by dissolution of carbonate material and cementation. Dissolution occurs because meteoric waters enter the ground undersaturated with respect to $CaCO_3$. Metastable phases of $CaCO_3$, aragonite and high-Mg calcite, are dissolved by these waters and when the waters become saturated or supersaturated with respect to calcite, low-Mg calcite cements may precipitate. Because of the wetting effect of water on the carbonate grains, the water within the pores is distributed around the grain contacts. Precipitation of cement is constrained by the water's distribution and thus mimics it, forming meniscus bridges between grains and pendants beneath grains (James and Choquette, 1984). The morphology of vadose cements stand in contrast to those that form within the phreatic zone.

Phreatic zone pores are completely filled by liquid and, as a result, cements that form in this zone occur as crusts, equally distributed, around grains (James and Choquette, 1984). A change downsection in the morphology of cements from vadose- to phreatic-type distribution is, thus, a guide to the level of the water table in ancient carbonates (Land, 1970).

Cements with a meniscus distribution include A1 nonluminescent calcite beneath surface vii and microcrystalline calcite beneath surface xvii in the Sadlerochit Mountains. The cement forms a meniscus distribution between ooid grains. The distribution of cements precipitated in modern subaerial vadose environments leads to the conclusion of a similar origin for such cements in the Lisburne Group. The microcrystalline calcite also is highly ferroan and it is not clear whether this is the original mineralogy or if it is due to a later recrystallization event.

Numerous examples of crosscutting relationships between features of subaerial exposure and A1 multibanded and A1 nonluminescent calcite are present at exposure surfaces in the Lisburne Group. For example, at surface vii, Sunset Pass, A1 multibanded calcite is crosscut by early fractures filled with yellow clays. The same is true below surface vii at the Shublik Mountains section; A1 nonluminescent calcite, and additionally B1 calcite, in autoclastic breccia are crosscut by infiltrated sediment. A similar relationship is present at surfaces viii and x. A1 nonluminescent calcite is cross-cut on the edges of clast margins by infilled sediment in autoclastic breccia at surface viii. A1 nonluminescent calcite, in early fractures at surface x, is crosscut by later fractures filled with more A1 nonluminescent calcite. At the Mississippian-Pennsylvanian boundary, surface xiii, A1 and some B1 calcites in the lower Wahoo Limestone are crosscut by sediment that fills early fractures developed during subaerial exposure. In upper Morrowan strata of the Wahoo Limestone, A1 multibanded calcite is crosscut by early fractures filled with an argillaceous lime mud. Such features also are

found at surface xvii at the Fourth Range section, where B1 calcite is crosscut by early cracks that were later filled by black shale.

These crosscutting relationships serve, firstly, as evidence that A1 calcites, and some B1 calcites, are no younger than the next higher surface of subaerial exposure. As each exposure surface crosscuts the early calcites beneath it, the early calcites become successively younger upsection, such that early lithification of the Lisburne Group proceeded from the bottom upwards. Secondly, the crosscutting relationships serve to confine the possible diagenetic environments to two choices: marine or meteoric.

Clear evidence for marine calcite, as discussed above, is rare in the Lisburne Group. Evidence for a meteoric origin is more positive. At surface viii in the Shublik Mountains, A1 nonluminescent calcite forms crusts around clasts of autoclastic breccia. Infiltrated sediment overlies these cements, showing that precipitation of A1 nonluminescent calcite was synchronous with subaerial exposure. At surface x, A1 nonluminescent calcite is present in early fractures that are cut by more early fractures filled with A1 nonluminescent calcite.

Besides crosscutting relationships at the exposure surfaces, the abundance of A1 calcite is most common in rocks just below a surface of subaerial exposure and decreases in abundance downsection towards the next lower exposure surface. A reasonable explanation for this trend is that A1 calcites were precipitated from meteoric waters that were introduced during the subaerial exposure episode. The trends in abundance, coupled with observations of crosscutting relationships at the exposure surfaces suggest that A1 nonluminescent, A1 multibanded and some B1 calcites precipitated from meteoric waters during development of subaerial exposure surfaces i through xviii.

Diagenetic phases that predate the sub-Permian unconformity

Crosscutting relationships between calcite cements and reworked Lisburne Group pebbles in the Echooka Formation and with infiltrated sediments in the karst breccia of the top of the Lisburne show that there are six cement phases whose timing is limited by the sub-Permian unconformity. A1 nonluminescent, A1 multibanded, B1, C1, B2, and A2 calcites all predate the sub-Permian unconformity. Crosscutting relationships with exposure features and the stratigraphic distribution of A1 and B1 calcites relative to surfaces of subaerial exposure indicate that these cements formed in meteoric waters. The sequence of events that follows meteoric precipitation of A1 and B1 calcite is precipitation of C1, B2, and A2 calcite, followed by the sub-Permian unconformity. How then, might such a sequence of zones, bracketed by meteoric events, have formed?

Cross-cutting relationships between calcite cements and reworked pebbles in the Echooka Formation derived from the Lisburne Group and infiltrated sediment in the karst breccia at the top of the Lisburne indicate that six cement phases in the upper part of the Lisburne are older than the sub-Permian unconformity (pre-Leonardian). A1 nonluminescent, A1 multibanded, B1, C1, B2, and A2 calcites all predate the sub-

Permian unconformity and are pre-Leonardian in age. Clasts of dolostone and chert derived from the Lisburne also occur in the basal conglomerate of the Echooka, thus, dating some phases of chert and dolomite as pre-Leonardian.

A1 and B1 calcites are also crosscut at surfaces of subaerial exposure within the Lisburne Group. This demonstrates that A1 and B1 calcites lower in the Lisburne represent separate cementation events that predate A1 and B1 calcites in the upper part of the Lisburne. Crosscutting relationships at surfaces of subaerial exposure were used as the primary argument for the interpretation that A1 and B1 calcites precipitated in a meteoric diagenetic environment (see above). Similarly, crosscutting relationships between features of subaerial exposure at the top of the Lisburne and C1, B2 and A2 calcites indicate that these cements may have precipitated from meteoric waters. Is the precipitation of such a sequence of cement zones compatible with a meteoric origin?

Fe and Mn are the two trace elements that define the CL zonation in Lisburne calcite cements. Fe and Mn are commonly carried as dissolved phases in meteoric groundwaters. Under oxidizing conditions, dissolved phase Fe and Mn are in +3 and +4 oxidation states, respectively. Calcite precipitated under oxidizing conditions is nonluminescent because a lattice substitution with the +2 charge of Ca in $CaCO_3$ is not possible. Under reducing conditions, dissolved phase Fe and Mn have +2 charges and can substitute for Ca in the calcite crystal lattice, resulting in luminescence (Barnaby and Rimstidt, 1989). Thus, the A1 nonluminescent calcite may have precipitated from meteoric waters under oxidizing conditions. Using similar reasoning, A1 multibanded calcites, that typically have wide bands of nonluminescent calcite and thinner, brightly luminescent zones, can be interpreted to have precipitated under conditions that were mostly oxidizing, but that were interrupted by relatively brief periods of reducing conditions. Such interpretations have been labeled as simplistic because they neglect numerous chemical and physical factors that affect luminescence in carbonate minerals (Machel and Burton, 1991). However, because crosscutting relationships in the Lisburne cements indicate that the cements most likely formed in meteoric diagenetic environments, their zonation and trace-element composition is best explained by variations expected in a meteoric groundwater system. If A1 nonluminescent and A1 multibanded calcites represent oxidizing and mostly oxidizing conditions, then B1 (dully luminescent nonferroan to low ferroan) calcite and C1 (very dully luminescent ferroan) calcite could represent progressively more reducing conditions in the meteoric waters residing in the Lisburne Group during subaerial exposure at the sub-Permian unconformity. The progressive nature of this transition is evident by the transitional concentration of $FeCO_3$ in B1 calcite, that ranges from nondetectable to slightly less than 0.1 wt.% $FeCO_3$, whereas C1 calcites have greater than 0.1 wt.% $FeCO_3$ (see geochemical results below). The highest concentration of $FeCO_3$ in the C1 cements are interpreted to representing the most reducing conditions. The transition to reducing conditions suggests that occlusion of porosity by A1 calcite cements inhibited the percolation of oxygen-rich meteoric waters into the pore-spaces. As groundwater flow low rates decreased due to progressive cementation, infiltrating meteoric waters would have had greater opportunity for dissolved oxygen to be consumed by microbial respiration, resulting in progressively more reducing conditions. The transition from C1

calcite to B2 calcite followed by A2 calcite may indicate a progressive return to oxidizing conditions during later stages of subaerial exposure at the top of the Lisburne. The return to oxidizing conditions is interpreted to be the result of continued erosion of Lisburne strata that decreased the length of the infiltration flow path for meteoric water.

Co-precipitation of dissimilar cement phases:

Facies changes in the cements upsection toward surfaces of subaerial exposure and along generally time-equivalent horizons between different Lisburne sections suggest that different cement zones may be time-equivalent, both vertically and laterally. A1 multibanded calcite occurs as the oldest cement in the middle of the Alapah Limestone sections in the Sadlerochit and Shublik Mountains. These cements disappear upsection toward the exposure surfaces in the upper Alapah (surfaces viii to xi) and A1 nonluminescent calcite occurs instead as the oldest cement in the pore space. This upsection change in the luminescent character of the oldest cements in the pores is interpreted to be the result of an increase in oxidizing conditions upsection caused by their closer proximity to newly introduced meteoric waters at the overlying exposure surfaces. The multibanded calcite in middle Alapah strata would then represent a downsection geochemical facies change in the paleo-groundwater system. Furthermore, the lower stratigraphic extent of multibanded calcite in the Alapah Formation at the Shublik Mountains section indicates that meteoric waters percolated downsection for 180 meters below the exposure surfaces in the upper Alapah Limestone .

A similar argument can be made for cements between different measured sections. At the top of the Wahoo at Marsh Creek, A1 nonluminescent calcite is the first cement phase in the pores. At Ledge Creek, B1 calcite is commonly the first cement in upper Wahoo strata. Because both of these phases are post-dated by the sub-Permian unconformity, it suggests that the two cement types represent time-equivalent, geochemical facies in the paleo-groundwater system.

Diagenetic phases that postdate the sub-Permian unconformity but predate Cretaceous to Cenozoic tectonism

Quartz, B3 calcite, and C2 calcite occur as cements in the Permian Echooka Formation. Therefore, these three cements in the Lisburne Group are, at least, post-Pennsylvanian in age. Quartz, B3 calcite, and C2 calcite are commonly the last phases of cement in interparticle porosity in the Lisburne. Also, straight fractures within the Lisburne are filled by the same sequence of cement phases. The fractures may have developed by the loading of the Lisburne during burial, or, the fractures may have formed when the Lisburne, along with the rest of the Ellesmerian platform, was rifted away from its ancient continental roots during the Lower Cretaceous opening of the Arctic Ocean. Two stages of fracturing are apparent. The first fractures are filled by quartz and B3 calcite. These fractures are cut by fractures that are filled with C2 calcite cement. C2 calcite heals broken, compacted grains and preferentially replaces carbonate grains and earlier cements in zones adjacent to stylolites. Such features indicate that C2 calcite was deposited in deep burial conditions. The direct association of C2 calcite with

stylolites suggests that pressure solution of $CaCO_3$ and the leeching of Fe_2+ from insoluble residues is a probable source for C2 calcite.

Ferroan dolomite postdates ferroan calcite. Its place in the paragenetic sequence indicates that ferroan dolomite must also have developed during deep burial conditions.

Syntectonic to post-tectonic diagenetic phases

Some shear fractures are cemented by quartz first, indicating that quartz cement continued to form during tectonism. Some C2 calcites in fractures have curving twin planes. Such crystals have been interpreted as indicating that growth occurred during tectonism (Durney and Ramsay, 1973). If so, that would indicate that C2 calcite also formed during tectonic deformation of the Lisburne Group. However, the majority of oversized and shear fractures of tectonic origin are filled by B4 calcite cements. Tectonism began in the Cretaceous in the central Brooks Range (Mull, 1982) and may not have reached the northeastern Brooks Range until the Cenozoic (Wallace and Hanks, 1990). Hence, some quartz and C2 calcite cement, and all B4 calcite cement, is Cretaceous or younger in age.

Origin of changes in cementation down depositional slope

Origin of changes in cementation down depositional slope:

Variations in cement stratigraphy between the Sadlerochit, Shublik, and Fourth Range mountains illustrate changes in cementation down depositional slope. During deposition of the Lisburne Group, land was to the north and the basin deepened southward. The volume of A1 nonluminescent and A1 multibanded calcite decreases southward from the Sadlerochit Mountains to the Fourth Range. Conversely, C1 calcite increases toward the south. These trends may be a reflection of at least two factors: 1) during gradual sea level falls, the southward paleoslope of the platform caused the more southerly sections to experience shorter periods of subaerial exposure and less cementation by oxidizing meteoric groundwaters; 2) the southward loss of some subaerial exposure surfaces into conformable successions resulted in less of an opportunity for oxygenated groundwaters to invade the more southerly sections. Both of these factors would have imparted a greater probability of reducing conditions affecting the more southerly sections compared with sections to the north in the Sadlerochit Mountains.

A2 calcite is most abundant at the most northerly section, Marsh Creek in the Sadlerochit Mountains, where A2 calcite is limited to the upper 100 m of the Wahoo. In contrast, the Ledge Creek section in the Sadlerochit Mountains has only trace amounts of A2 calcite. If A2 calcite represents precipitation from oxygen-rich meteoric waters as proposed above, then such conditions did not reach the Ledge Creek section, only 5 km southeast from Marsh Creek. The southward disappearance of A2 calcite implies that recharge of the paleo-groundwater system during development of the sub-Permian unconformity was to the north of the Sadlerochit Mountains and that meteoric waters

became more reducing towards the south. A2 calcite is also rare in the Shublik and Fourth Range Mountains. However, stratigraphic correlations indicate that perhaps an additional 60 m of upper Wahoo strata at these localities was removed by erosion beneath the sub-Permian unconformity. This inhibits interpretation of a southward geochemical facies change toward more reducing conditions.

SUMMARY OF LISBURNE GROUP CEMENT STRATIGRAPHY

Microcrystalline calcite, A1 nonluminescent calcite, and A1 multibanded calcite are cross-cut by features of subaerial exposure at a number of surfaces of subaerial exposure surfaces in the Lisburne Group. These subaerial exposure features consist of early fractures, sediment in fissure fills, and clast margins. Hence, these cements predate or are synchronous with the development of surfaces of subaerial exposure within the Lisburne Group. Such relationships date these cements relative to the exposure event as well as strongly indicate that the cements were precipitated from meteoric waters. At the top of the Lisburne Group, A1 nonluminescent and A1 multibanded calcite, as well as B1, C1, B2, and A2 calcite, are crosscut by solution karst and infiltrated sediment. Also, the primary cements of Lisburne Group clasts in the basal conglomerate of the Echooka Formation are A1, B1, and C1 calcites, and these cements are truncated at the clast margins. Thus, A1 through A2 calcites in the upper part of the Lisburne are pre-Leonardian in age. The crosscutting relationships suggest that these cements were precipitated from meteoric waters during development of the sub-Permian unconformity. In this case, B1 and C1 calcites could represent progressively reduced conditions during the filling of pore space in Lisburne sediments, and B2 and A2 calcite could represent the return of oxidizing conditions due to continued removal of upper Lisburne strata by erosion. Quartz, B3 and C2 cements are present in the Permian Echooka Formation above the Lisburne Group and, thus, are Early Permian or younger (post-Leonardian) in age. These cements fill fractures and C2 calcite heals broken grains as well. Thus, quartz, B3 calcite and C2 calcite may be burial cements with C2 calcite representing deepest burial. Some quartz and C2 calcite cements partly fill shear fractures, whereas most shear fractures are filled by B4 calcite. Compressional tectonism in the northeastern Brooks Range is dated as Cretaceous to Oligocene, hence some quartz and C2 calcite cement, and all B4 calcite cement is Cretaceous or Cenozoic in age.

GEOCHEMICAL ASPECTS OF CALCITE CEMENTS IN THE LISBURNE GROUP

INTRODUCTION

The chemical aspects of calcite cements are governed by several factors: initial fluid and rock composition, composition of diagenetic fluids, degree of water/rock interaction, temperature, and pressure (Bathurst, 1975). Numerous studies, aimed at determining the conditions of calcite precipitation, have turned to an analysis of the trace element composition and the stable isotope ratios of O^{18}/O^{16} and C^{13}/C^{12} in calcite cements to formulate and support interpretations of rock diagenesis (Brand and Veizer, 1980; Land, 1980; Allan and Matthews, 1982; Meyers and Lohmann, 1985;

Lohmann, 1988; Algeo et al., 1992). The hope of such studies is that, given a knowledge of the distribution coefficients of trace elements and stable isotope ratios, the composition of diagenetic pore fluids can be interpreted from the trace element and isotope chemistry of the cements and, thus, provide a basis for further interpretation of diagenetic history.

Trace element and stable isotope data are presented here to describe the calcite cement chemistry of separate cathodoluminescence (CL) zones in calcite cements of the Lisburne Group. The data serves as a check against interpretations of petrographic data concerning the origins of the zones.

METHODS OF GEOCHEMICAL STUDIES

The concentrations of $MgCO_3$, $FeCO_3$, $MnCO_3$, and $SrCO_3$ in calcite cements of the Lisburne Group were determined using an electron microprobe, a Cameca SX150, housed at the Department of Geology and Geophysics at the University of Oklahoma in Norman, Oklahoma. The microprobe equipment was operated by the author with the assistance of Maggy Piranian, the microprobe technician. Operating conditions during trace element analysis were a 10-micron spot size, a current of 15 nannoamps, and counting times of 60 seconds for $MgCO_3$ and 120 seconds for $FeCO_3$, $MnCO_3$, and $SrCO_3$. The data were collected during three runs bracketed by analyses of standards to detect drift in the instrument during operation. Drift was less than one percent for all standards, except calcite, which ranged from 0.5 to 9.1% difference (Table 3-1). The standards used were dolomite for $MgCO_3$, siderite for $FeCO_3$, rhodochrosite for $MnCO_3$, and strontianite for $SrCO_3$. Minimum detection limits were estimated by Piranian, who measured concentrations of laboratory-prepared standards of $MgCO_3$, $FeCO_3$, $MnCO_3$, and $SrCO_3$ against increasing counting times. One standard deviation of the slope of the derived line was taken as the limit of detection. The minimum limits reported were 0.0065 wt.% $MgCO_3$, 0.02 wt.% $FeCO_3$, and 0.0197 wt.% $MnCO_3$ and $SrCO_3$.

An estimate of the precision of the measurements during analysis was attempted by measuring clusters of four or five points, each point approximately 20 microns apart, on five separate samples (Table 3-2). The 95% confidence limits of the clusters range from 0.110 to 0.008 wt.% $FeCO_3$, 0.196 to 0.025 wt.% $MgCO_3$, 0.046 to 0.01 wt.% $MnCO_3$, and 0.032 to 0.010 wt.% $SrCO_3$. Heterogeneity in trace element distribution probably contributes to the wide dispersion of some of the measurements. This is especially prominent when the concentration of the trace element approaches or exceeds 1.0 wt.%. Conversely, when the concentration of the trace element is low, the spread is much less. One would expect that at lower concentrations, heterogeneity would be less of a factor. If, on the basis of heterogeneity, one excludes sets of measurements with confidence limits exceeding 0.1 wt.%, then the measurements give average confidence limits of 0.04 wt.% $MgCO_3$, about 0.02 wt.% $MnCO_3$ and $SrCO_3$, and, what is surely an underestimate, 0.01 wt.% $FeCO_3$.

Trace-element data were obtained from 217 points on various compositional zones within the calcite cements from 20 samples of Lisburne rocks. The samples

Table 3-1.

Standards at start and end of microprobe runs 1, 2, and 3.

Run	Element	Start	End	Start Avg.	End Avg.	% Difference
1	FeCO3	95.159	94.696	95.2175	94.716	0.5
1	FeCO3	95.276	94.736			
1	MgCO3	46.486	46.265	46.3605	46.332	0.1
1	MgCO3	46.235	46.399			
1	MnCO3	98.615	98.382	98.8785	98.5855	0.3
1	MnCO3	99.142	98.789			
1	SrCO3	96.809	96.372	96.488	96.2585	0.2
1	SrCO3	96.167	96.145			
1	CaCO3	100.646	100.035	100.4725	99.9715	0.5
1	CaCO3	100.299	99.908			
2	FeCO3	94.095	93.884	94.095	94.56	0.5
2	FeCO3		95.236			
2	MgCO3	45.876	46.121	45.876	46.121	0.5
2	MnCO3	98.84	98.504	98.84	98.504	0.3
2	SrCO3	95.743	95.602	95.743	95.5436667	0.2
2	SrCO3		95.508			
2	SrCO3		95.521			
2	CaCO3	100.119	103.422	100.119	101.7875	1.6
2	CaCO3		100.153			
3	FeCO3	93.478	93.124	93.478	93.6625	0.2
3	FeCO3		94.201			
3	MgCO3	46.367	46.569	46.367	46.272	0.2
3	MgCO3		45.975			
3	MnCO3	98.627	98.125	98.627	98.125	0.5
3	SrCO3	96.722	96.403	96.722	96.084	0.7
3	SrCO3		95.765			
3	CaCO3	100.926	83.522	100.926	91.734	9.1
3	CaCO3		99.946			

Table 3-1: Measurement of standards at the beginning and end of microprobe runs. Differences are from 0.1 to 0.7% for the trace element standards. The low concentration of the trace elements makes the difference significant to only the third decimal place of the trace element measurements. All values in weight percent.

Table 3-2.

sample	cement zone	FeCO3	t 95%	MgCO3	t 95%	MnCO3	t 95%	SrCO3	t 95%
90RC22 67	C2 calcite	0.281	0.101!	1.003	0.131!	0	0.03	0	0.013
90RC22 67	C2 calcite	0.238		0.875		0.038		0.006	
90RC22 67	C2 calcite	0.135		0.91		0		0.008	
90RC22 67	C2 calcite	0.253		1.053		0		0.02	
90RC18 475.7	C1 calcite	0.96	0.11!	0.589	0.025	0.02	0.015	0.006	0.023
90RC18 475.7	C1 calcite	0.993		0.621		0		0.02	
90RC18 475.7	C1 calcite	1.038		0.622		0		0.032	
90RC18 475.7	C1 calcite	0.874		0.605		0.01		0	
90RC18 13.5	B1 calcite	0	0*	1.312	0.196!	0.026	0.017	0.015	0.032
90RC18 13.5	B1 calcite	0		1.218		0.014		0.046	
90RC18 13.5	B1 calcite	0		1.242		0		0.004	
90RC18 13.5	B1 calcite	0		1.024		0.011		0.004	
90RC9 326A	A1 nonlumin.	0	0.008	0.366	0.046	0.016	0.046	0.073	0.025
90RC9 326A	A1 nonlumin.	0.006		0.408		0		0.072	
90RC9 326A	A1 nonlumin.	0.01		0.364		0		0.073	
90RC9 326A	A1 nonlumin.	0.01		0.42		0		0.041	
90RC9H	B4 calcite	0	0.01	0.353	0.043	0.018	0.01	0.168	0.01
90RC9H	B4 calcite	0.006		0.351		0		0.162	
90RC9H	B4 calcite	0.02		0.346		0		0.174	
90RC9H	B4 calcite	0.002		0.339		0.005		0.155	
90RC9H	B4 calcite	0.001		0.424		0		0.155	
Average 95% confidence limits			0.057		0.088		0.024		0.021

Table 3-2: Measurements of clusters of points and their 95% confidence limits. Each point is approximately 20 microns apart and confined to a single cement zone. The clusters of measurements serve as an estimate of the precision of the microprobe. See text for further discussion.
* Disgregarded in calculation of average.
! Heterogeneity in trace element distribution.

represent a range of stratigraphic positions within the Lisburne Group along a transect across the Lisburne platform. The points of trace element analysis were designed to analyze separate CL compositional zones to track changes in trace element composition during cementation. For some individual samples, the trace element analyses are positioned along transects across successively younger cement zones within the same crystal of calcite. In other samples the cement zones analyzed are from separate crystals.

Ratios of O^{18}/O^{16} and C^{13}/C^{12} were analyzed by R. A. Fifer, at the Benedeum Stable Isotope Laboratory, Providence, R. I., under the direction of R. K. Matthews. The analyses were conducted during three different runs over a three-year period (1990-92). Laboratory precision was estimated from duplicate measurements of the lab standard gas (Table 3-3). For the three runs, 95% confidence limits for the lab standards ranged from 0.047 to 0.091 per mill delta C^{13} and 0.048 to 0.064 per mill delta O^{18}. Reproducibility during sample analyses was estimated by running splits of a few samples during each period of analyses. The mean half ranges were from 0.137 to 0.235 per mill delta C^{13} and from 0.211 to 0.307 per mill delta O^{18} (Table 3-4).

Separate zones of calcite cements were sampled by drilling out the cements from polished thin sections. The thin sections were examined with CL microscopy to note the succession of cements zones and then stained with potassium ferricyanide to differentiate nonferroan and ferroan zones and to guide the sampling during drilling. The sampling equipment used was a dental drill fitted onto a binocular microscope and illuminated with reflected light. The drill bit was ground to a diameter smaller than the width of the cement zone to be sampled. Zones narrower than about 100 microns could not be sampled without expecting contamination from adjacent zones.

A total of 209 separate components and whole rock samples of Lisburne rocks were analyzed for stable isotope ratios of carbon and oxygen; 135 separate samples of Lisburne rocks were used. The components measured consisted of 153 samples of seven calcite cement zones from levels throughout the Lisburne Group, 34 whole rock samples spanning a well developed paleosol in the lower Alapah Limestone, eight brachiopods, six weathering crusts of modern caliche, four rhizoliths, three laminated crusts, and one sample each of a fibrous calcite and a marble.

RESULTS OF GEOCHEMICAL STUDIES

Trace elements

$FeCO_3$ concentration is highest (0.313 to 0.43 wt.%) in C1, C2 and microcrystalline calcite cement (Table 3-5). All measurements of C1 calcite are equal to or greater than 0.1 wt.% $FeCO_3$. In three cases, $FeCO_3$ concentration shows an increase from earlier to later C1 calcites (Fig. 3-10, b, e, and f). A similar increase in $FeCO_3$ is present in one case for early C2 calcites versus later C2 calcite (Fig. 3-10, q). However, for most of the samples there are too few intrazonal measurements of C1 and C2 calcite to adequately describe variations in $FeCO_3$ within the zones. Average $FeCO_3$ content in C2 calcites is somewhat lower than that of C1 calcites. High $FeCO_3$ concentrations in these cements are apparent from petrographic studies of stained thin sections. Studies

Standard id.	date	transducer	J C13 (rel)	J O18 (rel)	year	t 95% J C13	t 95% J O18
BP-4 FI	1/30/90	16.7	-3.72	-4.88			
BP-4 MI	1/30/90	21.1	-3.6	-4.71	1990	0.091	0.048
BP-4 LI	1/30/90	34.8	-3.78	-4.74	1991	0.047	0.063
BP-4 FF	1/30/90	18.5	-3.37	-4.79	1992	0.069	0.064
BP-4 MF	1/30/90	14.4	-3.45	-4.74			
BP-4 LF	1/30/90	17.4	-3.51	-4.73			
BP-4 FI	1/31/90	18.2	-3.65	-4.74			
BP-4 MI	1/31/90	2.2	-3.54	-4.58			
BP-4 FF	1/31/90	16.3	-3.4	-4.73			
BP-4 MF	1/31/90	14.1	-3.47	-4.79			
BP-4 LF	1/31/90	25.9	-3.68	-4.76			
BP-4 FI	9/17/91	5.9	-3.58	-4.58			
BP-4 MI	9/17/91	23	-3.39	-4.27			
BP-4 LI	9/17/91	13	-3.42	-4.39			
BP-4 FF	9/17/91	7	-3.66	-4.98			
BP-4 MF	9/17/91	14.4	-3.54	-4.67			
BP-4 LF	9/17/91	12.6	-3.41	-4.48			
BP-4 FI	9/18/91	11.5	-3.33	-4.56			
BP-4 MI	9/18/91	8.9	-3.36	-4.51			
BP-4 LI	9/18/91	3.7	-3.35	-4.4			
BP-4 FF	9/18/91	6.7	-3.39	-4.51			
BP-4 MF	9/18/91	19.6	-3.2	-4.44			
BP-4 LF	9/18/91	10.7	-3.39	-4.65			
BP-4 FI	9/19/91	10	-3.43	-4.57			
BP-4 MI	9/19/91	11.5	-3.39	-4.51			
BP-4 LI	9/19/91	26.7	-3.43	-4.43			
BP-4 FF	9/19/91	25.9	-3.45	-4.67			
BP-4 MF	9/19/91	29.3	-3.53	-4.68			
BP-4 LF	9/19/91	21.9	-3.41	-4.62			
BP-4 FI	9/20/91	7	-3.54	-4.64			
BP-4 MI	9/20/91	8.1	-3.42	-4.51			
BP-4 LI	9/20/91	11.5	-3.41	-4.57			
BP-4 FF	9/20/91	9.6	-3.47	-4.7			
BP-4 MF	9/20/91	13	-3.41	-4.58			
BP-4 LF	9/20/91	11.1	-3.73	-4.84			
BP-4 MI	9/24/92	28.5	-3.36	-4.64			
BP-4 LI	9/24/92	34.1	-3.54	-4.54			
BP-4 LI	9/25/92	4.8	-3.57	-4.68			
BP-4 MF	9/25/92	20.4	-3.28	-4.68			
BP-4 LF	9/25/92	10	-3.27	-4.64			
BP-4 MI	9/28/92	3.7	-3.49	-4.7			
BP-4 LI	9/28/92	15.9	-3.54	-4.69			
BP-4 FF	9/28/92	5.9	-3.02	-4.92			
BP-4 MF	9/28/92	5.6	-3.22	-4.84			
BP-4 LF	9/28/92	8.1	-3.23	-4.69			
BP-4 LI	9/30/92	6.3	-3.27	-4.41			
BP-4 FF	9/30/92	6.7	-3.25	-4.68			
BP-4 F	10/2/92	21.5	-3.47	-4.65			
BP-4 MI	10/2/92	3.3	-3.47	-4.56			
BP-4 LI	10/2/92	8.9	-3.42	-4.6			
BP-4 FI	10/5/92	3	-3.41	-4.43			
BP-4 MI	10/5/92	8.9	-3.6	-4.6			
BP-4 LI	10/5/92	1.9	-3.41	-4.59			
BP-4 MF	10/5/92	5.6	-3.28	-4.42			
BP-4 LF	10/5/92	13.3	-3.31	-4.39			

Table 3-3: Isotopic standards and 95% confidence limits of the standards for each year. All values relative to lab standard gas BIG-5.

Table 3-4.

Sample id.	JC13 min.	JC13 max.	1/2 range	JO18 min.	JO18 max.	1/2 range	date	status
86RC19, 42	-0.15	0.36	0.51	-6.38	-5.84	0.54	1990	
86RC19, 67	0.65	1.02	0.37	-6.05	-5.71	0.34	1990	
86RC19, 198	2.55	2.57	0.02	-6.64	-6.5	0.14	1990	
86RC19, 200	2.46	2.5	0.04	-6.53	-6.42	0.11	1990	
86RC19, 290	-0.84	-1.57	0.73	-8.91	-7.53	1.38	1990	S
90RC2, -1.2SE	-0.5	0.12	0.31	-11.49	-10.91	0.29	1991	
90RC24, 35.5R	-1.95	-0.87	0.54	-8.6	-6.93	0.84	1991	
90RC24, 39.5R	-2.45	-2.42	0.02	-6.62	-6.47	0.08	1991	
90RC2, BFCA	3.19	3.9	0.36	-15.44	-14.58	0.43	1991	
90RC24, 26W	-0.71	-0.51	0.1	-8.29	-7.5	0.4	1991	
90RC24, 32.5W	-2.4	-2.39	0.01	-6.62	-6.53	0.05	1991	
90RC24, 37.5W	-2.49	-1.95	0.27	-6.66	-6.55	0.06	1991	
90RC12, 69A1	1.73	1.89	0.08	-4.14	-3.94	0.1	1992	
90RC12, 70.5A1	1.67	1.83	0.08	-5.69	-5.35	0.17	1992	
90RC16, C442BR	3.01	3.05	0.02	-4.96	-4.94	0.01	1992	
90RC18, 374B2	-1.37	-1.3	0.04	-12.84	-12.81	0.01	1992	
90RC18, 374XA1	2.06	2.06	0	-4.26	-4.21	0.03	1992	
90RC18, 482.1B2	0.91	1.1	0.1	-8.83	-8.71	0.06	1992	
90RC18, 482B1	0.27	0.35	0.04	-9.73	-9.38	0.18	1992	
90RC2, QB3	-9.92	-9.58	0.17	-27.08	-26.47	0.31	1992	
90RC20, PA1	1.17	1.19	0.01	-5	-4.54	0.23	1992	
90RC23, A1	0.26	0.99	0.37	-6.69	-5.07	0.81	1992	
90RC24, 39B1	-2.36	-0.76	0.8	-6.64	-5.57	0.54	1992	
90RC24, 39L	-1.99	-1.74	0.13	-6.63	-6.51	0.06	1992	
90RC9, 113.5A1	-1.19	-1.08	0.06	-7	-6.83	0.14	1992	
90RC9, 374CA	-0.05	-0.01	0.02	-8.97	-8.37	0.3	1992	
1990 mean half range ∫C13		0.235						
1990 mean half range ∫O18		0.283						
1991 mean half range ∫C13		0.23						
1991 mean half range ∫O18		0.307						
1992 mean half range ∫C13		0.137						
1992 mean half range ∫O18		0.211						

Table 3-4: Measurements of splits of samples as an estimate of the precision of the isotope analyses.
S - Suspect value not included in calculated mean half-ranges.
All values relative to lab reference gas BIG 5.

	mean	std. dev.	std. error	variance	coef. variance	min.	max.	t 95%	n
MgCO3									
A1 multibanded	0.877	0.366	0.089	0.134	41.801	0.325	1.719	0.188	17
A1 nonlumin.	0.823	0.444	0.105	0.197	54	0.179	1.582	0.221	18
microcrystalline	1.367	0.105	0.047	0.011	7.659	1.219	1.47	0.13	5
B1	0.716	0.33	0.05	0.109	46.067	0.098	1.312	0.102	43
C1	0.75	0.259	0.036	0.067	34.521	0.259	1.51	0.073	51
A2	0.352	0.143	0.082	0.02	40.545	0.212	0.497	0.354	3
B3	0.753	0.248	0.072	0.062	35.951	0.323	1.213	0.158	12
C2	0.807	0.191	0.037	0.036	23.65	0.446	1.261	0.075	27
B4	0.55	0.447	0.093	0.2	81.394	0.179	1.896	0.193	23
SrCO3									
A1 multibanded	0.059	0.058	0.014	0.003	98.43	0.006	0.202	0.03	17
A1 nonlumin.	0.045	0.027	0.006	0.001	60.998	0	0.093	0.014	18
microcrystalline	0	0	0	0	0	0	0	0	5
B1	0.038	0.03	0.005	0.001	78.376	0	0.116	0.009	43
C1	0.025	0.018	0.002	0.0003	70.57	0	0.068	0.005	51
A2	0.016	0.027	0.016	0.001	167.931	0	0.048	0.068	3
B3	0.037	0.025	0.007	0.001	68.484	0.001	0.075	0.016	12
C2	0.044	0.046	0.009	0.002	103.831	0	0.148	0.018	27
B4	0.352	0.833	0.174	0.694	236.604	0	3.13	0.36	23
FeCO3									
A1 multibanded	0.014	0.017	0.004	0.0003	121.631	0	0.05	0.009	17
A1 nonlumin.	0.019	0.025	0.006	0.001	127.33	0	0.083	0.012	18
microcrystalline	0.322	0.058	0.026	0.003	18.031	0.243	0.406	0.072	5
B1	0.028	0.032	0.005	0.001	114.599	0	0.137	0.01	43
C1	0.43	0.319	0.045	0.102	74.052	0.1	1.559	0.09	51
A2	0.015	0.01	0.006	0.0001	65.516	0.006	0.025	0.024	3
B3	0.121	0.152	0.044	0.023	125.809	0	0.495	0.097	12
C2	0.313	0.251	0.048	0.063	80.213	0.05	0.953	0.099	27
B4	0.004	0.005	0.001	2.93E-05	138.248	0	0.02	0.002	23
MnCO3									
A1 multibanded	0.006	0.008	0.002	0.00006	131.939	0	0.021	0.004	17
A1 nonlumin.	0.001	0.004	0.001	0.00002	287.654	0	0.016	0.002	18
microcrystalline	0.01	0.009	0.004	0.00008	83.438	0	0.024	0.011	5
B1	0.008	0.01	0.002	0.0001	123.059	0	0.032	0.003	43
C1	0.025	0.018	0.002	0.0003	70.57	0	0.068	0.005	51
A2	0.017	0.016	0.009	0.0003	92.548	0.002	0.034	0.04	3
B3	0.01	0.011	0.003	0.0001	113.779	0	0.03	0.007	12
C2	0.007	0.012	0.002	0.00015	170.062	0	0.038	0.005	27
B4	0.005	0.007	0.001	5.04E-05	152.63	0	0.027	0.003	23

Table 3-5: Summary of trace element analyses for separate calcite cement zones in the Lisburne Group. All values given in weight percent.

Figure 3-10.

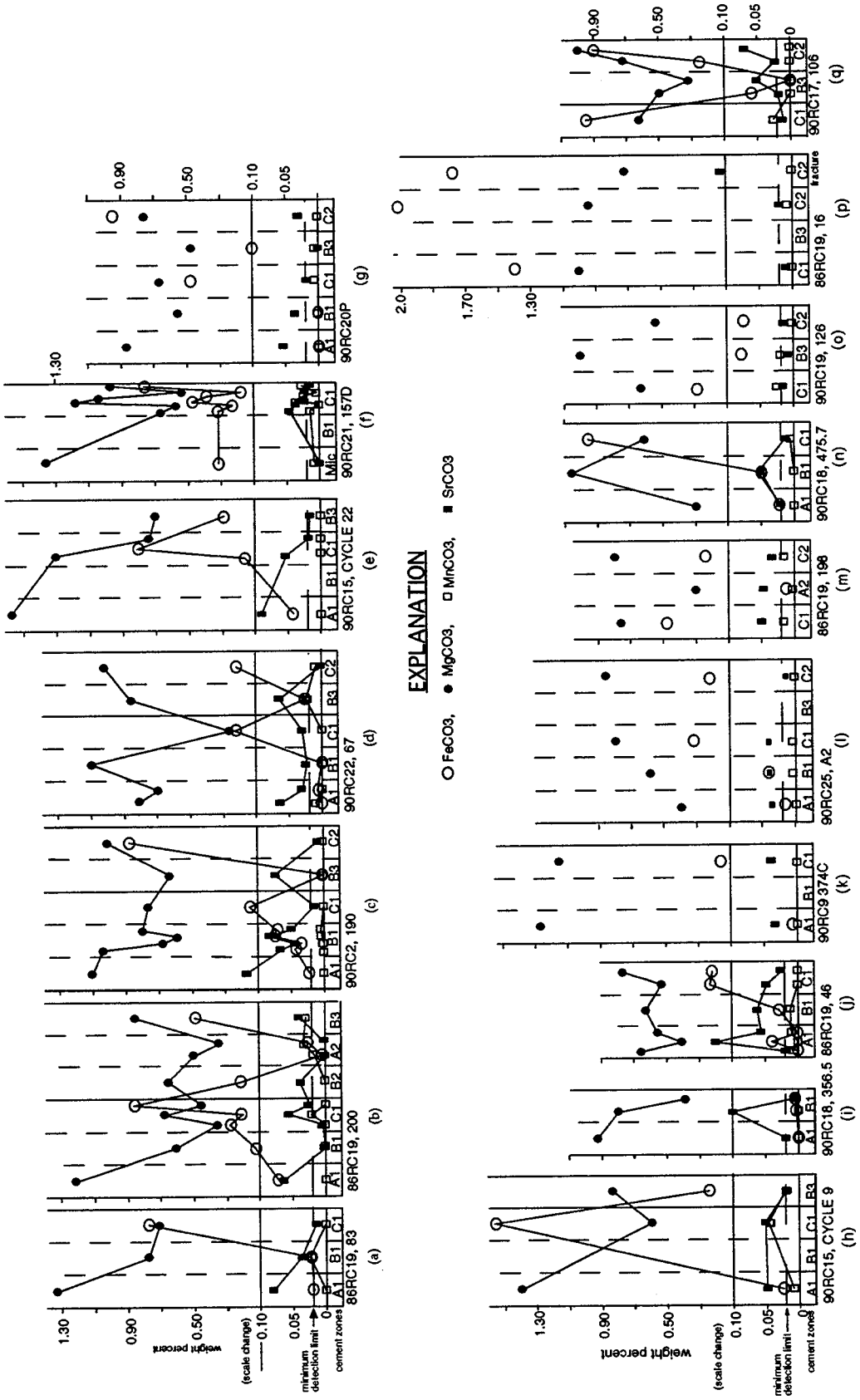


Figure 3-10. Trace element concentrations of MgCO3, FeCO3, MnCO3, and SrCO3 in successive cement zones. Oldest to youngest cements are depicted left to right. Points connected by lines are successive zones within the same calcite crystal.

of stained thin sections did not show the presence of $FeCO_3$ in A1, B1, or B3 calcites, but the microprobe analyses show that $FeCO_3$ also can be present in these zones. For A1 multibanded and A1 nonluminescent calcite, there are 9 out of 35 cases where $FeCO_3$ is greater than 0.02 wt.%. In 13 out of 43 analyses of B1 calcite, $FeCO_3$ content is between 0.02 and 0.1 wt.%, and in rare cases slightly exceeds 0.1 wt.%. $FeCO_3$ concentrations of 0.02 to 0.01 wt.% in B1 calcites fall in a transitional area between very low $FeCO_3$ concentrations in A1 calcites (less than 0.02 wt.%) and very high $FeCO_3$ concentrations in C1 calcites (greater than 0.1 wt.%). The extent of ferroan concentration in B3 calcite was unrealized as well. Microprobe analyses show that, although there is a sharp drop in $FeCO_3$ from C1 to B3 calcite, the concentration of $FeCO_3$ in B3 calcites commonly remains above 0.1 wt.%. B4 calcite, the last stage of cement in the Lisburne Group, has very low $FeCO_3$ concentrations.

Average $MgCO_3$ concentration is highest in microcrystalline calcite and lowest in A2 calcite. A1 multibanded, A1 nonluminescent, B1, C1, B3, and C2 calcite have similar $MgCO_3$ concentrations, their means range from 0.75 to 0.845 wt.%. In many cases, $MgCO_3$ appears to either decrease or increase in concentration with successively younger cements (Fig. 3-10). For the most part, these trends have too few points to be tested adequately for statistical significance, with the traverses having only one to five degrees of freedom.

Mean concentration of $SrCO_3$ is highest (0.392 wt.%) in B4 calcites, the last cement phase precipitated, and lowest (0 wt.%) in microcrystalline calcite, one of the earliest cement phases formed. Mean $SrCO_3$ concentration appears similar in A1 multibanded calcite (0.057 wt.%) and A1 nonluminescent calcite (0.45 wt.%) and nearly identical in B1 calcite and B3 calcite (0.038 wt.% and 0.037 wt.%, respectively). Similar mean $SrCO_3$ concentrations are present in C1 and C2 calcites (0.023 to 0.025 wt.%) and low $SrCO_3$ content is present in A2 calcite (0.016 wt.%). $MnCO_3$ concentrations are low in all of the cement phases. Thin bright bands in A1 multibanded and A2 calcite are presumed to be due to enrichment of $MnCO_3$, but these were not singled out for study. As such, trace element measurements of A1 multibanded calcite usually reflect the character of the wider nonluminescent bands. The maximum $MnCO_3$ concentration measured (0.0859 wt.%) is from a wide, bright zone in an early cement in the lower Alapah Limestone. Some C1 and C2 calcites have as much as 0.05 wt.% $MnCO_3$. A2 calcites have the greatest mean $MnCO_3$ content (0.017 wt.%).

Variations in trace element concentrations across the Lisburne Group carbonate platform may reflect changes in the chemistry of the diagenetic pore fluids. Average trace element concentrations in the calcite cement zones from the Sadlerochit, Shublik, and Fourth Range sections are summarized in Table 3-6. Unfortunately, the meaningfulness of this data is limited, sometimes severely so, by the small number of measurements for each cement zone at each locality. Furthermore, the whole of each stratigraphic section of Lisburne strata is, by no means, fully represented by the samples. Comparisons of the cements from the three stratigraphic sections show few differences in the trace element concentrations in each calcite cement zone.

Table 3-6.

	A1 multi			A1 non			B1			C1		
	mean	S	n	mean	S	n	mean	S	n	mean	S	n
Wt. % FeCO3												
Sadlerochit Mtns.	0.015	0.014	8	0.043	0.04	4	0.047	0.035	17	0.33	0.235	24
Shublik Mtns.	0.017	0.024	3	0.012	0.014	10	0.013	0.017	13	0.461	0.335	18
Fourth Range Mtns.	0.011	0.02	6	0.015	0.013	4	0.019	0.029	13	0.639	0.394	9
Wt. % MgCO3												
Sadlerochit Mtns.	0.668	0.36	8	0.874	0.235	4	0.538	0.304	17	0.726	0.286	24
Shublik Mtns.	1.222	0.442	3	0.948	0.494	10	0.733	0.293	13	0.787	0.242	18
Fourth Range Mtns.	0.982	0.124	6	0.457	0.309	4	0.931	0.277	13	0.737	0.233	9
Wt. % MnCO3												
Sadlerochit Mtns.	0.003	0.005	8	0.00025	0.001	4	0.007	0.007	17	0.008	0.013	24
Shublik Mtns.	0.007	0.012	3	0.002	0.005	10	0.01	0.013	13	0.011	0.017	18
Fourth Range Mtns.	0.009	0.009	6	0.003	0.005	4	0.009	0.011	13	0.01	0.011	9
Wt. % SrCO3												
Sadlerochit Mtns.	0.081	0.072	8	0.04	0.031	4	0.035	0.025	17	0.03	0.02	24
Shublik Mtns.	0.051	0.016	3	0.054	0.023	10	0.054	0.03	13	0.024	0.016	18
Fourth Range Mtns.	0.034	0.043	6	0.027	0.032	4	0.027	0.032	13	0.004	0.01	9

	B3			C2			B4		
	mean	S	n	mean	S	n	mean	S	n
Wt. % FeCO3									
Sadlerochit Mtns.	0.174	0.278	3	0.257	0.152	21	0.005	0.005	5
Shublik Mtns.	0.149	0.125	5	0.47	0.464	4	0.004	0.006	16
Fourth Range Mtns.	0.046	0.032	4	0.58	0.473	2	0	0	2
Wt. % MgCO3									
Sadlerochit Mtns.	0.784	0.136	3	0.838	0.186	21	0.233	0.053	5
Shublik Mtns.	0.855	0.289	5	0.622	0.129	4	0.63	0.467	16
Fourth Range Mtns.	0.601	0.231	4	0.853	0.216	2	0.697	0.684	2
Wt. % MnCO3									
Sadlerochit Mtns.	0.021	0.012	3	0.008	0.012	21	0.003	0.004	5
Shublik Mtns.	0.011	0.009	5	0.008	0.017	4	0.005	0.008	16
Fourth Range Mtns.	0	0	4	0	0	2	0.007	0.011	2
Wt. % SrCO3									
Sadlerochit Mtns.	0.059	0.02	3	0.049	0.049	21	0.083	0.041	5
Shublik Mtns.	0.022	0.022	5	0.015	0.014	4	0.264	0.686	16
Fourth Range Mtns.	0.039	0.024	4	0.047	0.034	2	1.731	1.978	2

Table 3-6: Trace element concentrations in calcite cement zones grouped by location. Sadlerochit Mtns. - most proximal marine position, Fourth Range Mtns. - most distal marine position.

Stable isotope studies

A1 multibanded, A1 nonluminescent, B1, C1, B3, and C2 calcites have similar delta C^{13} means (Table 3-7 and Fig. 3-11) and range from 2.223 to 3.277 per mill (PDB). Delta O^{18} measurements show more variation between the CL zones. The mean delta O^{18} of A1 nonluminescent, B1, and C1 calcites, ranges from -6.153 to -6.396 per mill. B3 and C2 calcites have a much more negative delta O^{18} signature (-8.968 and -8.139, respectively) compared with A1, B1, and C1 calcites. The most negative average delta O^{18} values are those of B4 calcites at -11.7 per mill.

Cements that are pre-Permian in age, A1 nonluminescent, A1 multibanded, B1, and C1 calcites, form a broad field in a cross plot of delta C^{13} and delta O^{18} (Fig. 3-11). Delta C^{13} ranges from about 0 to +6 per mill, and the range of delta O^{18} is from -2.68 to -9.98 per mill. Popcorn caliche from weathered Lisburne outcrops was sampled to compare modern isotope ratios with Lisburne cements. Delta O^{18} in the caliche ranges from -11 to -15.8 per mill, and delta C^{13} ranges from 3.2 to 6.2 per mill. Compared with pre-Permian calcites, post-Pennsylvanian calcites, B3, C2, and B4, have more negative delta O^{18} values (Fig. 3-12). B3 calcite displays the greatest dispersion of delta C^{13} and delta O^{18} values. C2 and B4 calcites also have a greater dispersion of delta O^{18} values than the pre-Permian calcites. The isotopic signature of marbleized calcite, delta O^{18} of -11.69 per mill and delta C^{13} of 1.42 per mill, falls well within the fields of B3 and B4 calcites.

In addition to describing variation of average isotope ratios of the cement zones, delta C^{13} and delta O^{18} were collected to describe variations in the stratigraphic succession across surfaces of subaerial exposure. Whole rock samples were collected spanning surface vii in the lower part of the Alapah Limestone at the West Sunset Pass Section in the Sadlerochit Mountains (Fig. 3-13). Samples below surface vii have more negative delta C^{13} ratios, by about 2 per mill, than samples from above surface vii. A few samples of rhizoliths and ancient laminated crusts from below surface vii were analyzed also and these show no differences from whole rock samples below surface vii. Even though there is a positive shift in delta C^{13} as one crosses surface vii, delta C^{13} measurements in samples above surface vii are still more negative than most other samples of early calcites collected from other locations. Delta O^{18} shows no variation across surface vii.

A set of samples across exposure surface xiii, the Mississippian-Pennsylvanian boundary (Carlson, 1987) was analyzed from the Wahoo Limestone at Marsh Creek. These isotope data show some variations relative to subaerial surfaces (Fig. 3-14). There is a suggestion of an upward trend towards more negative delta C^{13} values towards surface xiii, and a positive shift occurs crossing surface xiii. Delta O^{18} in multibanded calcite below surface xiii displays an upwardly positive trend (Fig. 3-14).

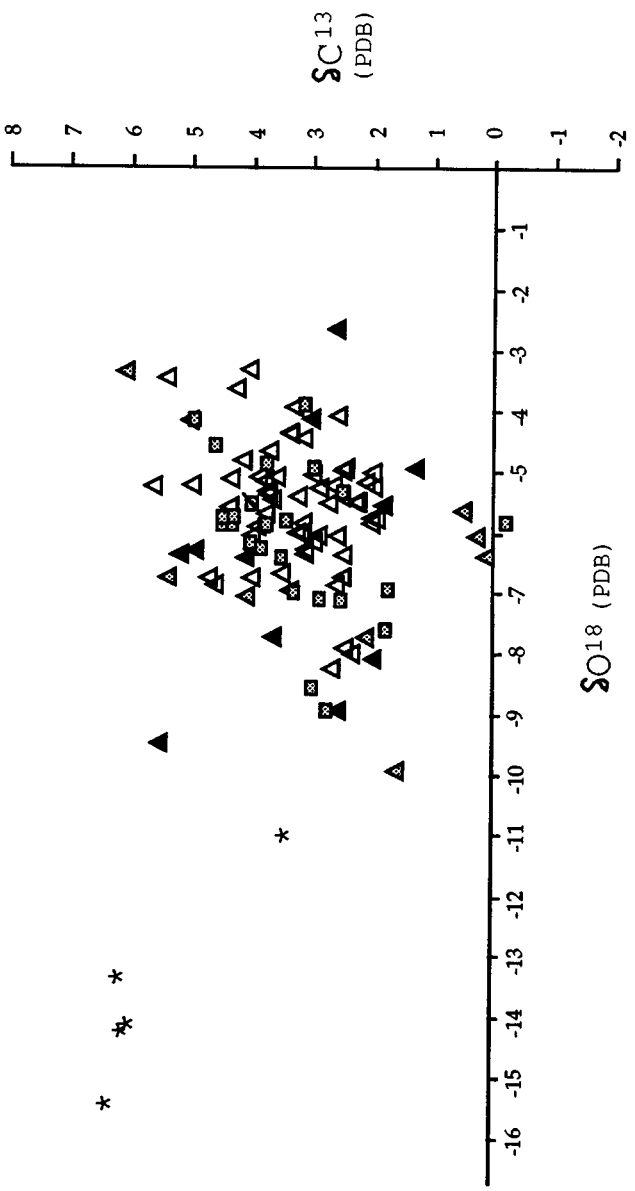
Upsection from surface xiii, delta C^{13} becomes more negative as surface xiv is approached. However, no measurements above surface xiv were obtained to test for a positive excursion relative to the cements below. Delta O^{18} shows a positive trend

Table 3-7.

	mean	S	Se	V	coef. V	min.	max.	t 95%	n
∫C13									
A1 multibanded †	3.338	0.934	0.129	0.871	27.965	1.88	5.58	0.26	52
A1 nonlumin.	2.711	1.537	0.397	2.363	56.692	0.21	6	0.851	15
B1	3.057	1.308	0.414	1.711	42.793	1.23	5.11	0.936	10
C1 √	3.335	1.189	0.259	1.413	35.641	-0.21	4.97	0.541	21
B3	2.895	1.055	0.282	1.114	36.462	0.865	4.03	0.609	14
C2 √	2.798	0.724	0.193	0.524	25.863	1.21	3.57	0.418	14
B4	1.867	1.663	0.416	2.767	89.116	-1.32	5.87	0.886	16
∫O18									
A1 multibanded †	-5.47	0.972	0.135	0.945	-17.767	-8.24	-3.39	0.271	52
A1 nonlumin.	-6.587	1.462	0.377	2.136	-22.191	-9.98	-3.36	0.81	15
B1	-6.153	1.885	0.596	3.553	-30.636	-8.93	-2.68	1.349	10
C1 √	-6.117	1.25	0.273	1.563	-20.435	-8.95	-3.9	0.569	21
B3	-9.17	3.53	0.943	12.462	-38.496	-18.09	-5.99	2.039	14
C2 √	-7.33	0.495	0.132	0.245	-6.758	-8.38	-6.5	1.88	14
B4	-10.808	5.79	1.448	33.524	-53.569	-30.4	-5.83	3.086	16

Table 3-7: Summary of stable isotope analyses for separate calcite cement zones in the Lisburne Group. All values relative to PDB.
† A1 multibanded calcites may have contamination from echinoderm grains and B1 calcite.
√ C1 and C2 calcite may be mixed in some analyses where the intervening phases, A2 and B3, are not present.

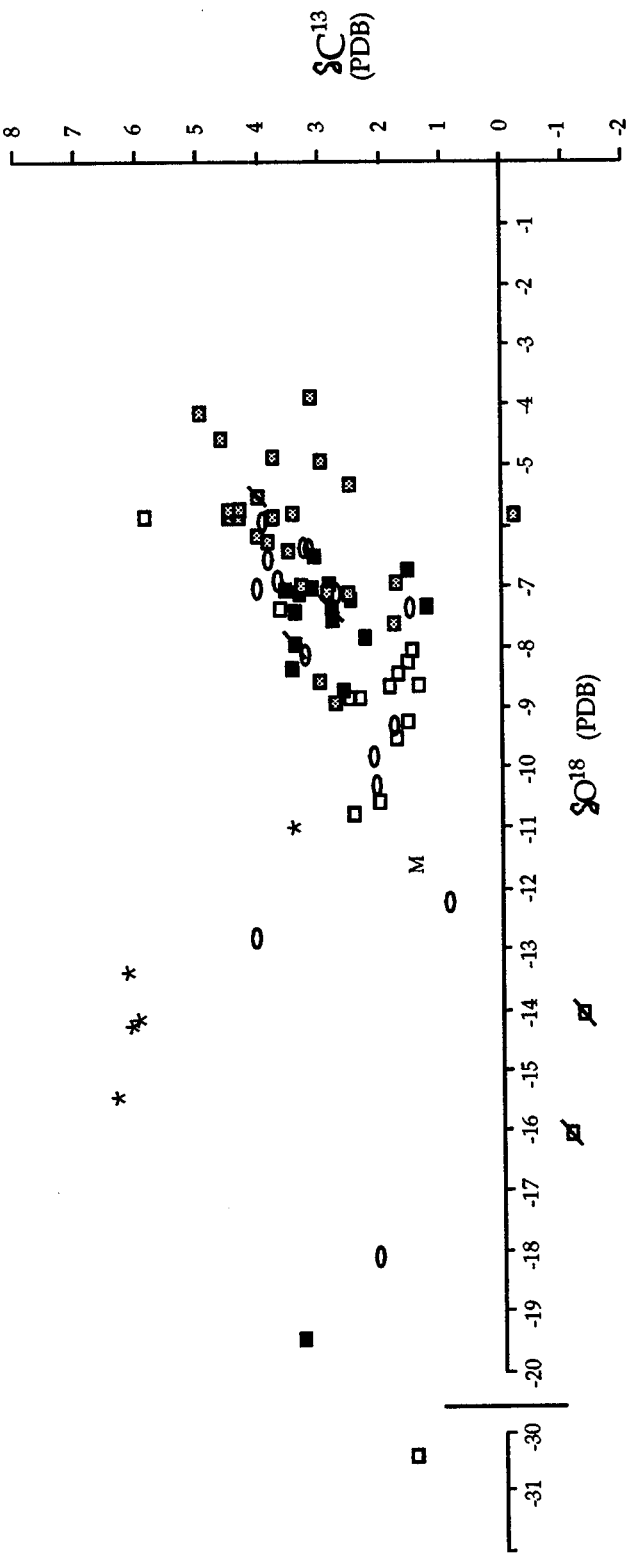
Figure 3-11.



- A1 nonluminescent calcite cements.
- A1 multibanded calcite + B1 calcite + crinoids
- B1, nonferroan, dully luminescent calcite.
- C1 calcite, ferroan, very-dully luminescent.
- C1 calcite in fractures.
- * popcorn caliche, Recent.

Figure 3-11. Crossplot of delta C13 versus delta O18 for calcite phases, A1 nonluminescent, A1 multibanded, B1, C1, and modern popcorn caliche. A1, B1, and C1 calcites form a field that ranges from +6 to -1.2 per mill, delta C13, and -2.5 to -9.8 per mill, delta O18.

Figure 3-12.



* popcorn caliche, Recent.

□ B4 calcite, nonferroan, coarsely-crystalline calcite in cavernous porosity and large fractures.

B4 calcite, nonferroan, calcite cement in breccia porosity in upper Alapah exposure surfaces.

M marbleized limestone in a shear zone, top of Alapah Fm.

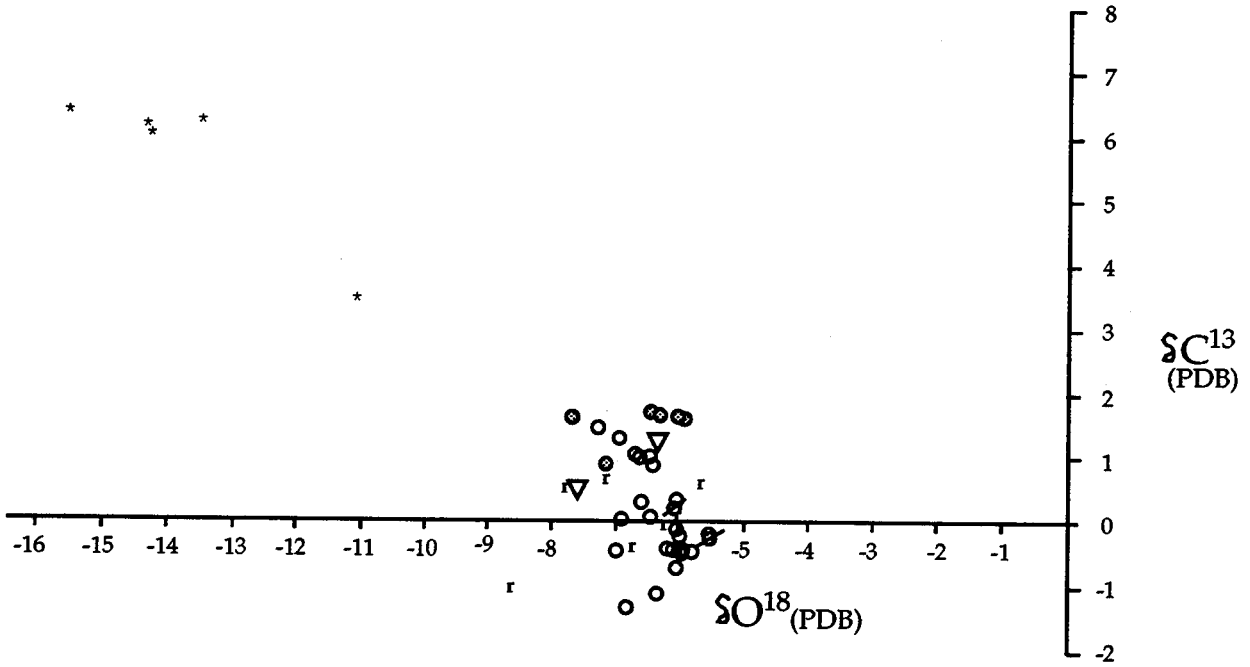
C2, ferroan calcite cement in fractures.

■ C2, ferroan calcite cement in BP and MO.

0 B3 calcite, medium ferroan, dully luminescent.

⊠ C1 calcite, ferroan, very-dull luminescent.

Figure 3-12. Crossplot of delta C13 versus delta O18 for C1, C2, B3, and B4 calcite and modern caliche. C1 calcite has the least negative delta O18, ranging from -4 to -9 per mill. The more negative portion of the C1 field overlaps with C2 calcite. B3 and B4 calcite, as well as modern caliche, have much more negative delta O18 than C1 calcite. B3 and B4 calcites have a greater dispersion of values compared with other calcites. One measurement of a marble (M) falls in the middle of the B4 calcite field.



- o whole rock samples below subaerial exposure surface vii.
- ⊗ whole rock samples above subaerial exposure surface vii.
- r rhizoiths and laminated crusts subaerial exposure surface vii.
- ⊘ nonluminescent pendant cements below subaerial exposure surface vii.
- ∇ whole rock samples of peloidal packstone and lime mudstone, uppermost Wahoo.
- * popcorn caliche.

Figure 3-13. Crossplot of delta C^{13} versus delta O^{18} for whole rock samples taken across subaerial exposure surface vii, in the lower Alapah Limestone, West Sunset Pass section, Sadlerochit Mountains.

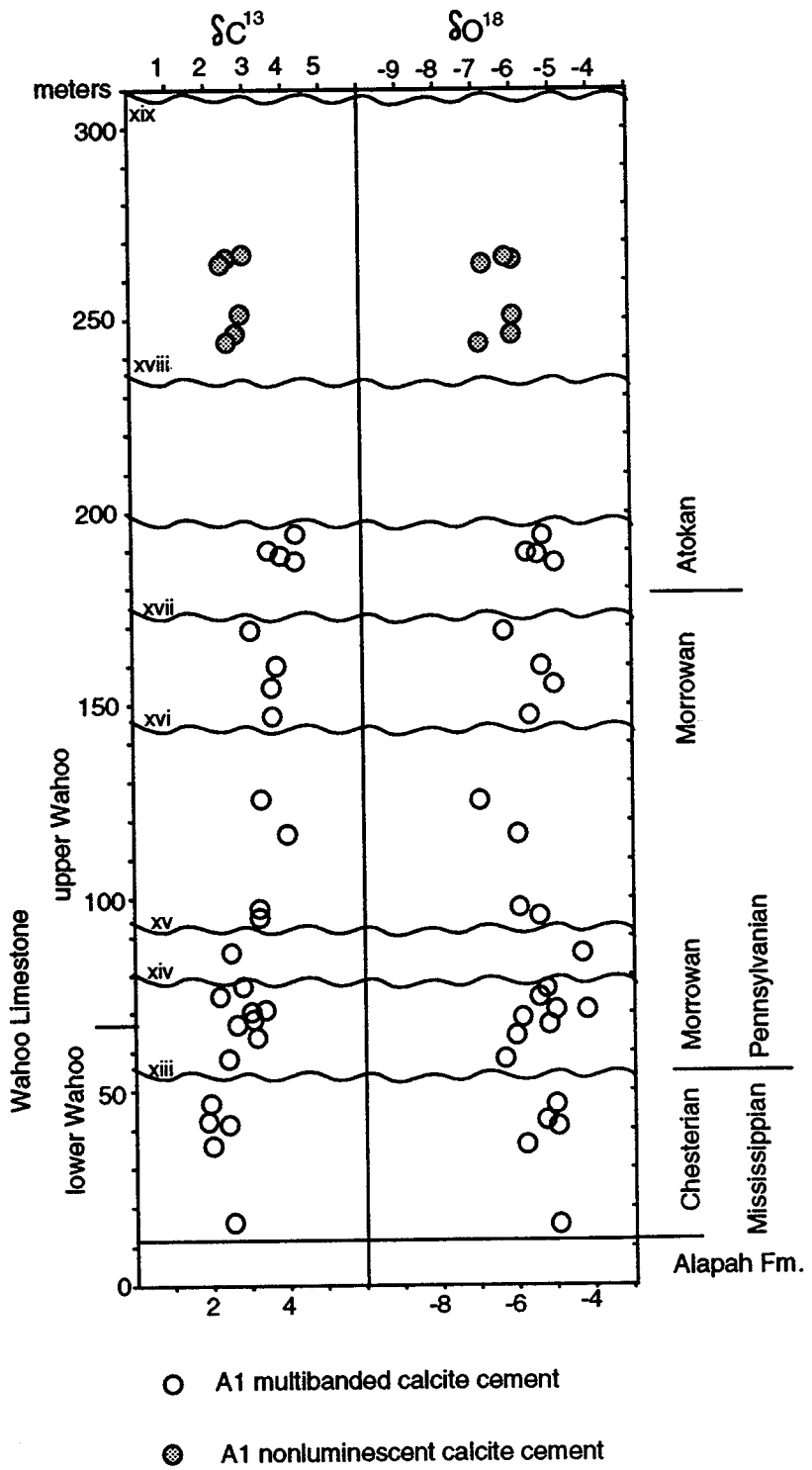


Figure 3-14. Stratigraphic distribution of delta C13 and delta O18 in calcite cements of the Wahoo Limestone, Marsh Creek section. Subaerial exposure surfaces are marked xiii through xix.

upward toward surface xiv, similar to the trend below surface xiii. A1 multibanded calcite above surface xv displays a positive shift delta C^{13} and a negative shift in delta O^{18}, relative to A1 multibanded calcite below surface xv. An upwardly more negative trend in delta O^{18} is suggested by measurements beneath subaerial surfaces xvi and xvii, however, the number of measurements are probably insufficient to draw conclusions. A1 nonluminescent calcite in the upper one-third of the Wahoo Limestone has more negative delta C^{13} values compared with A1 multibanded calcites in the middle of the Wahoo above surface xiii. Delta O^{18} of the A1 nonluminescent calcite is about one per mill more negative than A1 multibanded calcite in the lower two-thirds of the Wahoo.

CONCLUSIONS

Eighteen subaerial exposure surfaces were recognized within the Lisburne Group based on field observations of a downdip transect of three composite stratigraphic sections in the northeastern Brooks Range. A nineteenth subaerial exposure surface marks the unconformity at the top of the Lisburne Group beneath the Echooka Formation. In the lower part of the Alapah Limestone, several subaerial exposure surfaces occur in the southernmost sections, but apparently lap out northward. However, the highest (surface vii) can be traced between all three localities. In the upper Alapah, four subaerial exposure surfaces associated with peritidal deposits can be traced between the two northern sections, but only two are recognized farther downdip to the south. Cave deposits and evidence of subaerial exposure (surface xii) occur at the contact between the Alapah and Wahoo Limestone. In the lower Wahoo, subaerial exposure surface xiii coincides with the Mississippian-Pennsylvanian boundary. Surface xiv in the lower part of the upper Wahoo is associated with localized intertidal deposits in northern ANWR. Other exposure surfaces in the upper Wahoo are mostly restricted to the northern ANWR, except for surface xvii that is near the Morrowan-Atokan boundary. A major unconformity truncates the top of the Lisburne Group with evidence of significant erosion on a regional scale; this subaerial exposure surface is marked by localized conglomerates, red paleosols, karst breccias and moldic porosity.

Based on petrographic cathodoluminescence studies, calcite cements in the Lisburne Group can be divided into the following zones. Three types of early cements occur, A1 nonluminescent, a nonferroan calcite; A1 multibanded, a nonferroan calcite with one to several sets of nonluminescent-bright-dull or nonluminescent-bright subzones; and, a rarely occurring cement, microcrystalline calcite. Earliest calcite cement zones are followed by, from oldest to youngest, B1 calcite, low ferroan and dully luminescent; C1 calcite, ferroan and very-dully luminescent; B2 calcite, ferroan and dully luminescent, and preceding quartz cement; A2 calcite, nonferroan and with 1 or 2 sets of nonluminescent and bright zones; B3 calcite, ferroan and dully luminescent, and post-dating quartz cementation; C2 calcite, ferroan and very-dully luminescent; and B4 calcite, nonferroan and very-dully luminescent.

Cross-cutting relationships with diagenetic features imposed under different diagenetic regimes, such as subaerial exposure, burial, and tectonism, allow relative

dates to be assigned to the cement zones (Carlson and Goldstein, 1992). Microcrystalline calcite, A1 nonluminescent calcite, and A1 multibanded calcite can, in many cases, be shown to predate or be synchronous with the development of features formed at surfaces of subaerial exposure within the Lisburne Group. Similarly, A1 nonluminescent and A1 multibanded calcites, as well as B1 calcite, C1 calcite, B2 calcite, and A2 calcite, are cross-cut by features developed during the sub-Permian unconformity at the top of the Lisburne Group. Thus, those cements are all pre-Permian/Leonardian in age. Using the same reasoning, B3 calcite and C2 calcite that are present in Permian sandstones and conglomerates overlying the Lisburne Group, can be dated as post-Pennsylvanian in age. Features of compaction and pressure solution further constrain the timing of C2 calcites as coincident with deep burial of the Lisburne. B4 calcites commonly fill, tectonically induced, shear fractures, hence, B4 calcites are Cretaceous or younger, resulting from tectonism in the northeastern Brooks Range (Mull, 1982, Wallace and Hanks, 1991).

CHAPTER 4

PRELIMINARY MICROFACIES ANALYSIS AND CYCLICITY OF THE WAHOO LIMESTONE, LISBURNE FIELD, NORTH SLOPE, ALASKA

By Susan K. Morgan and K.F. Watts

ABSTRACT

A well from the Lisburne field near Prudhoe Bay was examined in core, thin section, and on well logs for comparison with Wahoo Limestone in the Arctic National Wildlife Refuge (ANWR). Carbonate cycles (parasequences) are well developed in both areas but the greater abundance of terrigenous sediment and associated carbonate facies indicate that the study well is located in a more landward position on the Wahoo carbonate ramp, closer to a source of terrigenous sediment. This report presents the **preliminary** results of microfacies analyses that have been conducted on 424 of a total 1,115 thin sections from the study well.

The stratigraphic nomenclature extended from ANWR (the type locality of the Wahoo Limestone) is different that the terminology previously used for the subsurface Lisburne Group near Prudhoe Bay. We distinguish informal lower and upper members within the Mississippian to Pennsylvanian Wahoo Limestone which overlies the Mississippian Alapah Limestone. Our upper Alapah corresponds to the middle Alapah of previous workers (Dolomite interval" of Jamison et al., 1980). Our lower Wahoo Limestone member corresponds to the upper Alapah of previous workers ("Grainstone-packstone interval" of Jamison et al., 1980). Our upper Wahoo Limestone member corresponds to the previous Wahoo Limestone and is the major hydrocarbon reservoir at the Lisburne field, which is characterized by well-developed carbonate cycles (parasequences). The major change in the nature of the Lisburne carbonate platform occurs between our Alapah and Wahoo, representing a depositional sequence boundary. This sequence boundary and another sequence boundary at the lower and upper Wahoo transition are both marked by major influxes of terrigenous sediment.

We further subdivide the Wahoo Limestone into 8 zones bounded by 2- to 11-foot thick intervals of shale or argillaceous limestone. These zones generally correspond to the zonation for the Wahoo previously used by industry, but includes an additional zone (Zone 1) corresponding to our lower Wahoo member. Stratigraphic columns for each zone illustrate the lithologies, gamma-ray logs, and interpretation of carbonate cycles (parasequences). Each zone contains characteristic microfacies organized into carbonate cycles (parasequences). Idealized models illustrate the vertical succession of microfacies characterizing parasequences in each zone. This is an ongoing study that will be completed as part of Morgan's Ph.D.. dissertation.

INTRODUCTION

The Lisburne field is located near Prudhoe Bay, Alaska, and is a heterogeneous hydrocarbon reservoir within the Carboniferous Lisburne Group. The Lisburne Group consists of a thick succession of limestone and dolostone with minor amounts of shale and sandstone that crops out across the Brooks Range and extends into the subsurface of the North Slope petroleum province of Alaska (Fig. 4-1). The Lisburne Group is divided into the Mississippian Alapah Limestone and the Mississippian-Pennsylvanian Wahoo Limestone (Fig. 4-2). The Alapah contains a thick interval of relatively porous dolostone but is mostly below the oil-water contact in the Prudhoe Bay area. The upper part of the Wahoo is the main reservoir rock in the Lisburne field (Okland et al., 1987; Jameson, in review). Although the Wahoo is dominated by grainstones that indicate deposition in high-energy, shallow-marine environments (Jameson, 1990b, in review), a variety of carbonate lithologies occur. Their organization into numerous shallowing-upward carbonate cycles (parasequences) indicate repeated fluctuations of different carbonate environments.

As part of our work on carbonate cycles of the Wahoo, a well in the Lisburne field was chosen for comparison with our studies of the Wahoo cropping out in the Arctic National Wildlife Refuge (ANWR). The Wahoo Limestone at the Lisburne field formed on the inner part of a carbonate ramp in an area closer to a source of terrigenous sediment (eg. the Colville high) than correlative rocks in ANWR. This study is part of an ongoing Ph.D. dissertation project aimed at comparing carbonate cycles that developed in different positions on the Wahoo carbonate ramp. This report presents the **preliminary** results of microfacies studies together with initial interpretation of carbonate cycles (parasequences) in the study well. To date, the microfacies analysis has been completed for 424 of a total 1,115 thin sections from the study well. Continued research will refine the definition and paleoenvironmental interpretation of different microfacies and their organization into carbonate cycles (parasequences).

After analyses of the carbonate cyclicity of the study well are completed, these data will be compared with carbonate cycles that formed in more seaward positions of the Wahoo carbonate ramp (locs. 27, 8, & 13 on Fig. 4-1). This will allow us to test our ability to use carbonate cycles as a means of correlation over long distances and to better understand the mosaic of carbonate facies comprising the Wahoo Limestone. Another future goal of this study is to compare core and microfacies analyses with well log data to determine if the heterogeneities within carbonate cycles (parasequences) can be characterized by log data. Both datasets are in the Wahoo computerized database (see Chapter 5), allowing us to quantify any correlatable attributes. However, one of the original goals of the study, to compare reservoir characteristics with heterogeneities resulting form carbonate cycles, appears to be difficult because of the importance of fracturing within the Lisburne field(Missman and Jameson, 1991; Jameson, 1991, in revision).

Figure 4-1.

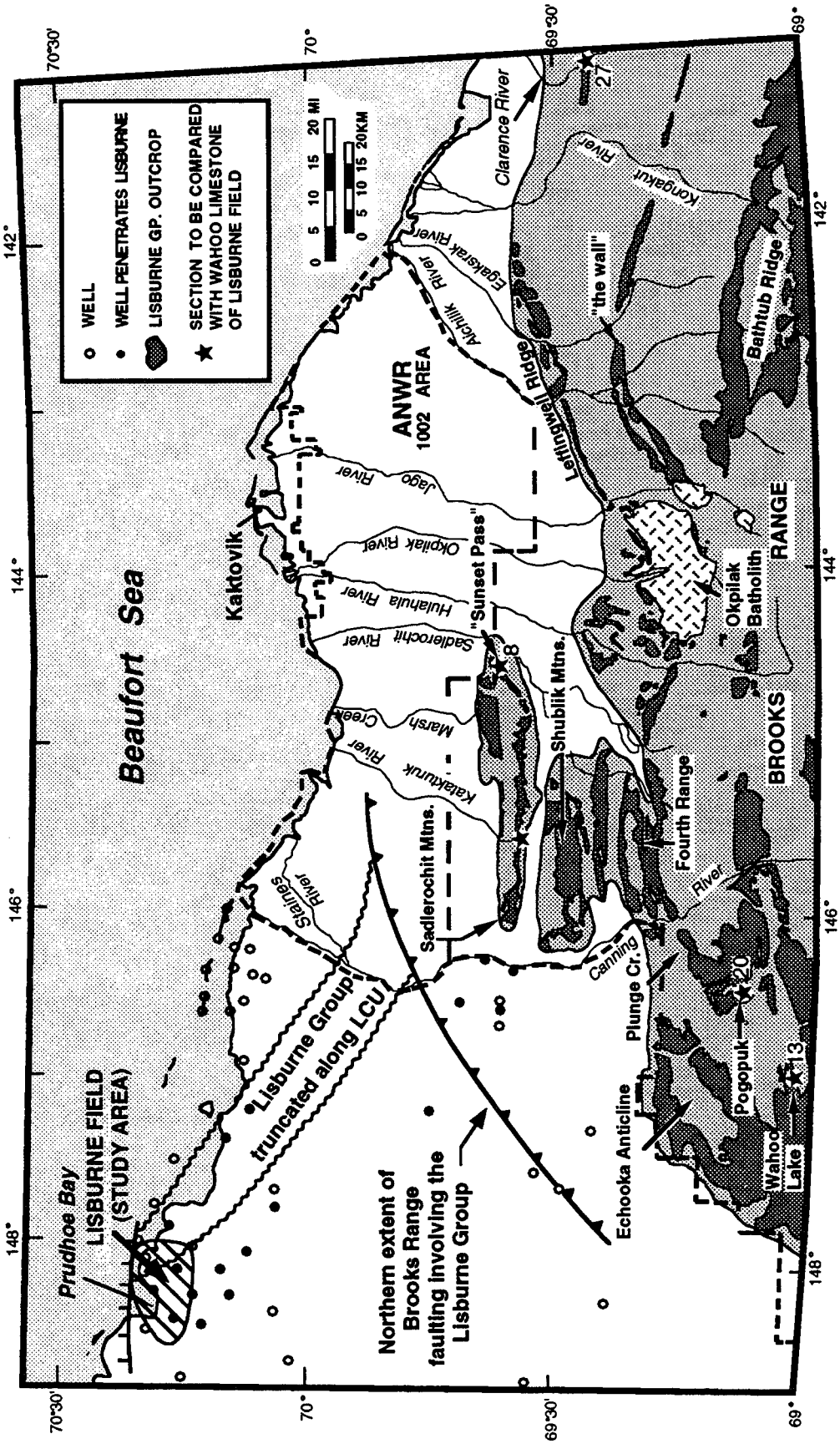


Figure 4-1. Map shows the locations of Lisburne field at Prudhoe Bay and outcrops of the Lisburne Group in the northeastern Brooks Range. Carbonate cycles in the Wahoo Limestone at the study well will be compared with those at localities 27, 8, 20, and 13 (modified from Bird et al., 1987 and Bader and Bird, 1986).

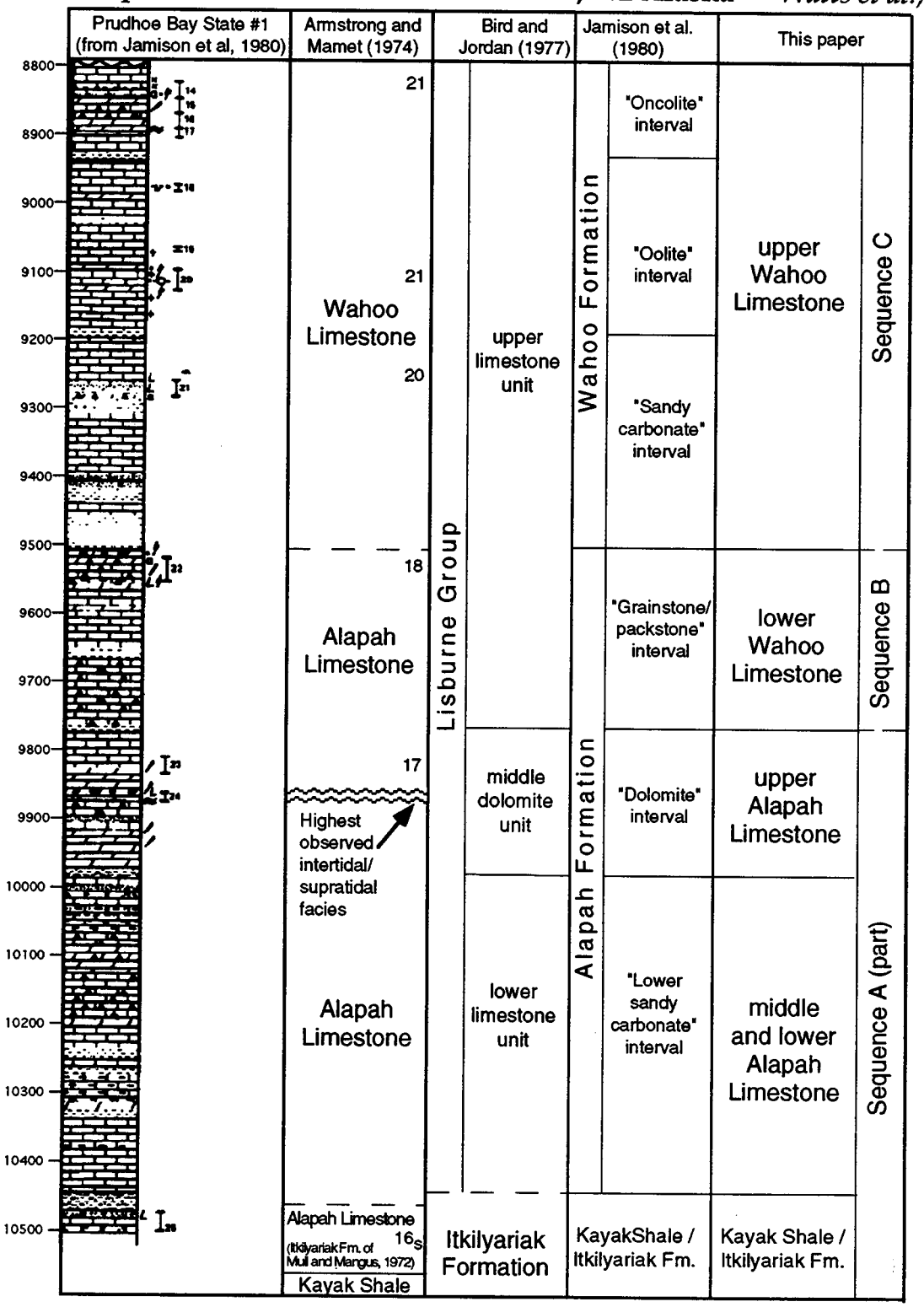


Figure 4-2. Diagram compares our nomenclature that was extended to the Lisburne field from the type locality of the Wahoo Limestone in ANWR with previous terminology used for the subsurface Lisburne Group. Our interpretation of depositional sequences in the Lisburne Group is also shown.

METHODS OF STUDY

ARCO Alaska (and their partners Exxon and BP Alaska) allowed us to analyze cores from a well in the Lisburne Field (the name and precise location of this well are not to be disclosed as part of our agreement). The well was selected for detailed analysis because of its excellent recovery and continuous coring through the Wahoo Limestone and upper part of the Alapah Limestone. Cores from the study well were described at the ARCO Bayview core repository in Anchorage, Alaska. The opportunity to examine cores was particularly useful for documenting bedding relationships and sedimentary structures (these are more apparent in core than in outcrop where obscured by lichens or weathering patina). Thin sections were made from the core plugs (at one-foot intervals) curated at the Alaska Materials Center in Eagle River, Alaska. Computerized well log data were obtained from the Alaska Oil and Gas Commission, processed using a *Logitech* computer system, and downloaded into the *Wahoo* computerized database for comparison with our microfacies data (see Chapter 5). All the depths given in this report are uncorrected, measured core depths; calibration points for correlation with well log depths are given on Fig. 4-3. Most of these correlation points are located at the base of shale intervals that are evident in cores, thins sections, and gamma-ray logs (argillaceous sediment has relatively high gamma-ray log readings).

Microfacies analyses and core descriptions were used to characterize carbonate cycles of the Wahoo Limestone and to interpret depositional environments. Microfacies analysis is an approach developed by Wilson (1975) and Flügel (1982) that utilizes thin section analyses to distinguish micropaleontological and petrographic details to characterize and classify lithofacies and biofacies. Together with analyses of sedimentary structures and bedding relationships, microfacies analysis provides a powerful tool for facies characterization, depositional environment interpretation, and the development of facies models. Microfacies analyses of the Wahoo allowed construction of detailed stratigraphic columns and identification of cycles (parasequences) within the vertical succession of microfacies comprising the Wahoo. Diagenetic features evident in core and microfacies analyses were also described, providing additional information that relates to reservoir behavior. All microfacies data were recorded on forms for entry into the Wahoo database (see Chapter 5, Form 5-1; results summarized in Appendix A). The semiquantitative abundance of different components (eg. different grains/allochems) were recorded as follows: rare (< 1%), minor (1% to 10%), common (10% to 50%), and abundant (> 50%).

STRATIGRAPHY AND FORMATION BOUNDARIES

Three lithostratigraphic units within the Lisburne Group (the Alapah Limestone and informal lower and upper members of Wahoo Limestone) were defined in the study well using criteria extended from outcrop studies of the Lisburne Group in the Arctic National Wildlife Refuge (ANWR; Fig. 4-1; Carlson, 1987; Gruzlovic, 1991; Morgan, 1992; and Watts, 1992). As noted in Chapter 1, the terms Alapah and Wahoo have not been used consistently by previous workers, resulting in confusion in

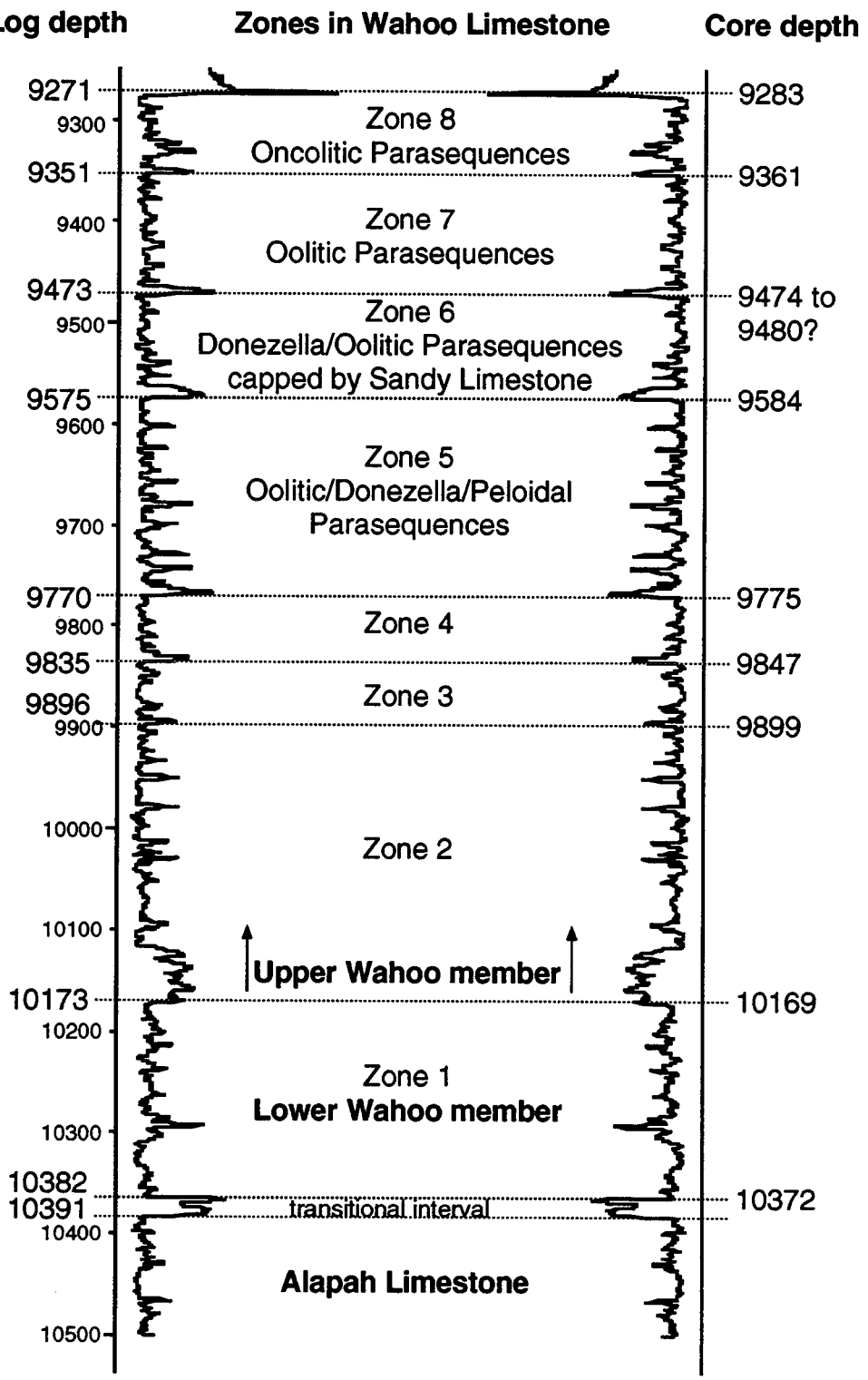


Figure 4-3. Mirror image gamma-ray log shows the different zones in the Wahoo Limestone. The trace on the left is the well log depth whereas the trace right shows correlative uncorrected measured depths (depth recorded on the cores, plugs and thin sections).

stratigraphic nomenclature. Our definitions of lithostratigraphic boundaries are different than previous terminology at Prudhoe Bay, but are more consistent with the original definition of the Wahoo Limestone and correspond to **the** major change in depositional regime in the Lisburne Group of both areas (Figure 4-2; Brosgé et al, 1962). The major difference is that our lower Wahoo member replaces the upper Alapah of previous workers (Jamison et al., 1980; Jameson, in revision).

In ANWR, the contact of the Wahoo Limestone with the underlying Alapah Limestone is marked by a lithologic change from dark, slope-forming microdolomite and lime mudstone of the Alapah to light-colored cliff-forming coarse-grained fossiliferous grainstone and packstone of the Wahoo (Chapter 1 in this report; Krumhardt et al., in press). Using similar criteria for the study well, the Alapah-Wahoo contact occurs at 10,372 feet. The contact is gradational with a 19-foot-thick transitional interval from 10,391 to 10,372 feet containing 1- to 3-foot-thick (30-100 cm) beds of green, noncalcareous and slightly calcareous siltstone intercalated with bioturbated, quartz-rich, bryozoan wackestone and packstone. The transition zone is overlain by a thick interval of fossiliferous grainstone and packstone, typical of the lower Wahoo Limestone. Thus, the uppermost Alapah at Prudhoe contains terrigenous sediments that are different from the Alapah of ANWR, but herald the maximum regression in an area closer to a source of terrigenous sediment, the Colville high. This represents a major lowstand and a sequence boundary as indicated on Figure 4-2. Our upper Alapah corresponds to the middle "Dolomite" Alapah interval of Jamison and others (1980).

In ANWR, the Wahoo Limestone is subdivided into informal lower and upper members. The lower Wahoo is a cliff-forming unit characterized by bryozoan-pelmatozoan packstone, grainstone and wackestone organized into a few (4-5) indistinct thick cycles or parasequences (Gruzlovic, 1991). The upper Wahoo is characterized by numerous thin cycles/parasequences containing a variety of bryozoan-pelmatozoan limestones punctuated by intervals of oolitic grainstone and rare shale (Gruzlovic, 1991). The lower Wahoo is Late Mississippian (late Chesterian) to Early Pennsylvanian (Morrowan) in age and the upper Wahoo is Early to Middle Pennsylvanian (Morrowan to Atokan) in age. The boundary between the informal members is abrupt (in northern ANWR) to gradational and is marked by an upward transition into ledge-and-slope topography resulting from well-developed cycles/parasequences in the upper Wahoo (Gruzlovic, 1991; Morgan, 1992). The contact can be arbitrarily placed at the first bed of orange-weathering wackestone or mudstone in the upper Wahoo. The boundary between the members is near the sequence boundary marking the maximum regression within the Wahoo as indicated by local cryptalgalaminate and/or spiculitic mudstone.

Applying similar criteria to the study well, the lower Wahoo is 203 feet thick (61 meters), extending from 10,372 feet to 10,169 feet. Our lower Wahoo represents the "Grainstone/Packstone interval" of the upper Alapah of Jamison and others (1980). It contains a few indistinct cycles/parasequences composed of bryozoan-pelmatozoan wackestone, packstone, and grainstone, peloidal packstone and grainstone with lesser intervals of superficial oolitic and oolitic grainstone and dolomite. At 10,169 feet, the lower Wahoo is overlain abruptly by a 27- foot-thick interval of green, bioturbated,

bryozoan packstone and wackestone that contains very thin beds (1-3 cm) of green, noncalcareous siltstone. The upper Wahoo is 887 feet thick (269 meters), extending up to the unconformity beneath the Sadlerochit Group at 9,287 feet. The upper Wahoo contains as many as 55 cycles/parasequences composed of a variety of lithologies, including thick oolitic and oncolitic intervals. Thus, the influx of terrigenous sediment in the lower part of the upper Wahoo (base of the "Sandy Carbonate" interval of the Wahoo of Jamison et al., 1980) again corresponds to a maximum regression and sequence boundary (Fig. 4-2). The Prudhoe Bay area remained closer to a source of terrigenous sediment (eg. the Colville high) than correlative rocks in ANWR that formed farther down the Wahoo carbonate ramp.

In summary, extending stratigraphic nomenclature from ANWR to the study well results in a change in terminology from that currently used for the Lisburne Group at Prudhoe Bay (Fig. 4-2. Using previous terminology, the Wahoo-Alapah contact is located at the base of the first major down-hole gamma-ray log kick, corresponding to the interval of green silty limestone. This represents the boundary between our informal lower and upper members of the Wahoo as defined in this report (Fig. 4-3). We place the Alapah-Wahoo contact at the top of the second major down-hole gamma-ray log kick that corresponds to the green siltstone and mudstone interval above the dolomite interval in the upper Alapah. Using previous terminology, this would mark the contact between the middle "dolomitic interval" and upper "Grainstone-packstone interval" of the Alapah Formation (Jamison et al., 1980).

MICROFACIES DESCRIPTIONS

The following preliminary microfacies descriptions are based on microfacies analyses of 424 thin sections from the study well. Arbitrary letters are used to label each microfacies with no reference to environment or position within a progradational sequence. The microfacies are characterized by dominant grain types (allochems) and texture (the abundance of lime mud, using Dunham's classification). Thirteen microfacies are identified and include; (A) oncolitic and algal grainstone and packstone, (B) bryozoan-pelmatozoan grainstone, (C) dolomitic and calcitic mudstone and spiculitic wackestone, (D) peloidal grainstone, packstone, and wackestone, (E) sandy limestone, (G) oolitic and superficial oolitic grainstone and packstone, (H) chert, (J) sandstone, (K) pelmatozoan-brachiopod grainstone, (L) bryozoan-pelmatozoan packstone, (M) wackestone, (N) foraminiferan grainstone and packstone, and (O) *Donezella* grainstone and packstone. There are no microfacies F or I; these were redefined as other similar microfacies. Upon completion of the microfacies analysis, the microfacies will be labeled in a logical succession with respect to paleoenvironments and position on the Wahoo carbonate ramp and within progradational successions (parasequences). For example, sandy limestone would be adjacent to sandstone with the latter being closer to a terrigenous source area.

Most of the major microfacies are further subdivided into sub-microfacies based on secondary characteristics such as grain composition and abundance, amount of detrital quartz, amount of mud matrix, and average grain size. Attributes described in

core such as color, sedimentary structures, and diagenetic features associated with each microfacies are integrated into the microfacies descriptions.

Grain types and the presence or absence of mud can be used as indicators of water energy and water depth and are used for interpretation of depositional environments (Wilson, 1975). Using accepted criteria for microfacies analysis (Wilson, 1975; Flügel, 1982), each microfacies description is followed by a generalized interpretation of possible depositional environments. More detailed paleoenvironmental analyses will be done after microfacies analyses of the entire thin section collection for the study well is completed. Understanding the interrelationships between adjacent microfacies within parasequences will allow better definition of depositional environments and determination of the typical progradation succession of microfacies comprising the Wahoo in the Lisburne field (as in Fig. 1-24 in Chapter 1).

MICROFACIES A: ONCOLITIC AND ALGAL GRAINSTONE AND PACKSTONE

Oncoids and other algally-encrusted grains are the dominant allochems of oncolitic and algal grainstone and packstone microfacies. Oncoids most likely are composed of the algae *Osagia* and vary from well developed with multiple algal coatings to poorly developed with few coatings. Oncoids range in size from 0.25 to 1.20 mm and have nuclei of brachiopods, bryozoans, trilobites, bivalves, foraminifers, and gastropods. Some grains having irregular algal encrustations are not considered to be oncoids. In rare instances, algae occur between allochems, apparently binding the grains together.

Minor accessory grains include pelmatozoans, bryozoans, brachiopods, intraclasts, gastropods, foraminifers, bivalves, *Archaeolithophyllum*, *Donezella*, ostracods, and peloids. Oncolitic and algal grainstone and packstone is light tan. Some intervals are ripple-laminated to planar-laminated. Diagenetic features include tan chert nodules, brown silty stylolaminations, and high-amplitude stylolites.

A-1: Oncolitic-superficial oolitic-grainstone and packstone

Oncoids are moderately to well developed and range in size from 0.50 to 1.00 mm. They have nuclei of foraminifers, whole gastropods, and pelmatozoan and bryozoan fragments. Superficial ooids are small and occur in varying amounts. Minor accessory grains include intraclasts composed of wackestone, mudstone, and spiculitic mudstone, rounded bryozoan fragments, bivalves with micrite envelopes, foraminifers, whole articulated and fragmented brachiopods, pelmatozoan fragments, and *Archaeolithophyllum*. Grains commonly have micritic rims.

A-2: Algal grainstone

Algae occur as thin and intermittent coatings preferentially encrusting bryozoan fragments with only minor, moderately developed oncoids. Pelmatozoans, bivalves, *Archaeolithophyllum*, foraminifers, and intraclasts of fossiliferous wackestone occur in minor amounts. *Donezella* is present in some intervals.

A-3: Oncolitic grainstone

Large (1.20 mm diameter), well-developed oncoids dominate with minor accessory grains of uncoated, rounded bryozoan, pelmatozoan, and brachiopod fragments. Recrystallized bivalves and gastropods with micritic envelopes rarely occur. Euhedral dolomite rhombs have formed within the oncoids.

A-4: Oncolitic packstone

Oncoids are moderately to well developed and are associated with minor fragments of bryozoan, pelmatozoan, and bivalve. The packstone matrix is composed of microdolomite with scattered small euhedral dolomite rhombs. Pyrite occurs in minor amounts scattered in the matrix and rarely replaces allochems.

A-5: Oncolitic-bryozoan grainstone

Moderately- to well-developed oncoids and bryozoans are the dominate grain types with minor amounts of peloids, intraclasts of spiculitic wackestone, ostracods, gastropods, brachiopods, bivalves with micritic envelopes, and foraminifers. The matrix material has a peloidal appearance in poorly washed areas

Depositional environment of Microfacies A

Oncoids can form in a variety of environments (Carozzi et al., 1983; Dahanayake, 1983; Wright, 1983). Oncoid morphology, grain associations, the presence and absence of matrix, stratigraphic succession of microfacies, and sedimentary structures all are used to determine the environment of deposition.

Oncoids range from rounded to asymmetric growth forms and commonly display a spongy microfabric. The asymmetric morphology and spongy microfabric may represent growth in low to moderately agitated waters in partially restricted-platform environments. Rounded oncoids and planar-laminated to cross-laminated intervals most likely represent higher-energy shoal conditions. The presence of varied skeletal grains, particularly pelmatozoans indicates normal salinity.

MICROFACIES B: BRYOZOAN-PELMATOZOAN GRAINSTONE

Bryozoan-pelmatozoan grainstone is composed primarily of fine-grained, rounded and abraded bryozoan and pelmatozoan fragments. The following allochems occur in minor amounts: foraminifers, brachiopods, ooids, bivalves with micritic envelopes, peloids, gastropods, intraclasts, and *Asphaltina*. Bryozoan-pelmatozoan grainstone is light tan-gray and contains minor planar-laminated intervals. High-amplitude stylolites are common whereas black to dark-gray, very fine-grained laminae randomly occur.

B-1: Fine-grained bryozoan-pelmatozoan grainstone

Bryozoan and pelmatozoan fragments of 0.25 mm mean size dominate with minor accessory grains of foraminifers and brachiopods. These allochems are fragmented and moderately abraded.

B-2: Medium-grained bryozoan and coarse-grained pelmatozoan grainstone

Bryozoan and pelmatozoan fragments, 0.50 to 1.00 mm in size, are common whereas large (>1.00 mm) pelmatozoan fragments are scattered throughout. Minor accessory grains include irregularly algally-coated pelmatozoans and brachiopods, micritized and normal ooids, brachiopods, bivalves, *Asphaltina* algae, gastropods, and intraclasts composed of spiculitic wackestone. Some intervals contain peloids.

B-3: Bryozoan-pelmatozoan-peloidal grainstone

Bryozoan and pelmatozoan fragments range from 0.50 to 1.50 mm and are rounded and abraded. Peloids possibly may be micritized ooids. Foraminifers and brachiopod fragments occur in minor amounts.

Depositional environment of Microfacies B

Bryozoan-pelmatozoan-peloidal grainstone represents high-energy skeletal banks. The absence of ooids indicate that the skeletal banks may have formed in slightly deeper water environments on the flanks of ooid shoals or other areas which did not favor ooid formation. The good sorting and lack of lime mud indicate deposition above fair-weather wave-base. However, these skeletal grainstones could have formed in somewhat deeper water above storm wave base if storm-generated waves/currents provided sufficient energy to rework skeletal material into banks and winnow away mud. Where interbedded with muddy carbonates, microfacies B probably represents storm deposits that were transported to areas below storm wave base.

MICROFACIES C: DOLOMITIC AND LIME MUDSTONE AND SPICULITIC WACKESTONE

Carbonate mudstones contains from <1% to 10% skeletal grains and may be composed of lime mud or microdolomite. Spiculitic wackestone contains up to 15% sponge spicules with no accessory grains. Lime mudstone and wackestone are dark to medium gray, dark brown, and green. Contacts with adjacent beds are commonly abrupt and less commonly gradational. Where upper contacts are abrupt, mudstone and wackestone intraclasts are incorporated in the overlying bed. Bioturbation and burrow mottling are common. Minor intervals have planar laminations. Pyrite commonly is associated with mudstones.

C-1: Mottled mudstone

Mottled lime mudstone contains minor amounts of pelmatozoan fragments, fenestrate bryozoan fronds, and sponge spicules scattered in a lime mud or microdolomite matrix. The mudstone is burrowed and mottled. Scattered pyrite occurs in minor amounts.

C-2: Mudstone

Minor amounts of pelmatozoan fragments and fenestrate bryozoan fronds occur in microdolomite or lime mud matrix. No spicules occur in this facies. As much as 10% detrital quartz and 1% to 4% pyrite can be scattered throughout the mudstone.

C-3: Laminated or mottled mudstone with quartz

Rare fenestrate bryozoans, pelmatozoan fragments, whole brachiopods, and sponge spicules occur in lime mudstone with up to 5% detrital quartz. Hematite and pyrite are minor to rare. The mudstone can be planar-laminated or mottled due to bioturbation. Laminations (0.25 to 1.20 mm thick) are evident in concentrations of detrital quartz.

C-4: Spiculitic wackestone

Spiculitic wackestone contains approximately 15% sponge spicules. Monaxon spicules are common and triaxon spicules are rare. The wackestone is planar-laminated or homogeneous.

C-5: *Donezella* mudstone

Donezella mudstone contains minor *Donezella* fragments and rare brachiopod and pelmatozoan fragments. The skeletal grains occur in lime mud or microdolomite matrix with minor scattered pyrite.

Depositional environment of Microfacies C

Mudstones indicate deposition in quiet water where fine-grained material can settle out of suspension. Quiet water deposition may occur within a variety of deep or shallow-water conditions. Thus, individual mudstone microfacies must be analyzed with respect to interrelationships with adjacent lithologies to determine the environment of deposition.

Skeletal grains within the mudstones are not necessarily environment specific. Sponges can inhabit a variety of inhospitable environments including restricted lagoons and open-marine, deeper water environments. *Donezella*, bryozoans, and pelmatozoans can inhabit niches within shallow open-platform environments adjacent to low-energy mudstone environments. Skeletal grains also can be transported and deposited by episodic storm events and mixed into mudstone by bioturbation.

Preservation of laminations in mudstones may indicate hypersalinity, anoxia, or other inhospitable conditions that are not conducive to bioturbating organisms. However, the lack of evidence of evaporites may preclude hypersaline conditions.

MICROFACIES D: PELOIDAL GRAINSTONE, PACKSTONE, AND WACKESTONE

Peloidal grainstone, packstone, and wackestone are fine grained, dominated by peloids, and may contain a variety of other allochems. Intervals can be planar laminated, ripple laminated, and cross laminated. Peloidal grainstone, packstone, and wackestone are brown, tan, and tan-gray with occasional scattered chert nodules and high-amplitude stylolites. Commonly, the lower contacts are abrupt whereas upper contacts are abrupt to gradational.

D-1: Peloidal-skeletal packstone

Peloids and skeletal allochems dominate the peloidal-skeletal packstone. Skeletal allochems include fragments of bryozoans, pelmatozoans, brachiopods, foraminifers, ostracods, and algae. Allochems commonly have micritic rims. As much as 2% detrital quartz is present.

D-2: Peloidal packstone and wackestone

Peloidal packstone and wackestone contain abundant peloids with minor amounts of ostracods, foraminifers, whole thin-shelled brachiopods, algae, and pelmatozoan fragments. Ooids and *Donezella* are rare. As much as 7% detrital quartz occurs along with minor amounts of pyrite. Peloidal packstone and wackestone are planar-laminated or homogeneous.

D-3: Peloidal grainstone with rare packstone

Fine-grained (0.25 to 0.50 mm) peloids dominate this microfacies with minor amounts of the following fine-grained allochems: foraminifers, pelmatozoan and bryozoan fragments, brachiopod fragments, algae, ooids, and whole ostracods. Calcispheres and bivalves with micritic envelopes are rare. Micritic rims are common. Peloidal grainstone is planar-laminated to cross-laminated.

D-4: Peloidal, poorly washed grainstone

Peloids dominate and occur in a grainstone indicating a near wave-base environment. In places, matrix material is poorly washed and has a clotted peloidal fabric. Bryozoan, pelmatozoan, and brachiopod fragments, and intraclasts composed of spiculitic wackestone are minor allochems.

D-5: Peloidal-bryozoan-intraclastic grainstone and packstone

Peloids, rounded bryozoan fragments, and intraclasts of spiculitic wackestone dominate with minor amounts of pelmatozoan and brachiopod fragments, foraminifers,

and algae. Peloids are spherical, well rounded, well sorted, and recrystallized and contain small euhedral dolomite rhombs.

D-6: Peloidal-foraminiferan grainstone with minor packstone

Peloids and foraminifers are common and fine grained (0.25 to 0.50 mm mean size). Pelmatozoan, bryozoan, and brachiopod fragments, calcispheres, algae, ostracods, and dasycladacean algae are minor grains. *Donezella* can be present. Micritic rims are minor.

Depositional environment of Microfacies D

Peloids are well-rounded, structureless aggregates of micrite, rarely larger than 0.5 mm, that have several modes of formation (Flügel, 1982; Enos, 1983). Fecal peloids dominate recent restricted subtidal and low-energy intertidal zones and are characterized by good sorting, association with large amounts of organic matter, and can be concentrated in localized areas and burrows. Algal peloids usually are poorly sorted and have irregular shapes. Peloids can result from the micritization of allochems, especially ooids, by endolithic algae and bacteria. Peloids formed by micritization of allochems are most common in shallow waters in the photic zone where endolithic algae are able to colonize grain surfaces, particularly where sedimentation rates are slow. The reworking of carbonate mud by currents also leads to the formation of a peloids. Generally, fecal peloids represent quiet-water restricted-platform environments where detritus-feeding organisms can pelletize sediment. Peloidal grainstone and packstone commonly are ripple-laminated, planar-laminated, or cross-laminated, indicating deposition by currents, possibly tidal currents (Shinn, 1983).

MICROFACIES E: SANDY PACKSTONE AND WACKESTONE

Sandy packstone and wackestone contain from 10% to 25% very fine-grained detrital quartz with dark-gray to greenish argillaceous (?) lime mud matrix and occurs in 1 to 3 foot (30 to 100 cm) intervals. Sandy limestone displays abrupt to gradational lower and upper contacts and is planar-laminated with rare ripple-laminations.

E-1: Sandy-skeletal packstone

Approximately 10% to 25% very fine-grained detrital quartz sand occurs in sandy-skeletal packstone along with minor brachiopod, pelmatozoan, and bryozoan fragments. The matrix is lime mud or microdolomite. Rare sponge spicules can be present. Lime mudstone occurs as laminae and/or lenses scattered throughout. Sandy-skeletal limestone is mottled as a result of bioturbation, and is planar-laminated and cross-laminated. Quartz is concentrated along certain laminae.

E-2: Sandy-peloidal packstone

Sandy-peloidal packstone contains 15% very fine-grained (0.12 to 0.25 mm) detrital quartz and peloids and is planar-laminated to cross-laminated. Minor grains

include foraminifers, calcispheres, and fragments of algae, pelmatozoans, brachiopods, and bivalves.

E-3: Sandy wackestone and packstone

Sandy wackestone and packstone contain 20% very fine-grained detrital quartz that is irregularly distributed. Very fine-grained fragments of sponge spicules or pelmatozoans occur in a stylolaminated lime mud matrix. Low-angle cross-laminations are common with minor pyrite scattered throughout.

Depositional environment of Microfacies E

Sandy limestones probably formed in environments close to the paleoshoreline and near a source of terrigenous sediment. These marginal marine environments apparently had normal marine salinity as indicated by minor pelmatozoan fragments. The presence of lime mud indicates relatively low-energy conditions, perhaps indicating open platform conditions protected behind shoals.

MICROFACIES G: OOLITIC AND SUPERFICIAL OOLITIC GRAINSTONE AND PACKSTONE

Ooids and superficial ooids dominate this microfacies. Ooids range from 0.20 to 1.20 mm in diameter and vary from well developed with many (> 20) cortex coatings to poorly developed with few (< 10) coatings. Ooids display both radial and tangential cortex structures and are moderately to well sorted with packed to open fabrics. Ooids can be micritized and can have spar-filled rim moldic to oomoldic porosity, dropped nuclei, and slightly spalled rims. Superficial ooids have 1 to 5 cortex coatings and commonly are medium to fine grained. High amplitude stylolites are common. Oolitic and superficial oolitic grainstone commonly is planar-laminated to cross-laminated.

G-1: Fine- to medium-grained, oolitic-superficial oolitic grainstone

Fine- to medium-grained ooids and superficial ooids are common to abundant. Many ooids are micritized completely, however, preservation of quartz or pelmatozoan nuclei indicate that the grains were originally ooids. Brachiopod spines, foraminifers, pelmatozoans, and recrystallized bivalves with micritic rims are minor grains. Some micritized ooids have rim moldic spar-filled porosity and dropped nuclei. Ooid nuclei are fragments of *Donezella*, foraminifers, pelmatozoans, and bryozoans, and rarely quartz. The grainstone commonly is planar-laminated and cross-laminated. Pyrite is a minor constituent.

G-2: Oolitic grainstone

Large (1.0 mm) well-developed ooids with radial to tangential cortex dominate the oolitic grainstone. Large (1.0 mm) foraminifers, algal-coated allochems, pelmatozoans with micrite rims, bryozoans, and bivalves are minor grains. Ostracods, trilobite fragments, gastropods, and intraclasts composed of ooids and superficial ooids

are rare. *Archaeolithophyllum* and *Donezella* can be present. Ooid nuclei consist of fragments of gastropods, pelmatozoans, bryozoans, bivalves, and foraminifers. Rim moldic spar-filled porosity and spalled rims are rare.

G-3: Oolitic-superficial oolitic packstone

Ooids and superficial ooids are common. Ooids are moderately to well developed. Minor accessory grains include oncoids, pelmatozoans, foraminifers, spiculitic intraclasts, rounded bryozoans, gastropods, bivalves, ostracods, and rounded *Asphaltina*. Some ooid rims are replaced by clear euhedral rhombic dolomite.

G-4: Superficial oolitic grainstone and packstone

Superficial oolitic grainstone and packstone are composed of abundant superficial ooids with minor ooids. Dropped nuclei and spar-filled rim moldic porosity are common whereas only minor amounts have slightly spalled rims. Gastropods, bryozoans, bivalves, rounded *Asphaltina*, large rounded and spherical peloids, pelmatozoans, and algae are minor grains.

G-5: Superficial oolitic-*Donezella* grainstone

Superficial ooids and *Donezella* dominate with minor ooids, foraminifers, and pelmatozoans. Brachiopods, algae, bivalves, and ostracods are rare. Allochems are well rounded and moderately abraded.

Depositional environment of Microfacies G

Commonly warm, shallow (2 to 5 meters deep), high-energy, agitated waters are required for ooid development (Scoffin, 1987). Superficial ooids may form in more marginal conditions on flanks of ooid shoals or in slightly deeper water. Oolitic packstone probably formed adjacent to shoals where ooids may be washed into less agitated environments. Dropped nuclei and rim moldic spar-filled porosity indicate leaching, possibly by undersaturated meteoric waters associated with subaerial exposure surfaces during relative lowstands of sea level (see Chapter 3).

MICROFACIES H: CHERT

Some thin sections are entirely composed of microcrystalline chert, therefore, chert was designated as a microfacies. Two chert microfacies were defined by the presence or absence of recognizable ghosts of carbonate allochems.

H-1: Chert with ghosts of allochems

Microcrystalline chert dominates with minor ghosts of brachiopods, pelmatozoans, bryozoans, and peloids. The chert contains 5% detrital quartz.

H-2: Chert with no ghosts

This microcrystalline chert has no evidence of ghosts of carbonate allochems. The chert contains up to 5% detrital quartz.

Depositional environment of Microfacies H

Chert is entirely diagenetic and is not restricted to any environment or lithology.

MICROFACIES J: SANDSTONE

Microfacies J is uncommon and consists of 1- to 2-foot-thick intervals of sandstone composed of fine- to very fine-grained detrital quartz with rare chert grains. The sandstone is cemented by calcite and contains minor amounts of pyrite. It is dark to medium green and is planar-laminated to cross-laminated.

Depositional environment of Microfacies J

Sand most likely was deposited in shallow-water conditions close to the paleoshoreline and a source of terrigenous sediment. The influx of terrigenous sand may indicate a lowering of sea level. As significant amounts of terrigenous detrital material spread over the inner (or exposed?) carbonate platform, carbonate production ceased yielding a bioclast-free sandstone.

MICROFACIES K: PELMATOZOAN-BRACHIOPOD GRAINSTONE

Pelmatozoan-brachiopod grainstone contains abundant pelmatozoan fragments (most likely crinoids) with common thin-shelled brachiopods. Minor peloids, foraminifers, bryozoans, calcispheres, and algal-coated allochems occur along with rare ooids.

Depositional environment of Microfacies K

Grainstones occur above wave base where wave action winnows away lime mud. The dominance of pelmatozoan and brachiopod fragments indicate normal-marine conditions. The pelmatozoan-brachiopod grainstone most likely formed above wave base within open-platform environments, however, the presence of minor amounts of peloids, algal-coated allochems and calcispheres indicate a close association with restricted-platform environments.

MICROFACIES L: BRYOZOAN-PELMATOZOAN PACKSTONE

Bryozoans and pelmatozoans are the dominant grain types with a variety of accessory allochems. Many of the skeletal grains are whole and articulated. The matrix is lime mud or microdolomite and commonly contains scattered euhedral dolomite rhombs.

L-1: Bryozoan-pelmatozoan packstone

Bryozoans and pelmatozoans dominate with minor amounts of whole brachiopods, bivalves, algally-coated grains, foraminifers, gastropods, *Asphaltina*, and algae. Peloids and ostracods are rare. Dolomitic matrix with euhedral dolomite rhombs can contain up to 5% detrital quartz. Many allochems are large and/or whole.

L-2: Bryozoan-pelmatozoan-oolitic-superficial oolitic packstone

Bryozoan and pelmatozoan fragments along with ooids and superficial ooids are the dominate grains. Brachiopods, bivalves, foraminifers, algally-coated allochems, gastropods, and *Asphaltina* are minor grains. Areas appear to have a clotted fabric that may be algal. Allochems are large and unbroken.

L-3: Mottled bryozoan-pelmatozoan packstone

Bryozoan and pelmatozoan fragments dominate with minor peloids, algae, foraminifers, *Asphaltina*, whole brachiopods, and ostracods. The packstone is commonly mottled due to bioturbation.

Depositional environment of Microfacies L

Bryozoan-pelmatozoan packstone forms in low-energy, normal-marine conditions near or below wave-base where waters are not agitated enough to winnow away lime mud. These conditions may occur in open-platform environments protected behind shoals or in open-marine environments below wave base. Distinction between these environments depends on the vertical succession of associated lithologies.

MICROFACIES M: WACKESTONE

Wackestone contains minor amounts of a variety of allochems with no dominant grain type supported within a muddy matrix. The grains include peloids, foraminifers, fenestrate bryozoan fragments, thin-shelled brachiopods, pelmatozoan fragments, sponge spicules, algae, ostracods, calcispheres, bivalves, ooids, intraclasts, and trilobite fragments . The allochems commonly are whole and unabraded. Minor amounts of very fine-grained detrital quartz can be present. Wackestones are tan to brown and are either planar-laminated or mottled as a result of bioturbation.

M-1: Wackestone

No one grain type dominates. Minor amounts of peloids, foraminifers, thin-shelled brachiopods, pelmatozoan and bryozoan fragments, sponge spicules, algae, ostracods, and calcispheres occur. Pyrite, hematite, and limonite are present along stylolaminations. As much as 2% to 3% detrital quartz is scattered throughout a lime mud or slightly dolomitic matrix. The wackestone microfacies is commonly mottled and rarely planar-laminated.

M-2: Wackestone with dolomitized matrix

The lime mud matrix of many wackestones is preferentially dolomitized. Minor amounts of brachiopods, peloids, fenestrate bryozoans, pelmatozoans fragments, ostracods, foraminifers, and bivalves occur with rare trilobites, algally-coated allochems, ooids, and intraclasts of mudstone and oolite. Some full-frond (unabraded) fenestrate bryozoans and whole brachiopods occur. Wackestone commonly is burrowed and/or mottled, a result of bioturbation.

Environment of Deposition For Microfacies M

Wackestones form in a variety of low-energy conditions generally below normal wave base in open-marine or open-platform conditions (Flügel, 1982). Wackestones with whole fossils and few bioclasts may represent deposition in an open platform (open-circulation shelf lagoon). An increase in allochem diversity indicates better circulation in open-platform or open-marine conditions (see Chapter 1). The presence of ostracods and peloids indicate proximity to restricted-platform environments. Ooids were transported from shoals into adjacent quiet water areas behind the shoal or seaward into open-marine below wave base environments (Flügel, 1982). Thus the composition of different wackestones and their position within a progradational succession help to define specific depositional environments.

MICROFACIES N: FORAMINIFERAN GRAINSTONE AND PACKSTONE

Foraminifers dominate some intervals of grainstone and packstone. Minor accessory grains include peloids, calcispheres, ostracods, brachiopods, bryozoans, intraclasts, ooids, algae, and superficial ooids. Allochems are poorly sorted and exhibit moderate to strong grain abrasion.

N-1: Foraminiferan-pelmatozoan grainstone and packstone

Foraminifers and pelmatozoans are the dominant grains with minor amounts of peloids, calcispheres, ostracods, and brachiopod and bryozoan fragments. Ooids are rare. Some areas within the packstone have a clotted fabric that may be algal. Packstone may be bioturbated.

N-2: Foraminiferan-pelmatozoan-algally-coated allochem grainstone

Foraminifers, pelmatozoan, and algally-coated allochems dominate and range in size from 0.50 to 1.00 mm. Minor accessory grains consist of brachiopods, calcispheres, algae, mudstone intraclasts, *Asphaltina*, ooids, and superficial ooids. *Stacheia* and *Archaeolithophyllum* are rare. *Donezella* may be present.

Depositional environment of Microfacies N

Foraminiferan packstone and grainstone microfacies is uncommon. This microfacies contains a wide diversity of allochems indicative of mixing of grains

derived from a variety of depositional environments. Peloids, calcispheres and ostracods occur in restricted-platform environments whereas ooids form in high-energy shoal conditions and brachiopods and bryozoans occur in normal-marine conditions. The foraminiferan grainstone and packstone are interpreted to represent channel deposits occurring within tidal and subtidal platform environments. The variety of grain types most likely is a result of mixing of allochems in channels.

Alternatively, this microfacies could represent storm ebb deposits (G. J. Palko, pers. comm. 1993). Strong storm surges would certainly mix sediment types and the ebb flow can dissipate rapidly preventing any significant sorting from occurring. If these deposits occur in thin and seemingly random beds, with sharp basal contacts and sedimentary structures indicative of high energy (e.g. size grading), then they may represent marker beds of storm events. Such deposits would be more widespread than lenticular tidal channel deposits and might be useful for correlation.

MICROFACIES O: *DONEZELLA* GRAINSTONE AND PACKSTONE

Donezella is a segmented branching calcareous alga and generally occurs as very fine-grained (0.06 to 0.12 mm) to fine-grained (0.12 to 0.25 mm) fragments. Minor allochems include ooids, foraminifers, pelmatozoan and bryozoan fragments, bivalves *Asphaltina*, *Archaeolithophyllum*, and algally-coated grains. Grains are moderately to well sorted and are moderately abraded.

O-1: *Donezella*-ooid grainstone and packstone

Donezella dominates with lesser amounts of well-developed ooids and minor amounts of *Archaeolithophyllum*, foraminifers, pelmatozoans, bryozoans, brachiopods, bivalves, algally-coated allochems, and *Asphaltina*. Intraclasts are rare. The grainstone can be planar-laminated.

O-2: *Donezella* grainstone and packstone

Donezella also dominate other grainstones and packstones that contain minor amounts of pelmatozoans, foraminifers, and algae. Rare bryozoans, brachiopods, ostracods, calcispheres, and peloids can be scattered through this microfacies.

Depositional environment of Microfacies O

Donezella are associated with allochems typical of high-energy shoal and normal-marine environments (ooids, foraminifers, *Archaeolithophyllum*, pelmatozoans, bryozoans, and brachiopods) and with allochems characteristic of restricted-platform environments (ostracods, calcispheres, and peloids). Thus, *Donezella* grainstone and packstone microfacies formed in moderate energy environments located behind ooid shoals, most likely in open-platform environments that were closely association with restricted-platform conditions. *Donezella* can form small bioherms in these somewhat protected, shallow marine environments.

PARASEQUENCES AND ZONES OF THE WAHOO LIMESTONE

The Wahoo Limestone of the Lisburne field is extremely heterogeneous, with the above noted microfacies organized into numerous thin carbonate cycles/parasequences. Our preliminary analyses of the study well recognize as many as 59 coarsening-upward parasequences in the Wahoo (55 in the upper Wahoo and 4 in the lower Wahoo). The coarsening-upward parasequences have shale, siltstone, calcareous mudstone, or lime mudstone at the base and pass gradationally upward into grainstone. Where such muddy lithologies do not occur, parasequence boundaries are marked by abrupt changes in lithology in contrast to gradational lithologic changes within parasequences. These coarsening-upward parasequences, however, may not precisely coincide with shallowing-upward cycles because coarser grained lithologies do not necessarily indicate shallower conditions. For example, tidal flat or lagoonal deposits may be muddier than more seaward shoal deposits. The definition of shallowing-upward (progradational) cycles is based on interpretations of depositional environments using microfacies analysis and considering interrelationships between adjacent lithologies within individual parasequences. The interpretation of some microfacies, such as sandy limestones, are uncertain at this point and require additional paleoenvironmental analysis. After more detailed analysis of Wahoo cyclicity, the position of parasequence boundaries may be changed to more correctly define progradational shallowing-upward cycles bounded by marine flooding surfaces.

The Wahoo Limestone can be subdivided into eight zones that each contain several parasequences having similar characteristics (Fig. 4-3; core depths are uncorrected measured depths). Each zone is bounded by 2- to 11-foot-thick intervals of moderately calcareous to noncalcareous green to tan siltstone, mudstone or shale. These argillaceous intervals are widespread and easily recognizable on gamma-ray logs and have been used for correlation within the Lisburne field (Fig. 4-3; Jameson, 1990a&b, in revision). Previous studies of the Lisburne field have recognized seven zones bounded by argillaceous intervals within our upper Wahoo (Okland et al., 1987; Kaldi et al., 1990; Jameson, 1990a&b, in revision; Stanulonis and Tran, 1992). Our zonation scheme generally corresponds to this previously established zonation but we recognize an eighth zone corresponding to our lower member of the Wahoo Limestone (the upper Alapah of previous workers).

The upper Wahoo Limestone member contains as many as 55 coarsening-upward parasequences and is subdivided into seven zones, Zone 8 at the top of the Wahoo descending through Zone 2 above the upper-lower Wahoo contact. Microfacies analyses have been completed for Zones 8 through 5 allowing construction of detailed lithologic columns that are presented below. Each zone contains parasequences composed of characteristic lithologies as illustrated in a series of idealized models that summarize the progradational succession of lithologies encountered in parasequences for each zone. However, the parasequences within each zone are more complicated than shown in these simplified models, having more variable lithologic successions and/or basal lithologies. Together, the different parasequences represent a spectrum of

progradational shallow subtidal microfacies and associated paleoenvironments that formed along the inner part of the Wahoo carbonate ramp.

The lower Wahoo Limestone member represents a single zone (Zone 1) and contains at least 4 parasequences as defined by core descriptions and gamma-ray log data. However, additional parasequences may be distinguished following more detailed microfacies analysis. It is bounded above and below by relatively thick argillaceous intervals; both are major terrigenous influxes associated with sequence boundaries (see above). Lithologies within the lower Wahoo include bryozoan-pelmatozoan packstone and grainstone, ripple-laminated, peloidal grainstone-packstone, oolitic grainstone, and microdolomite.

ZONE 8: ONCOLITIC PARASEQUENCES

Zone 8 is 79 feet thick (24 m), extending from the unconformable contact between the Wahoo Limestone and the Sadlerochit Group at 9282 feet down to the base of an argillaceous interval at 9361 feet. The zone is characterized by oncolitic coarsening-upward parasequences and contains four parasequences ranging from 8 to 18 feet thick (Fig. 4-4). In ascending order, the idealized model for oncolitic coarsening-upward parasequence (Fig. 4-6) contains: (1) planar-laminated to bioturbated calcareous and dolomitic mudstone; (2) planar-laminated to bioturbated bryozoan-pelmatozoan packstone; (3) cross-laminated to ripple-laminated bryozoan-pelmatozoan-peloidal grainstone and packstone; (4) oncolitic intraclastic grainstone and packstone. Mudstone does not occur at the base of all the oncolitic parasequences in Zone 8; bryozoan pelmatozoan packstone forms the basal part of some parasequences.

ZONE 7: OOLITIC-CAPPED PARASEQUENCES

Zone 7 is at least 113 feet thick (34 m) and contains seven parasequences that are 8 to 23 feet thick (Fig. 4-7). The top of Zone 7 is at the base of the shaly interval at 9361 and its base lies between 9474 to 9480 feet (the intervening interval had incomplete core recovery). Although we originally placed the zone boundary above a sandstone at 9474 feet, it may be lower as suggested by high gamma-ray log kick at 9480 (see Fig. 4-9) that probably indicates an argillaceous interval not recovered by coring. In ascending order, the idealized model for oolitic-capped coarsening-upward parasequences (Fig. 4-8) contains: (1) a basal spiculitic calcareous and dolomitic mudstone; gradationally overlain by (2) bryozoan-pelmatozoan packstone that commonly contains articulated fossils and dolomitic matrix; (3) peloidal-foraminiferan grainstone that includes minor intervals of packstone; capped by (4) cross-laminated and planar-laminated oolitic and superficial oolitic grainstone. Ooids commonly have dropped nuclei and spar-filled rim-moldic porosity and some ooids are micritized. Sandy limestone and oncolitic grainstone cap some of the parasequences rather than oolitic grainstone or packstone. The highest parasequence contains a thick interval of oncolite similar to those in Zone 8 but falls below the gamma-ray log kick at 9361 (the boundary between zones 7 and 8).

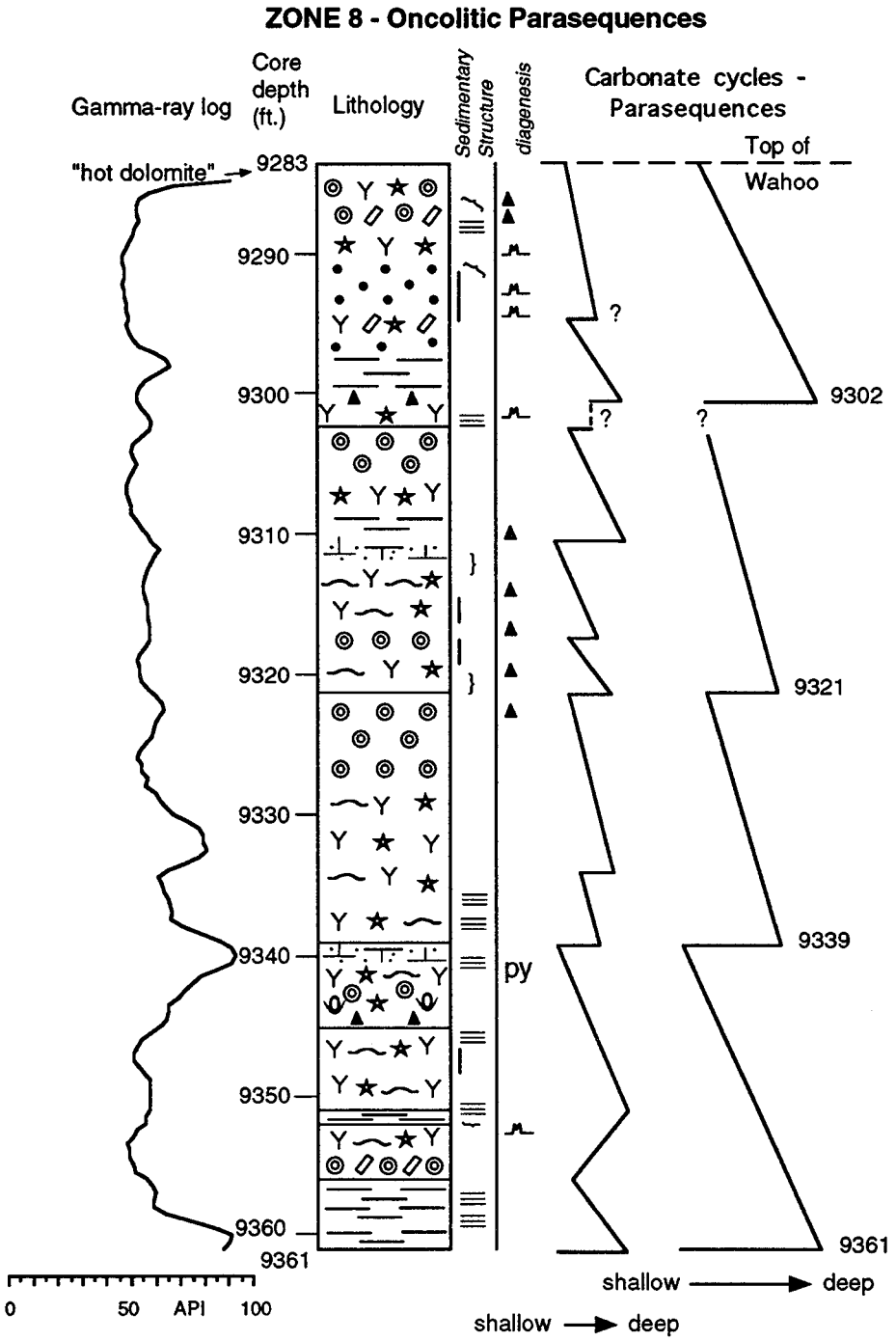
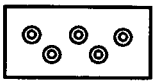
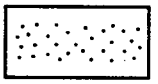


Figure 4-4. Stratigraphic column for the Zone 8 shows different lithologies, tentative interpretations of carbonate cycles (parasequences) and a gamma-ray log trace imported from the Wahoo database (converted to uncorrected measured depth).

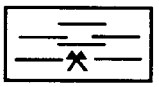
EXPLANATION

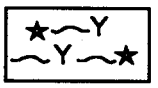

Oncolitic and algal grainstone and packstone

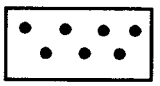

Sandstone

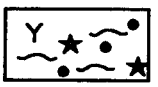
Bryozoan and pelmatozoan grainstone

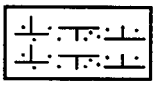
Pelmatozoan and brachiopod grainstone

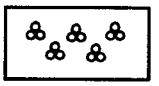

Dolomitic and lime mudstone and spiculitic wackestone

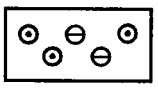

Bryozoan and pelmatozoan packstone

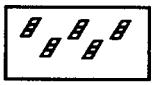

Peloidal grainstone, packstone, and wackestone

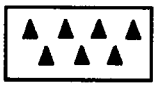

Dolomitic and lime skeletal peloidal wackestone


Sandy limestone


Foraminifer grainstone and packstone


Oolitic and superficial oolitic grainstone


Donezella grainstone and packstone


Chert

Grain Types				Sedimentary Structure		Diagenetic Features	
	intraclast	•	peloid	≡	planar laminae	▲	chert
★	pelmatozoan	◎	oncolite		cross-bedded		stylolites
Y	bryozoan	⊙	ooid		ripple laminae	py	pyrite
	foraminifer	⊖	superficial ooid		bioturbated		
	brachiopod		sponge spicules		highly bioturbated		

Figure 4-5. Key to symbols used on stratigraphic columns.

Idealized Oncolitic Coarsening Upward Parasequence Characteristic of Zone 8

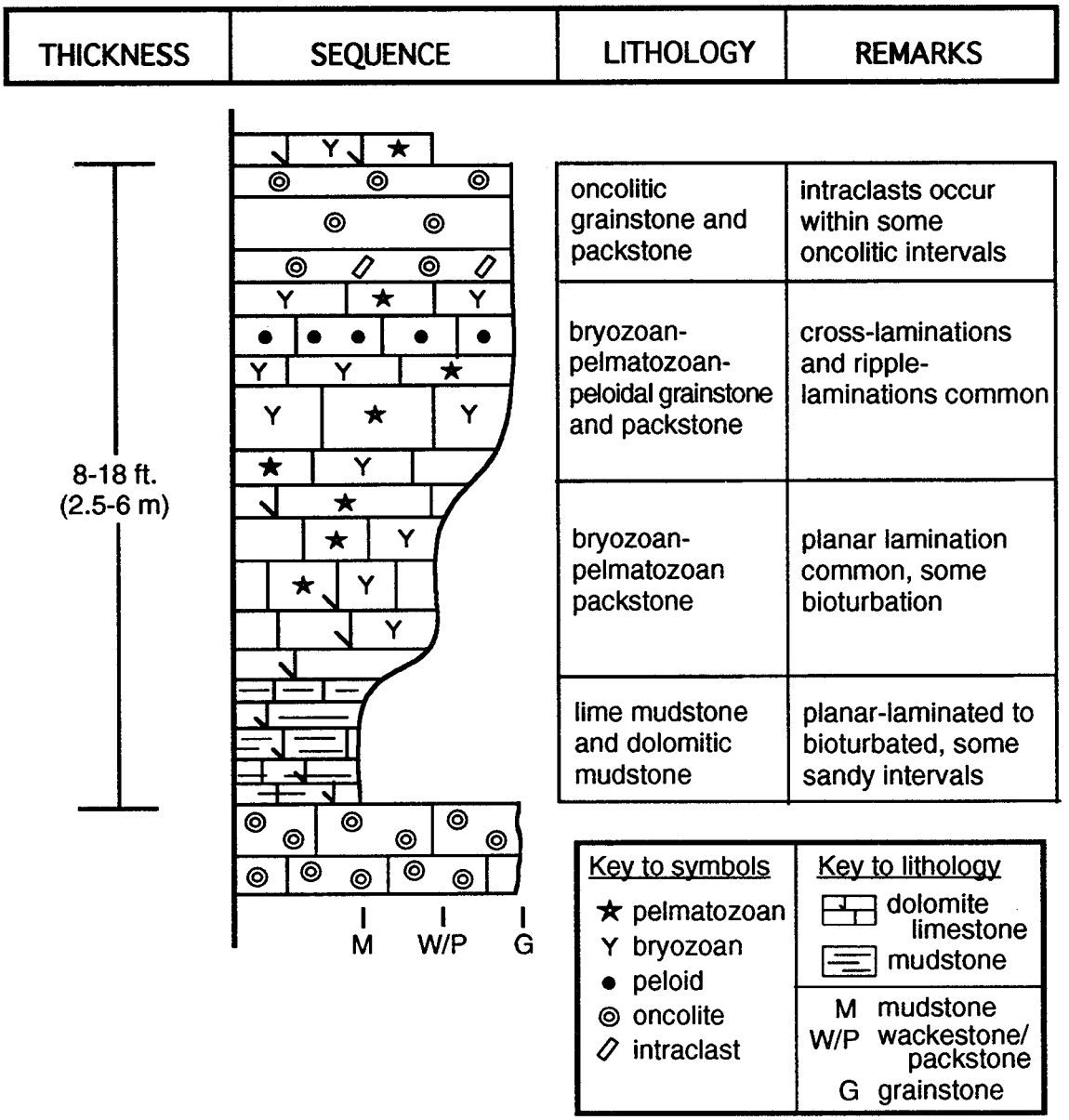


Figure 4-6. Idealized model for parasequences in Zone 8.

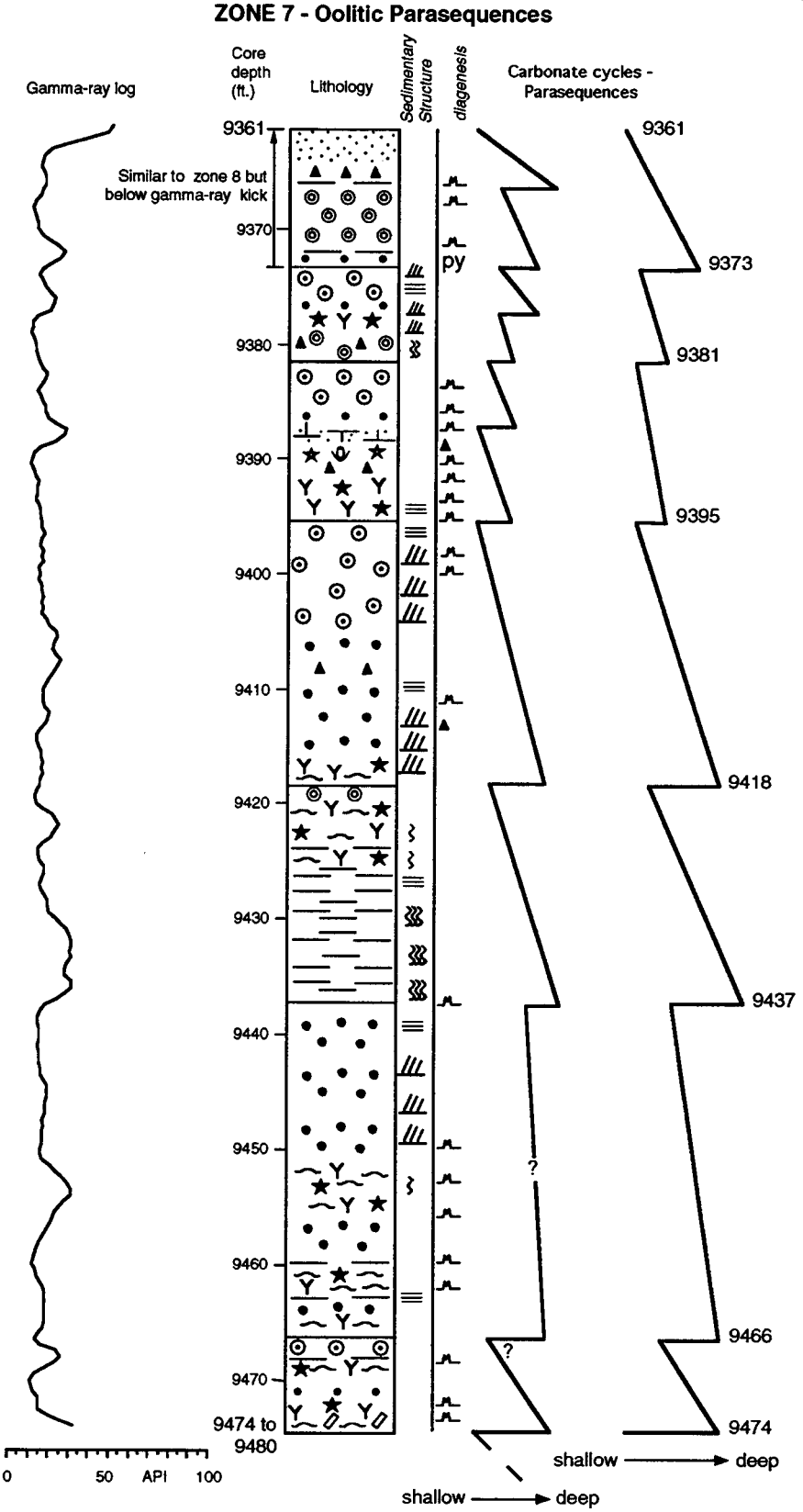


Figure 4-7. Stratigraphic column for the Zone 7 shows different lithologies, tentative interpretations of carbonate cycles (parasequences) and a gamma-ray log trace imported from the Wahoo database (converted to uncorrected measured depths).

Idealized Oolitic Coarsening-upward Parasequences Characteristic of Zone 7

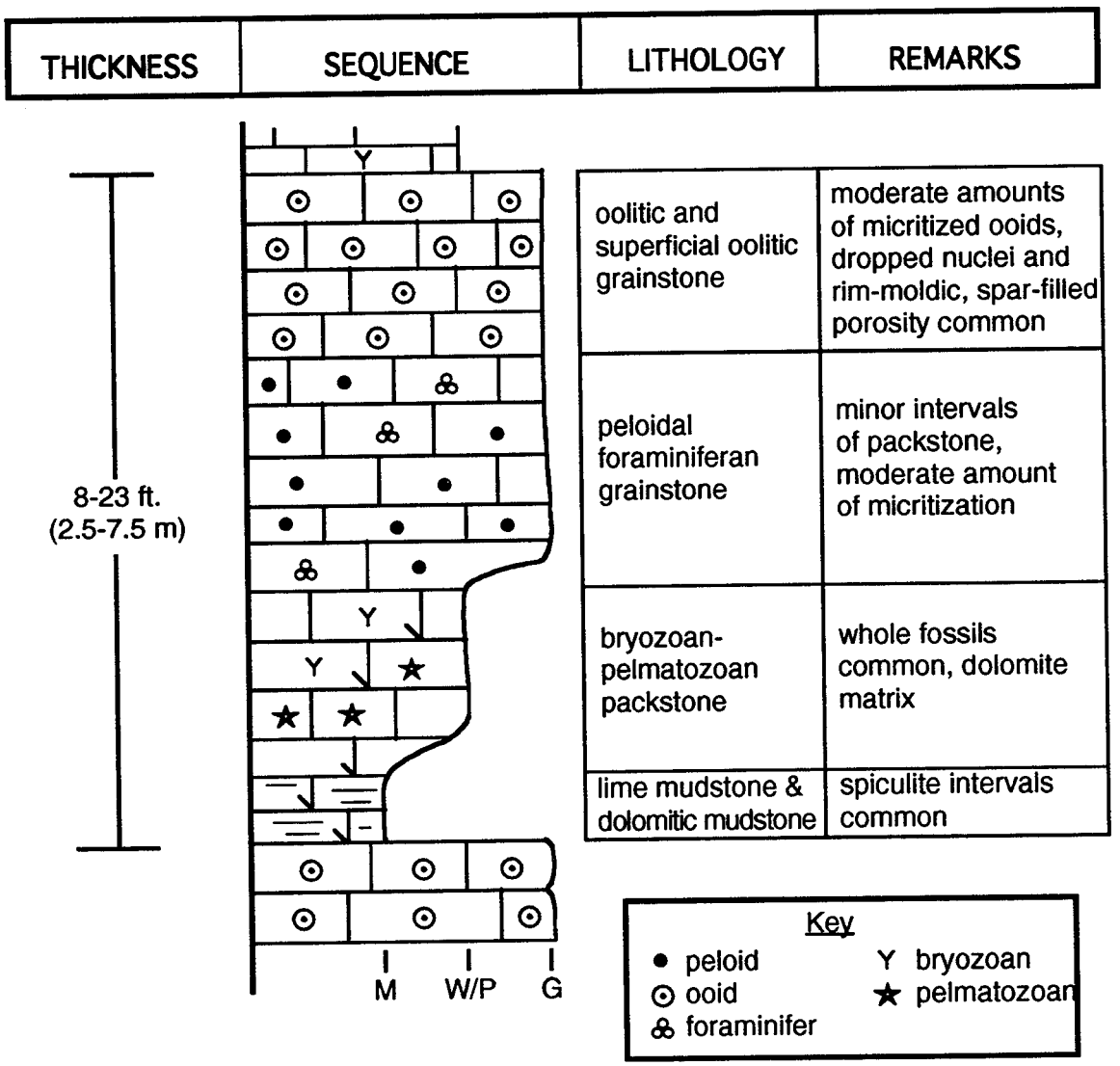


Figure 4-8. Idealized model for parasequences in Zone 7.

ZONE 6: *DONEZELLA*-OOLITIC PARASEQUENCES

Zone 6 is 104 -110 feet thick (31-33m) and contains six parasequences that are characterized by abundant *Donezella* algae and ooids and commonly are capped by sandy skeletal limestone (Fig. 4-9). Zone 6 extends from 9474 at the top (possibly as low as 9480; see discussion in Zone 7) down to the base of a well-defined shaly interval at 9584 feet. In ascending order, the idealized model for *Donezella*-oolitic coarsening-upward parasequences (Fig. 4-10) consists of: (1) bioturbated calcareous and dolomitic mudstone; (2) bioturbated bryozoan-pelmatozoan packstone and wackestone that commonly contain articulated skeletal grains; (3)*Donezella* grainstone and packstone with minor well-developed ooids; abruptly overlain by (4) generally cross-laminated oolitic and superficial oolitic packstone with minor oncoids and skeletal fragments; and capped by (5) planar-laminated sandy (up to 25% quartz) skeletal limestone. Half of the parasequences within this zone are incomplete, lacking sandy caps or mudstone bases. Incomplete parasequences generally are capped with *Donezella* or oolitic grainstone. Other incomplete parasequences begin with bioturbated bryozoan-pelmatozoan packstone and wackestone at the base.

ZONE 5: OOLITIC-*DONEZELLA*-PELOIDAL PARASEQUENCES

Zone 5 is 191 feet (58 m) thick and contains as many as eleven 9- to 26-foot-thick oolitic-*Donezella*-peloidal parasequences (Fig. 4-11). Zone 5 is bounded by well-developed shaly intervals at 9584 and 9775 feet (Fig. 4-3). In ascending order, the idealized model for the oolitic-*Donezella*-peloidal coarsening-upward parasequences (Fig. 4-12) contains: (1) planar-laminated to bioturbated calcareous and dolomitic mudstone; (2) peloidal-skeletal packstone; (3) planar-laminated to non-laminated *Donezella* grainstone (bafflestone) and packstone; (4) superficial oolitic-*Donezella* grainstone; and is capped by (5) **rarely** cross-laminated oolitic and superficial oolitic grainstone. The majority of the parasequences in Zone 5 are incomplete and contain a wide range of lithologies. Two intervals contain sandy-skeletal limestone and another contains 3 foot (1 m) thick interval of calcite-cemented quartz sandstone. Basal lithologies in parasequences include mudstone, peloidal, and skeletal packstone. The parasequences are capped by intervals of oolitic or *Donezella*, grainstone and sandstone.

ZONES 4 THROUGH 1

Detailed microfacies analysis has not been completed for Zones 4 through 1. The following thicknesses of these zones and numbers of parasequences or cycles within each zone are derived from gamma-ray log and core descriptions and may be subject to change following microfacies analyses. Zone 4 extends from 9775 to 9839 feet and may contain as many as four parasequences. Zone 3 also contains up to four parasequences and extends from 9839 to 9899 feet. Zone 2 extends from 9899 to 10,169 feet and contains as many as 15 parasequences. Zone 1 represents the lower Wahoo, extending from 10,169 to 10,372 and is made up of at least four parasequences.

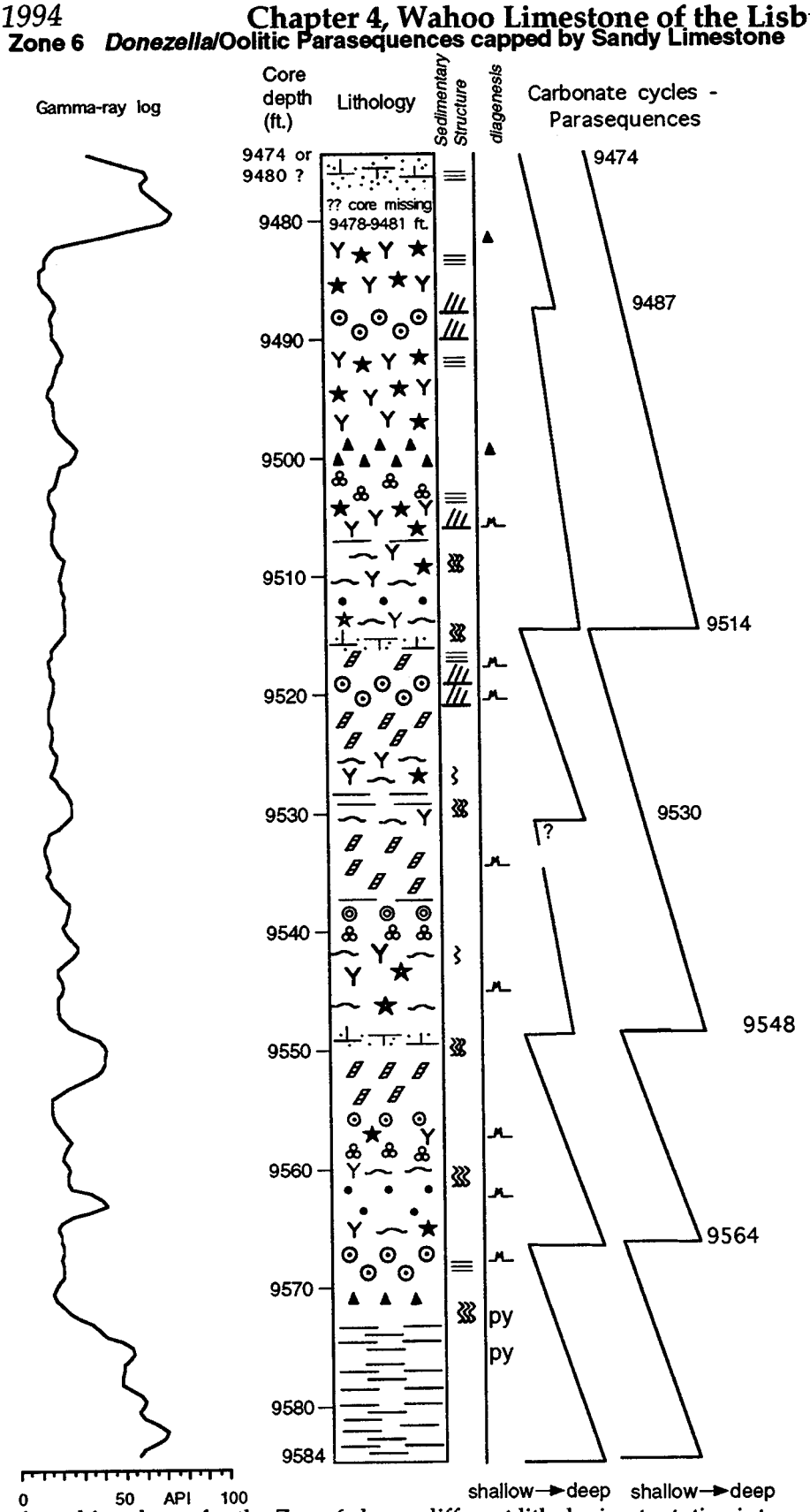


Figure 4-9. Stratigraphic column for the Zone 6 shows different lithologies, tentative interpretations of carbonate cycles (parasequences) and a gamma-ray log trace imported from the Wahoo database (converted to uncorrected measured depths).

Idealized *Donezella*/Ooid Coarsening-upward Parasequence Characteristic of Zone 6

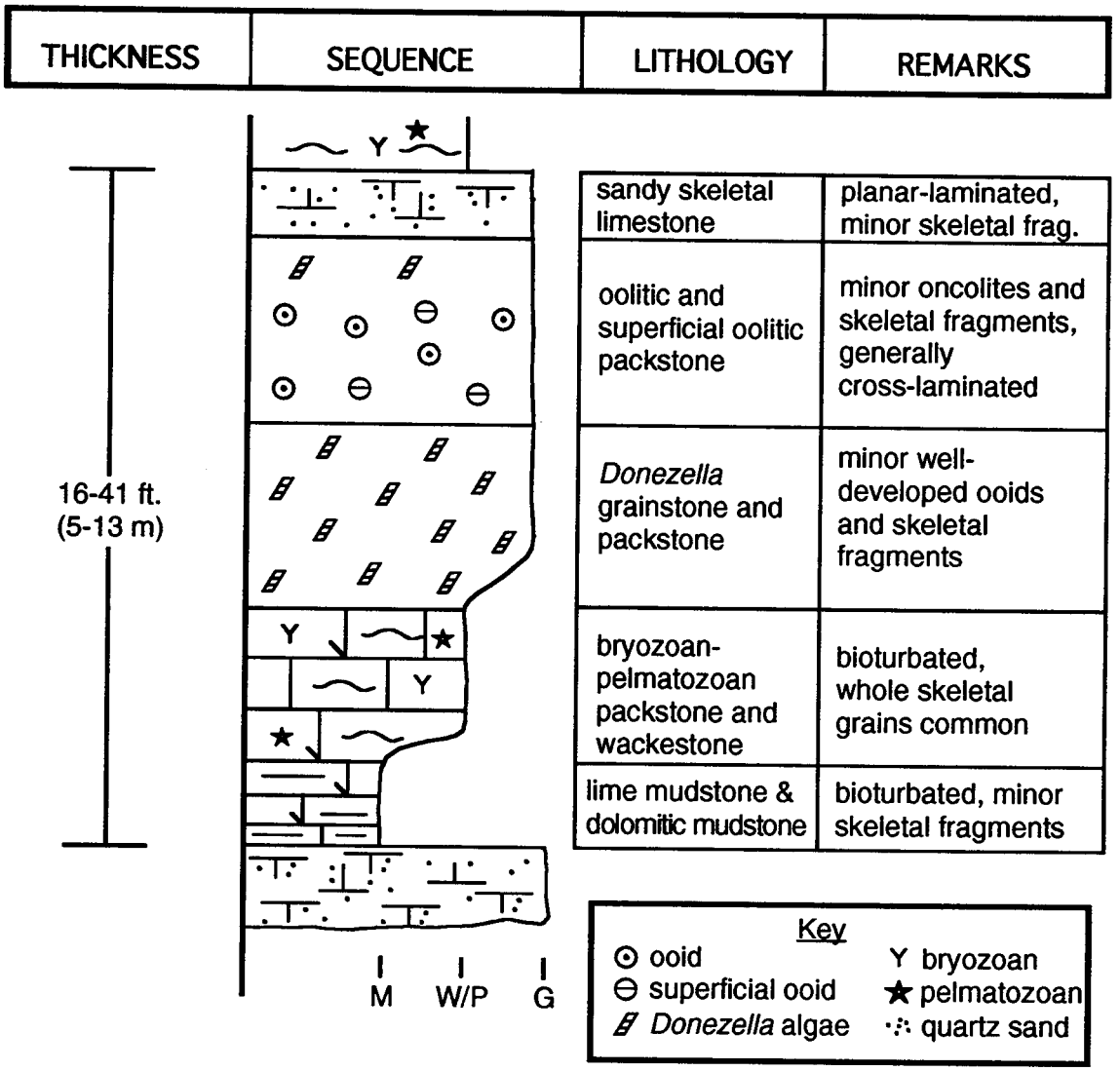


Figure 4-10. Idealized model for parasequences in Zone 6.

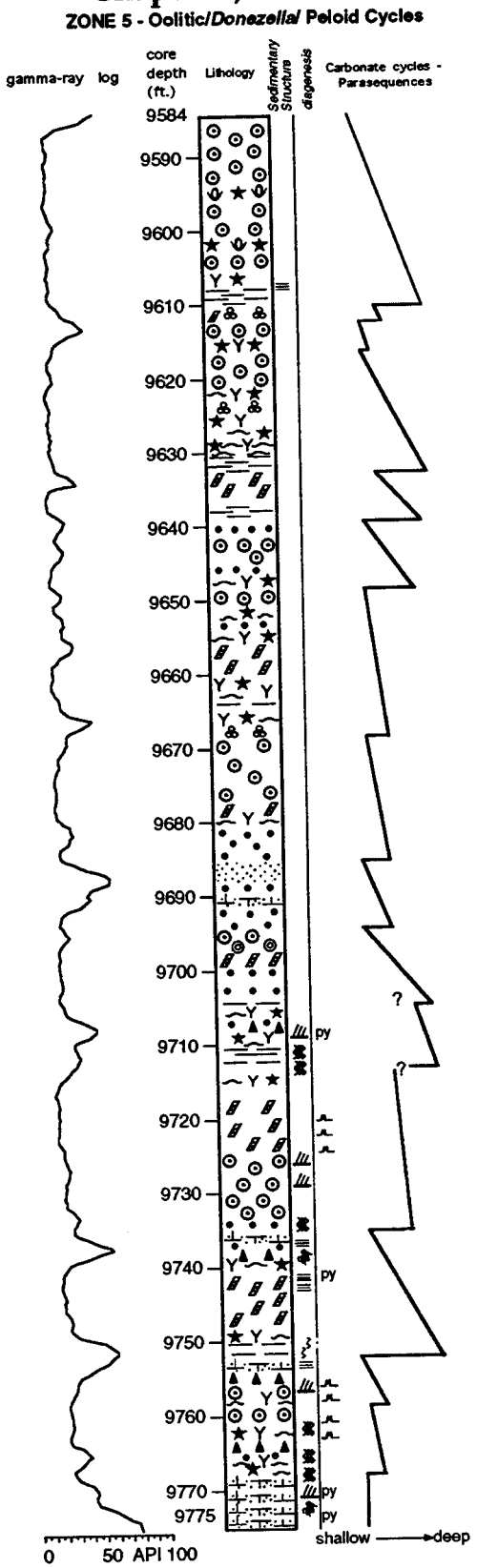


Figure 4-11. Stratigraphic column for the Zone 5 shows different lithologies, tentative interpretations of carbonate cycles (parasequences) and a gamma-ray log trace imported from the Wahoo database (converted to uncorrected measured depths).

Idealized Oolitic-*Donezella*-Peloid Coarsening Upward Parasequence Characteristic of Zone 5

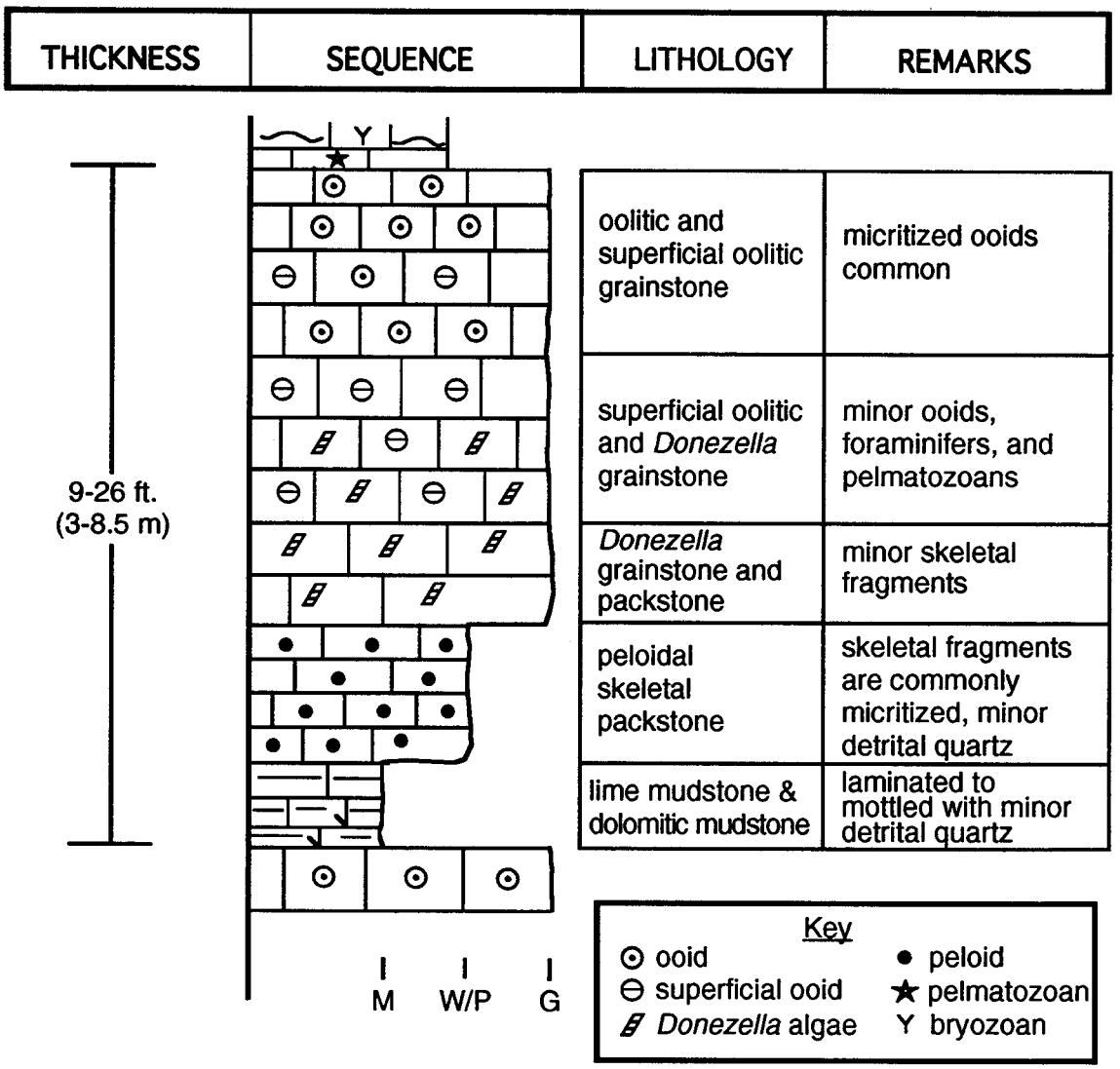


Figure 4-12. Idealized model for parasequences in Zone 5.

SIGNIFICANCE OF TERRIGENOUS SEDIMENT

The Wahoo Limestone at Prudhoe Bay contains significantly more terrigenous sediment than the Wahoo exposed farther east and south in the Arctic National Wildlife Refuge (ANWR). The distribution of terrigenous material within the Wahoo was probably influenced by the interplay of sea-level fluctuations, carbonate platform geometry, and proximity to sources of terrigenous clastic sediment.

Thick intervals containing abundant terrigenous sediment mark major sequence boundaries between the lower and upper members of the Wahoo Limestone (at 10,118-10,173 feet) and between the Wahoo and Alapah limestones (at the 10382-10,391). The study well also contains several 2- to 11-foot-thick intervals of green shale and 1- to 3-foot-thick intervals of fine-grained sandstone. Thinner argillaceous intervals and admixtures of quartz in several microfacies indicate additional terrigenous influxes. In contrast, sandstone is absent and only minor intervals of shale (less than 1 foot / .3 meters thick) occur in the Wahoo exposed in ANWR (Carlson, 1987; Gruzlovic, 1991; Morgan, 1992).

Bird and Jordan (1977) noted that siliciclastic sediments increase within the Lisburne Group north of the Brooks Range in the Prudhoe Bay region. The Lisburne near Prudhoe Bay contains more siliciclastic sediment to the northwest with sandstone representing 30% of the Lisburne at the Milne Point well. The siliciclastic sediments include buff to light-gray, subangular, moderately sorted quartz and chert-grain sandstone cemented with calcite and minor amounts of red to gray shale that are interbedded with limestone and dolostone (Bird and Jordan, 1977). Jameson (in revision) also discusses this northward increase in terrigenous sediment, suggesting that a landmass was located some 8-16 kilometers north of Prudhoe Bay during the Pennsylvanian. The northwestward increase in siliciclastic sediment is interpreted to represent proximity to a northern paleoshoreline, perhaps along the Colville high or some other persistent basement high (eg. the Barrow Arch). In ANWR, the northeasternmost section (Clarence River, loc. 27 on Fig. 4-1) contains the most siliciclastic sediment and is interpreted to be the ANWR locality closest to the paleoshoreline.

The abundance to terrigenous sediment is probably related to its proximity to point sources of terrigenous sediments (i.e., rivers and deltas; c.f. Maxwell and Swinchatt, 1990). Thus, the relative abundance of terrigenous sediments in the Lisburne Group in the Prudhoe Bay region probably resulted from its proximity to an exposed landmass and paleoshoreline (Bird and Jordan, 1977; Jamison et al., 1980; Jameson, in revision). Areas that were distant from these terrigenous sources (eg. ANWR) were dominated by carbonate sediments lacking a significant terrigenous component. The Sadlerochit high in ANWR was apparently buried beneath the Lisburne carbonate platform following onlap in the late Mississippian (Chesterian, Mamet Zone 16s; see Chapter 1) and did not represent a source of terrigenous detritus during the Pennsylvanian. An intervening depocenter located near the Canning River (see Fig. 4-1)

and other irregularities on the Lisburne carbonate platform probably influenced distribution patterns of terrigenous sediment.

Terrigenous sands in carbonate successions have been ascribed to sea-level low stands and proximity to a paleoshoreline. Studies of the Great Barrier Reef shelf environment indicate that most terrigenous sediment is trapped in nearshore bathymetric lows during sea-level high stands, whereas terrigenous sediments are transported seaward across the emergent shelf during sea level lowstands (Maxwell and Swinchatt, 1990). However, the ramp geometry of the Wahoo carbonate platform is different than the northeastern Australia shelf and was characterized by migration of broad facies belts during sea level fluctuations. Thus it is possible that nearshore siliciclastic sediments represent lowstand deposits.

Intervals of terrigenous mud within carbonate parasequences have been interpreted to result from relatively rapid flooding events (Osleger and Read, 1991; Gruzlovic, 1992). In these models, condensed intervals of fine-grained terrigenous sediment accumulate after rapidly deepening waters causc incipient platform drowning and resultant decrease in carbonate production. After carbonate production resumes, however, carbonate sediments quickly accumulate to fill available accommodation space until a new flooding episode begins the cyclic pattern anew. Thus, widely distributed terrigenous muds may be more indicative of incipient platform drowning events.

In summary, terrigenous sediments are more abundant in the Prudhoe Bay region because of its proximity to a landmass that supplied terrigenous sediment. The shale to argillaceous limestones in the Wahoo typically occur at the base of shallowing upward cycles (parasequences) and seem to represent relatively condensed intervals that formed during relative sea-level highstands. However, the sandstones and sandy limestones may represent low-stand deposits that cap shallowing-upward cycles (parasequences). Thus, the distribution of terrigenous sediments within the Wahoo Limestone may be complex, possibly representing both sea level highstand and lowstand deposits.

FUTURE ANALYSES

A major focus of Morgan's continuing Ph.D. studies will be analysis of carbonate cycles in the study well. After completing the remaining microfacies analyses, the interrelationships of different microfacies will be used to confirm the position of parasequence boundaries and develop a better understanding of the progradational succession of lithologies comprising the Lisburne Group and their associated depositional environments. The study well extends our understanding of cyclicity to the inner part of the Wahoo Limestone carbonate ramp where terrigenous influx played an important role. A final goal will be comparison of carbonate cycles in the Lisburne field with correlative but different carbonate cycles that formed farther down the Wahoo carbonate ramp in ANWR (locs. 27, 8, & 13 on Fig. 4-1; see also Chapter 1). Analyses of the study well will also include comparison between well logs and microfacies analyses

recorded the Wahoo computerized database (see Chapter 5), and consideration of the relationship between different microfacies and reservoir characteristics. Although determining the relationship between different lithologies comprising carbonate cycles (parasequences) and reservoir characteristics was identified as a goal in our original research proposal, recent work by industry indicates that fracturing may be more important than carbonate microfacies in controlling hydrocarbon production in the Lisburne field Jameson, 1990a, 1991). However, variations in porosity and permeability are certainly related to different microfacies, and play an important (albeit secondary) role in reservoir behavior in the heterogeneous Lisburne field.

Chapter 5

Instruction manual for the *Wahoo* Computerized Database

by Dan Lasota and Keith Watts

ABSTRACT

As part of our research on the Lisburne Group, we have developed a powerful relational computerized database to accommodate the huge amounts of data generated by our multi-disciplinary research project. Using *4th Dimension* database program on an Apple Macintosh IIx or better computer (e.g., Quadra), we have established a menu-driven structure that allows easy input and output of data. The *Wahoo* database has data files on petrographic data, conodont analyses, locality and sample data, well logs and diagenetic (cement) studies. The database is a useful research tool that has helped us record and quantify the nature of the complex carbonate microfacies of the Lisburne Group.

Chapter 5 is essentially an instruction manual that summarizes some of the unique attributes and operating procedures of the *Wahoo* database. The user should also refer to the general instruction manual provided with 4th Dimension for basic information on the use of this program. The main purpose of a database is to allow users to manipulate their data and produce reports and graphs for presentation. We present a variety of data tables in appendices at the end of this report, each encapsulating a small part of the data contained in the *Wahoo* database. All the data are sorted and listed by map index number and stratigraphic position (depth).

The Locality data table (Appendix A) lists all the stratigraphic sections examined in our study. It gives names of study areas, stratigraphic units studied, locality information, and researchers. Most localities are keyed to a geologic map that shows the distribution of the Lisburne Group and location of our sections in ANWR.

Petrographic reports (Appendix B) are detailed summaries of data the composition and texture of the Lisburne Group carbonates. The relative abundance of different carbonate grains (allochems) and carbonate texture are listed using symbols that portray data in a format similar to stratigraphic columns. This enables researchers to recognize trends in the evolution of the Lisburne carbonate platform and to check their paleoenvironmental interpretations in a stratigraphic context. Some of the figures in Chapter 1 were made using the *Wahoo* database (Figs. 1-27 & 1-28).

INTRODUCTION

The *Wahoo* database is a powerful relational database that uses the *4th Dimension* (*4-D*) database program (copyright by Acius Inc.) on a Apple Macintosh computer. It contains information on rock samples, localities, petrographic analyses (carbonate microfacies), conodont analyses, diagenetic characteristics, and subsurface well logs from the Carboniferous Lisburne Group of the northern Alaska. A menu-driven input and manipulation structure allows easy data input and systematic analysis of data obtained from previous and ongoing research. The strength of the computerized database is its ability to search for selected characteristics (e.g., lithology or composition) and to quantify and/or illustrate variations in a heterogeneous rock unit, either within a vertical stratigraphic succession or between different localities.

The *Wahoo* database presently contains 12,689 sample records, 105 locality records, 3055 petrographic records, 342 conodont records, 5842 well log records, 378 cement (diagenesis) records, and other data. The data file alone contains over 22 megabytes of information. Because the user of this database is concerned with manipulating and analyzing these data, this manual will focus on data output procedures. Data input procedures also will be discussed in this manual. However, any data input or modifications made to the data files should be done on the primary database located at the University of Alaska Fairbanks in order to be permanently recorded. In most cases, changes made on computers other than the primary database cannot be accommodated (i.e., any changes made elsewhere will be lost when the database is updated). If necessary, data input at remote computers can be achieved and transferred to the primary *Wahoo* database via disk (see below, "Importing and exporting"). Editorial changes to existing records, however, cannot usually be transferred and still maintain the integrity of the database. However, it is possible for the user to have a copy of their own data and use it as they see fit. Another option is for a remote user to be temporarily in charge of the master set of data while they add or modify their records.

PURPOSE OF THIS MANUAL

From the beginning of the design phase, the *Wahoo* database was created with ease of use in mind. While the interface of *Wahoo* may look simple, its structure is not. There are a multitude of functions that the database is capable of performing. Many of these functions are an integral part of the 4th Dimension (*4-D*) database program and are discussed in its instruction manuals. It is intended that the *Wahoo* manual point out only those features that are unique to the *Wahoo* database or that may not immediately be apparent in the *4-D* User's manual.

Most of the questions that might arise on using *Wahoo* are covered in the *4-D* User's manual. For example, the *4-D* User's manual explains how to search a database file for certain records using the standard *4-D* search command. Another source of help

is balloon help (a system 7.0 feature). Many of the buttons and menus in *Wahoo* have helpful messages attached to them that become visible when balloon help is turned on.

WHAT YOU NEED TO USE *WAHOO*

The *Wahoo* database requires certain hardware and software:

Hardware: Mac II or better (such as LC's, Centris, or Quadra), full page display monitor or larger is best (13" monitor will work, but is cumbersome), hard drive with 25 MB free, and 8 MB of RAM.

Software: System 7.0 or later, *4th Dimension* or *4-D* Runtime version 2.2.2 or later.

Fonts: Palatino 9, 10, 12, 14, 24 New York, Geneva, Helvetica, and Carbonate (Carbonate fonts are symbols used for different carbonate grain types and are provided along with the *Wahoo* database).

You should also have access to the *4-D* User's Guide that describes standard *4-D* procedures such as searching, reporting and graphing.

The user is assumed to have basic Macintosh skills such as handling the mouse, using Macintosh files, and keyboard use and a knowledge of carbonate sedimentology.

DIFFERENT OPTIONS FOR *4-D* PROGRAM

The current version of *4-D* version is 3.0.5. The database was developed in version 2.2.3 and has not been modified to utilize the more advanced version. At this time, the complete programmer's version of *Fourth Dimension* 2.2.3 costs about $450. A less-featured, less-expensive version of the program called *4-D Runtime* costs around $80. The only difference between the two programs is that the runtime program allows only data entry and manipulation. Developing or modifying a database (programming, page layouts, and interface design, etc.), requires the complete version of the program.

BASIC DATABASE THEORY AND OPERATION

Very simply, a database can be defined as a program that lets you record information and retrieve it at a later date. A good analogy for a *4-D* database file is a Rolodex card file. The Rolodex file contains a number of cards, each representing a record. In a Rolodex file, each record might contain information on several parameters (e.g., name, phone number, address, etc.). Another Rolodex file might contain a similar list of names but record other parameters (e.g., name, sex, income, profession, etc.). These two files could be related by the name but otherwise contain different information. A relational database goes far beyond a Rolodex file, however, in that it allows the data to be manipulated (e.g., searched or sorted using selected parameters) as desired by the user.

Wahoo is a relational database, allowing different files to linked or related via same shared parameter (e.g., sample number links the different *Wahoo* files). The data stored in a relational database can be represented in tables of rows and columns. However, this logical representation of the data is independent of its physical storage characteristics. A relational database uses a single high-level language for sorting, manipulating, linking, searching, and displaying information. It must support relational operations like selection, projection, and join and support set operations like union, intersection, difference, and division. It also provides alternate ways of viewing the same data, differentiates between unknown values and blank entries, and allows checks for integrity, authorization, transactions, and recovery. The inner structure of *Wahoo* adheres to strict mathematical definitions that define a relational database. As a user of the database, you will not have to worry about how the information is saved but will be able to take advantaged of the relational aspect of *Wahoo* to display and use the information as you see fit.

STRUCTURE OF THE *WAHOO DATABASE*

The *Wahoo* database consists of two Macintosh files (Fig. 5-1). One is called *"wahoo.comp"* the other is called *"wahoo.data."* *Wahoo.comp* is the operational program and contains all of the objects that you see on the screen including the menus, pictures, layouts and all the programming that is required to make the database function. It is the compiled version of the Wahoo database program and works more quickly than the uncompiled version. Wahoo.data contains all the information that has been recorded by the geologists and is linked to *wahoo.comp*. By splitting up *Wahoo* in this manner, upgrades to the operational part of the database can be accomplished without sacrificing the data.

WAHOO FILES

Wahoo.comp and *wahoo.data* are both subdivided into a number of *Wahoo* files* that each contain different types of data. The different *Wahoo* files appear on a list when *Wahoo* is opened (Fig. 5-2). Each *Wahoo* file contains information for numerous records (samples). Each record holds data for all the different parameters that are recorded in that file (Fig. 5-3, Forms 5-1 to 5-5).

The *Sample* file is the master file which links all other files and allows parameters within all other files to be related. The *Locality* file contains information on geographic location and is the same for all records at a particular stratigraphic section (locality). The *Petrographic* file contains a variety of petrographic data including information on the composition, lithology, sedimentary structures, and diagenesis. The *Conodont* file holds

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* NOTE: Throughout this manual, the term "file" refers to part of the Wahoo database structure. In order to avoid confusion, files (applications, documents, tools, etc.) that appear in the Macintosh finder will be called Macintosh files.

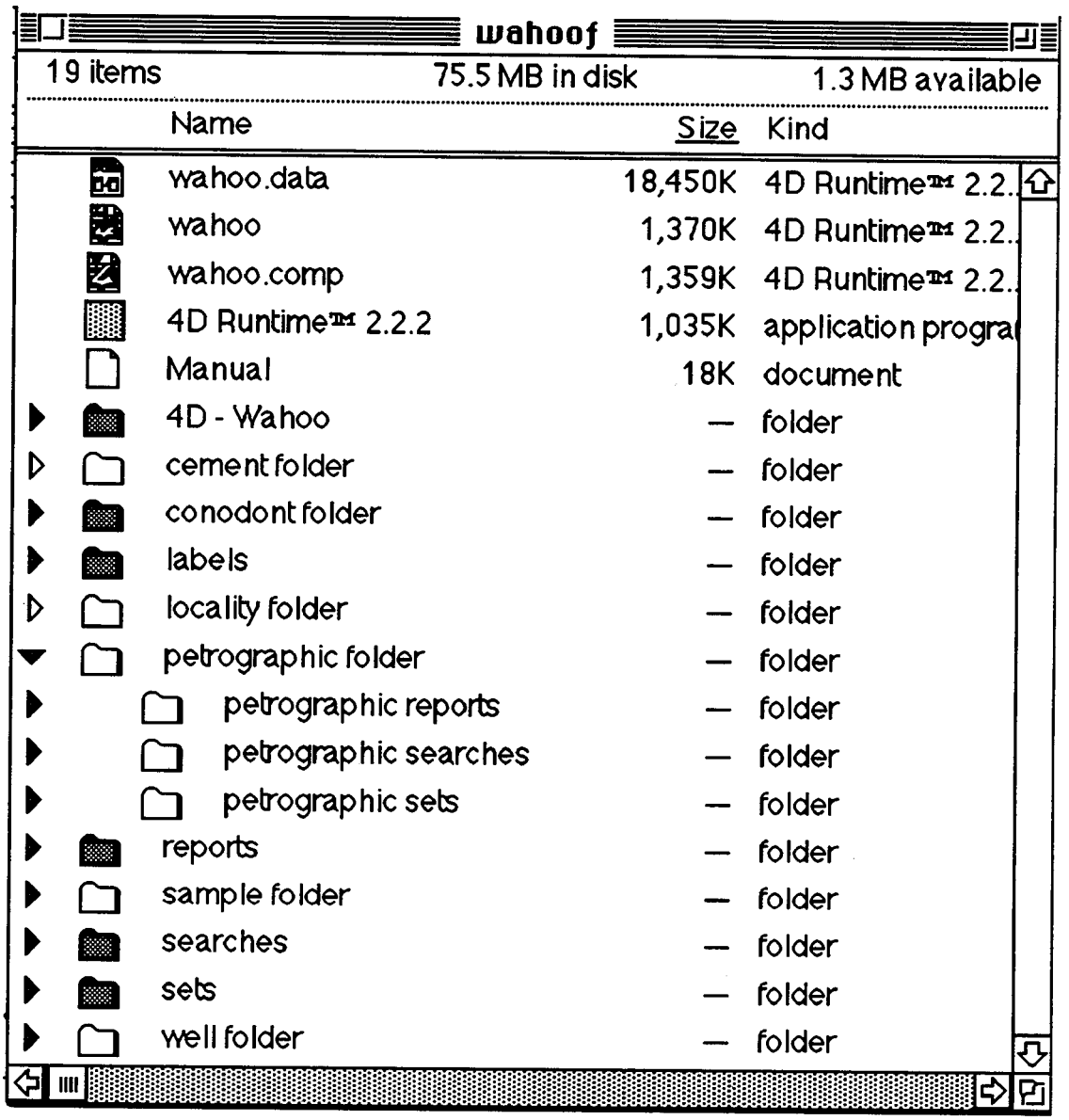


Figure 5-1. Window showing folders and files in the Wahoo *f* folder.

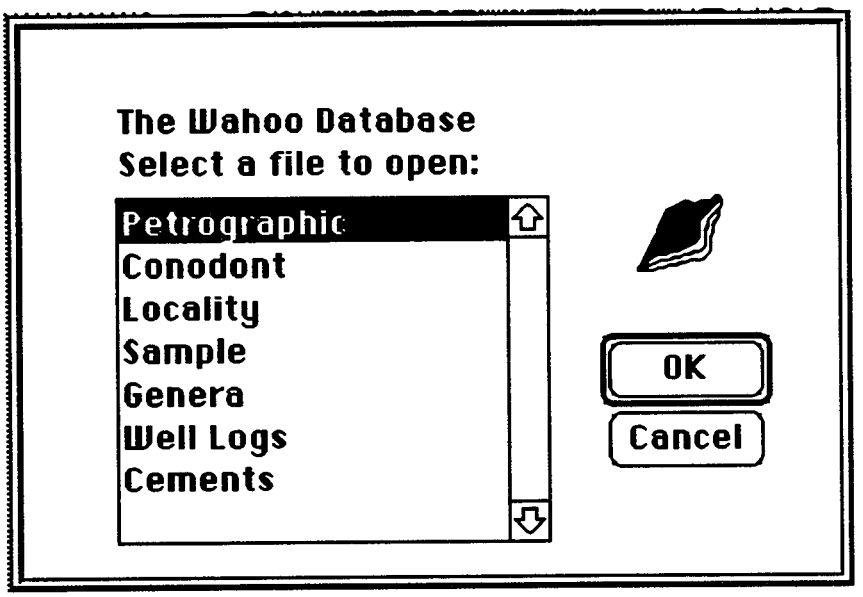


Figure 5-2. Dialog box for opening *Wahoo* shows a list of *Wahoo* files that can be selected by choosing a file then clicking "OK".

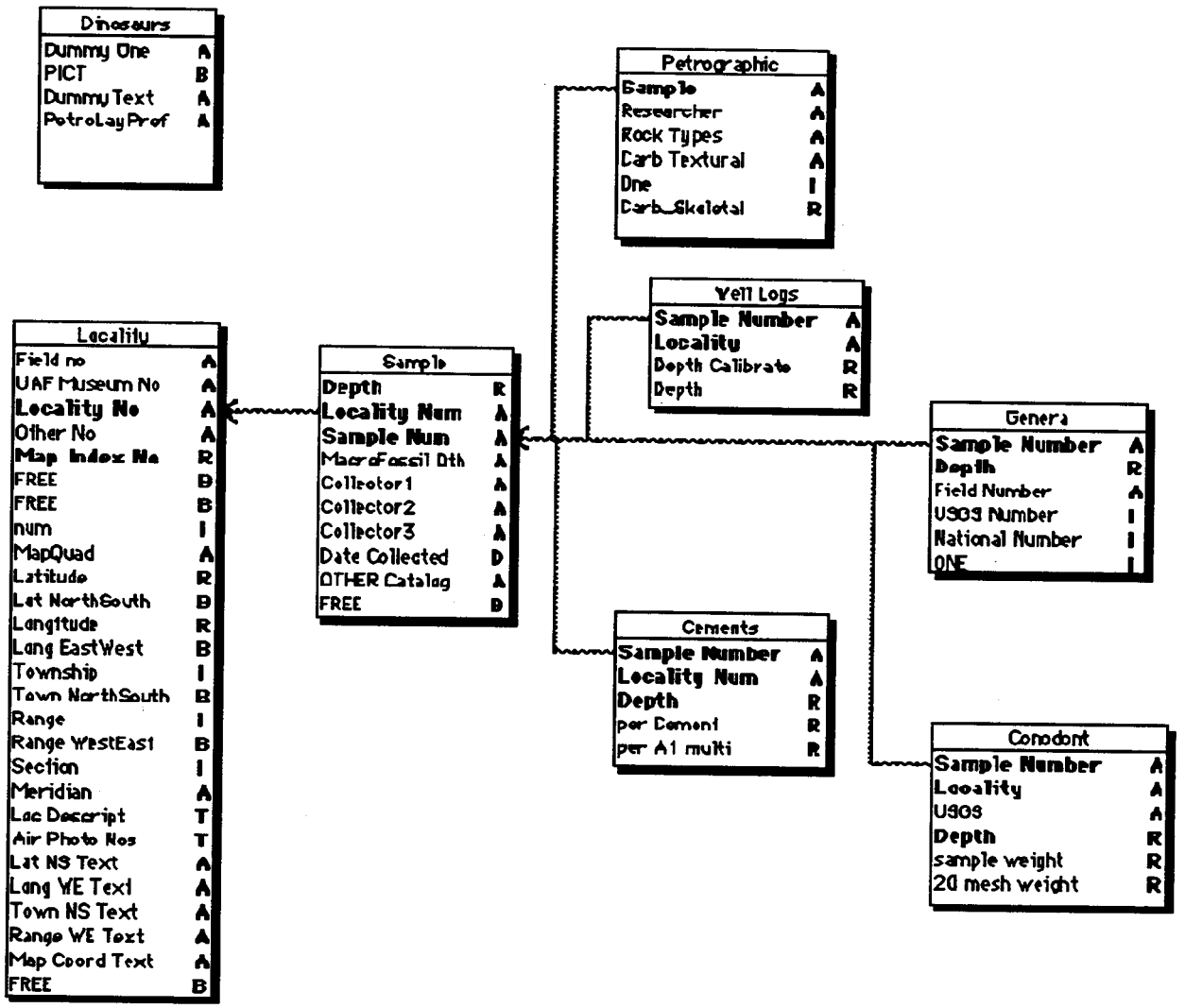


Figure 5-3. Organizational chart shows the general structure of Wahoo with lists of some of the parameters contained in the different Wahoo files (see the data input sheets on Forms 5-1 to 5-5 for more complete listing of fields). The main field that links the different records is sample number (locality + depth).

PETROGRAPHIC DESCRIPTION

Sample
Researcher(s)
Depositional Environment
Rock Types
Carb Types
Microfacies number:

Comments

Follow Up

Date of Last Entry

Skeletal Grain

- Bryozoans
- fenestrate
- ramose
- Echinoderms
- columnules
- plates
- Brachiopods
- Bivalves
- Gastropods
- Foraminifera
- Ostracodes
- Trilobites
- BioClasts
- OTHER

- Algae
- Asphaltina
- Archaeolithophyllum
- Donezella
- Osagia
- Oncolites
- Cyanobacterial Mats
- Calcispheres
- Sponge Spicules
- Corals
- fragments
- solitary
- colonial
- Radiolaria
- Conodonts

Component

Components
- grains
- matrix
- cement

Carbonate Grain Types
- Skeletal (Total)
- Ooid
- Superficial Ooid
- Peloid
- Limeclast
- Lump (Grapestone)
- Pisoid

Bed Descriptions

Color

Bed thickness

Non-carbonate material
- detrital quartz
- glauconite
- phosphate
- anhydrite
- gypsum
- pyrite
- hematite
- fluorite

Texture

Grain size (Udden-Wentworth scale)

Present

cly slt vf f m c vc gr peb cob bld

Mean

Maximum

Grain recrystallization
- none
- weak
- moderate
- strong

Grain size sorting
- very poorly
- poorly
- moderately
- well
- very well

Grain abrasion
- none
- weak
- moderate
- strong

Packing

Compaction

Grain packing
- matrix supported
- point contacts
- straight contacts
- concavoconvex
- sutured contacts
- collapsed micritic grains
- strained grains
- calcitic twins - strain lamelli

A C M R 0 - Abundant (>50%), Common (10-50%), Minor (1-10%), Rare (<1%), 0 (none), E (Exact number from point count)

Form 5-1a. Standard petrographic data form (page 1 of 2).

Sample: [ ]

Diagenetic Features

Dolomite

Content [ ]
Xstal Size Min: [ ] µ
Xstal Size Mean: [ ] µ
Xstal Size Max: [ ] µ
Xstal Shape: [ ]
Replacement Fabric: [ ]
Type [(non)ferroan]: [ ]
Distribution: [ ]

Chert Replacement

Content [ ]
Concentration: [ ]

Diagenetic Quartz

Content [ ]

Clay Material

Content: [ ]
Concentration: [ ]

- [ ] laminated crust
- [ ] circumgranular cracks
- [ ] paleosols
- [ ] veins
- [ ] fractures
- [ ] chert nodules
- [ ] calcareous nodules
- [ ] evaporite nodules
- [ ] evaporite molds
- [ ] autoclastic breccias
- [ ] geopetal structures
- [ ] styolites
- [ ] oil stain (bitumen)

Biogenic Structures

- [ ] corals in growth position
- [ ] articulated crinoid stems
- [ ] full-frond fenestrate bryozoans
- [ ] " " " in growth position
- [ ] articulated brachiopods
- [ ] algae in growth position
- [ ] organically bound
- [ ] vertical burrows
- [ ] horizontal trace fossils
- [ ] general bioturbation
- [ ] mottling
- [ ] massive structureless bedding
- [ ] stromatolites
- [ ] cryptalgal mats
- [ ] rootlets (rhizoliths)
- [ ] plant debris
- [ ] OTHER

Cements

- [ ] calcite cements
- [ ] syntaxial overgrowths
- [ ] equant blocky spar
- [ ] bladed spar
- [ ] fibrous cement
- [ ] isopachous rims
- [ ] neomorphic microspar
- [ ] blocky void filling spar
- [ ] micritic cement
- [ ] meniscus cement
- [ ] pendant cement

Sedimentary Structures

- [ ] even parallel laminae (<3mm)
- [ ] even parallel laminae (>3mm)
- [ ] coarse-grained parallel laminae
- [ ] low-angle cross-laminae
- [ ] low-angle truncations
- [ ] indistinct laminae
- [ ] wavy laminae
- [ ] current ripples
- [ ] wave ripples
- [ ] small-scale cross laminae (<5cm)
- [ ] large-scale cross laminae (>5cm)
- [ ] graded bedding
- [ ] inverse grading
- [ ] scoured surfaces
- [ ] hardground/bored surfaces
- [ ] fenestral fabric
- [ ] desiccation cracks
- [ ] shale partings
- [ ] soil horizon
- [ ] intraclastic conglomerate
- [ ] imbricated clasts
- [ ] thin bed of debris (lag deposit)
- [ ] deformed bedding
- [ ] convolute lamination
- [ ] load casts
- [ ] flute casts & other sole markings
- [ ] OTHER

Micritization of grains

- [ ] micritic rim
- [ ] micritization

Porosity

F	O	
[ ]	[ ]	vuggy
[ ]	[ ]	moldic
[ ]	[ ]	intercrystalline
[ ]	[ ]	intraparticle
[ ]	[ ]	interparticle
[ ]	[ ]	fracture
[ ]	[ ]	fenestral

Moldic Type [ ]

A C M R 0 - Abundant (>50%), Common (10-50%), Minor (1-10%), Rare (<1%), 0 (none), E (Exact number from point count)

Form 5-1b. Standard petrographic data form (page 2 of 2).

Sample [0]
Researcher(s [Keith Watts]
Rock Types [ ]
Carb Types [ ]

SKELETAL GRAINS

- [ ] Bryozoans
- [ ] Pelmatazoans
- [ ] Ostracods
- [ ] Brachiopods
- [ ] Sponge Spicules
- [ ] Foraminifera
- [ ] Calcispheres
- [ ] Gastropods
- [ ] Bivalves
- [ ] Trilobites
- [ ] Coral (solitary)
- [ ] Coral (colonial)
- [ ] Algae (undiff.)
- [ ] Donezella
- [ ] Asphaltina
- [ ] Bioclasts (undiff.)
- [ ] Fenestrate
- [ ] ramose
- [ ] OTHER

NON-SKELETAL GRAINS

- [ ] Ooid
- [ ] Superficial ooids
- [ ] Peloids
- [ ] Intraclasts
- [ ] Oncolites
- [ ] Qtz sand or silt
- [ ] Glauconite
- [ ] Pyrite
- [ ] Phosphate grains
- [ ] Grapestone
- [ ] Hematite
- [ ] Diagenetic quartz

MEAN GRAIN SIZE

vf [ ] f [ ] m [ ] c [ ] vc [ ]

PRESERVATION OF GRAINS

Recrystalization of grains
○ none ○ slightly ○ moderate ○ well

Grain Borings:
◉ none ○ slightly ○ moderate ○ well

Micritic Envelope Development:
partial complete
◉ none ○ slightly ○ moderate ○ well

Grain Roundness
○ well ○ moderate ○ poorly

GRAIN SORTING
○ well ○ moderate ○ poorly

DOLOMITE

Content [ ]
Xstal Size Min: [0 µm]
Xstal Size Mean: [0 µm]
Xstal Size Max: [0 µm]
Xstal Shape:
Replacement Fabric:

Date of Last Entry 5/4/94

CLAY MATERIAL

Content [ ]
Concentration: [ ]

CHERT REPLACEMENT

Content [ ]
Concentration: [ ]

OIL STAIN
○ high ○ moderate ○ low ◉ none

SEDIMENTARY STRUCTURES

- [ ] Parallel laminae
- [ ] Small-scale X-laminae
- [ ] Wavy laminae
- [ ] Graded bedding
- [ ] Bioturbation
- [ ] Geopetal structures
- [ ] Stromatolite
- [ ] Fenestrae
- [ ] Birdseyes
- [ ] Breccia
- [ ] Evaporite repl. nods.
- [ ] articulated crinoid stems
- [ ] vertical burrows
- [ ] Scoured surfaces
- [ ] Imbricated clasts
- [ ] OTHER

CEMENTS

- [ ] Syntaxial overgrowths
- [ ] Equant blocky spar
- [ ] Drusy blocky spar
- [ ] Isopachous rims
- [ ] Neomorphic microspar
- [ ] Blocky spar cavity fills
- [ ] Micritic

POROSITY

- [ ] Vuggy
- [ ] Moldic
- [ ] Intercrystalline
- [ ] Intraparticle
- [ ] Interparticle
- [ ] Fracture

COMPACTION [ ]

- [ ] Sutured grains
- [ ] Broken rims or coats
- [ ] Strained grains
- [ ] Bent twins
- [ ] Styolites
- [ ] Fractures

Depositional Environment [ ]

Comments

Form 5-2. Alterantive petrographic data form developed by Paul Gruzlovic.

Conodont Biostratigraphy

Sample Number

USGS Collection Number

USNM Number

General Locality

Quadrangle or Area

Referred By

Depositional Env.

Report By

Formation

	Hemisphere	Degrees	Minutes
Latitude	N		
Longitude	W		

Ichthyos	
Steinkerns	
Other	

Comments

Indet. bar, blade and platform fragments	0

sample weight (kg) 0

+20 mesh weight (g) 0

light residue weight (g) 0

insoluble residue/undissolved carbonates

elements per kg 0

magnetic seperates

non-magnetic separates

Textural Alteration

Abrasion

Biofacies

☐ Has Petrographic Record

Color Alteration Index

Min 0

Max 0

	Period	Mod	Stage	Zone
Minimum				
Probable				
Maximum				

Form 5-3a. Conodont data entry form (page 1 of 2)

Conodont Recovery

Genus1 ?	Species1	P	Pa	Pb	M	Sa	Sb	Sc	Sd	S Ind	Rela	Genus2	Species2	

Form 5-3b. Conodont data entry form (page 2 of 2).

LOCALITY INFORMATION

Locality Number: _____

UAF Museum Number: _____

Other ID Numbers: _____

Location

Map - quad 1:250,000 [ ]

1:63,360

	8	7	6	5	4	3	2	1
D								
C								
B								
A								

Latitude-Longitude

	Hemisphere	Degree	Minute
Latitude	N		
Longitude	W		

Dates: 00/00/00

Collector(s): _____

Township-Range-Section

T [ ] R [ ] Sec [ ] Meridian [ ]

Location Description

[ ]

Air Photo Numbers: _____

Stratigraphic section: _____

SAMPLE INFORMATION

Date: _____

Locality Number: _____

Sample Number: _____

Lithological Unit: _____

Age: _____

strike: [ ] **dip:** [ ]

Lithology

- ☐ (Cg) conglomerate
- ☐ (Gw) graywacke
- ☐ (Md) mudstone
- ☐ (Vc) volcanic rock
- ☐ (Dl) dolostone
- ☐ (Bx) breccia
- ☐ (St) siltstone
- ☐ (Cl) claystone
- ☐ (Pl) plutonic rock
- ☐ (Ch) chert
- ☐ (Ss) sandstone
- ☐ (Sh) shale
- ☐ (Mt) metamorphic rock
- ☐ Other
- ☐ (Ls) limestone
  - (Gs) grainstone
  - (Ps) packstone
  - (W) wackestone
  - (M) lime mudstone
  - (Bs) boundstone

Sampled for

- ☐ (C) conodonts
- ☐ (D) diatoms
- ☐ (F) forams & algae
- ☐ (G) organic geochemistry
- ☐ (L) lithology
- ☐ (M) macrofosil
- ☐ (O) porosity & perm.
- ☐ (P) palynomorphs
- ☐ (R) radiolarians
- ☐ (T) thin section
- ☐ (V) vitrinite reflectance
- ☐ Other
- ☐ (Rd) radiometric dating
  - (A) 40Ar-39Ar
  - (Ft) Fission Track
  - (I) K-Ar
  - (R) Rb-Sr
  - (U) U-Pb

Comments

[ ]

Form 5-4. Locality and sample data forms.

Sample number	- Well name plus depth recorded on core and core chips.
Depth (ft)	- " " " " " " "
Depth Calibrated (ft)	- Depth interpolated between control points (shale intervals) on well logs to match core depths.
Depth Rounded (ft.)	- Calibrated depths rounded to nearest whole number to match depths recorded on cores for direct comparison.
OGR (API)	- Gamma-ray log .
POTA (%)	- Percent potassium calculated from spectral gamma-ray log.
SGR (API)	- Spectral gamma-ray log.
THOR (ppm)	- ppm Thorium calculated from spectral gamma-ray log.
URAN (ppm)	- ppm Uranium calculated from spectral gamma-ray log.
DT (µs)	- Sonic log (travel time in µs/ft.).
NPHI (%)	- Neutron log (% limestone porosity).
RHOB (bulk density)	- Density log

Form 5-5. Well log data imported from digital tape records.

Cements

Sample Number	
Locality Num	
Depth	
% Cement	
% A1 multi	
% non	
% B1	
% C1	
% B2	
% A2	
% B3	
% C2	
% B4	
Last Print Date	
Entry Date	

Form 5-6. Data on abundance of different cements imported from *Microsoft Excel* file of Randall Carlson.

general information on biostratigraphy, abundance of selected genera, biofacies, and conodont color alteration indices. The *Genera* and *Conodont Recovery* files are attached to *Conodont* and contain information on the abundance of different types of conodont elements for each genus or species identified within a sample. *Conodont Recovery* is a subfile within the *Conodont* file and cannot be directly accessed. *Genera* is derived from the data in *Conodont Recovery* and allows the user to search the database for specific conodont genera and/or elements. The *Cement* file contains estimated percentage of different cement phases distinguished using cathodoluminescence. *Well logs* contains subsurface data that were downloaded from publicly available computerized well logs (in this case from a well in the Lisburne oil field).

Wahoo files are an integral part of the *4-D* relational database and should not be confused with the files that are on the Macintosh desktop (we refer to these as Macintosh files). However, *Wahoo* creates and utilizes a number of templates stored as Macintosh files. *Wahoo* will ask you what to name these templates before saving them as Macintosh files. It is best to avoid confusion by naming the files to indicate the *Wahoo* file being used, or perhaps storing them in folders named after the *Wahoo* files. In order to logically organize these operational files (and prevent errors that result from switching between different *Wahoo* files), each of the *Wahoo* files has a folder (e.g., "Petrographic folder") that contains several other folders to hold the appropriate template files (e.g., "Petrographic searches," "Petrographic sets," and "Petrographic reports"). *4-D* automatically creates folders called labels, reports, searches, and sets that should <u>not</u> be used.

The one parameter contained in every record that links the different files is called "**Sample**" and can be subdivided into **"Locality"** and **"Depth."** The first alphanumeric part of the sample number represents **Locality** and is typically a University of Alaska Museum number (e.g., AK22M which is a stratigraphic section located in the eastern Sadlerochit Mountains). The second numeric part of the sample number, **Depth** is typically in meters measured above the base of a stratigraphic section. In unusual situations, stratigraphic sections (including the "WELL" locality at the Lisburne field, Prudhoe Bay) that were measured downsection from the top of a stratigraphic unit have negative depth numbers, so they will be listed in the proper stratigraphic order. All **Depth** measurements are given in meters, except the WELL locality that contains subsurface data from a well in the Lisburne oil field as measured in feet below the surface. Spot samples that weren't collected from a measured stratigraphic section are typically recorded as a field number which includes the year collected, collector's initials, and sequential number for the field season (e.g., 89KW7). In the *Petrographic* file, the depth and locality fields aren't located at the top of the list used for manipulating data but can be found by scrolling down the list (with practice and knowing the position of these fields, the scroll bar allows this to be done relatively quickly). Unfortunately, these fields cannot be moved to a more convenient position without damaging the database structure.

On the output layout (see below), samples are sorted by "**Map index number**" and **Depth** (in descending order). Map index number refers to a specific geographic

location on a locality map showing measured sections of the Lisburne Group in ANWR (see Fig. 1-2 and Appendix 1). The whole number part of the map index number corresponds to the number on the map. In some cases, several incomplete stratigraphic sections were measured to obtain a composite stratigraphic section for a particular locality. In order to illustrate the relative stacking order of the different component sections, the map index number has two decimal places. The first decimal indicates the relative stratigraphic position with .1 being the highest stratigraphic interval. For example, a composite stratigraphic section in the Shublik Mountains (loc. 10, Fig. 1-2) is comprised of three sections: the upper Wahoo Limestone (map index 10.1), the lower Wahoo (map index 10.2), and the underlying Alapah Limestone (map index 10.3). If the same stratigraphic section is reexamined then the second decimal is increased by .01. For example, the upper part of the type locality of the Wahoo Limestone was first examined in 1987 (map index 13.2) and was resampled in 1991 (map index 13.21) and in 1992 (map index 13.22). Listing data in stratigraphic order in this manner is an effective way to illustrate data from stratigraphic section(s), particularly petrographic analyses that are portrayed as if in stratigraphic columns. Where samples are spaced at regular intervals (e.g., samples from the upper Wahoo are typically spaced at 0.5m intervals), the lists of petrographic data accurately portray stratigraphic variations in limestone composition. However, the lists of petrographic data do not accurately portray the variable spacing of samples collected at irregular intervals, because sample records are evenly spaced on the lists.

Sample File—Linking *Wahoo* files by sample number

4-D requires that each *Wahoo* file keeps track of its records sequentially in the order entered into the database (+/- additions and deletions). Because the different files contain different numbers of records that were not necessarily entered in the same order, comparing the different files poses some difficulties. We were able to resolve this problem by establishing the *Sample* file to hold basic information (including **Sample** number) for all the records entered into the different *Wahoo* files. The *Sample* file serves as the hub that links all other *Wahoo* files by using the common parameter, **Sample** number. For this reason, comparing data between different *Wahoo* files must be done from within the *Sample* file (see below). When working in other *Wahoo* files, attempting to manipulate or report on data derived from different *Wahoo* files (such as both the "Petrographic" and "Conodont" files) will produce lists of nonsense data.

The *Sample* file is by far the largest file in *Wahoo* because it contains listings for all the records in *Wahoo*. Because manipulating data within this huge file is slower than for other files, it should only be used when comparing data between different *Wahoo files*. To reduce delays required for time-consuming searches, the results of searches should be saved as sets for later use (see below).

DATA INPUT AND OUTPUT LAYOUTS

Wahoo has two layouts for showing database records. The "**output layout**" is the format used for most database functions (Fig. 5-4). An output layout shows a listing of multiple records contained within a *Wahoo* file and lets you perform such actions as

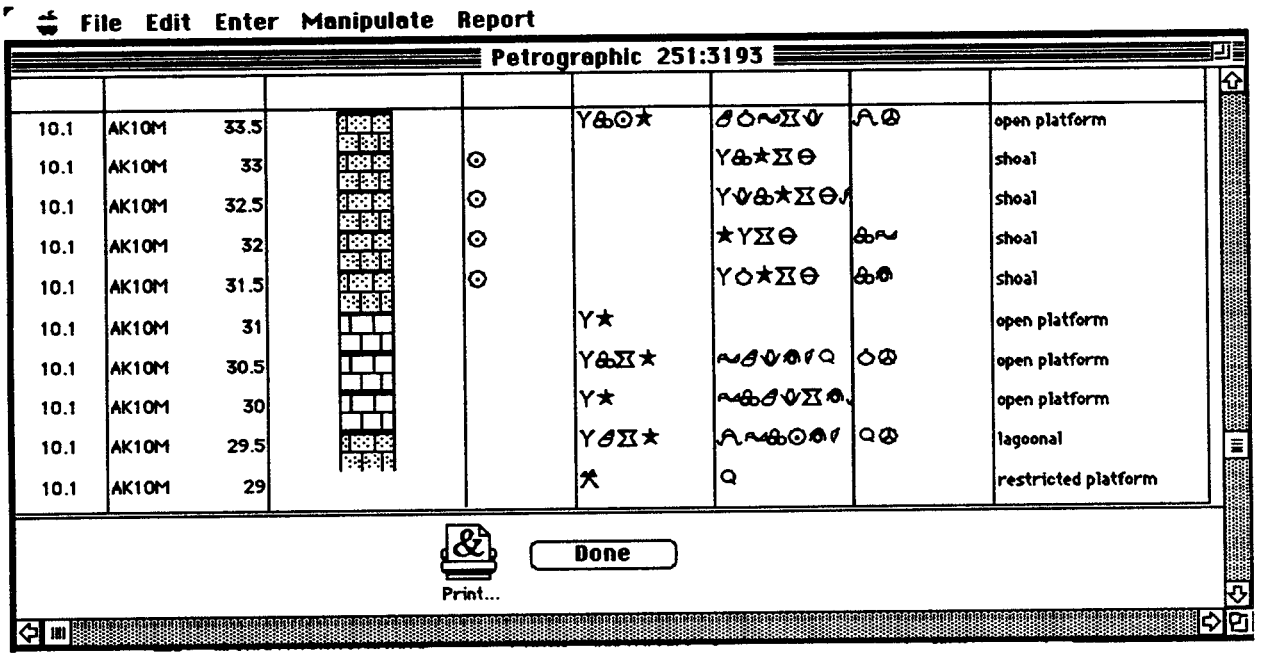
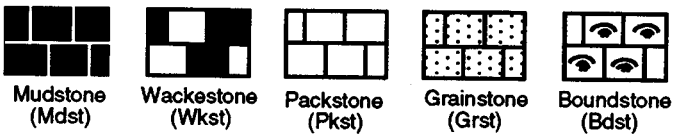


Figure 5-4. Window shows the output layout for the petrographic file and the standard 4D menu list that contains different commands on pull-down menus.

EXPLANATION

CARBONATE TEXTURAL CLASSIFICATION



SKELETAL GRAINS

- Pelmatozoan
- Bryozoan (undifferentiated)
- Bryozoan (full-frond fenestrate)
- Bryozoan (ramose, "stick")
- Brachiopod
- Bivalve
- Gastropod
- Foraminifer
- Trilobite
- Ostracod
- Sponge Spicule
- Coral (undifferentiated)
- Coral (colonial)
- Algae (undifferentiated)
- *Asphaltina sp.*
- *Archaeolithophyllum sp.*
- *Donezella sp.*
- *Calcisphaera sp.*
- Oncolite
- Bioclast (undifferentiated)

NON - SKELETAL GRAINS

- Ooid
- Superficial Ooid
- Peloid
- Intraclast
- Grapestone
- Q - Detrital Quartz

Figure 5-4b. Key to symbols used on Figures 5-4a and 5-22.

searching, sorting, graphing, deleting, and archiving selected records. Each horizontal line represents a single record. Each column represents an information field that was selected from the many parameters contained in a file. The "**input layout**" allows you to create new records or edit records that already exist. Input layouts look like the data input forms (see below) and allow you to work with only one record at a time.

INSTALLING *WAHOO*

Because of its size (more than 22 megabytes), the *Wahoo* database is most easily transferred using an external hard drive that is dedicated for this purpose (available through the University of Alaska Fairbanks Geophysical Institute, contact Dan Lasota at 907-474-5576). The entire *Wahoo* database, including the *Wahoo* program (or the compressed version - *Wahoo*.comp), the data (*Wahoo*.data) and associated manipulation procedures (see below, Fig. 5-1), are simply copied onto the user's computer. As stated previously, the user must own a version of the *4-D* program in order to utilize the *Wahoo* database. Follow the general installation instructions in the *4-D* manual.

STARTING *WAHOO*

After loading *Wahoo* onto your computer along with carbonate fonts, you are ready to start. The easiest way to start *Wahoo* is to double click on the *wahoo.comp* icon (Fig. 5-1). The first time you open *Wahoo*, *4-D* will ask you to locate the data file (*wahoo.data*). You will only have to do this once unless you move the database to another part of your hard disk or rename the folders containing it. *Wahoo* takes about a minute to start up on most Macintoshes. The first thing you will see after starting the database is the splash screen (a picture of a sea shell). At this point you can perform administrative tasks, set preferences, or open a file. Let's go through a practice session on opening and using a file:

- Double click on *Wahoo*.comp and wait for the splash screen to appear

- From the File menu select the "Open..." menu item. You will be presented with a dialog box asking you to select a file (Fig. 5-2).

- Click on the name of the desired *Wahoo* file and then click on the "OK" button.

- The output layout for the *Wahoo* file will show a list of records . Each horizontal line represents a single record. Each column represents an information field that was selected from the file (Fig. 5-4).

- You might choose to manipulate these data using the "Search" command from the "Manipulate" menu (see below).

- If you want to enter new data, select "New Record" from the "Enter" menu. This will take you to the input layout for the file you have chosen. Do this command now.

- After you have entered your information, either save the data (click on diskette icon) or click on cancel button (diskette with slash icon; see below on Fig. 5-12).

- You will be returned to the output layout for your file.

- If you want to examine or edit a record that has already been entered, double click on the horizontal line of data representing the record that you want to examine. After its data is loaded, the input layout for the record will be displayed.

- Save or cancel any changes to records in the input layout as noted above and you will be returned to the output layout.

- Choose "Quit" from the "File" menu. Your practice session with *Wahoo* is over.

USING OUTPUT LAYOUTS

When you open a file, note that the output layout has several pull-down menus in the menu bar that allows you to work with the data file (Figs. 5-4 & 5-5). "Enter" allows you to enter new records into the file or delete selected records. "Manipulate" includes a number of commands such as "search" that allow you to manipulate records in the database file (see below). "Report" allows you to generate reports and graphs of selected data.

MANIPULATING RECORDS

In most circumstances, you will want to manipulate the *Wahoo* database in order to select and organize a meaningful set of data for examination or to generate reports or graphs. All manipulation commands are general *4-D* routines located in the "Manipulate" menu bar in the output layout of each file (Figs. 5-4 & 5-5)

SELECTING RECORDS

On the title bar of the window you will see numbers in the form x:y. The x is the number of records being selected from the file (Fig. 5-4). The y is the total number of records in the file. When you first open a file, all its records will be listed (x=y). Typically, you will want to select certain records (e.g., a specific stratigraphic section or rock type), so that x will be a smaller number. This is usually done using different commands in the "Manipulate" menu ("Search" or "Load Set," see below). Alternatively, you can make a selection manually, by clicking on records individually or by grouping a number of records. You can select a group of contiguous records by holding the shift key down while clicking on first and last of the desired records. To select a group of records that aren't adjacent to each other, hold the command key down while selecting each of the desired records. You can remove records from the current selection by clicking on them and then choosing "Omit Selection..." from the Manipulate menu. By choosing "Show All Records" from the Manipulate menu, all the records in a file are displayed. In order to select a few records, first highlight all the

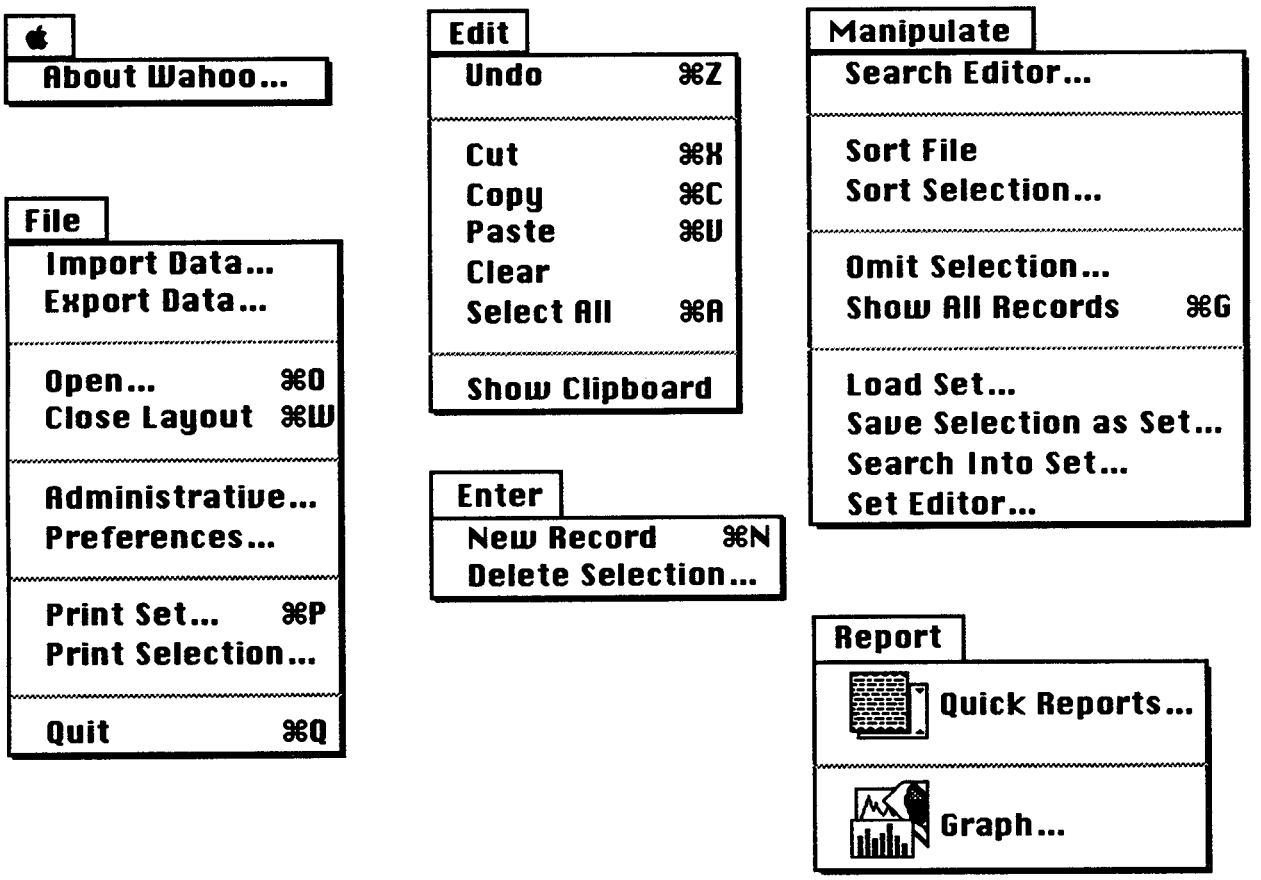


Figure 5-5. Window shows the menu lists for commands in output layouts.

records by choosing "Show All Records," then choose (unhighlight) the desired records by clicking on them and using the appropriate command or shift keys, and finally select "omit selection" that will remove all the records except for the ones desired. You can see how many records are in the current selection and how many are in the file by looking in the title bar of the output layout window.

SEARCHING

Searching is the main way to manipulate a *Wahoo* file, allowing specific data to be selected from a *Wahoo* file based on criteria that are specified by the user. By choosing "Search Editor..." from the Manipulate menu, a search dialog box will appear allowing you to design a search (Fig. 5-6). When doing a search, you ask the computer to find all the records that meet certain criteria (e.g., locality, rock type, carbonate grain types, conodont biofacies, depositional environment, etc.—choosing any of the parameters shown on the scroll list at left side of dialog box). Searches are essentially a series of instructions that define a subset of data. For example, all the petrographic records for the upper Wahoo Limestone in the Shublik Mountains stratigraphic section would be selected using the search shown on Fig. 5-6 with defining criteria listed in a logical progression. A certain locality was specified (AK10M=central Shublik Mountains section) and the stratigraphic interval was defined between the appropriate lower and upper depths for the unit (2.5m and 128m respectively). The search is completed by clicking "OK," causing the output layout to list the 245 records (samples) that meet the criteria stated (Fig. 5-4).

If desired, it is possible to narrow your search to the data already selected in the output layout by clicking on the "Search in selection" check box at the lower left in the Search dialog box (Fig. 5-6). This will speed things up by reducing the number of records being searched, but has the potential of missing records that are outside your initial selection. The logic and mechanics involved in performing a search are covered in the *4-D* User's Guide and will not be discussed here.

Saving and loading a search

Before completing the search (by clicking "OK"), a search routine can be saved as a "search file" for future use and/or modification by clicking on "Save" at the bottom of the "Search Editor..." dialog box (Fig. 5-6). Another dialog box will appear and ask you to name for the search file (e.g., Shublik-upper Wahoo-search) and place it in the appropriate folder (Fig. 5-7). Several search routines used in our petrographic studies have been saved in a folder called "Petrographic Searches" in the "Petrographic file" folder and provide useful examples that can be easily modified to allow similar searches for other localities, stratigraphic intervals (depths), etc.

By clicking on "Load" in the "Search Editor.." dialog box (Fig. 5-6), a list of search files appears in another dialog box (Fig. 5-8). By opening a search file (e.g., "Shublik-upper Wahoo -search"), the previously defined criteria are shown in the search editor dialog box (Fig. 5-6). Selecting "OK" will cause this search to be completed. Alternatively, you might utilize the search structure but modify the depths

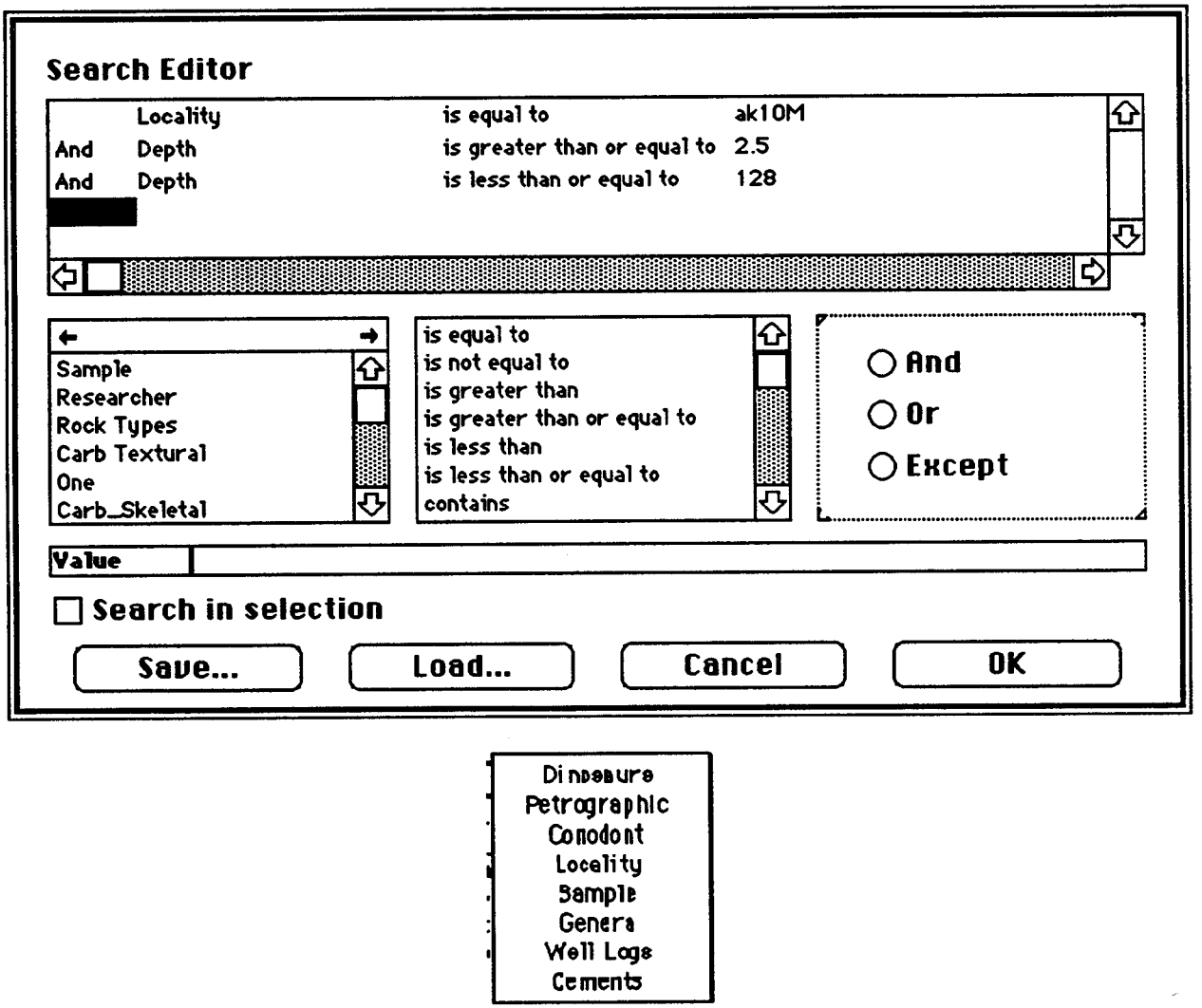


Figure 5-6. Dialog box for "Search Editor..." shows a typical search routine. The pop-up menu shown below this dialog box appears when the title bar above the list of parameters is clicked, allowing different *Wahoo* files to be selected for a search (**use within the *Sample* file only**).

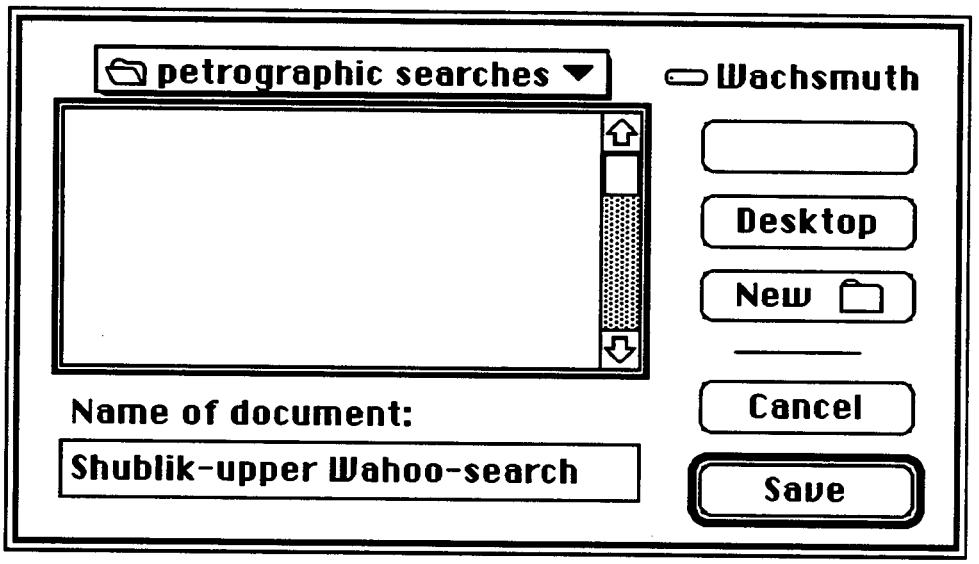


Figure 5-7. Dialog box for saving a search routine within the search editor.

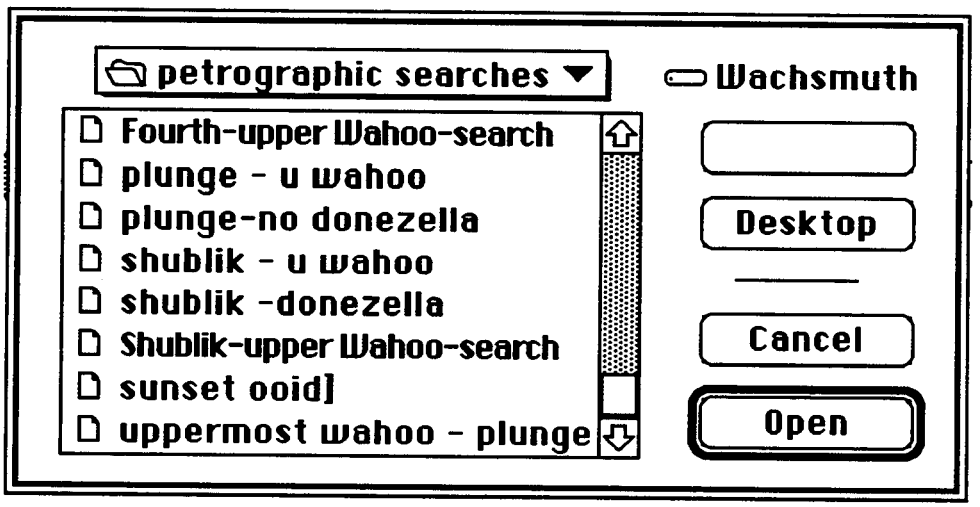


Figure 5-8. Dialog box contains a list of search routines available to be loaded within the search editor.

and/or locality and save the resultant search routine with an appropriate label (e.g., Fourth Range-upper Wahoo-search).

Indexed fields

Indexing is a way that the computer keeps lists of records of commonly used fields available for quick reference. A search based on information in an indexed field goes much faster than in a standard field. Indexed fields (e.g., **sample**, **depth**, or **locality**) are indicated on the list of fields by bold lettering that were established by the programmer. If you are doing a search that uses more than one field, the indexed field(s) should be given first when building your search criteria. This narrows the selection quickly before subsequent slower searches take place.

Searching within the *"Sample"* file

The *Sample* file allows comparison of data contained within different *Wahoo* files by linking them using the sample number. In designing a search, begin by selecting a locality from the sample file and, if necessary, range of depths. These indexed fields will speed up your search within the large *Sample* file (potentially very time consuming). By pulling down a pop-up button menu at the head of the selection column at left (Fig. 5-6), you can select any of the different *Wahoo* files necessary to complete your search. After selecting all necessary parameters from their appropriate files, click "Save" to record the search as a search file (putting it in the sample search folder) and/or click "OK" to complete the search. If data entry has been completed, it is usually worthwhile to save the resultant selection as a set to save time in utilizing this data selection in the future (see below).

SORTING

Sorting records is another common way to manipulate data. For example, a group of records (samples) from a stratigraphic section might be sorted by depth to list them in stratigraphic order. There are two kinds of sorts in *Wahoo,* temporary sorts and permanent sorts. Temporary sort affects the order of selected records only while you have the file open and is lost whenever you change the selected records. To temporarily sort, select a group of records, then click on "Sort Selection..." from the Manipulate menu (Fig. 5-5). You will be presented with a dialog box that lets you design your sort by sequentially listing the desired fields to be sorted and indicating the sort direction (increasing or decreasing values) for each field/parameter to be sorted (Fig. 5-9). For example, you might sort by locality then depth to obtain a list of records for several stratigraphic sections, each listed in stratigraphic order (Fig. 5-9). Review the *4-D* User's Guide for more information on sorting. As soon as you look at another file, change the selection of records, or quit *Wahoo* the records will revert back to their permanent sort order.

Each file maintains a permanent sort order. This order is only changed when records are deleted, added, or you request that the records be resorted. A permanent sort is done when you select "Sort File" from the Manipulate menu. Each file is sorted

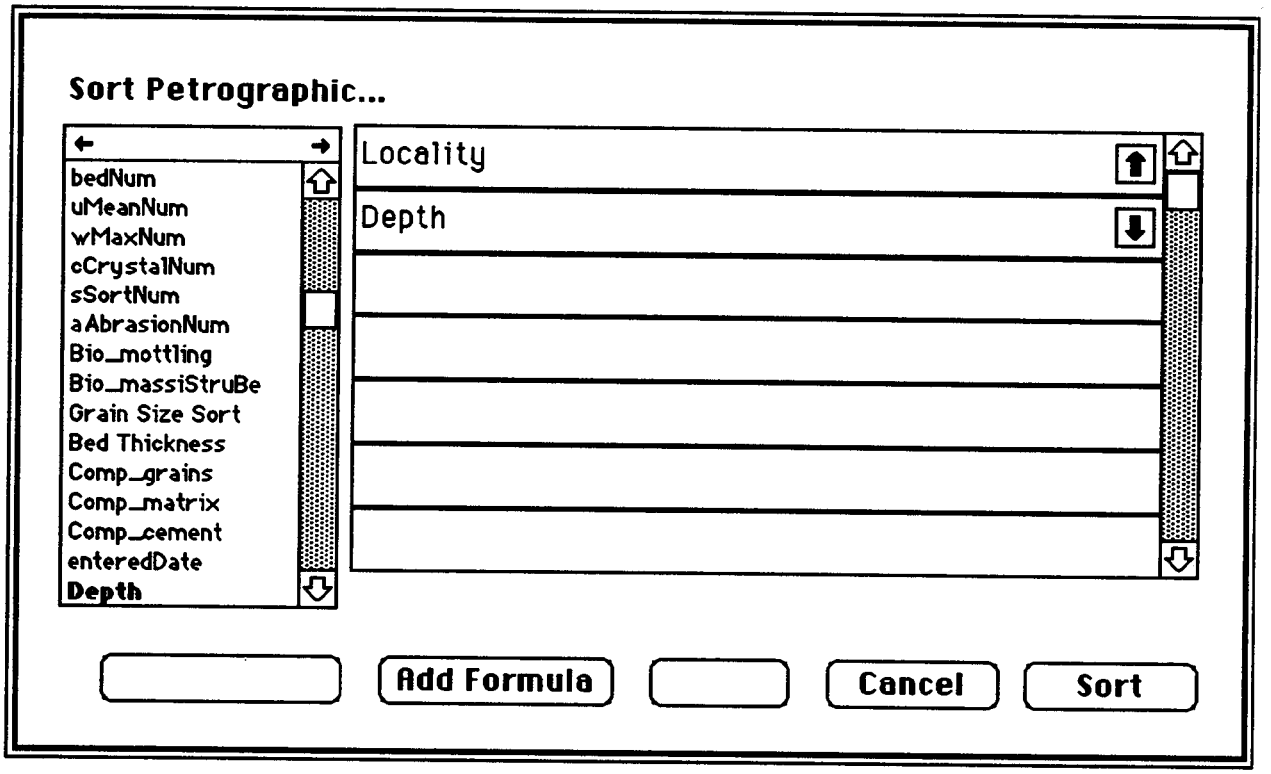


Figure 5-9. Dialog box for "Sort Selection..." contains a list for a typical sort.

by its key fields that are assigned by the programmer. The permanent sort order for *Wahoo* files is by **map index number** then **depth** (in descending order—from top down) so that data for each locality (stratigraphic section) are listed in stratigraphic order. Sections that were measured from the top downward have depths given in negative numbers to show them in the proper succession. The map index number for composite stratigraphic section has a series of decimals that arrange the different components in the proper stratigraphic order. Doing a permanent sort using "Sort File" will require a significant amount of time to reorganize and re-index all records, so it is best done when the computer won't be needed for other purposes. Changing the permanent sort order will affect previously defined sets (see below).

SETS

The last four menu items of the Manipulate menu deal with sets (Fig. 5-5). A set is a list of selected records that is stored on disk for rapid reference and to allow comparison between different sets of data. The main advantage of using sets is that the set can be recalled to the screen very, very quickly and you can compare and contrast different sets. However, a set is only valid as long as its main file is not modified because sets are not updated as the database is modified. Because the database keeps track of records by the record number (in the order entered), previously created sets may become invalid when records are added, edited, or deleted from *Wahoo or* if the sort order is changed. If these changes affect the organization of records in a *Wahoo* file or modify records contained with the set, the set must be recreated to capture all the new records that meet appropriate search criteria. For example, if additional samples are entered into a *Wahoo* file, all previously created sets for this file may need to be recreated, using the appropriate search and set commands. For this reason, it is best to start using sets after <u>all</u> data entry has been completed. If data entry is ongoing but you desire to use sets for rapid data manipulation, it is worthwhile to develop a search file (see above) for each set to allow them to be easily recreated to accommodate later changes.

<u>Saving a set</u>

A set file is created in *Wahoo* in one of three ways:

- Using the "Search into Set command" from the Manipulate menu (Fig. 5-5), you will be presented with the normal Search dialog box and asked to name the records resulting from this search as set file.

- Using the "Save Selection as Set" command from the Manipulate menu (Fig. 5-5), you will be asked to name the records shown on the output layout list as a set file.

- Within the "Set Editor" (see below), you can save the results of comparing different sets of data as a new set file.

Several set files have already been created in *Wahoo* and are recorded in the "_____ sets" folders within each of the different *Wahoo* file folders (e.g., *Petrographic* sets) located in the "Wahoo *f*" folder.

Loading a set

Set files can be recalled from disk by choosing the "Load set..." command from the Manipulate menu (Fig. 5-10). A dialog box for "Load set.." will allow you to select a set file from a list within the "_____ set" folder for the *Wahoo* file being used. After choosing a set by double clicking or by clicking on "Open," the records within the selected set will be rapidly listed in the output layout. Note that sets can only be used in the *Wahoo* file in which they were created; using a set created in a different file will produce a list of nonsense data.

Set editor

By selecting the "Set Editor" command from the Manipulate menu (Fig. 5-5), you can calculate the Difference, Intersection, Union, or the Not Intersection of two sets (Fig. 5-11). In the set editor, you must first load a set into Set "A" and another into Set "B." Once this is accomplished you can click on the appropriate icon box on the right and a resultant set will be calculated. When you click the OK button the resultant set will be made the current selection of records.

For example, Set A might include all records from a specific stratigraphic section and Set B might contain all records containing abundant ooids. By comparing these two sets: an Intersection would list all samples in the stratigraphic section containing abundant ooids (the 26 records indicated on Fig. 5-11); a Difference would contain all samples in the stratigraphic section that lack abundant ooids; a Union would contain all samples in the stratigraphic section and all samples containing abundant ooids; a Not Intersection would contain all samples in the stratigraphic section and all samples containing abundant ooids except for those samples within the stratigraphic section that contain abundant ooids.

USING INPUT LAYOUTS

Input layouts are used to enter data into the different *Wahoo* files. The input layout allows you to create new records or edit records that already exist. Input layouts look like the data input forms (Forms 5-1 to 5-5) and allow you to work with only one record at a time.

CREATING AND ENTERING NEW RECORDS

When you want to create new records, open the *Wahoo* file of your choice and select "New Record" under the Enter menu. An input layout that is similar to a data entry sheet with blank data spaces will appear on the screen. The input layout varies somewhat depending on the size and shape of your monitor. The input layout can also

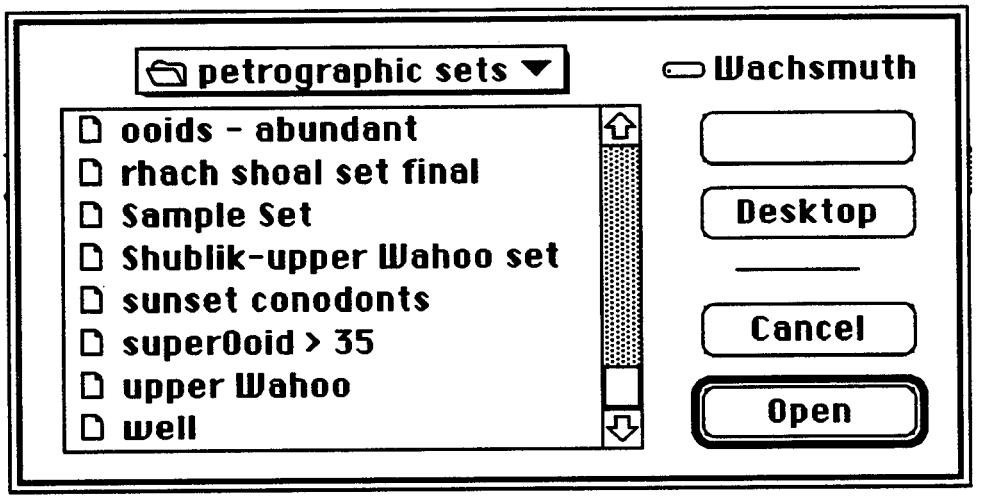


Figure 5-10. Dialog box contains a list of sets available to be loaded under "Load Set...".

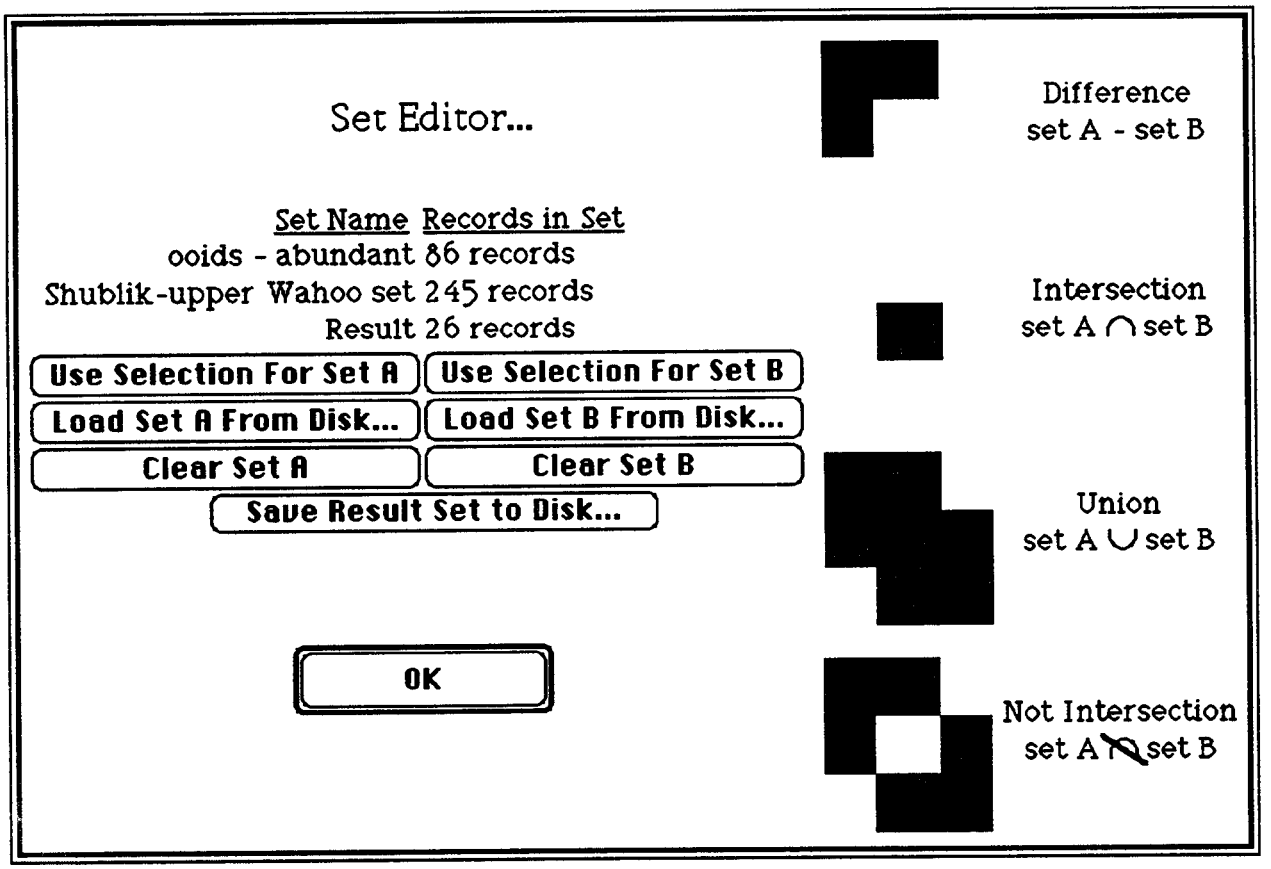


Figure 5-11. Dialog box for "Set Editor..." is used to compare different sets of data.

be changed by selecting different commands under "Preferences" (see below). On small screens (13"), the data entry page is subdivided into a number of smaller dialog boxes that are opened by pointing to the appropriate part of the small data-sheet "map" shown on the first screen (Fig. 5-12). On a large screen monitor, the screen looks like a data entry sheet, parts of which open dialog boxes similar to those used with the small monitor (inherited from when the database was originally created for a small monitor). Data are entered in a number of different ways depending on the nature of the data in the field.

- Alphanumeric data such as sample numbers are typed in after clicking on the appropriate field (long rectangular boxes). General descriptive text such as that recorded in "Comments" is also typed into the appropriate fields (Fig. 5-12).

- Specified text such as "Researcher" or "Depositional environment" are selected from lists that appear in dialog boxes after clicking on these fields (Fig. 5-13). These lists may be modified or appended but searches work best if consistent terminology is used and the number of categories on a list kept to a minimum.

- Specific names for fields such as "Rock type" or "Carbonate texture" are chosen from a dialog box listing different allowable choices that can be checked off in boxes which allow multiple entries (Fig. 5-14; e.g., grainstone and packstone).

- Semiquantitative and quantitative data such as the abundance of different carbonate grain types (e.g., back-shadowed boxes shown on Fig. 5-15) are entered on adjacent pull-down menus (Fig. 5-15b). Semiquantitative estimates are indicated as follows: A=Abundant (>50%), C=Common (10-50%), M=Minor (1-10%), and R=Rare (<1%). If E is selected, more precisely estimated percentages (or statistical point count data) can be typed into selected fields (Fig. 5-15b).

- Fields having a single value (e.g., grain abrasion) are selected from the appropriate radio buttons (filled-in circle). Fields having multiple possible values (e.g., different grain sizes present) are each selected using check boxes (Fig. 5-16).

- Some fields such as those for conodont age-data (Fig. 5-17) will cause more general categories (e.g., Period) to be automatically selected when a more specific field is selected (e.g., Stage or conodont Zone).

-The different pages of a data sheet are accessed by clicking on the page icons in the command field at the bottom of the input layout screen (5-17).

- The "date of last entry" will automatically be recorded to keep track of when data was last modified, allowing you to select new or modified records to be printed out, etc.

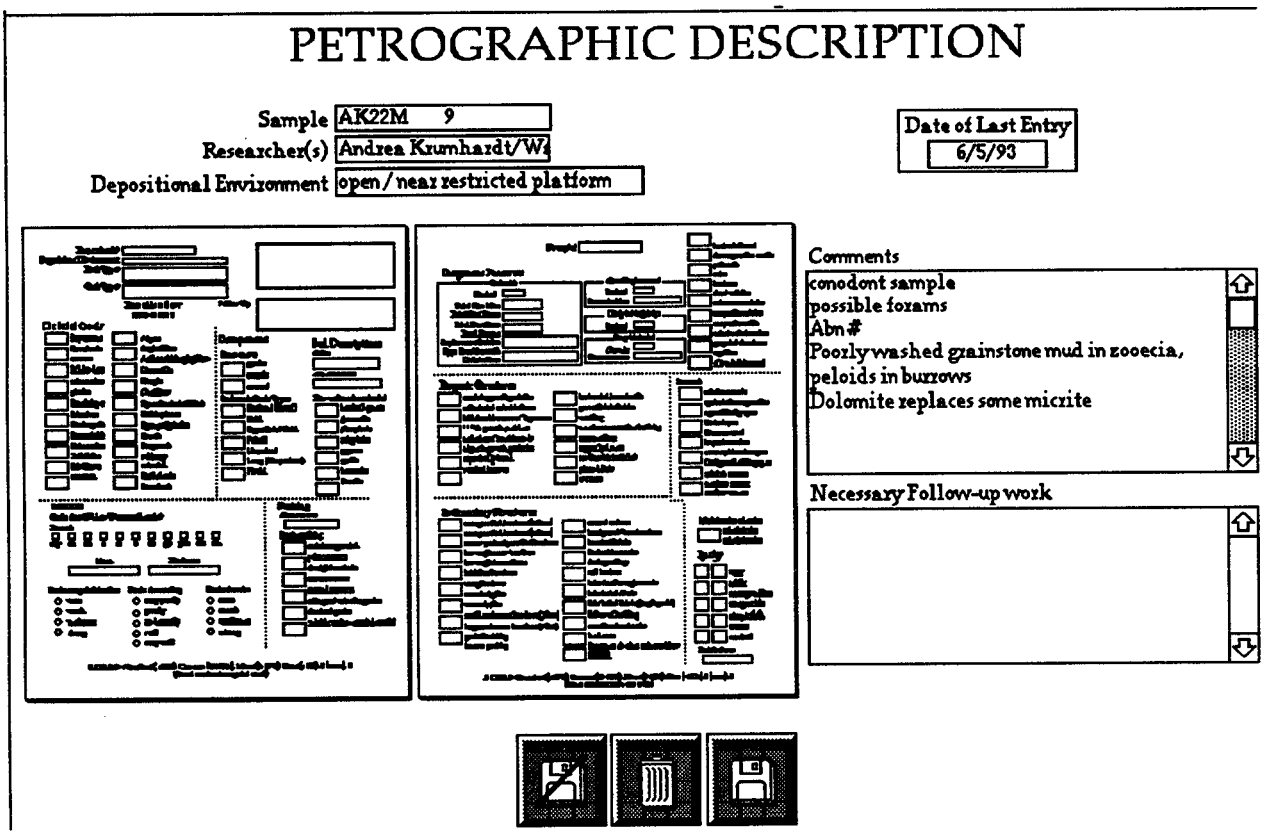


Figure 5-12. Data input screen for standard petrographic data form on a 13" monitor. By clicking on the appropriate part of the miniature form, dialog boxes will be opened for data entry.

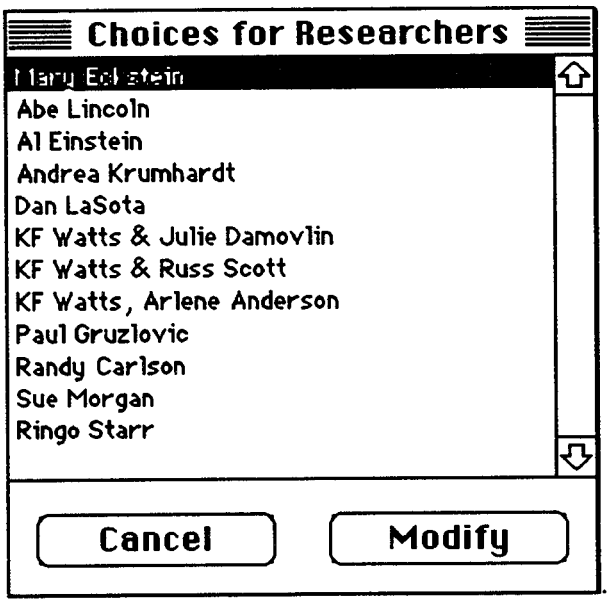


Figure 5-13. Dialog boxes such as for "Researcher" can be modified to allow new choices to be added.

Rock Types

- [x] limestone
- [ ] dolomitic limestone
- [ ] sandy or silty limestone
- [ ] cherty limestone
- [ ] argillaceous limestone
- [ ] dolostone
- [ ] calcareous dolostone
- [ ] sandy or silty dolostone
- [ ] cherty dolostone
- [ ] argillaceous dolostone
- [ ] sandstone
- [ ] calcareous sandstone
- [ ] dolomitic sandstone
- [ ] siltstone
- [ ] calcareous siltstone
- [ ] dolomitic siltstone
- [ ] shale
- [ ] calcareous shale
- [ ] dolomitic shale
- [ ] chert
- [ ] OTHER

Carbonate textural classification

- [x] Grainstone
- [x] Packstone
- [ ] Wackestone
- [ ] Mudstone
- [ ] Boundstone
- [ ] Bafflestone
- [ ] Framestone
- [ ] Bindstone
- [ ] Rudstone

Figure 5-14. Dialog box for entering rock type(s) and carbonate texture(s) allows multiple listings for samples containing more than one lithology.

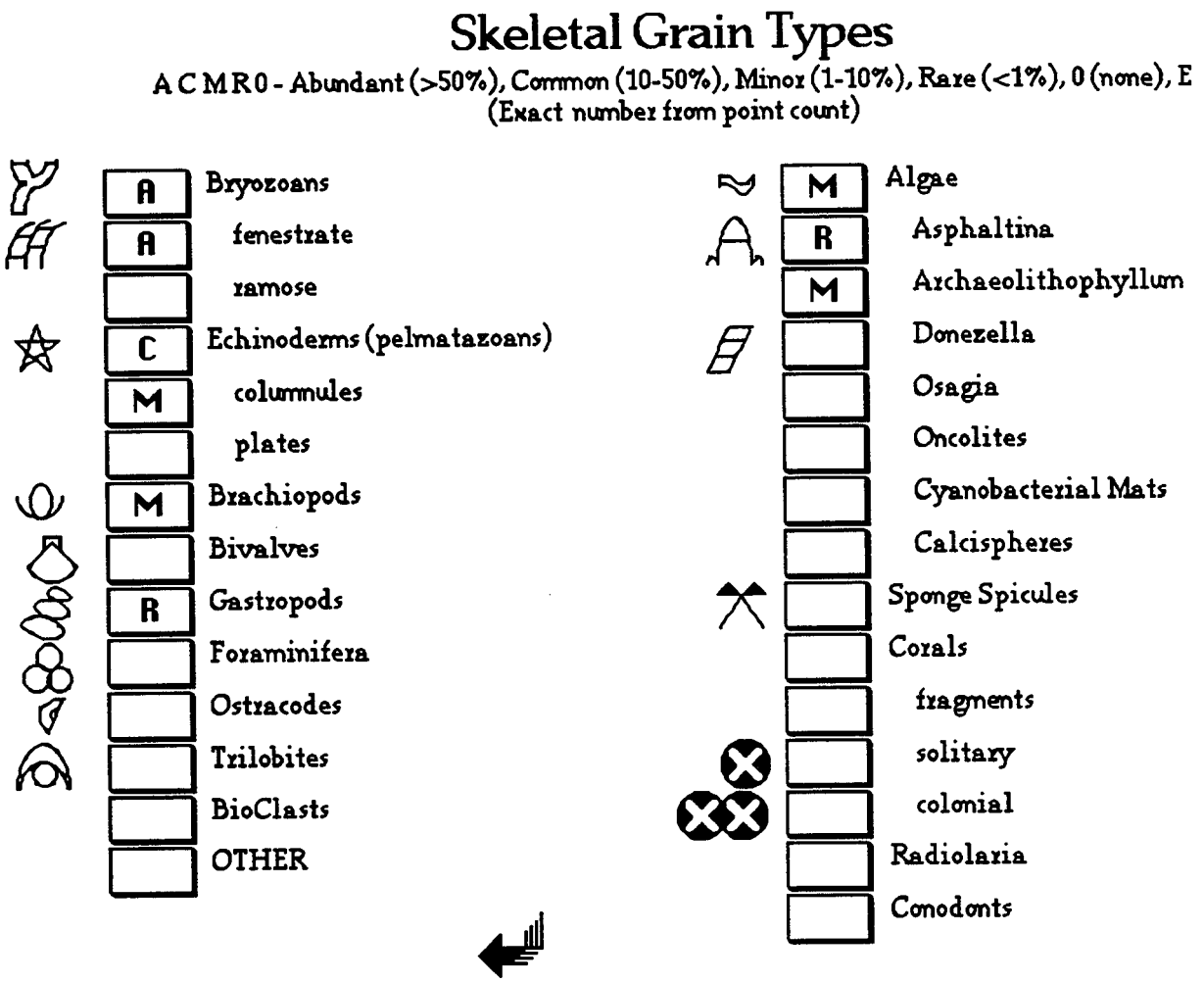


Figure 5-15a. Semi-quantitative (ACMR0) or quantitative (E -%) data is entered into back-shadowed boxes using pop-up menus

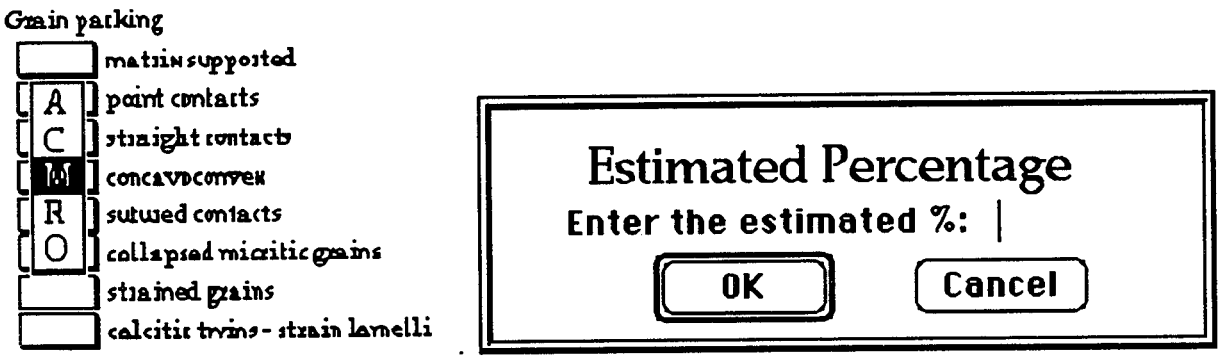


Figure 5-15b. Pop-up menu for choosing grain abundance appears when any of the back-shadowed boxes is selected. A=Abundant, C=Common, M=Minor, R=Rare, and E allows you to enter a more precise percentage in the dialog box shown at right.

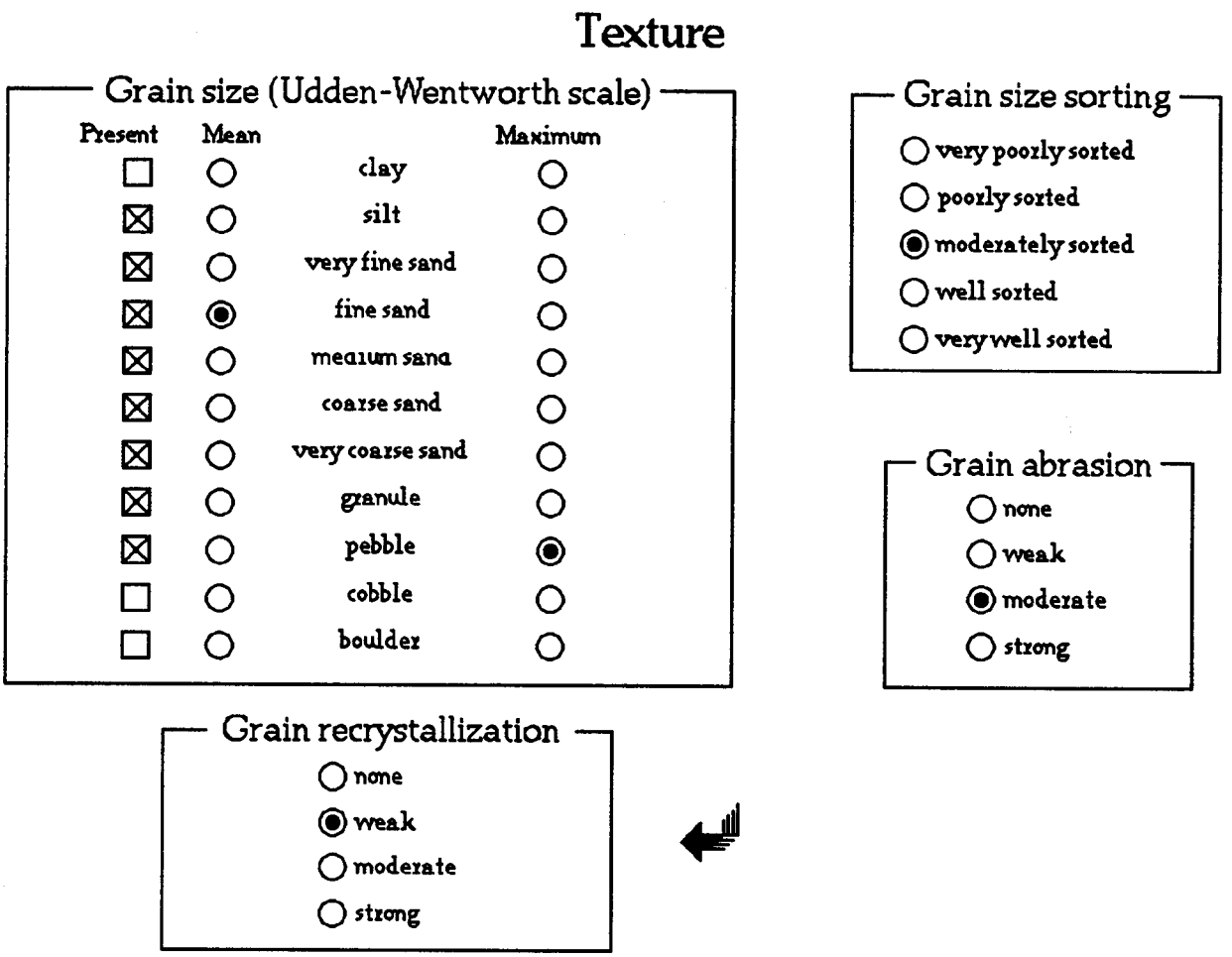


Figure 5-16. Variables having a single value are selected using a radio button (circles) whereas those having multiple values are each selected in the appropriate check boxes.

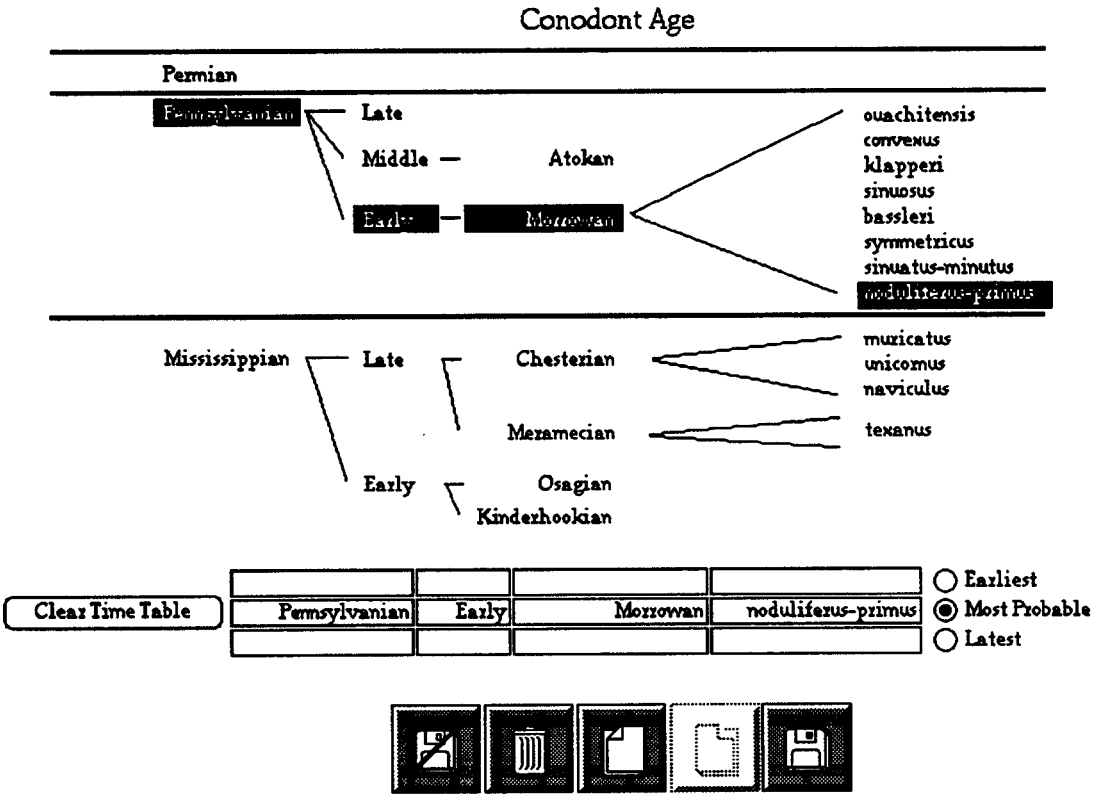


Figure 5-17. In some fields, such as those in conodont age data, selecting a field that contains detailed information (e.g., Stage or conodont zone) will cause related information to automatically appear in each of the more general categories (e.g., Periods). Note that because of time constaints and funding limitations, this dialog box has not been modified to replace previously established Morrowan zones abov e *D. noduliferus* with the *R. mnutus* and *Ideognathodus* Faunas recognized in the Lisburne Group.

SAVING DATA

When you click on the accept button (diskette icon at the bottom of the screen, Figs. 5-12 & 5-17), the record will be saved and a new blank input layout will automatically appear . This is for the next new record, assuming you will want to enter several records in a session. When you are finished with the last record to be entered click on the accept button as usual. When you see the next blank input form, click on the Cancel button (diskette icon with a slash through it, Figs. 5-12 & 5-17) to return to the output layout. With practice, the process of data entry using the menu-driven input layout is rapid and user-friendly.

Saving data in *Wahoo* requires several seconds for each record (depending on your computer's speed; old MAC II's may take up to a minute depending on the amount of available memory and data complexity). In order to make things go more smoothly, *4-D* initially saves your data to the RAM and periodically will save the accumulated data to hard disk (approximately every 15 minutes). At these times, you may hear the disk write data and see the cursor change into a page that scrolls to fill with black. This indicates that the data is being transferred from RAM memory to a more permanent place on your hard drive. Don't worry, if you quit sooner, the data will, of course, be saved.

EDITING EXISTING RECORDS

In order to edit an existing record within a *Wahoo* file, double click on the horizontal line of data representing the record that you want to modify. After its data is loaded (requiring several seconds), the input layout for the record will be displayed. Any necessary changes can be made and saved as outlined above (see under entering and saving records).

PRINTING OUT INPUT FORMS FOR SELECTED RECORDS

You may desire hard-copy print-outs of completed datasheets to cross-check accuracy of data entered into *Wahoo* with that on the original datasheets or to share your data with other workers who don't have access to *Wahoo*. In order to print out completed input layout forms for selected records, select the desired records using appropriate search or set, highlight the selection using "Select All," and click on the print icon at the bottom of the screen (Fig. 5-4). Alternatively you can manually select specific records using the mouse (see above) by highlighting individual records or groups of records to be printed. By selecting the print icon at the bottom of the screen, a dialog box will appear asking which type of form you desire. Select the appropriate radio button and standard print dialog boxes will allow you to choose the page orientation and number of copies, etc. Printing can be a time consuming process and is best done when you don't have other needs for the computer or printer.

REPORTS

After all is said and done, a database wouldn't be any good unless it helped you analyze your data and produce reports. The two main ways of examining and reporting data within *Wahoo* are tabular reports and graphs, using the "Quick Reports..." and the "Graph..." commands under the "Report" menu. Both commands use the standard *4-D* graph and report interface so you might want to refer to the *4-D* User's Guide for specifics. Before you actually use these features, select a meaningful data set to be analyzed (see above).

QUICK REPORTS

"Quick Reports.." allows you to generate tabular reports listing selected parameters (sample number, rock type, etc.). By selecting "Quick Reports...," a new window will appear that allows you create a table of data using the parameters listed at the left margin (Fig. 5-18). For example, Fig. 5-18 shows a report designed to list the sample number, carbonate texture, relative abundance of carbonate grain types, and depositional environment for selected records (samples) in the petrographic file. Tables can be designed to your own specifications with the ability to select fonts, column widths, perform calculations, and much more (refer to *4-D* User's Guide for specifics). Close "Quick reports.." by clicking the "OK" box on the lower left corner of its window. The last quick report used during a *Wahoo* session will appear by default the next time "Quick report.." is opened, making it easy to compare the same list of parameters between different data sets examined during a working session.

Saving a quick report

After you have created or modified a Quick report, you can save it for future use by selecting "Save" from the "File" menu. When a dialog box appears asking you to name the report file, give it a logical name (e.g., "petrographic data") and save it to the appropriate folder (e.g., "Petrographic reports" folder in the "Petrographic file" folder) to keep organized (Fig. 5-19).

Opening a quick report

Utilizing a previously created report file is easy, simply choose "Open" from the "File" menu and a dialog box will appear (Fig. 5-20). Select the appropriate report file from the appropriate file folder.

Printing a quick report

By selecting print (at bottom left of window or in the "File" menu), a print dialog box will appear (Fig. 5-21). If desired, the data table resulting from the quick report can be previewed on the screen by checking the "preview on screen" check box (as shown on lower left of Fig. 5-21) that will allow examination of successive pages of data prior to actual printing (Fig. 5-22). Printing large files can be time consuming and is best done

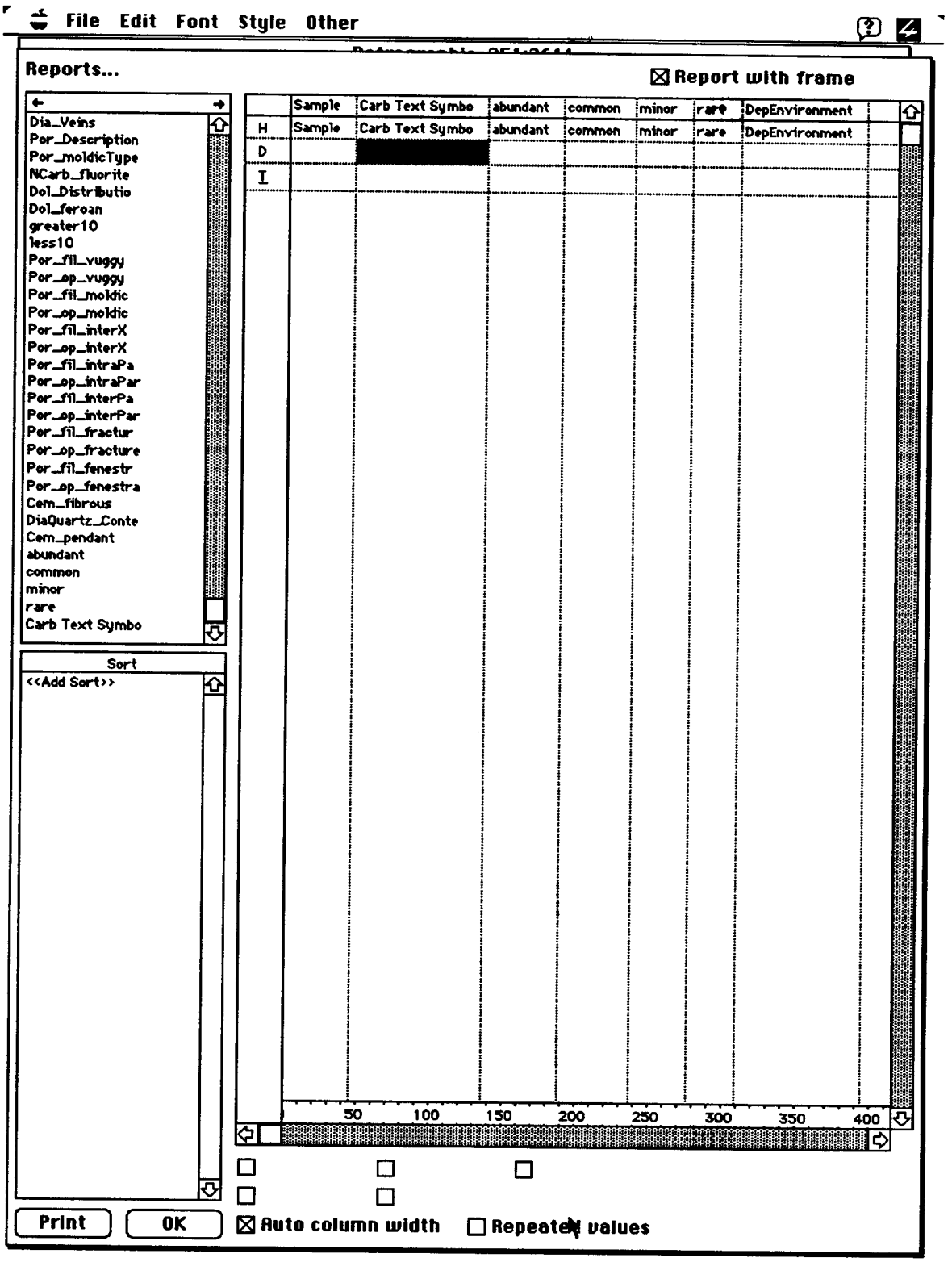


Figure 5-18. Window for "Quick Reports..." showing a typical tabular report form.

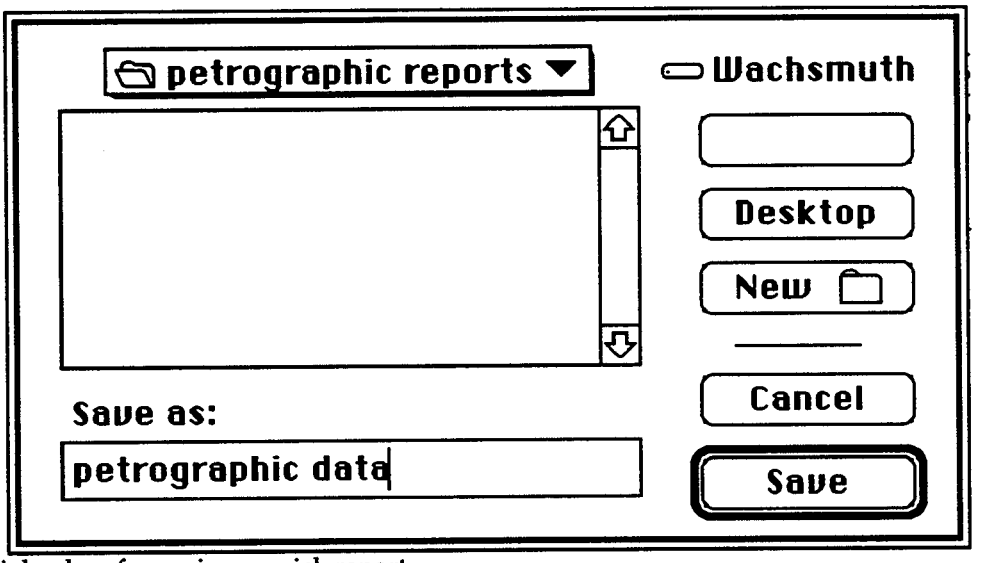


Fig 5-19. Dialog box for saving a quick report.

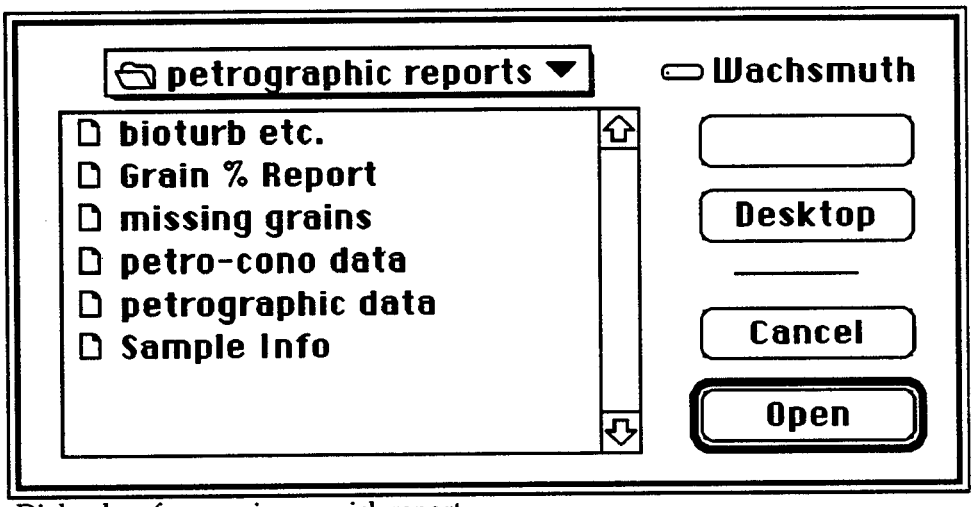


Figure 5-20. Dialog box for opening a quick report.

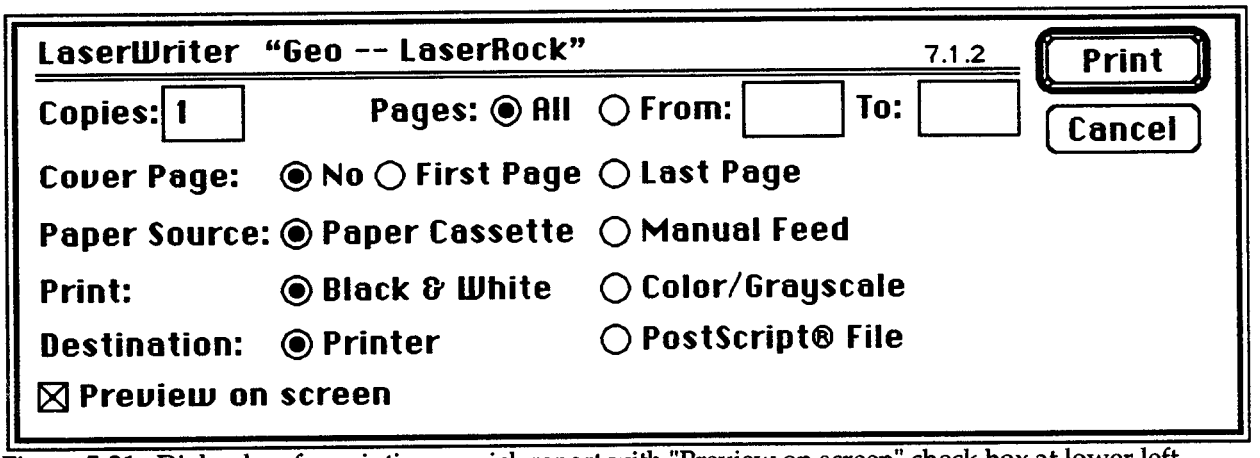
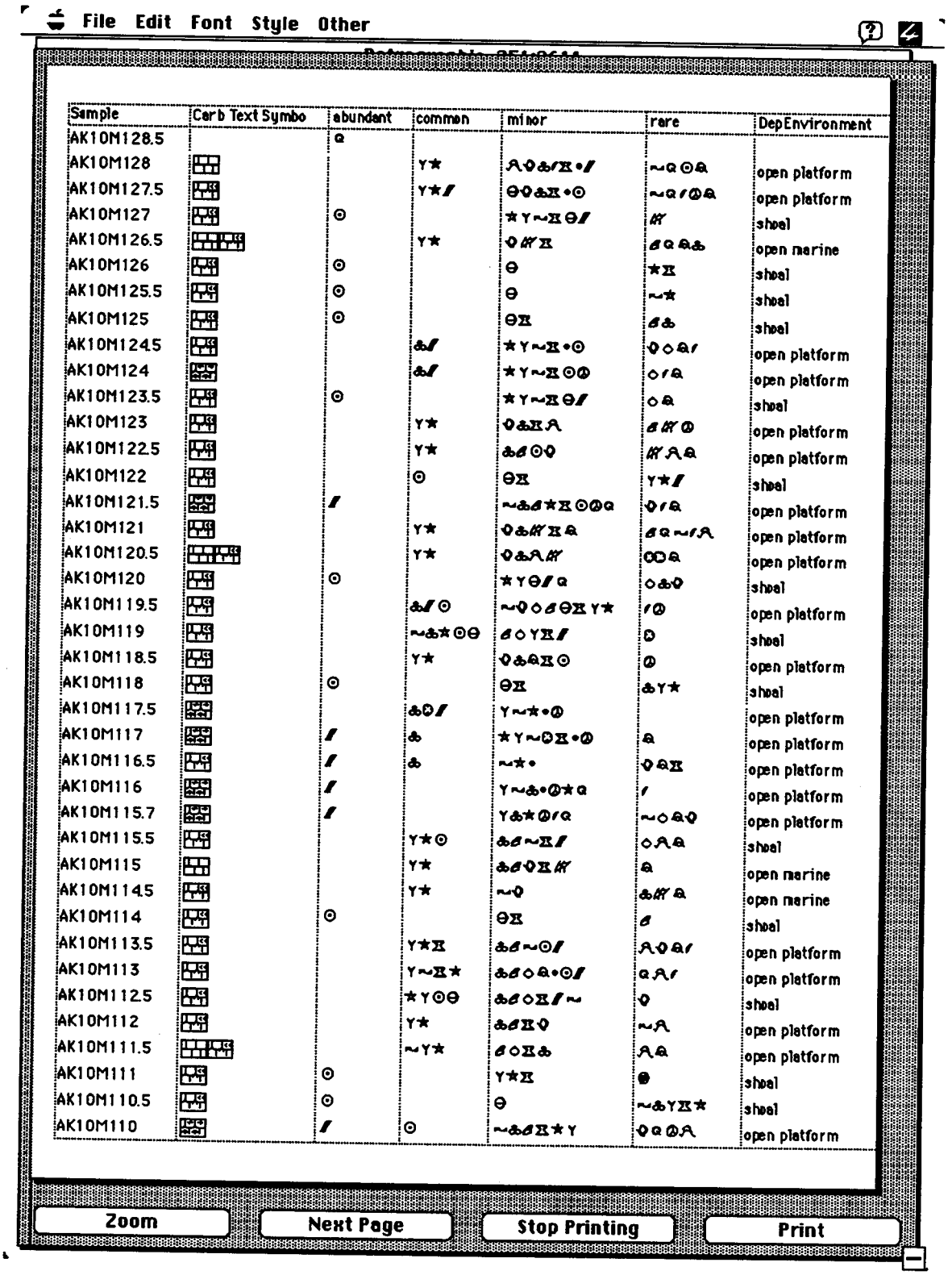


Figure 5-21. Dialog box for printing a quick report with "Preview on screen" check box at lower left.



Sample	Carb Text Symbo	abundant	common	minor	rare	DepEnvironment
AK10M128.5		⍝				
AK10M128			⍒⍋	⍝⍋⍀⍀⍁⍁⍁	⍁⍝⍉⍝	open platform
AK10M127.5			⍒⍋⍁	⍉⍋⍀⍀⍉	⍁⍝⍁⍉⍝	open platform
AK10M127		⍉		⍋⍒⍁⍉⍉⍁	⍀⍀	shoal
AK10M126.5			⍒⍋	⍋⍀⍀⍀	⍀⍝⍝⍀	open marine
AK10M126		⍉		⍉	⍋⍀	shoal
AK10M125.5		⍉		⍉	⍁⍋	shoal
AK10M125		⍉		⍉⍀	⍀⍀	shoal
AK10M124.5			⍀⍁	⍋⍒⍁⍉⍉	⍋⍉⍝⍁	open platform
AK10M124			⍀⍁	⍋⍒⍁⍉⍉⍉	⍉⍁⍝	open platform
AK10M123.5		⍉		⍋⍒⍁⍉⍉⍁	⍉⍝	shoal
AK10M123			⍒⍋	⍋⍀⍀⍀	⍀⍀⍀	open platform
AK10M122.5			⍒⍋	⍀⍀⍉⍋	⍀⍀⍝⍝	open platform
AK10M122			⍉	⍉⍀	⍒⍋⍁	shoal
AK10M121.5		⍁		⍁⍀⍀⍋⍀⍉⍉⍉⍝	⍋⍁⍝	open platform
AK10M121			⍒⍋	⍋⍀⍀⍀⍀⍝	⍀⍝⍁⍁⍝	open platform
AK10M120.5			⍒⍋	⍋⍀⍝⍀⍀	⍉⍉⍝	open platform
AK10M120		⍉		⍋⍒⍉⍁⍝	⍉⍀⍋	shoal
AK10M119.5			⍀⍁⍉	⍁⍋⍉⍀⍀⍉⍀⍀⍒	⍁⍉	open platform
AK10M119			⍁⍀⍋⍉⍉	⍀⍉⍒⍀⍀⍁	⍉	shoal
AK10M118.5			⍒⍋	⍋⍀⍝⍀⍉	⍉	open platform
AK10M118		⍉		⍉⍀	⍀⍒⍋	shoal
AK10M117.5			⍀⍉⍁	⍒⍁⍋⍉⍉		open platform
AK10M117		⍁	⍀	⍋⍒⍁⍉⍀⍉⍉	⍝	open platform
AK10M116.5		⍁	⍀	⍁⍋⍉	⍋⍝⍀	open platform
AK10M116		⍁		⍒⍁⍀⍉⍉⍋⍝	⍁	open platform
AK10M115.7		⍁		⍒⍀⍋⍉⍁⍝	⍁⍉⍝⍋	open platform
AK10M115.5			⍒⍋⍉	⍀⍀⍁⍀⍀⍀⍁	⍉⍝⍝	shoal
AK10M115			⍒⍋	⍀⍀⍋⍀⍀⍀	⍝	open marine
AK10M114.5			⍒⍋	⍁⍋	⍀⍀⍝	open marine
AK10M114		⍉		⍉⍀	⍀	shoal
AK10M113.5			⍒⍋⍀	⍀⍀⍁⍉⍁	⍝⍋⍝⍁	open platform
AK10M113			⍒⍁⍀⍋	⍀⍀⍉⍝⍉⍉⍁	⍝⍝⍁	open platform
AK10M112.5			⍋⍒⍉⍉	⍀⍀⍉⍀⍀⍁⍁	⍋	shoal
AK10M112			⍒⍋	⍀⍀⍀⍋	⍁⍝	open platform
AK10M111.5			⍁⍒⍋	⍀⍉⍀⍀	⍝⍝	open platform
AK10M111		⍉		⍒⍋⍀	⍉	shoal
AK10M110.5		⍉		⍉	⍁⍀⍒⍋⍀	shoal
AK10M110		⍁	⍉	⍁⍀⍀⍀⍋⍒	⍋⍝⍉⍝	open platform

Figure 5-22. Report form lists data as it appears with preview on screen in print selected.

when you don't need your computer for other purposes (i.e., start printing at end of work day to be accomplished during off hours).

Printing to a file for export

By selecting "Print to.." on the "File menu," you have the option of choosing where to print your data table (Fig. 5-23). In some cases, it may be preferable to export your data as an ASCII file to a spreadsheet or graphing program (such as EXCEL or Cricket Graph) to allow more control on the layout of graphs (see below) or to allow statistical analysis.

Sample file—Linking parameters from different *Wahoo* files

Because the different *Wahoo* files have different numbers of records and types of data, linking them by sample number in the "Sample" file presented special problems in program development that must be considered in producing reports or graphs. Fig. 5-24 shows a quick report that links *petrographic* and *conodont* files.

If you want to create a report based on records in the sample file that utilizes information from related records (for individual samples) in the other files you will have to do the following:

1 Create the report by selecting fields from the file you want to relate (as in Figs. 5-18 and 5-24). The different files are accessed by selecting them from a pull-down menu that appears when you click on the title bar above the list of different fields (at left). In Figure 5-24, columns C2 and C3 in this quick report each contain formulas that instruct *4-D* to link the *petrographic* and *conodont* files using their common sample number. These formula columns are grayed out, indicating that they will not appear in the report. A formula bar must precede all the fields listed from a particular file in order to obtain the appropriate data.

2 To create formula columns like C2, select the first column of data for a particular file and use the "Insert Column" command from the menu. After a blank column appears, choose "Edit Formula.." from the menu.

3 You will be presented with a dialog box (Fig. 5-24). This dialog allows you to type a 4D command that will relate the records from the file containing the subsequent fields .

4 Type in one of the formulas as listed below as appropriate for the file being used:

Petrographic = SEARCH([Petrographic];[Petrographic]Sample=[Sample]Sample Num)

Cements = SEARCH([Cements];[Cements]Sample Number=[Sample]Sample Num)

Conodont = SEARCH([Conodont];[Conodont]Sample Number=[Sample]Sample Num)

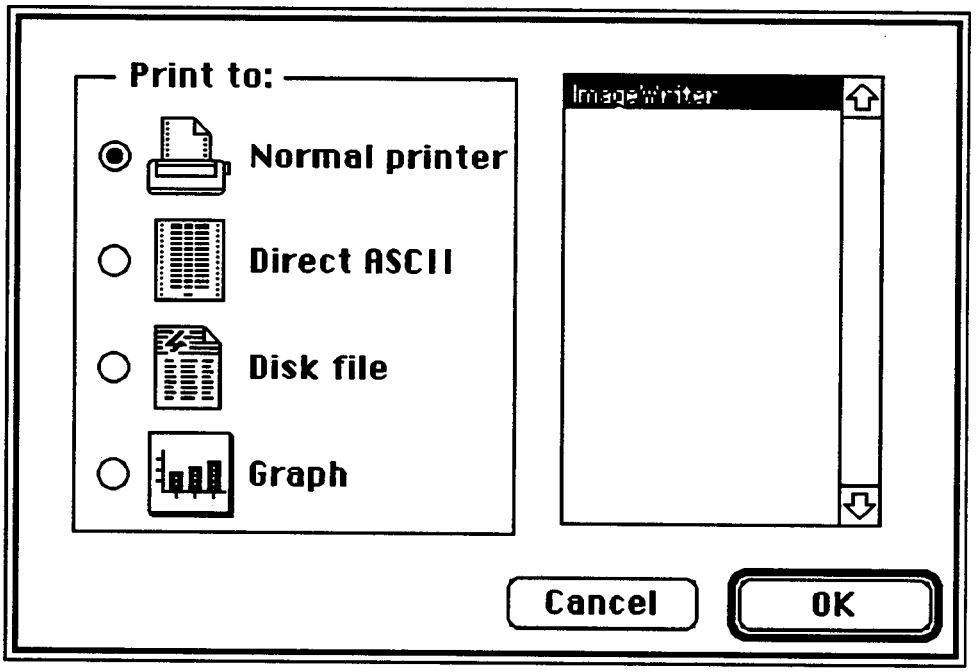


Figure 5-23. Dialog box for printing quick report to different types of Macintosh files.

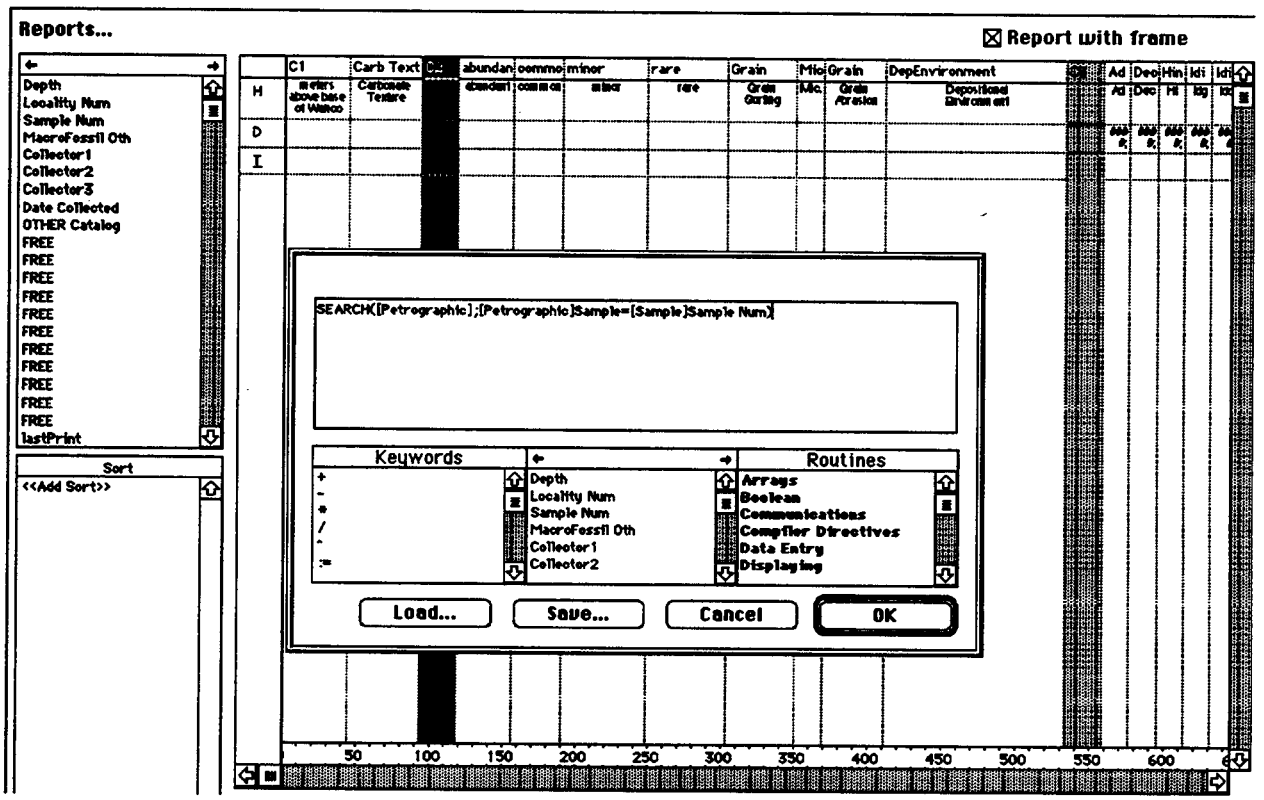


Figure 5-24. Quick report for sample file shows the formula columns that link the *petrographic* and *conodont* files.

Genera = SEARCH([Genera];[Genera]Sample Number=[Sample]Sample Num)

Well Logs = SEARCH([Well Logs];[Well Logs]Sample Number=[Sample]Sample Num)

5 Note that formula column C2 appears immediately to the left of all the fields in the report that are from the Petrographic file. Listing them otherwise will cause errors in data retrieval.

Changing the values of fields in reports—"Editing a formula"

Some fields having a choice of two variables were designated as Boolean fields to reduce memory requirements. The computer records these as true-false values, rather than as their actual values (e.g., north or south). The function booleanPrint can be used to replace field values of true or false with values that you choose. For example, the field "Town NorthSouth" from the Locality file is Boolean. Fig. 5-24 shows a dialog box from the "Edit a Formula" menu on the Quick reports screen. The syntax for the function is booleanPrint("sub1"; "sub2"; field) where "sub1" is the word you want to substitute for all true values (e.g., north) and "sub2" is the word you want to substitute for all false values (e.g., south).

Another function that may be helpful is printAbundance. As mentioned previously, the semiquantitative values of abundant (A), common (C), minor (M) and rare (R) have all been given a number (A=50%, C=35%, M=5%, and R=1%) to allow them to be quantified in graphs. In some cases, it is better to have the value listed on a report as the letters ACMR0. In order to make these changes, choose "Edit a formula" and type in the syntax printAbundance(field). PrintAbundance will return one of the letters "A, C, M, R, or 0" depending on the value of the field for each record. For example, the field "Mic_micritiz." might be selected to illustrate variation in degree of micritization. The field must be one of the fields entered with a ACMR0 pop up button.

GRAPH

At the onset, the user is warned that the graphing capabilities within *4-D* are somewhat limited and are easily overwhelmed by large datasets. The graphs are linked to *Wahoo's* data in mysterious ways that can yield unexplainable errors. For this reason, we recommend that you export your data to a spreadsheet/graphing program (see below). Nonetheless, *4-D's*, graphing capabilities are a useful tool for quickly examining your data to look for trends and compare different data sets. These preliminary analyses allow selection of specific data sets worthy of detailed analyses and more laborious transfer of data to the graphing programs. In this manual, we will briefly discuss how to create some of the more commonly used graphs. See the *4-D* User's manual for detailed information on how to utilize its graphing capabilities.

First, you should select a data set using the search or set commands (e.g., a specific locality and stratigraphic interval). By selecting "Graph.." from the Report menu, a dialog box will allow you to create a variety of graphs that illustrate variations

in most of the different parameters recorded in *Wahoo* (Fig. 5-25). Most commonly, you will probably want to show variability of different parameters (e.g., ooid abundance) versus stratigraphic position (depth). For example, Fig. 5-25 is a line graph showing variations in the abundance of ooids versus stratigraphic position (depth) in the Petrographic file.

All the parameters recorded as semi-quantitative data (ACMR) are converted to numbers to allow them to be graphed quantitatively: Abundant = 50%, Common = 35%, Minor = 5%, and Rare = 1%. Thus, the graphs have collections of data points clustered at these values (Fig. 5-26). If the variables are truly quantitative (e.g., data in cement types or well logs), the precise values of these parameters will be plotted.

Graphs showing depth on a proportional scale

In most graphs produced within *4-D*, the x-axis is evenly divided by the number of records in a given data set so that records are evenly spaced regardless of their actual spacing relative to each other. When trying to portray the actual stratigraphic position of records (with "**depth**" on the x-axis) in *Wahoo*, only two types of graphs, scatter graphs and line graphs, allow data to be graphed proportionally on the x-axis. Initially, your graphs will be drawn with evenly spaced records. In order to show these graphs proportionally, you must select "Scales" from the "Options" menu in the "Graph.." window (Fig. 5-26) that will open a dialog box (Fig. 5-27). For the x-axis, select the check box for "proportional," uncheck the automatic box, and type in the appropriate range of depths for your data set (e.g., 100 to 125 meters). The resulting graph will have registration marks and labels at regular intervals depending on the range of depths (e.g., every 5 meters as shown on Fig. 5-26).

Graphs showing the relative abundance of selected parameters

Parameters that contain text information are more difficult to quantify in order to make graphs. However, it is possible to show the proportion of different items listed under certain parameters/fields in a data set (such as rock type or carbonate texture). For example, you might want to illustrate the proportion of different carbonate textures occurring in a certain stratigraphic interval and/or locality. By selecting "carb. texture" on the x-axis and "one" on the y-axis, a graph will show the percentages of grainstone, packstone, etc. (Fig. 5-28).

Printing graphs and copying graphs for export to graphics programs

Standard "Page set-up" and "Print" commands are available in the file menu. *4-D* will automatically vary the size of the graph axes to fill the available page area rather than printing what you see on the screen, so you should select the appropriate layout to suit your needs. In most cases, you will want to modify the graphs (changing labels, adding titles, etc.) by exporting the graph to a graphics program (e.g., Fig. 5-29). This is done by simply selecting "Copy" from the "edit" menu, opening your graphics program (such as MacDraw or Canvas), pasting in your graph, and making necessary modifications. Before copying the graph, modify patterns or colors (in area or bar

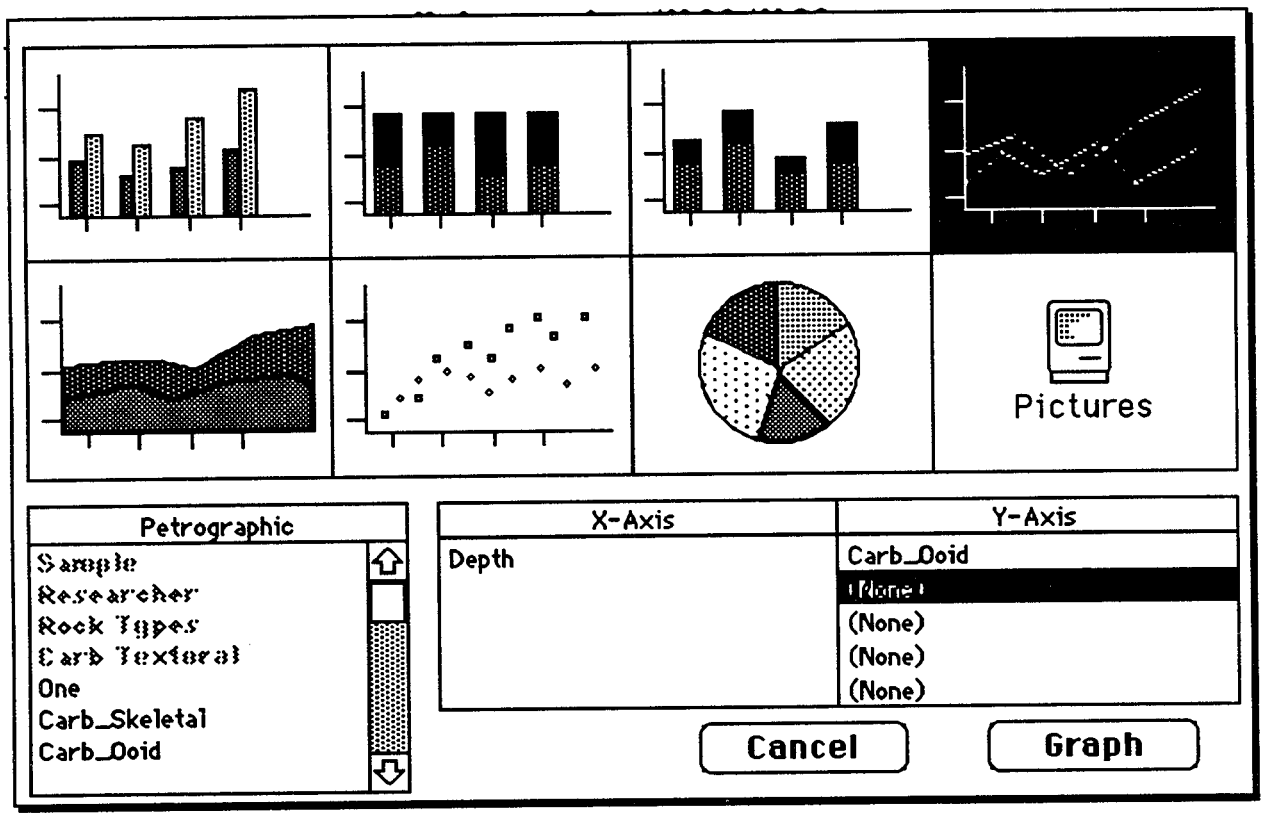


Figure 5-25. Window for "Graphing..." shows the different types of graphs available and lists parameters that can be dragged to the x-axis (a single parameter such as depth) or y-axis (multiple parameters possible).

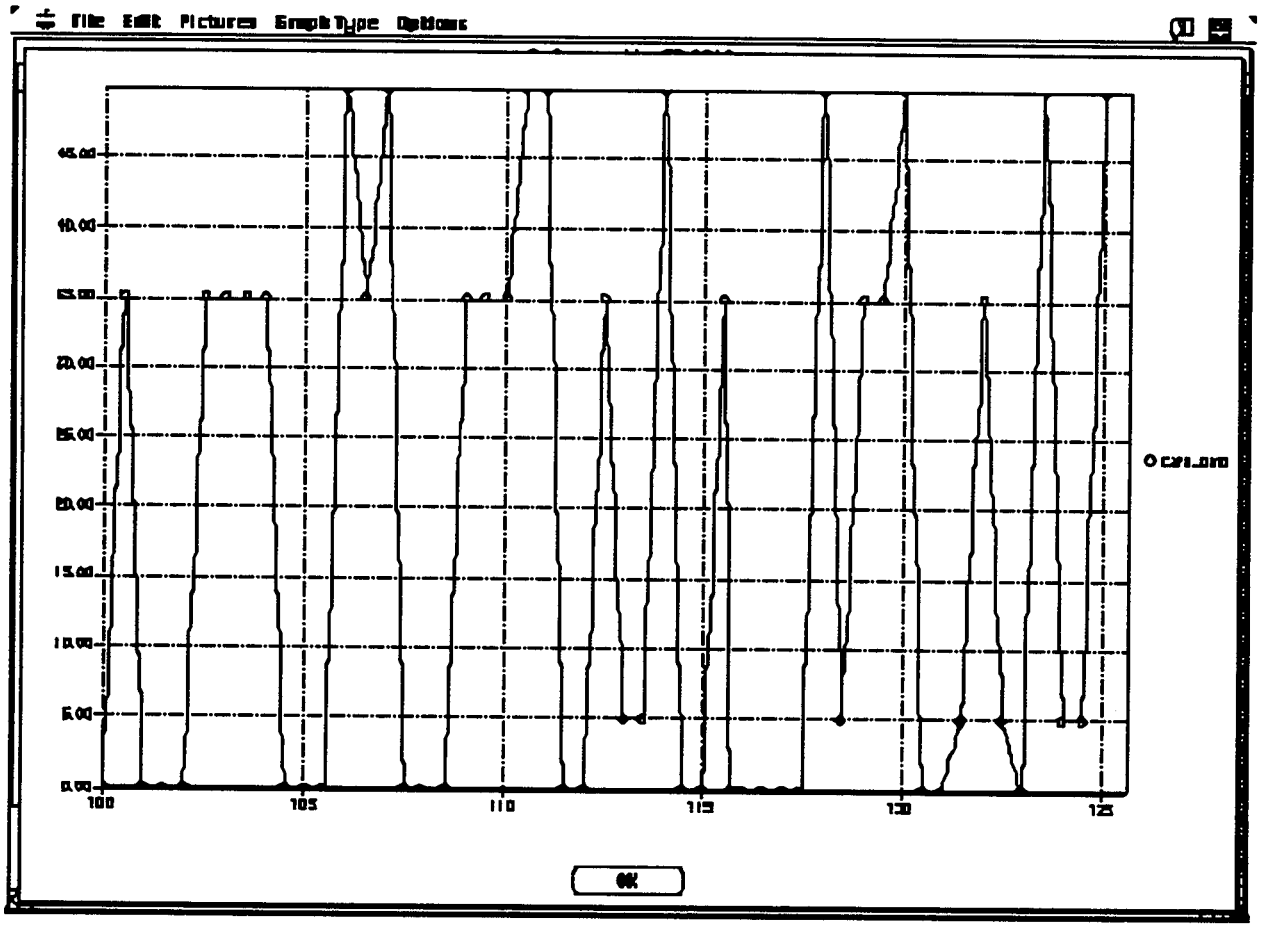


Figure 5-26. Graph showing the variations in abundance of ooids versus depth for the uppermost Wahoo Limestone in the central Shublik Mountains (localityAK10M)

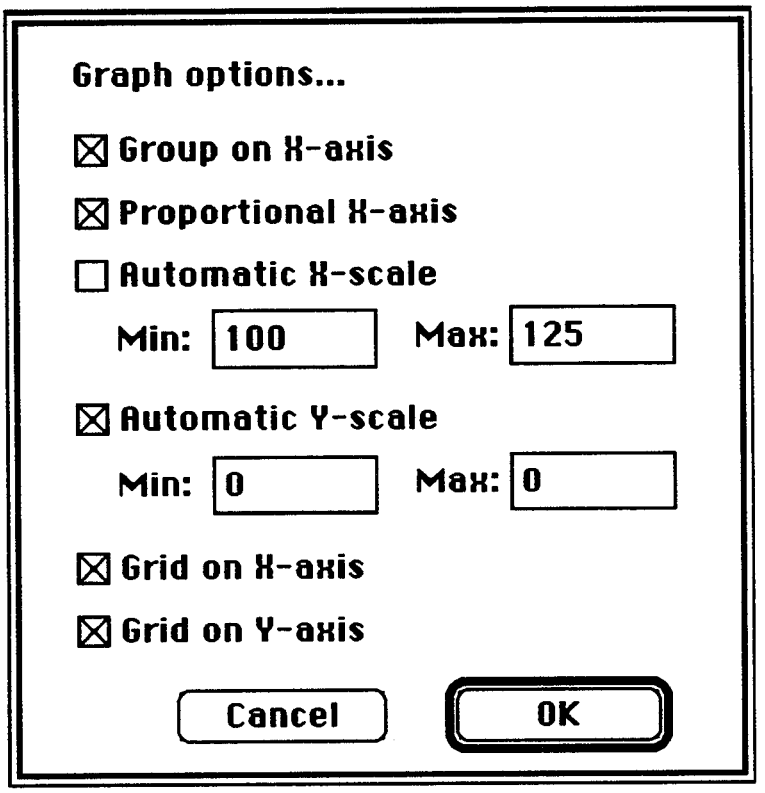


Figure 5-27. Dialog box for "scales" is used for making the x-axis a proportional scale (the depths used created the graph shown in Figures 5-26 and 5-29).

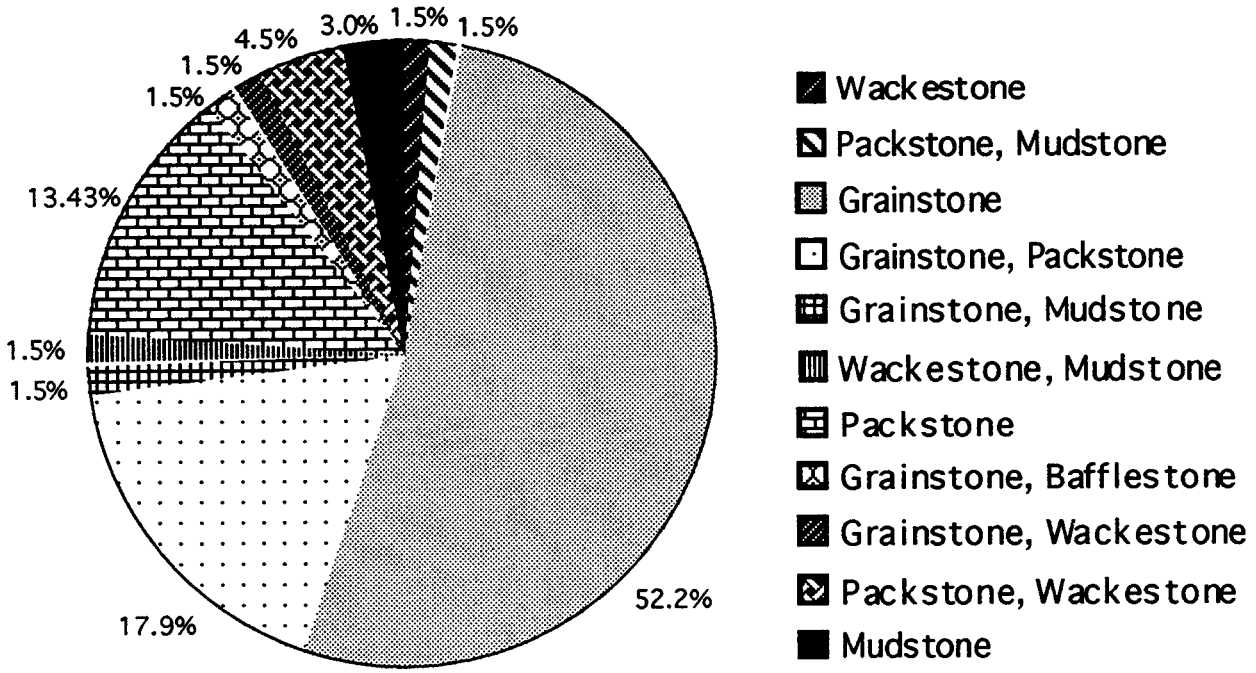


Figure 5-28. Graph showing the relative percentages of different carbonate textures represented by all the conodont samples from the eastern Sadlerochit Mountains section.

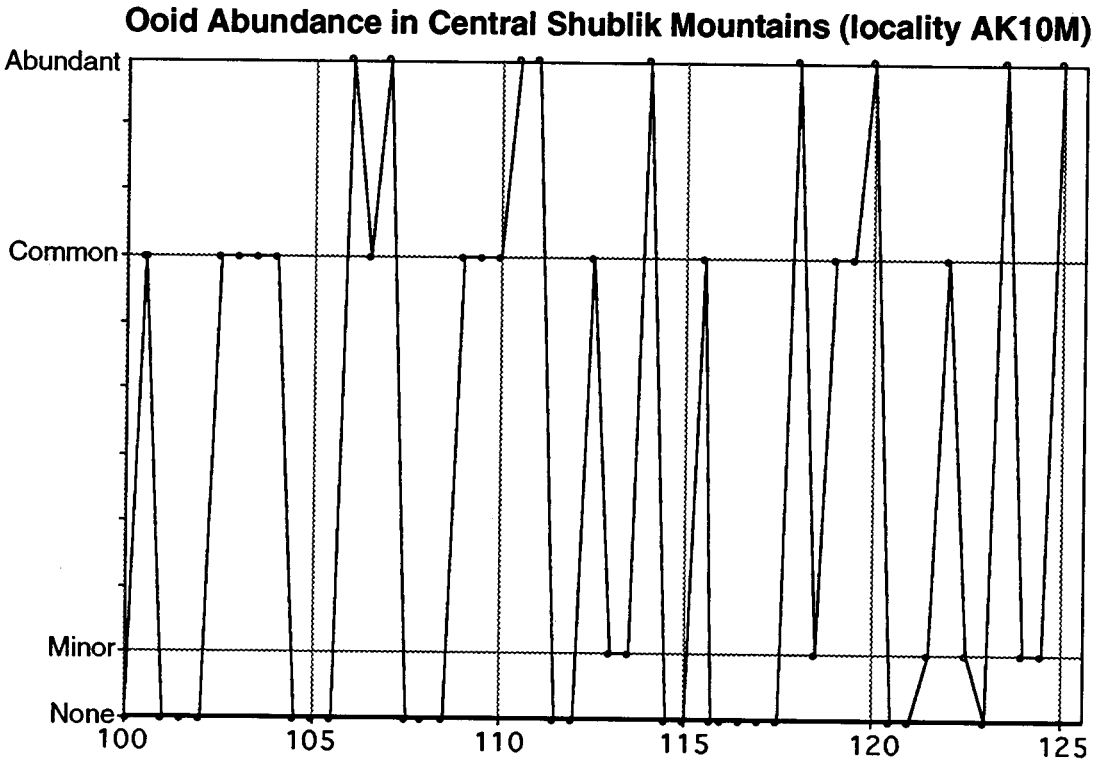


Figure 5-29. Graph shown on Fig. 5-26 was transferred to a graphic program (Canvas 3.0) and modified for publication.

graphs) while in *4-D* by clicking on the pattern fill areas shown in the legend which causes a dialog box to appear for making your desired changes (e.g., Fig. 5-28). This allows the changes to be made simultaneously on all parts of the graph linked to that pattern before copying the file over to your graphics program as a PICT file (where each line or area might have to be selected individually).

Exporting data to graphing programs

The graphing capabilities within *4-D* are somewhat limited, so you will probably want to export your data to a more powerful graphing program. For example, if you want to create graphs using large data sets (>~ 50 records), the graphing capabilities of *4-D* may become overloaded. As noted above, tables of data produced within "Quick reports.." can be exported as ASCII files and imported into spreadsheet/graphing programs such as EXCEL and Cricket Graph. Such programs list your data in spreadsheets that allow their accuracy to be verified. Their graphing functions permit considerably more flexibility in controlling the layout of graphs than in *4-D*. For example, you can define the size of the graph axes and copy your graph layouts for future reference; such consistency will allow direct visual comparison of individual graphs for a number of selected parameters. The graphs produced by these programs can be saved, printed out, or copied into other programs (particularly graphics programs such as Canvas or MacDraw).

Using graphs within the "Sample" file

As noted above, the sample file allows comparison of data contained within the different files in *Wahoo*. Because of the complexity of this part of the database, we recommend exporting this data from Quick reports to a graphing program as described above. However, if you desire, graphs can be produced within the sample file using by clicking on the graph icons located near the base of the output layout for the sample file (Fig. 5-30). The functions of the graph button on the sample file output layout work much better when the memory allocation for *4-D* is at least 5 MB; the machine may jam with less memory available.

IMPORTING AND EXPORTING

Wahoo allows records from its different files to be exported (archived) or imported as Macintosh files (Fig. 5-5). When naming a Macintosh file during an export, you should include some reference on which *Wahoo* file it represents so that it can be imported into the proper file. An apt name for the Macintosh file might be "Sample-AK22M-all conodonts" for sample data on all conodont samples in section AK22M.

Exporting Reports—Archiving

By choosing "Export Data..." from the File menu (Fig. 5-5), a dialog box will give you a choice of exporting ("archiving") all the records in a file or all the records in a search (Fig. 5-31). Because of the huge size of the *Wahoo* database, you will probably

File Edit Enter Manipulate Report

Sample 9558:9558

KW90K	373.5	Alapah	Mississippian	thin section
KW90K	373.8	Alapah	Mississippian	macrofossil, Other
KW90K	374.0	Alapah	Mississippian	macrofossil, Other
KW90K	374.1	Alapah	Mississippian	macrofossil, Other
KW90K	374.5	Alapah	Mississippian	conodonts, thin section
KW91A	0.2	Alapah	Mississippian	conodonts, thin section
KW91A	1.0	Alapah	Mississippian	thin section
KW91A	5.7	Alapah	Mississippian	thin section
KW91A	11.0	Alapah	Mississippian	macrofossil
KW91A	13.2	Alapah	Mississippian	macrofossil
KW91A	14.2	Alapah	Mississippian	macrofossil
KW91A	20.3	Alapah	Mississippian	thin section
KW91A	23.0	Alapah	Mississippian	thin section
KW91A	25.0	Alapah	Mississippian	thin section
KW91A	33.4	Alapah	Mississippian	thin section

Print... Percentage Graph Relational Graph Done

Figure 5-30. Window for sample file with the "Graph..." icons near base.

Archive Records...

Select method of archiving records:

○ Archive all records

◉ Archive records based on search

Cancel OK

Figure 5-31. Dialog box for exporting/archiving selected records.

want to make a smaller selection using the search dialog box provided for archiving selected records.

It is important to note that while the records have been archived to a Macintosh file, they still exist in *Wahoo*. If you want them removed from the database for some reason, then you need to select these records using the appropriate search command, highlight the records using "Select All," and then delete the entire selection of records using the delete command. **This is very dangerous and may result in loss of data!**

Importing Reports

Importing records into the database is done by selecting "Import Data..." from the File menu (Fig. 5-5). In order to import the records properly, you must be in the output layout of the appropriate file. The *Wahoo* file structure that archived/exported the data must be the same as the *Wahoo* file into which it is imported. If records are imported from one *Wahoo* file into a different *Wahoo* file, you will generate garbage records. Make sure you select the appropriate file. This method allows data to be imported from off-site computers. For example, if a user entered new petrographic records, they could export these data as explained above along with any new associated sample and locality data records. The data can then be imported to the appropriate *Wahoo* files.

PREFERENCES

CHOOSING AN INPUT LAYOUT

Some *Wahoo* files have multiple input layouts to allow variations in monitor size and different data input formats. To select an input layout that is different from the one that is normally used, the command "Preferences..." should be chosen from the File menu (Fig. 5-5). This can be done as long as you are not already viewing an individual record using an input layout. The appropriate input layout is selected using pop up buttons for the *Wahoo* files listed under the column *User Input Preferences*, (Fig. 5-32) Click on the present layout indicated for the desired file to get a pop up menu with other choices and select the desired input layout (Fig. 5-32). When you have completed your changes, click "OK" to return to the output layout.

ADMINISTRATIVE TASKS

Certain parts of the data in *Wahoo* are not directly affected by the input of data. Thus, certain procedures must periodically take place to update these data. Normally these tasks, sometimes called "massaging the data" can be handled by an in house programmer. However, in an effort to make *Wahoo* as easy to use as possible, these tasks have been automated and need only a click of a button from the user (5-33). All the tasks are performed by choosing "Administrative..." from the File menu (Fig. 5-5) when you are at the splash screen (before you load a *Wahoo* file).

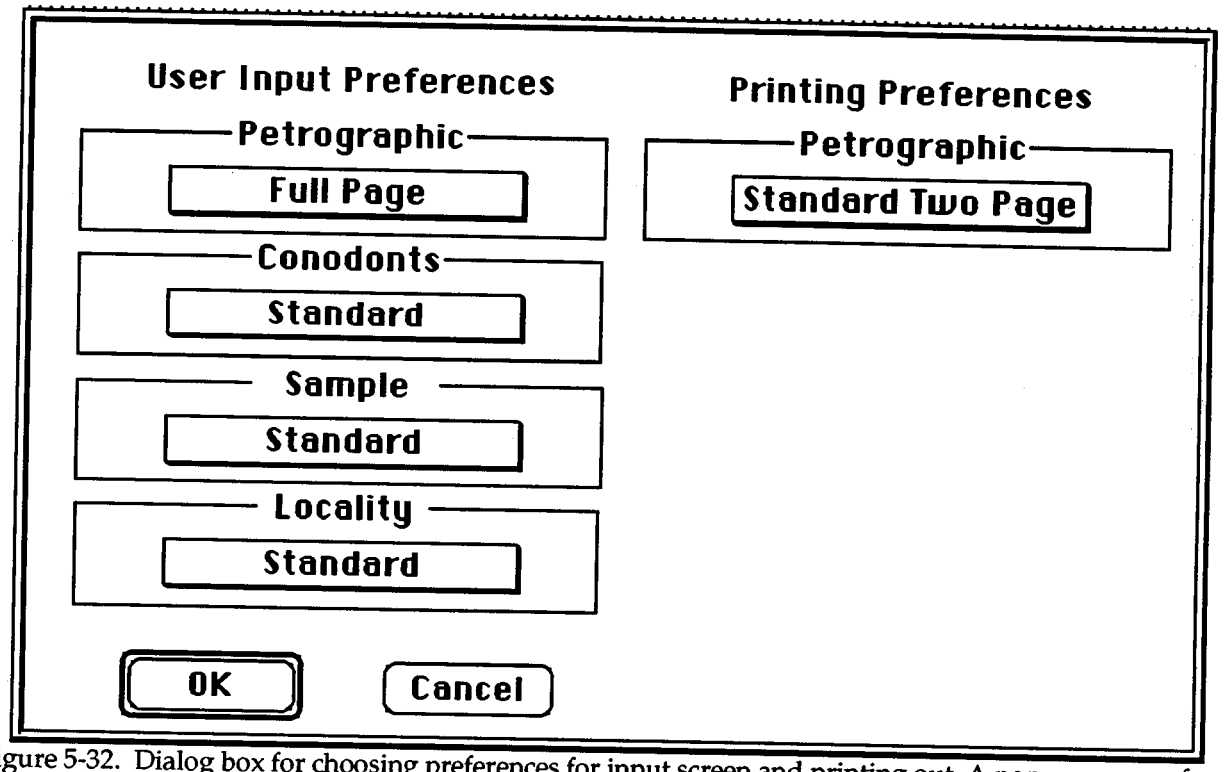


Figure 5-32. Dialog box for choosing preferences for input screen and printing out. A pop-up menu of possible selections appears when each box is clicked.

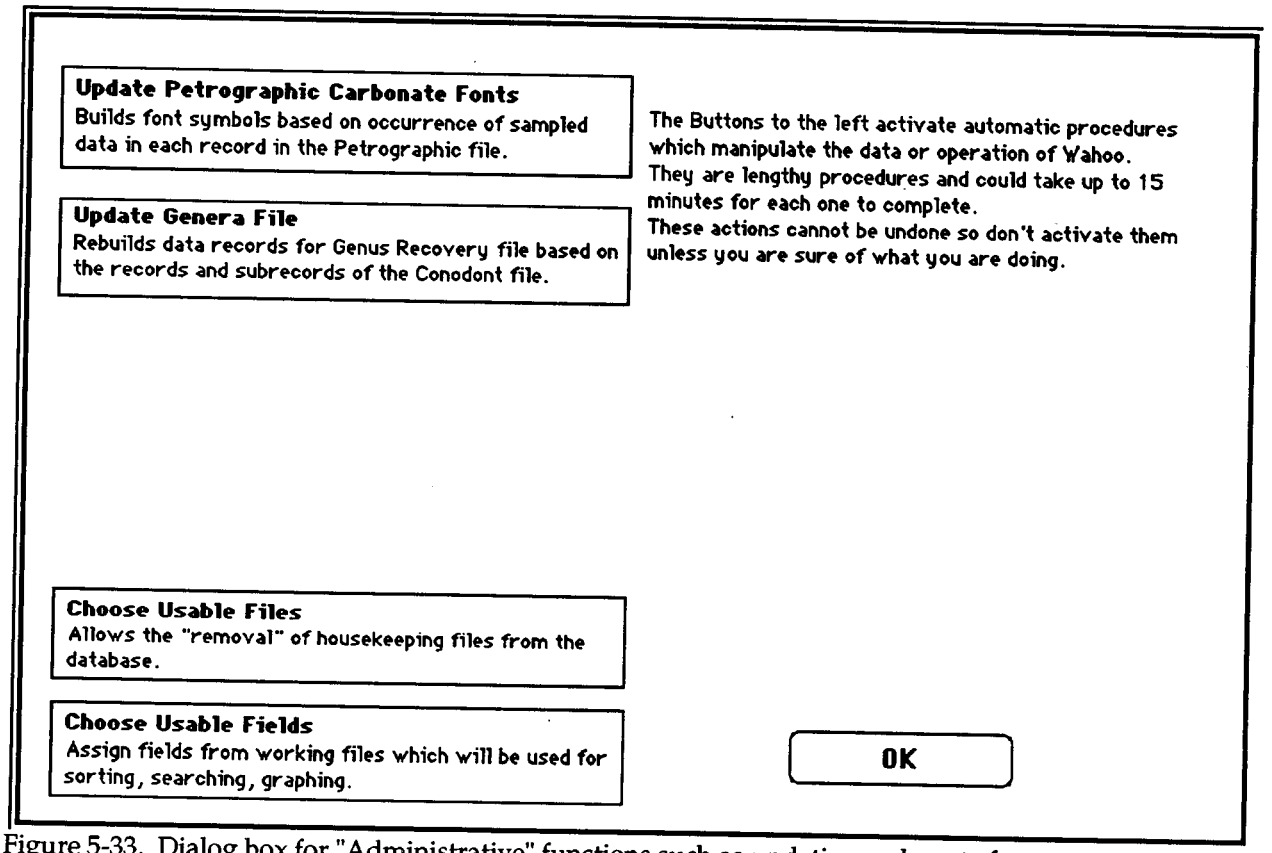


Figure 5-33. Dialog box for "Administrative" functions such as updating carbonate fonts.

UPDATING PETROGRAPHIC CARBONATE FONTS

The carbonate fonts seen on the output layout for the *Petrographic* file (Figs. 5-4 & 5-15) are hieroglyph-like symbols (each grain type has a symbol) that are listed to show the relative abundance of carbonate (and other) grains that were recorded in petrographic analyses. The abundance columns (Abundant, Common, Minor, and Rare) were each derived to tally all the appropriate grain types (fonts) that are recorded separately in the petrographic file. If any records in the *Petrographic* file are added or edited to change abundance of any grain types, the carbonate fonts shown in the abundance columns will need to be updated to show these changes. The *Updating Petrographic Carbonate Fonts* command affects only the listing of relative grain abundance seen in the output layout and generated by quick reports (Fig. 5-33). As this procedure takes a long time to accomplish (several minutes), it should be done only when records have been added or edited in a way that would affect grain abundance. Unless needs are urgent, it is best done when you don't need your computer for other purposes (i.e., start update at end of work day to be accomplished during off hours).

UPDATING GENERA FILE

Update Genera File will delete all the records presently in the Genera File and replace them with records derived procedurally by extracting information from the Conodont File (Fig. 5-33). This must be done to be able to access any new records that have been added since the last update.

CHOOSING USABLE FIELDS

Choose Usable Fields can only be performed on the uncompiled version of *Wahoo*. In essence, you must do this to the uncompiled version and then compile the database over again (*Wahoo.comp*). This limitation may be fixed when ACIUS upgrades their version of the compiler.

CHOOSING USABLE FILES

Choose Usable Files can be done with any version of *Wahoo*. if necessary (Fig. 5-33) You will see a dialog box with all the files in the database. Those with check marks next to their names are activated. Some files should not be used, however, and are present for convenience in programming. For example, the "Dinosaurs" file does not contain any useful data and should not be used. You may want to temporarily turn off files if you are only going to enter data into one file for a while in order to speed up data entry.

CHAPTER 6

SUMMARY AND INTERPRETIVE SYNTHESIS

ABSTRACT

This chapter summarizes the major advances made through our integrated geological studies of the Lisburne Group in northern Alaska. The depositional history of the Lisburne Group is discussed in a framework of depositional sequence stratigraphy. Although individual parasequences (small-scale carbonate cycles) of the Wahoo Limestone cannot be correlated with certainty, parasequence sets can be interpreted as different systems tracts within the large-scale depositional sequences, providing insights on the paleoenvironments, paleogeography and platform geometry. Conodont biostratigraphy precisely established the position of the Mississippian-Pennsylvanian boundary within an important reference section, where established foraminiferal biostratigraphy is inconsistent with respect to conodont-based time-rock boundaries. However, existing Carboniferous conodont zonations are not readily applicable because most zonal indicators are absent, so a local zonation scheme was developed. Diagenetic studies of the Lisburne Group recognized nineteen subaerial exposure surfaces and developed a cement stratigraphy that includes: early cements associated with subaerial exposure surfaces in the Lisburne Group; cements associated with the sub-Permian unconformity; and later burial cements. Subaerial exposure surfaces in the Alapah Limestone are easily explained, being associated with peritidal environments at the boundaries of Sequence A. However, subaerial exposure surfaces in the Wahoo are more problematic, occurring near maximum transgressions (highstand systems tracts) in Sequences B and C, adjacent to the Mississippian-Pennsylvanian and Morrowan-Atokan boundaries respectively. The Lisburne Group at Prudhoe Bay is similar to that in ANWR in many respects, being organized into three depositional sequences, but contains more terrigenous sediments that were derived from adjacent paleotopographic highs. In contrast, the Lisburne Group in allochthonous thrust sheets in the central Brooks Range is older and apparently formed farther down depositional dip. The sea-level fluctuations represented by depositional sequences and parasequences of the Lisburne do not generally correspond to those shown on existing sea-level curves for the Carboniferous, except for the Kaskaskia-Absaroka sequence boundary of Sloss (1963, 1988). The large amounts of data collected in this research program have been recorded in the *Wahoo* computerized database which includes files on locality and sample information, petrographic analyses, conodont biostratigraphy and biofacies, cement zonation, and well log data. The appendices included in this report were produced by the database program that is a powerful tool for continued analyses of the Lisburne Group. The Lisburne exposed in ANWR is generally tightly cemented and supermature, but could still be a good reservoir target in the adjacent subsurface of ANWR given the appropriate diagenetic, deformational and thermal history. Our ongoing research on the Lisburne Group will hopefully provide additional insights in future publications.

DEPOSITIONAL HISTORY OF THE LISBURNE GROUP OF ANWR

The Lisburne Group of ANWR can be subdivided into three major depositional sequences (transgressive-regressive sequences) that provide a framework for understanding its depositional history (Fig. 6-1). This organization is generally similar to the Lisburne at Prudhoe Bay (Lisburne oil field; Fig. 1-30), but is different than the Lisburne Group within allochthonous thrust sheets in the central Brooks Range.

SEQUENCE A—MISSISSIPPIAN (KINDERHOOKIAN TO LATE CHESTERIAN)

In ANWR, the first onlap of the Ellesmerian sequence over irregular paleotopography beneath the sub-Mississippian unconformity resulted from a progressive rise in base level, apparently representing the onset of passive margin subsidence coupled with a eustatic rise in the Early Mississippian (Tournaisian; Figs. 6-2 & 1-32; Ross and Ross, 1988; LePain, 1993). The Kekiktuk Conglomerate was derived from uplifted sub-Mississippian rocks (much is of local derivation) and was deposited in paleovalleys that were progressively flooded until estuarine clastics were inundated by marginal marine black shale of the Kayak Shale (Figs. 6-1 & 6-2; LePain, 1993). The abundance of land plant material, the presence of coal, and the types of pollen indicate lush vegetation in a humid (LePain, 1993) and tropical climate (Ravn, 1992). Initial attempts to establish carbonate sedimentation in the Kayak Shale were thwarted by continued terrigenous influx, including terrestrial organic matter that resulted in anoxic conditions (LePain, 1993). The oldest limestones recognized in the Kayak are late(?) Kinderhookian (Tournaisian), occurring only in southern ANWR (Fig. 2-8; south of Bathtub Ridge, Anderson, 1993) and more commonly in the central and western Brooks Range. Small bioherms formed in shallow, oxygenated water but were repeatedly smothered by anoxic black shale. The gradational transition from argillaceous limestones and black shale of the Kayak Shale into progressively more pure carbonates heralds northward transgression and onlap of the Lisburne carbonate platform. On the North American craton, the Kaskaskia II subsequence of Sloss (1988) also began with anoxic conditions and, with continued transgression in Early Mississippian time, evolved to carbonate-dominated seas having open circulation (Savoy, 1992).

With the relative rise in sea level in ANWR, terrigenous sediment dispersal systems retreated northward and well-oxygenated conditions allowed carbonate sedimentation to prevail. Continuous carbonate sedimentation was first established in the south (Marsh Fork, loc. 26, Figs. 6-2, 1-2 & 2-7) in Osagean to Meramecian time with the deposition of spiculitic limestones in either restricted platform or relatively deep-marine conditions. In the central Brooks Range (Wachsmuth Limestone type section at Shainin Lake, Figs. 6-2, 1-1 & 2-6), shallow-marine carbonate sedimentation clearly was established by Osagean time (see Chapters 1 & 2). During Meramecian time, carbonate environments lapped northward (locs. 10 & 11, Figs. 6-2, 1-2, 1-7 & 2-7). Coralline boundstone and associated spicular packstone in the uppermost Kayak Shale and lower Alapah Limestone may represent small coral-

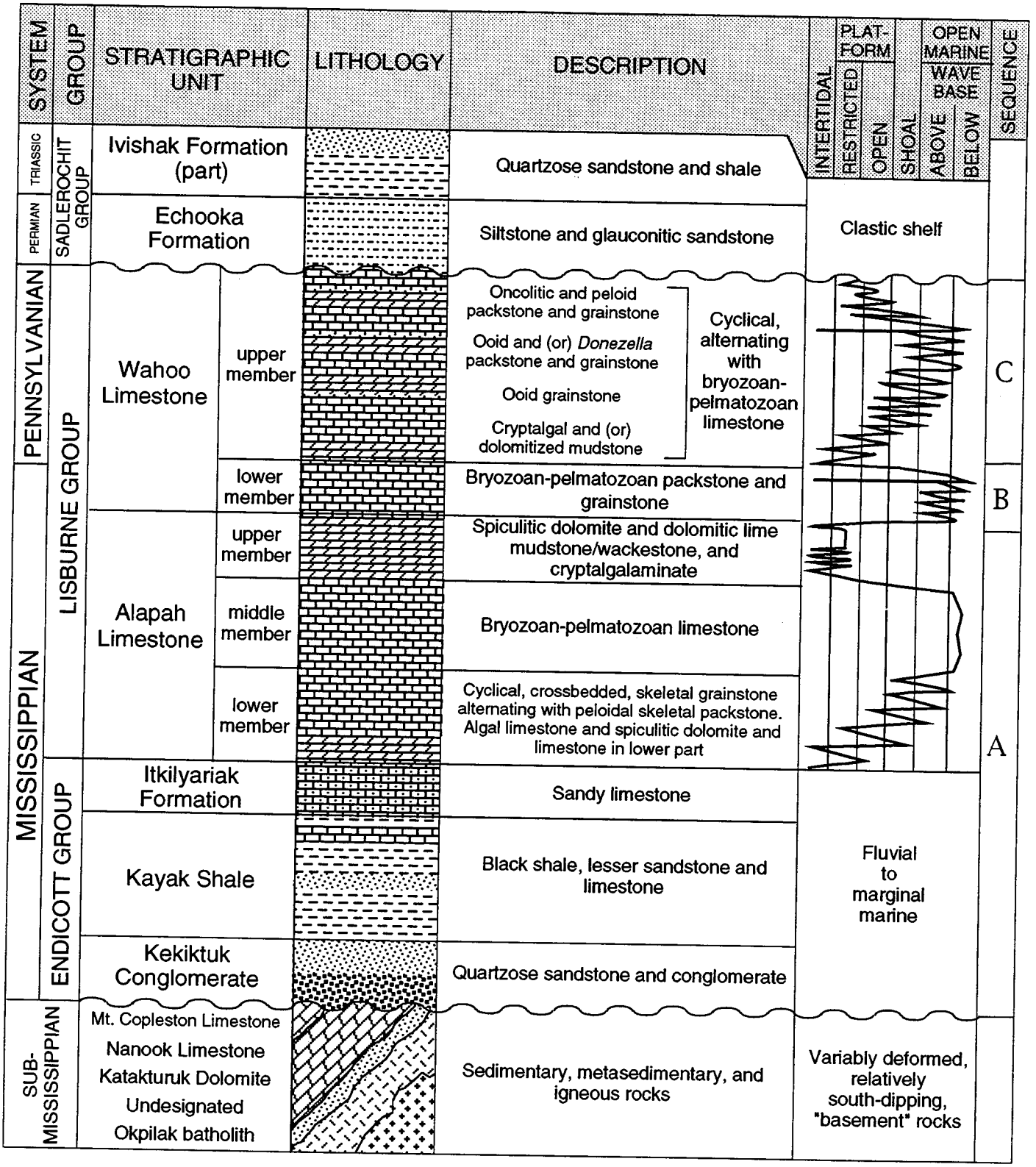


Figure 6-1. Generalized stratigraphy of the Carboniferous Endicott and Lisburne groups and the Permian Echooka Formation in northern ANWR (modified from Krumhardt, 1992).

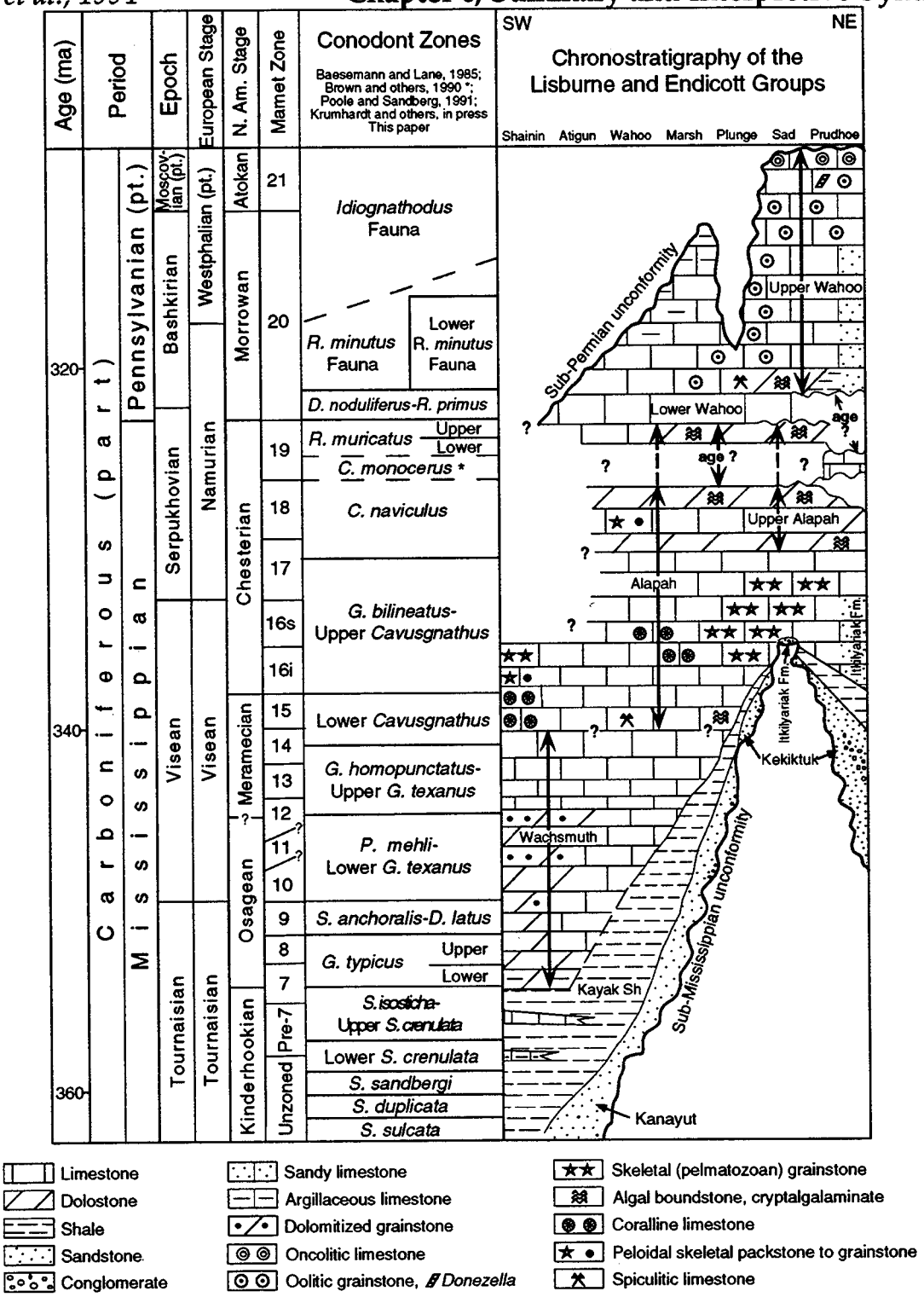


Figure 6-2. Chronostratigraphy of the Lisburne Group. See Chapter 2 for detailed chronostratigraphic charts and discussion of biostratigraphic criteria used for age determinations. Localities on Fig. 1-2 include: Sad." (loc. 8), Plunge (loc. 12), Wahoo (loc. 13), Marsh (loc. 28). Atigun is near Trans-Alaska Pipeline and Shainin is in the central Brooks Range (Fig. 1-1). See also Figs. 1-7, 1-9, 1-11, 1-12, 1-14, 1-30, and 1-31.

sponge bioherms that formed in protected environments behind skeletal shoals but near the transition between the carbonate and terrigenous systems. Upsection, algal bafflestones indicate shallow-water, low-energy lagoonal conditions on the northern margin of the expanding Lisburne platform. Cryptalgal dolomite and fenestral fabric at the top of parasequences in the lower Alapah indicate shallowing to intertidal conditions, and laminated crusts suggest that subaerial exposure occurred during relative low-stands of sea level. Local evaporites indicate that the climate was relatively arid in contrast to the humid climate that prevailed during Endicott Group sedimentation (LePain, 1993). This shift appears to coincide with globally warmer conditions (Ross and Ross, 1988). Thus, shallow water depths within the photic zone prevailed at the initiation of carbonate sedimentation, but the carbonate platform was periodically and locally exposed within or above the intertidal zone.

In early Chesterian time (Mamet Zone 16i and later), several intervals of cross-stratified grainstone in the lower Alapah Limestone indicate repeated migration of skeletal shoals across northern ANWR (Fig. 1-20). These shoal deposits are dominated by highly abraded fragments of pelmatozoans, bryozoans, and other organisms that indicate normal-marine conditions. Lesser ooids occur in northern areas that were dominated by high-energy conditions (Fig. 1-20). The shoal deposits formed on a high-energy carbonate ramp and pinch out to the south and west into open-marine to open-platform packstone containing a varied fauna and flora (calcareous algae) and lacking carbonate cycles (parasequences). At the Sadlerochit Mountains high (Armstrong, 1974; Armstrong and Mamet, 1975), the sub-Mississippian rocks formed a paleotopographic high that was onlapped directly by relatively high-energy shoal deposits of the lower Alapah. Localized terrigenous sediments of the Itkilyariak Formation at its type section apparently were derived locally from metasedimentary and metavolcanic rocks beneath the sub-Mississippian unconformity. These initial shoal deposits are younger than those to the south (Chesterian, Mamet Zone 16s), indicating their northward onlap onto paleotopographic highs that may be an extension of the Barrow Arch. The Okpilak batholith apparently formed another paleotopographic high as indicated by very coarse terrigenous quartz in sandy limestones of the Itkilyariak Formation (sensu lato). The Itkilyariak Formation is best developed in the subsurface near Prudhoe Bay where terrigenous sediment was derived from the adjacent Colville high and/or Barrow Arch (Mull and Mangus, 1972; Jamison et al., 1980; Jameson, in revision).

Skeletal shoal deposits occur in cyclical parasequences alternating with flanking restricted-platform (lagoonal) and open-marine deposits that formed during repeated migration of these environments across a south-facing carbonate ramp (Fig. 1-16). Such cyclical carbonates are typical of the middle Visean and may reflect glacioeustatic cycles (Veevers and Powell, 1987; Ross and Ross, 1988). Although this shoal-dominated northern margin has a ramp geometry, the overall Lisburne carbonate platform probably was very extensive with an irregular paleogeography (Fig. 1-15). The irregular paleotopography inherited from the sub-Mississippian unconformity was progressively filled by variable carbonates of the

Alapah Limestone. With continued transgression and northward migration of the shoal deposits of the lower Alapah, open-marine conditions prevailed, as indicated by fossiliferous packstone and wackestone of the middle Alapah (Fig. 6-1). These relatively muddy carbonates represent the maximum transgression (transgressive/retrogradational highstand systems tract and maximum flooding surface) in Sequence A. Depositional patterns in the Alapah indicate considerable variability, possibly related to paleotopography along the sub-Mississippian unconformity surface and/or possible movement along pre-existing(?) faults. During the Visean, active faulting occurred at the Endicott oil field (Woidneck et al., 1987; Hubbard et al., 1987).

Later, in Chesterian time (early Namurian), restricted and intertidal environments indicate progressive shallowing of the Lisburne carbonate platform, representing a progradational highstand systems tract (FIg. 6-1). The gradational transition from open-marine and open-platform facies into restricted-platform facies indicates that circulation became progressively more restricted with time, perhaps because the shallow Lisburne carbonate platform became more expansive and inhibited water circulation (Fig. 1-17). Sponge spicules, ostracods, and associated evaporites indicate deposition in a restricted-platform (possibly hypersaline) environment (Wilson, 1975; Flügel, 1982; Warren and Kendall, 1988). By late Chesterian (Mamet Zone 18 or the lower part of the Upper *muricatus* conodont Subzone - the precise age is uncertain because of inconsistencies between conodont and foraminiferan-based age determinations), this restricted platform was extensive, covering the region from beyond the northernmost exposures of the Lisburne Group to at least as far south as Marsh Forks of the Canning River (Fig. 1-21). The presence of intertidal to supratidal cryptalgalaminate, evaporite pseudomorphs, and several subaerial exposure surfaces indicate the maximum regression (Fig. 6-1). No unconformity is apparent in ANWR so this represents a Type 2 sequence boundary. However, farther updip at Prudhoe Bay, dolostones of the middle Alapah (our upper Alapah) are late Chesterian (Mamet Zone 18) in age and an unconformity may truncate the unit in a landward direction (Schoennagel, 1977; Jameson, in revision). Thus, the sequence boundary near the top of the Alapah is dated as latest Mississippian but within the Chesterian, coinciding with the Kaskaskia-Absaroka sequence boundary (Sloss, 1963, 1988). A maximum lowering of eustatic sea level near the end of the Mississippian could be a major causal factor for the shallowing event in ANWR and for the cratonic sequence boundary (Ramsbottom, 1979, Sloss, 1988), but it has been placed at the Mississippian-Pennsylvanian boundary by many authors because of the hiatus typically spans this boundary (i.e., approximately 1 m.y. later, e.g., Ross and Ross, 1988 on Fig. 1-32;).

The restricted platform deposits of the upper Alapah Limestone are much more extensive than the restricted marine (lagoonal?) deposits of the lower Alapah (Fig. 1-21). In the southern part of the ANWR study area, a transitional interval in the upper Alapah containing both open-platform and restricted-platform deposits indicates more normal-marine conditions. At one southern locality (loc. 22, Figs. 1-2 & 1-9), localized skeletal grainstones could represent part of a belt of barrier shoals

that helped inhibit circulation to the northern restricted platform. Although the Egaksrak grainstone of the lower Alapah clearly record northward migration of shoals in the transgressive systems tract, no evidence of southward migration of shoals exists in the progradational highstand systems tract of the upper Alapah. However, shoals may have developed on shallow parts of the platform in the south, possibly along structural highs. This might be viewed as a rimmed platform in which parts of the platform interior became restricted and locally aggraded to sea level and/or were periodically subaerially exposed (Figs. 3-2 & 1-17). Evaporite brines probably developed in restricted, intertidal, or supratidal environments, but they apparently percolated downward to be precipitated in a variety of sediments beneath the subaerial exposure surfaces (even extending down into open-platform deposits of the middle Alapah member). A lack of evaporites above the subaerial exposure surfaces supports this interpretation and indicates the beginning of a marine transgression in the next depositional sequence.

SEQUENCE B—LATEST MISSISSIPPIAN TO EARLIEST PENNSYLVANIAN (LATEST CHESTERIAN TO EARLY MORROWAN)

In the latest Chesterian (upper part of the upper *muricatus* Subzone, or Mamet Zones 18 & 19 -the precise age is uncertain because of inconsistencies between conodont and foraminiferan-based age determinations), a relatively rapid flooding of the Alapah carbonate platform led to development of a south-facing, high-energy carbonate ramp of the Wahoo Limestone (Fig. 1-18). A thin transitional interval in the upper Alapah Limestone passed from restricted-platform conditions into partially restricted-platform conditions as indicated by pelmatozoans and other normal marine organisms. The gradual loss of peloids and sponge spicules and an increase in open-marine fauna in the lowest Wahoo Limestone indicate continued deepening and/or freshening upward in a transgressive (retrogradational highstand) systems tract. Lithologic changes in the unit are subtle, but four or five thick parasequences, passing from bryozoan-pelmatozoan packstone and wackestone up into grainstone, are interpreted to have formed below and above wave base in an open-marine setting on the Wahoo ramp in response to small-scale sea-level fluctuations (Fig. 6-3). Overall, the transgressive-regressive succession of Sequence B represents a large-scale (possibly third-order) Type 2 depositional sequence with maximum transgression (maximum flooding surface) immediately beneath the Mississippian-Pennsylvanian boundary (Fig. 6-1).

The Mississippian-Pennsylvanian boundary shows evidence of subaerial exposure and the development of a small amount (~ 1 meter) of relief (Fig. 6-4; Chapter 3), but it is not a significant unconformity as indicated by conodonts (Fig. 6-2; Chapter 2). Evidence of subaerial exposure so close to the maximum flooding surface is difficult to explain, because relatively deep-water facies occur both below and above this boundary (Fig. 6-1). Evidence of a more significant unconformity at one locality (Fourth Range, loc. 11 on Fig 1-2 & 1-25) is even more problematic, but the presence of late Morrowan conodonts directly above the Mississippian could indicate stratigraphic leak from higher levels (see below). However, the

Pennsylvanian part of the lower Wahoo contains oolitic grainstone and other features that indicate an overall shallowing in a highstand (progradational highstand) systems tract (Fig. 6-1). Redeposited Late Mississippian conodonts immediately above and for a considerable distance below the contact between the lower and upper Wahoo members also suggest erosion and the reworking of sediments derived from at least 15 meters lower in the section. Local erosional channels at the lower Wahoo to upper Wahoo contact suggest a paraconformity (Carlson, 1987), but the lack of evidence of subaerial exposure favors their interpretation as tidal channels. However, at most localities, the contact is gradational and probably conformable. The increase in detrital quartz silt in the lowest upper Wahoo Limestone indicates the approach of emergent terrigenous environments from the north and a maximum regression that marks the upper sequence boundary (Fig. 6-1). In the north (locs. 6-8, Figs. 6-2, 1-2 & 1-11), several localized intervals of cryptalgalaminate in the lowest upper Wahoo represent the most landward (intertidal) facies and approximate the sequence boundary. Farther south (locs. 10-12, Figs. 6-3 & 1-2), skeletal-spiculitic parasequences that formed in restricted platform (lagoonal) environments behind ooid shoals are the most landward facies, again approximating the sequence boundary.

Farther updip at Prudhoe Bay (Fig. 1-30), a relatively thick interval (70 feet/21 meters) of terrigenous sediment ("green shale") at and above this stratigraphic position corresponds to the terrigenous influx marking the Sequence B to Sequence C boundary in northern ANWR. Jameson (in revision) shows an unconformity at this stratigraphic position corresponding to our lower-to-upper Wahoo boundary, with Upper Mississippian (Mamet Zone 19) beneath Lower Pennsylvanian (Mamet Zone 20) rocks. Although the foraminiferan-based age determinations are slightly different than conodont-based age determinations in ANWR, this generally supports our interpretation of a sequence boundary at this level.

Sequence B was deposited over a much shorter interval of time than the other depositional sequences in the Lisburne Group, and shows only subtle differences in depositional environments from Sequence C. The Sequence A to Sequence B transition is much more marked in its lithologic changes and inferred changes in platform geometry (Fig. 6-1). Thus, Sequence B may be a higher-order sequence superimposed on a lower-order sequence that includes both Sequence B and Sequence C. Increased terrigenous influx at the sequence boundary may have caused the progradation and shallowing and could have resulted from uplift of terrigenous source areas and/or climatic changes. However, a drop in base level is indicated by the reworking of Mississippian conodonts. The timing of the sequence boundary within the Early Pennsylvanian (early Morrowan, Namurian, the *Declinognathodus noduliferus-Rhachistognathus primus* conodont Zone) could possibly correspond to eustatic low stands of this age (Fig. 1-32; Ramsbottom, 1979; Ross and Ross, 1988).

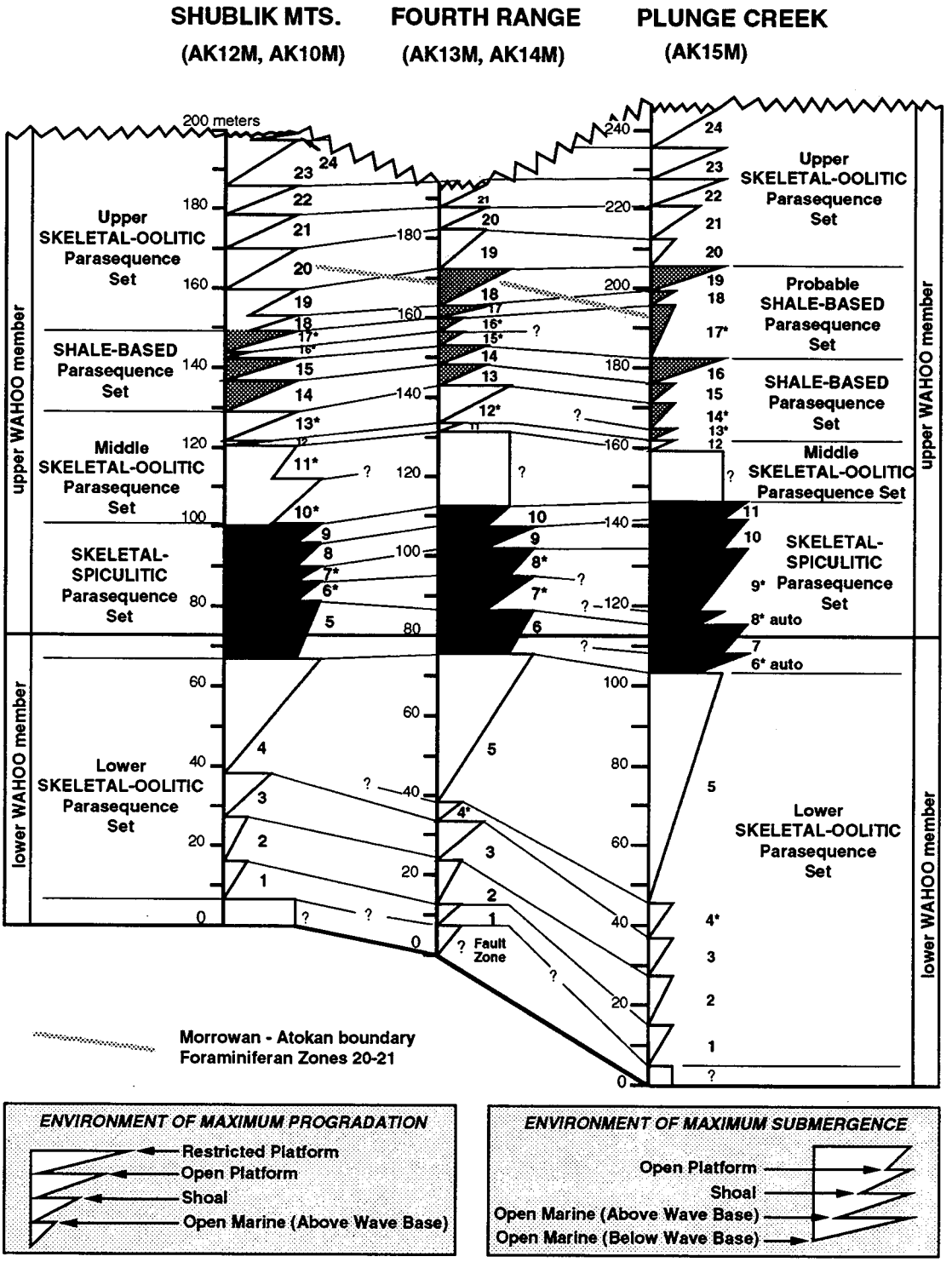


Figure 6-3a. Preliminary correlation of parasequences and parasequence sets in the Wahoo Limestone (from Gruzlovic, 1991). The zigzag lines show the environments of maximum submergence and progradation of each parasequence. Numbers refer to parasequences in ascending order from the base of the Wahoo; asterisks following number indicate parasequences that don't correlate between all the sections. This diagram does not account for new conodont data that indicate a possible intraformational unconformity within the lower Wahoo at the Fourth Range section (compare with Fig. 6-3b).

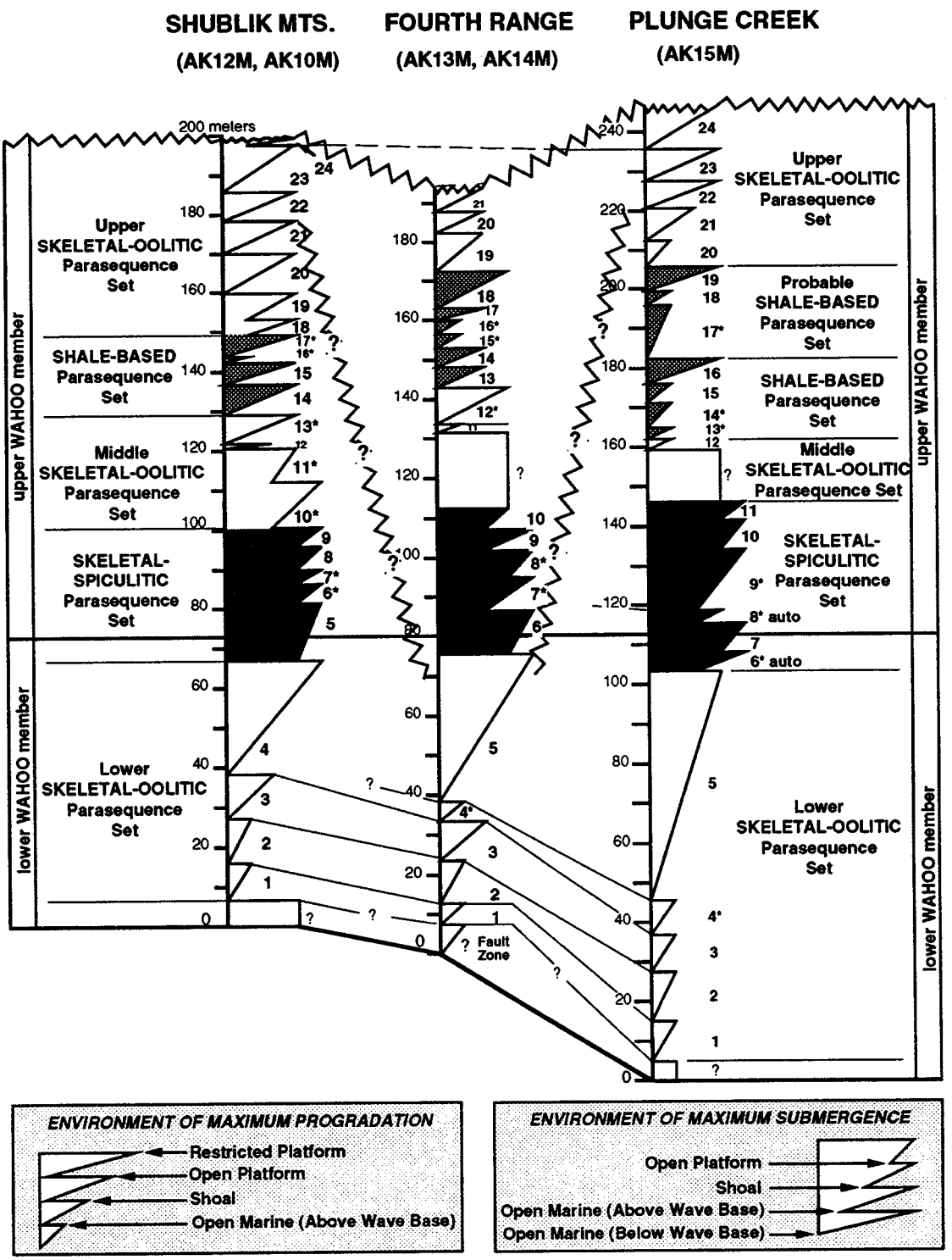


Figure 6-3b. The diagram shown in Fig. 6-3a is modified to show the effects of a possible unconformity at the Mississippian-Pennsylvanian boundary at the Fourth Range section. Conodont data indicate that upper Morrowan to lower Atokan rocks (*Idiognathodus* Fauna) directly overlie uppermost Chesterian rocks (upper *muricatus* Subzone).

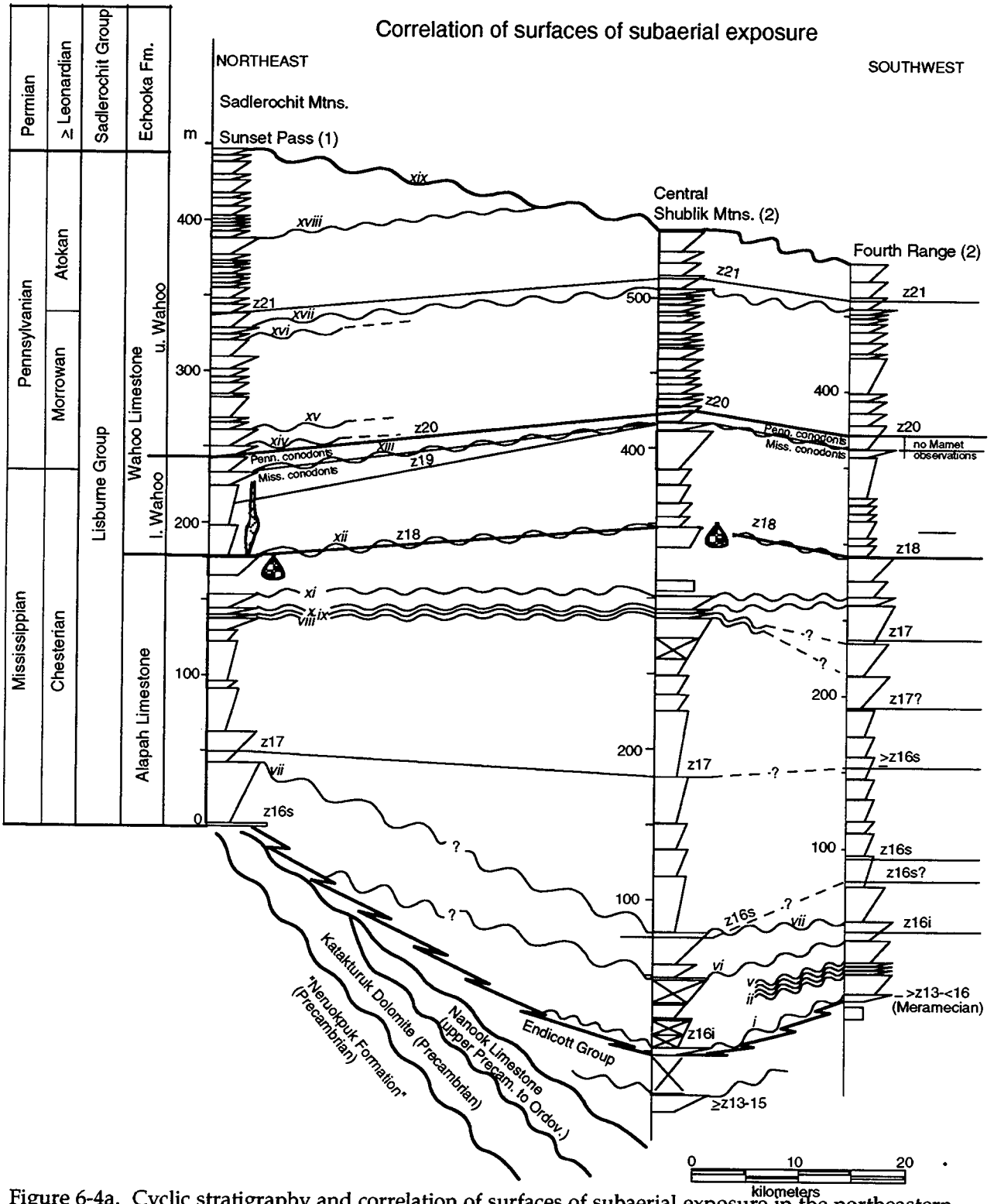


Figure 6-4a. Cyclic stratigraphy and correlation of surfaces of subaerial exposure in the northeastern Brooks Range, Alaska. Interpretation of carbonate cyclicity is based on descriptions of stratigraphic sections measured by Krumhardt, 1992 (AK22M; Sunset Pass) and Gruzlovic, 1991 (AK-10 to 12-M, Shublik Mountains; and AK13 to 14-M, Fourth Range). Does not account for the possible unconformity indicated by conodont data from the Fourth Range section shown in Figs. 6-3b and 6-4b. See explanation of symbols on Fig. 3-2.

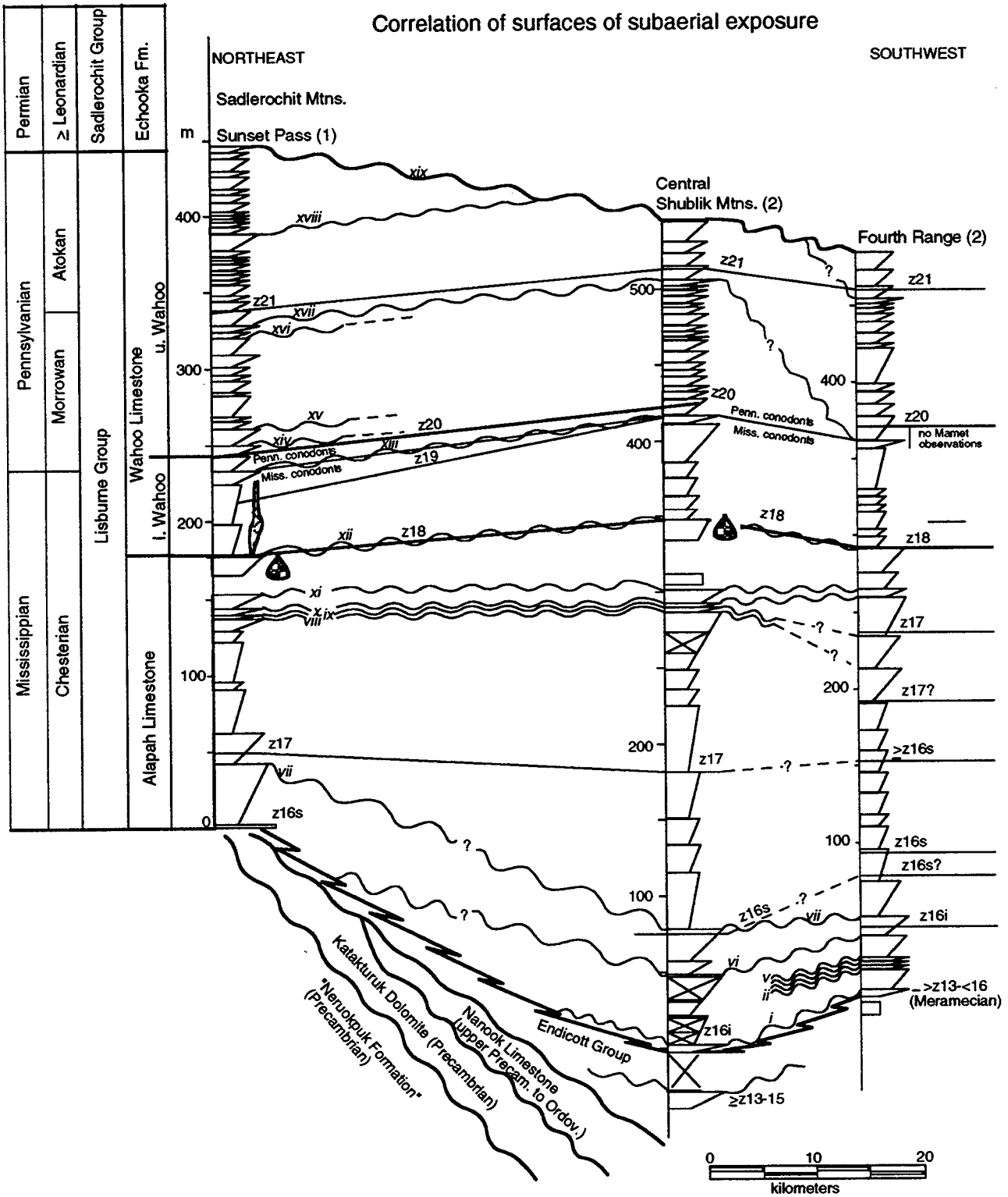


Figure 6-4b. The diagram shown in Fig. 6-4a is modified to show the effects of a possible unconformity at the Mississippian-Pennsylvanian boundary as described in Fig. 6-3b.

SEQUENCE C—EARLY TO MIDDLE PENNSYLVANIAN (EARLY MORROWAN TO ATOKAN)

Sequence C, comprising most of the upper Wahoo Limestone, is a large-scale transgressive-regressive succession (depositional sequence) composed of numerous parasequences (carbonate cycles; Fig. 6-3a) that formed due to repeated migrations of ooid shoals and adjacent paleoenvironments as a result of relative sea-level fluctuations (Fig. 1-32; cf. Veevers and Powell, 1987; Ross and Ross, 1988). In ANWR, the ooid shoal complex extends from the Sadlerochit Mountains through Leffingwell Ridge and Clarence River and on toward Canada (Fig. 1-22). Similar Pennsylvanian shoal deposits apparently continue westward along the Barrow Arch to the Lisburne oil field (Prudhoe Bay; Jamison et al., 1980; Jameson, in revision), the Colville Delta (Bird and Jordan, 1977) and on to the northeast Naval Petroleum Reserve Alaska (NPRA; Bird, 1978). This NNW-SSE-trending belt of discontinuous ooid shoals apparently formed on a gently dipping carbonate ramp as indicated by the broad downdip distribution of ooid-shoal deposits (over 40 km width) and their southward pinch out into deeper water facies (Fig. 1-22). A regional Type 1 sequence boundary beneath the Permian Echooka Formation, a hiatus of nearly 38 m.y., developed considerable erosional relief above the upper Wahoo (Fig. 1-33).

Superimposed on the transgressive-regressive succession of Sequence C, numerous parasequences having significant lateral facies changes reflect repeated migrations of a complex mosaic of carbonate environments across a south-facing, high-energy carbonate ramp (Figs. 1-18 &1-24). Throughout most of the sequence, ooid shoals repeatedly migrated southward across the Wahoo ramp with each advance terminated by rapid retrogradation (marine flooding surfaces). Overall, the shoals were best developed to the north, but occur in more southerly areas during the maximum regressions at the base and top of Sequence C (Fig. 6-3a). The nature of parasequences varies vertically and laterally depending on their position on the Wahoo ramp.

During the maximum regression (maximum lowstand, shelf-margin systems tract) at the base of the sequence, local intertidal conditions existed in the northern part of ANWR, as indicated by dolomitic cryptalgalaminate (Fig. 1-23). An associated influx of terrigenous quartz may be related to an interval of terrigenous sediment updip at Prudhoe Bay; both reflect a relative lowstand of sea level. Facies changes down the carbonate ramp to the south pass from restricted platform (lagoonal) into ooid shoals and open-marine (outer ramp) deposits (Figs. 6-3 & 1-22).

The transgressive (retrogradational highstand) systems tract begins with peloidal spiculitic parasequences (restricted platform) that pass up into skeletal-oolitic parasequences (shoals) and finally into shale-based parasequences (deeper-water outer ramp) in the central part of the ramp (Fig. 6-3). In southern areas, the shale-based parasequences (outer ramp) developed at maximum flooding surface, whereas skeletal-oolitic parasequences (ooid shoals) formed on the inner ramp to the north (Figs. 6-3, 1-23 & 1-24). The shale-based parasequences are relatively thin

with the more abundant condensed shales representing incipient platform drowning events, indicating that the deeper parts of the Wahoo carbonate ramp apparently had a longer lag time before carbonate production commenced. In shallower areas to the north, carbonate sedimentation was more rapid and continuous on shoals and in adjacent shallow-marine carbonate environments.

In the upper part of Sequence C, a highstand (progradational) systems tract in the north is represented by peloidal-oncolitic parasequences that formed in restricted-platform (lagoonal) environments on the inner ramp behind ooid shoals. This large-scale facies change suggests overall progradation of open-platform to restricted-platform (lagoonal) carbonate environments over the oolitic parasequences (Figs. 1-11 & 1-23). Farther south, skeletal-oolitic parasequences formed during this regression (Fig. 6-3). Unfortunately, much of the progradational part of the sequence has been removed by sub-Permian erosion (particularly to the south), so the nature of the youngest Wahoo ramp is uncertain (Figs. 1-33, 2-6 to 2-8). The establishment of relatively restricted-platform conditions in the north could indicate that the Wahoo ramp developed more well-defined and continuous barrier shoals (Carlson, 1987).

Evidence of subaerial diagenesis at three suspected paraconformities in Sequence C indicates the emergence of the inner Wahoo ramp during relative low stands of sea level (Fig. 6-4; see Chapter 3). However, most of the parasequences in the upper Wahoo are not marked by emergence, but instead indicate progressive southward migration of lagoons(?) and shoals over more open-marine outer-ramp limestones. The general lack of evidence of emergence or development of supratidal facies indicates that most of the parasequences did not build above sea level. Thus, the Wahoo ramp did not prograde into non-productive supratidal flats, which would have caused a concomitant reduction in subtidal carbonate production (James, 1984). Instead, rapid flooding events typically resulted in an abrupt transition from lagoonal or shoal facies (inner ramp) at the top of one parasequence to open-marine (outer-ramp) facies at the base of the next parasequence. The apparent regularity of the cyclical fluctuations in relative sea level recorded in the upper Wahoo Limestone suggest that they resulted from glacioeustatic sea-level fluctuations having Milankovitch rhythms and that this cyclicity is similar to that in Pennsylvanian cyclothems (Fig. 1-32; Ramsbottom, 1979; Saunders et al., 1979; Ross and Ross, 1985b; Veevers and Powell, 1987; Heckel, 1986).

The top of Sequence C is truncated by a major regional unconformity beneath the Permian Echooka Formation. This Type 1 sequence boundary is marked by an irregular ravinement surface incised into the upper Wahoo. The age of the top of the Wahoo is youngest (Atokan) in northern ANWR and generally older (Morrowan and Chesterian) to the south and west (Fig. 6-2; Watts et al., 1992). A slightly thicker and younger Atokan-age succession occurs at Prudhoe Bay (Armstrong and Mamet, 1974; Stanulonis and Tran, 1992; Barnes & Jameson, 1990, Jameson, 1990b, in revision). The age of the Echooka is not tightly constrained but ranges from Artinskian to Ufimian (Leonardian) in the south to Kazanian

(Guadelupian) in the north. This unconformity has been attributed to regional epeirogenic uplift, sometime between the Middle Pennsylvanian and Early Permian (Bird and Molenaar, 1987). It generally correlates with a sub-Permian unconformity in the Yukon Territory of Canada that also has been attributed to tectonic movements (Bamber and Waterhouse, 1972). Beauchamp (1992) stated that the "Melvillian Disturbance" of the Canadian Arctic Islands may correspond to the sub-Permian unconformity in Alaska and that tectonic events of similar age affecting the circumarctic region possibly resulted from major plate reorganization at this time (Fig. 1-33). However, the precise timing of deformation may vary somewhat between different areas.

CORRELATION OF THE CYCLIC STRATIGRAPHY OF THE WAHOO LIMESTONE

One of the goals of our detailed analyses of parasequences of the Wahoo Limestone was to determine if these carbonate cycles formed in response to glacioeustatic sea-level fluctuations and might serve as a means of correlation. Gruzlovic's (1991) analyses of parasequences of three stratigraphic sections along a down-dip transect indicate that individual parasequences cannot be correlated with confidence (Fig. 6-3a). The unequal number and different thicknesses of parasequences cause problems in correlation, possibly indicating that some parasequences formed by purely sedimentological (autocyclic) mechanisms. The lack of high-resolution biostratigraphic control for the Carboniferous inhibits our ability to define age-equivalent intervals that are thin enough to test correlations that are based on parasequence stratigraphy. However, parasequence sets appear to serve as correlatable packages that help define the vertical succession of facies representing different systems tracts within depositional sequence C (the upper Wahoo). Comparison of parasequence sets between different localities allows characterization and interpretation of lateral facies changes (Fig. 6-3a, 1-24, 1-26 to 1-28).

Although slight discrepancies exist between age-determinations based on conodont and foraminiferan biostratigraphy, biostratigraphic correlations generally support the correlations made using sequence stratigraphy and parasequence sets. However, conodont biostratigraphy at one locality (Fourth Range, loc. 11 on Fig. 6-3 & 1-25) indicates a possible hiatus between Upper Mississippian and Upper Morrowan rocks. The potential significance of these anomalous conodont occurrences are discussed below.

CONODONT BIOSTRATIGRAPHY VERSUS SEQUENCE STRATIGRAPHY

Systematic sampling for microlithofacies and conodont analysis at a relatively continuous section (~262 meters thick) in the eastern Sadlerochit Mountains shows that existing Carboniferous conodont zonations are not readily applicable because most zonal indicators are absent (Fig. 2-2; Krumhardt et al., in press; see Chapter 2). The following zones and faunal intervals were recognized: Upper *muricatus* Subzone (latest Chesterian); *noduliferus-primus* Zone (earliest Morrowan);

minutus Fauna (Morrowan); and an *Idiognathodus* Fauna (late Morrowan and/or early Atokan). The Mississippian-Pennsylvanian boundary is at 55 meters above the base of the Wahoo (Fig. 2-2). Established foraminiferal biostratigraphy is inconsistent with respect to conodont-based time-rock boundaries in the study section.

Biofacies analyses of this section generally agree with interpretations of paleoenvironments and sequence stratigraphy based on microfacies analyses (Krumhardt et al., in press). The Mississippian part of the Wahoo Limestone was deposited under near restricted to normal-marine conditions in a chiefly open-platform to open-marine setting; it produces a chiefly cavusgnathid biofacies. The Pennsylvanian part of the Wahoo was deposited under predominantly normal-marine, high-energy conditions characterized by migrating ooid shoals; it produces a chiefly rhachistognathid biofacies. Abraded conodonts and bioclasts and mixed assemblages indicate considerable postmortem hydraulic mixing across the Pennsylvanian Wahoo carbonate ramp.

Systematic conodont sampling has been done for only five localities in ANWR (locs. 8, 11, 13, 20 & 27, Fig. 2-5). Conodont analyses have been completed only for the eastern Sadlerochit Mountains section. Ongoing analyses of conodont samples from other systematic collections are beginning to allow detailed biostratigraphic correlation (Figs. 2-6 to 2-8). Widely spaced reconnaissance samples at other localities provide some age control, but lack sufficient resolution for detailed correlation. In most cases, correlations based on conodont biostratigraphy are generally compatible with correlations based on sequence and parasequence stratigraphy.

However, in the Fourth Range (loc. 11, Fig. 2-5), conodont analyses may indicate a significant hiatus at the Mississippian-Pennsylvanian boundary that conflicts with previous correlations based on sequence/parasequence stratigraphy and foraminiferal biostratigraphy. The *Idiognathodus* Fauna of late Morrowan to early Atokan age first appears directly above the upper *muricatus* Subzone of latest Chesterian age. Evidence of karst at the top of the Lisburne in the Fourth Range support the notion that this anomalously low occurrence of the *Idiognathodus* Fauna is due to stratigraphic leak (as inferred in previous discussions; see Chapters 1 & 3). Stratigraphic leak means that conodonts derived from dissolution of upper Morrowan to early Atokan limestones were transported by downward percolating fluids to contaminate lower Morrowan to upper Chesterian rocks of the lower Wahoo.

If this hiatus actually exists in the Fourth Range, the correlations made based on sequence stratigraphy would be in error (compare Fig. 6-3a with 6-3b; Gruzlovic, 1991). The general organization of parasequences in the upper part of the Wahoo Limestone would <u>not</u> fit within a sequence stratigraphic framework with the shale-based parasequences forming at a time of a maximum transgression that effected the entire Wahoo carbonate ramp (Fig. 2-1). Modifying correlations to account for this unconformity would also require revising facies models and paleoenvironmental

interpretations for the upper Wahoo (Figs. 1-18 and 1-24). Correlation of subaerial exposure surfaces and cement stratigraphy would also require modification (compare Fig. 6-4a with 6-4b). Furthermore, a localized unconformity at the Fourth Range would imply that local uplift and active tectonism must have continued to affect northeastern Alaska until at least the late Morrowan (rather than simple passive margin subsidence since the Late Mississippian).

However, the large number of microfacies analyses that were used in developing the sequence and parasequence stratigraphy shown in Fig. 6-3a argue strongly against the presence of this unconformity (Gruzlovic, 1991). In order to resolve this problem, additional detailed studies of the conodont biostratigraphy of the Fourth Range section and other sections in ANWR are necessary.

SUBAERIAL EXPOSURE SURFACES VERSUS SEQUENCE STRATIGRAPHY

Eighteen subaerial exposure surfaces were recognized within the Lisburne Group based on field observations of a downdip transect of three composite stratigraphic sections in the northeastern Brooks Range (Fig. 6-4). A nineteenth subaerial exposure surface marks the unconformity at the top of the Lisburne Group beneath the Echooka Formation.

The subaerial exposure surfaces in the Alapah Limestone are readily explained within a sequence stratigraphic framework (Figs. 6-1 and 6-4a). Subaerial exposure surfaces i to vii all formed during the initial northward onlap of peritidal and shallow-marine carbonate environments in ANWR. The northward loss of most of these surfaces is due to the later onlap in that direction. In the upper Alapah, subaerial exposure surfaces viii to xii are all associated with peritidal carbonates near the upper boundary of Sequence A (maximum lowstand and sequence boundary). The southward loss of two of these surfaces probably resulted from lack of exposure in a restricted marine carbonate succession located seaward of the tidal flats. The latest Mississippian age of this sequence boundary (Upper *muricatus* conodont Subzone) coincides with the Kaskaskia-Absaroka sequence boundary (Sloss, 1963, 1988), suggesting that a eustatic lowstand contributed to the repeated exposure of the Alapah carbonate platform.

The two widespread subaerial exposure surfaces within the Wahoo Limestone are difficult to explain in a sequence stratigraphic framework (Figs. 6-1 & 6-4). Subaerial exposure surface xiii at the Mississippian-Pennsylvanian boundary generally approximately coincides with the maximum flooding surface in Sequence B of the Lisburne Group (Fig. 6-1). Similarly, subaerial exposure surface xvii near the Morrowan-Atokan boundary is slightly above the maximum flooding surface in Sequence C of the Lisburne. Although a eustatic lowstand has been proposed for the Mississippian-Pennsylvanian boundary (Ross and Ross, 1988; Fig. 1-31), carbonate microfacies analyses in the Wahoo do not indicate any significant shifts to shallower-water environments at this systemic boundary. Other subaerial exposure surfaces in the upper Wahoo were recognized only in the northernmost section,

possibly because of their position farthest up the Wahoo carbonate ramp. Two are associated with peritidal (lowstand) deposits near the boundary between sequences B and C.

If a major but localized unconformity exists at the Mississippian-Pennsylvanian boundary in the Fourth Range section (see above), then the Mississippian-Pennsylvanian boundary may represent exposure surface xvii (Fig. 6-4b). The highest exposure surface within the Wahoo might then correspond to subaerial exposure surface xviii, indicating less sub-Permian erosion of this section than is indicted on Fig. 6-4a.

With evidence of significant erosion on a regional scale, the sub-Permian unconformity is a subaerial exposure surface marked by localized conglomerates, red paleosols, karst breccias and moldic porosity. This Type-1 sequence boundary is particularly important in the diagenetic history of the Lisburne Group.

Based on petrographic cathodoluminescence studies, calcite cements in the Lisburne Group can be divided into the following cement zones. Three types of early cements occur: A1 nonluminescent, nonferroan calcite; A1 multibanded, nonferroan calcite with one to several sets of nonluminescent-bright-dull or nonluminescent-bright subzones; and rare microcrystalline calcite. These early calcite cements are followed by, from oldest to youngest: B1 - low ferroan and dully luminescent calcite; C1 - ferroan and very-dully luminescent calcite; B2 - ferroan and dully luminescent calcite, and preceding quartz cement; A2 - nonferroan calcite with 1 or 2 sets of nonluminescent and bright zones; B3 - ferroan and dully luminescent calcite and post-dating quartz cement; C2 - ferroan and very-dully luminescent calcite; and B4 - nonferroan and very dully luminescent calcite.

Cross-cutting relationships with diagenetic features imposed under different diagenetic regimes, such as subaerial exposure, burial, and tectonism, allow relative dates to be assigned to the cement zones (Carlson and Goldstein, 1992). Microcrystalline calcite, A1 nonluminescent calcite, and A1 multibanded calcite can, in many cases, be shown to predate or be synchronous with the development of features formed at the different subaerial exposure surfaces within the Lisburne Group. Similarly, A1 nonluminescent and A1 multibanded calcites, as well as B1 calcite, C1 calcite, B2 calcite, and A2 calcite, are cross-cut by features developed during the sub-Permian unconformity at the top of the Lisburne Group. Thus, those cements are all pre-Leonardian(?) in age. Using the same reasoning, B3 calcite and C2 calcite that also are present in Permian sandstones and conglomerates in the Echooka Formation, can be dated as post-Leonardian (?) in age. Features of compaction and pressure solution further constrain the timing of C2 calcites as coincident with deep burial of the Lisburne. B4 calcites commonly fill tectonically induced shear fractures, hence, B4 calcites are Cretaceous or Cenozoic, after the beginning of tectonism in the northeastern Brooks Range (Mull, 1982, Wallace and Hanks, 1991).

LOCAL AND REGIONAL SEA-LEVEL CURVES

The lack of adequate age control for the Lisburne Group inhibits developing high-resolution regional sea-level curves for correlation with available eustatic curves for the Carboniferous (Ross and Ross, 1978; Ramsbottom, 1979). However, local sea-level curves based on interpretation of carbonate microfacies have been completed for several stratigraphic sections (Fig. 6-3a; Gruzlovic, 1991; Carlson, 1987). As pointed out in previous discussions, small-scale parasequences cannot be correlated on an individual basis, particularly with the possibility of missing record along unconformities and subaerial exposure surfaces.

However, general comparisons of our sequence and parasequence stratigraphy with available eustatic curves provide some insights. The major sequence boundary between Sequences A and B of the Lisburne Group, generally coinciding with the transition between the Alapah and Wahoo limestones, is latest Chesterian (latest Mississippian) in age based on conodont biostratigraphy (Upper *muricatus* Subzone - foraminiferan-based age determinations may be slightly older in Zones 18 & 19), corresponding to the Kaskaskia-Absaroka sequence boundary (Sloss, 1963, 1988). This sequence boundary is a major hiatus in most of the North American midcontinent that spans the Mississippian-Pennsylvanian boundary. It is shown as a major sea-level fall on the generalized sea-level curve of Vail and others (1977), but is not a major drop on Hallam's (1984) curve (Fig. 1-32). Ross and Ross (1988) show the maximum sea-level drop to coincide with the Mississippian-Pennsylvanian boundary, later than the sequence boundary in ANWR. The Mississippian-Pennsylvanian boundary in ANWR is marked by a subaerial exposure surface, but no hiatus is evident based on conodont biostratigraphy and no significant change in carbonate facies and inferred depositional environments is apparent (besides the diagenetic evidence of subaerial exposure). The boundary between sequences B and C in ANWR is early Morrowan in age and could coincide with lowstands at this time (Vail et al., 1977; Ross and Ross, 1988). The duration of depositional sequences A, B, and C of the Lisburne are longer than and do not seem to correspond to the transgressive-regressive depositional sequences of Ross and Ross (1988). The numerous parasequence of the Wahoo Limestone have a higher frequency than these transgressive-regressive sequences. The major sub-Permian unconformity at the top of the Wahoo does not appear to correspond to any indicated eustatic lowstand (Fig. 1-32), except for the Early Permian lowstand of Vail et al. (1977)

In summary, available sea-level curves for the Carboniferous are rather contradictory and generally do not match the sea-level fluctuations apparent in the Lisburne Group. However, the most dramatic change in depositional conditions occurs in the latest Mississippian and may coincide with the Kaskaskia-Absaroka sequence boundary (Sloss, 1963, 1988). The depositional sequences and parasequence of the Lisburne Group are at lower and higher frequencies than shown on available eustatic curves (e.g., Ross and Ross, 1988).

PRELIMINARY ANALYSIS OF THE LISBURNE OIL FIELD

A well from the Lisburne field near Prudhoe Bay was examined in core, thin section, and on well logs for comparison with Wahoo Limestone in the Arctic National Wildlife Refuge (ANWR). Parasequences are well developed in both areas but the greater abundance of terrigenous sediment and the nature of the associated carbonate facies indicate that the Lisburne field is located in a more landward position on the Wahoo carbonate ramp, closer to a source of terrigenous sediment.

The stratigraphic nomenclature extended from ANWR (the type locality of the Wahoo Limestone) is different from the terminology previously used for the subsurface Lisburne Group near Prudhoe Bay (Fig. 1-30). We distinguish informal lower and upper members within the Mississippian to Pennsylvanian Wahoo Limestone which overlies the Mississippian Alapah Limestone. Our upper Alapah corresponds to the middle Alapah of previous workers ("Dolomite interval" of Jamison et al., 1980). Our lower Wahoo Limestone member corresponds to the upper Alapah of previous workers ("Grainstone-packstone interval" of Jamison et al., 1980). Our upper Wahoo Limestone member corresponds to the previous workers' Wahoo Limestone and is the major hydrocarbon reservoir at the Lisburne field (Armstrong and Mamet, 1974; Jameson et al., 1980). The Lisburne field is characterized by well-developed parasequences (Okland et al., 1987). The major change in the nature of the Lisburne carbonate platform occurs between our Alapah and Wahoo, and represents a major depositional sequence boundary. This sequence boundary and another sequence boundary at the lower and upper Wahoo transition are both marked by major influxes of terrigenous sediment. Thus, the Lisburne Group at Prudhoe Bay can be subdivided into three depositional sequences that correspond to those in the Lisburne of ANWR, but formed adjacent to a landmass where influxes of terrigenous sediment mark lowstands of sea level.

We further subdivide the Wahoo Limestone into 8 zones bounded by 2- to 11-foot thick intervals of shale or argillaceous limestone. These zones generally correspond to the zonation for the Wahoo previously used by industry (Jameson, in revision), but includes an additional zone (Zone 1) representing our lower Wahoo member. The zones are bounded by argillaceous intervals that are evident on gamma-ray logs (Figs. 4-3, 4-4, 4-7, 4-9, & 4-11). Each zone contains characteristic microfacies organized into parasequences (Figs. 4-5, 4-8, 4-10, & 4-12), some of which are bounded by intervals containing terrigenous mud and/or sand.

One of the original goals of the study - relating reservoir characteristics to different microfacies - may not be feasible because of the importance of fracturing in the Lisburne reservoir. Although reservoir behavior is partially controlled by the original depositional texture and composition of the Lisburne carbonates, these heterogeneous microfacies have been altered by complex diagenesis and fracturing (Jameson, 1990a &b, 1991, in revision). However, regional comparison of the sequence and parasequence stratigraphy of the Wahoo will illustrate how parasequences of the inner part of a carbonate ramp containing associated

terrigenous sediments differ from those that formed in more seaward parts of the Wahoo ramp in ANWR. This is an ongoing study that will be completed as part of S.K. Morgan's Ph.D. dissertation.

WAHOO COMPUTERIZED DATABASE

As part of our research on the Lisburne Group, we have developed a powerful relational computerized database to accommodate the huge amounts of data generated by our multi-disciplinary research project. Using the *4th Dimension* (*4-D*) database program on an Apple Macintosh IIx or better computer (e.g., Quadra), we have established a menu-driven structure that allows easy input and output of data. The *Wahoo* database has data files on petrography, conodont analyses, localities and samples, well logs and diagenetic (cement) studies. The database is a useful research tool that has helped us record and quantify the nature of the heterogeneous carbonate microfacies of the Lisburne Group. A variety of data tables produced by the *Wahoo* database are presented in appendices, each encapsulating a small part of the data contained in the *Wahoo* database. All the data are sorted and listed by map index number and stratigraphic position (depth).

The Locality data table (Appendix A) lists all the stratigraphic sections examined in our study. It gives names of study areas, stratigraphic units studied, locality information, and researchers. Localities in ANWR are keyed to a geologic map that shows the distribution of the Lisburne Group and location of our stratigraphic sections.

Petrographic reports (Appendix B) are detailed summaries of the composition and texture of Lisburne Group carbonates. The relative abundance of different carbonate grains (allochems) and carbonate texture are listed using symbols that portray data in a format similar to stratigraphic columns. This enables researchers to recognize trends in the evolution of the Lisburne carbonate platform and to check their paleoenvironmental interpretations in a stratigraphic context. Some of the figures in chapter 1 were made using the *Wahoo* database (Figs. 1-27 & 1-28).

The *Wahoo* database is available through the Geophysical Institute of the University of Alaska Fairbanks. Because this program and its very large data file presently require 22 megabytes, it is most easily transferred using a dedicated external hard drive. The entire *Wahoo* program and its data files are simply copied from this hard drive onto the user's computer. The user must have a copy of the *4-D* program and other essential Macintosh hardware and software. Although the Wahoo database was designed specifically for limestones of the Carboniferous Lisburne Group, it can be reprogrammed by Dan Lasota (the programmer who developed *Wahoo*) to be utilized in studies of other rock units having different compositions and characteristics.

HYDROCARBONS AND THE LISBURNE GROUP OF ANWR

Lisburne Group carbonates exposed in ANWR are mostly tightly cemented with little observable porosity. However, fracturing associated with compressional Brookian deformation in ANWR could enhance porosity and permeability, particularly in intervals of relatively brittle dolomite. Conodont CAIs are generally very high indicating that the Lisburne Group exposed in ANWR is supermature. Thus, the Lisburne beneath the coastal plain of ANWR would have to differ from that exposed in the northeastern Brook Range in order to be a viable hydrocarbon reservoir target.

The sabkha dolomites of the upper Alapah Limestone are probably the best reservoir target. This fine-grained dolomite unit was identified by Bird and Jordan (1977) as the best and most widespread hydrocarbon target in the Lisburne Group of the North Slope. A small reservoir in these dolomites located to the east of the main Lisburne field has excellent porosity and permeability, but lies mostly beneath the oil-water contact. Subaerial exposure surfaces near the sequence boundary approximating the top of the Alapah and associated cavernous porosity that is typically filled with late burial cements could result in significant porosity in areas where such cementation did not occur.

The coarse-grained dolomite in the Osagean part of the Wachsmuth Limestone in the central Brooks Range (Shainin Lake section) has the best porosity and permeability seen in the exposed Lisburne Group. The presence of bitumen in intercrystalline and vuggy porosity in these rocks made the Lisburne one of the original hydrocarbon targets in North Slope exploration.

Coarse dolomites with reservoir potential occur in the lower part of the Alapah Limestone in the southeastern part of the ANWR study area (Fig. 1-9). These appear to be more abundant in the south than in the north, so might not be prevalent beneath the coastal plain of ANWR.

Local karst and moldic porosity (particularly oomoldic porosity) occurs beneath the sub-Permian unconformity, but subsequent cementation occludes most porosity.

High and variable conodont color alteration indices indicate that the Lisburne exposed in ANWR is supermature and that hydrothermal fluids have migrated through these rocks. The lowest minimum CAIs (2.5, indicating minimum temperatures of 100-150°C) are adjacent to the coastal plain of ANWR. The Lisburne Group in structurally higher allochthons of the central Brooks Range has lower CAIs of 2.0-2.5 (mature to overmature).

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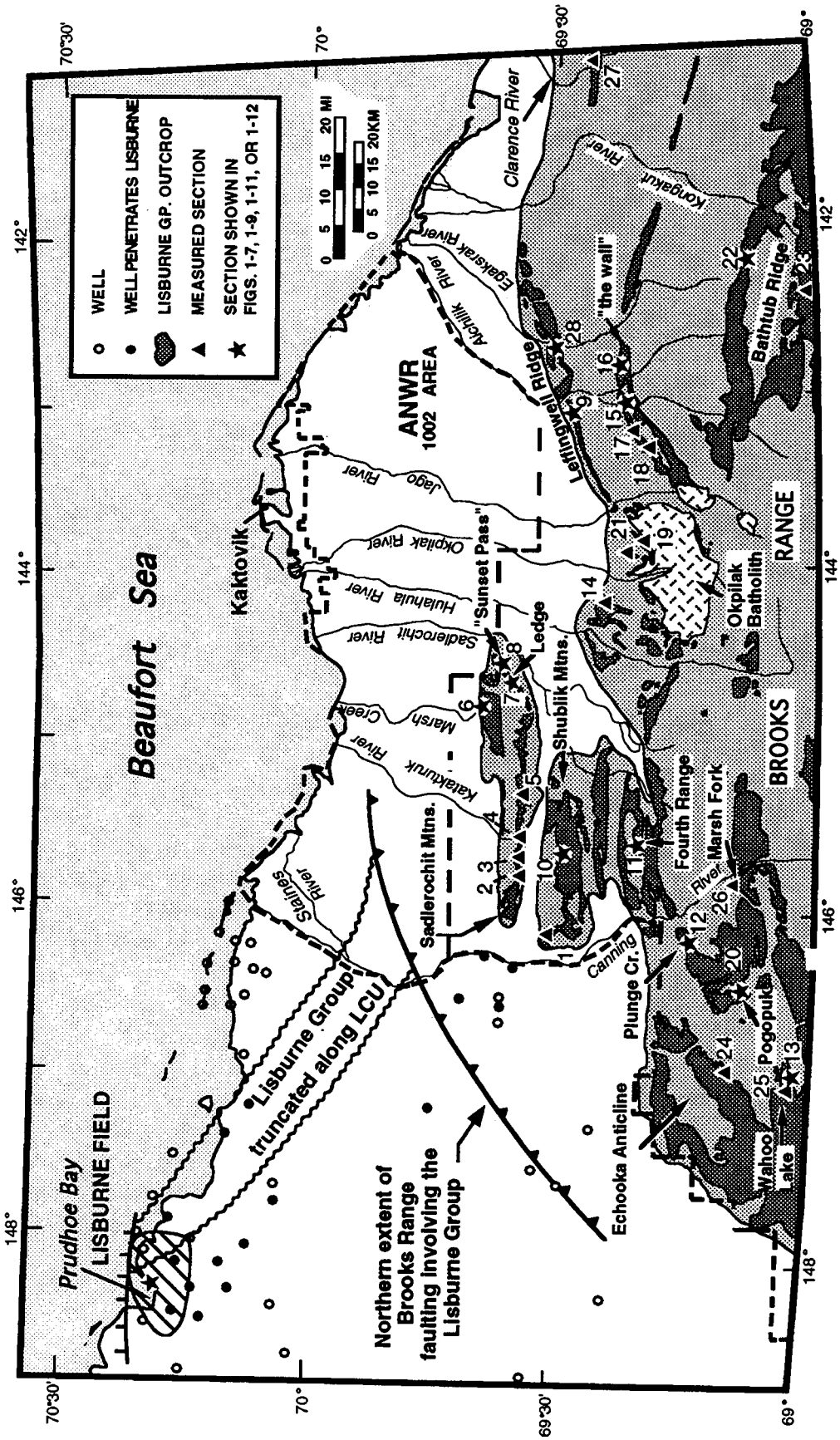
APPENDIX A - LOCALITY DATA

MEASURED STRATIGRAPHIC SECTIONS OF THE LISBURNE GROUP

Appendix A gives locality information for stratigraphic sections of the Lisburne Group included in this report and was generated from the *Locality* file of the *Wahoo* computerized database (see Chapter 5). For each stratigraphic section, it lists the map index number (Map #), University of Alaska Museum number (Locality), name and brief description, geographic coordinates and other map information. The map index number refers to a specific locality on an index map that shows the location of measured sections of the Lisburne Group in ANWR (Figure A-1). The whole number part of the map index number corresponds to the number on the index map. In some cases, several incomplete stratigraphic sections were measured to obtain a composite stratigraphic section for a particular locality. In order to illustrate the relative stacking order of the different component sections, the map index number has two decimal places. The first decimal indicates the relative stratigraphic position with .1 being the highest stratigraphic interval. For example, a composite stratigraphic section in the Shublik Mountains (loc. 10, Fig. 1-2) is comprised of three sections: the upper Wahoo Limestone (map index 10.1), the lower Wahoo (map index 10.2), and the underlying Alapah Limestone (map index 10.3). If the same stratigraphic section was reexamined in a later year, then the second decimal is increased by .01. For example, the upper part of the type locality of the Wahoo Limestone was first examined in 1987 (map index 13.2) and was resampled in 1991 (map index 13.21) and in 1992 (map index 13.22).



FigureA-1. Map showing outcrop belts of the Lisburne Group in ANWR and locations of measured sections. The general location of the truncation of the Lisburne Group beneath the Lower Cretaceous unconformity (LCU) is also shown extending southeastward from Prudhoe Bay (modified from Bird et al., 1987).

Appendix A- Locality data

Map #	Locality	Strat. Section Description	Lat. o	Lat. '	Long. o	Long. '	Map Quad	Map	1/4	Sec.	T.	N/S	R.	E/W	Collector
5	AK97M	KW86Z - "central Sadlerochit Mountains." - lower Wahoo	69	35.3	145	15.5	(ML) Mt. Michelson	C4	NW	30	3	N	28	E	K. Watts
6	AK4M	86RC19 - "Marsh Creek Section", north Sadlerochit Mountains - Wahoo	69	40.7	144	51	(ML) Mt. Michelson	C2	NE	30	4	N	30	E	R. Carlson
7.1	AK3M	86RC7 - "Ledge Creek"- eastern Sadlerochit Mountains - Wahoo	69	37.4	144	39.3	(ML) Mt. Michelson	C2	SW	12	3	N	30	E	R. Carlson
7.2	AK7M	ARCO Sadlerochit - "Ledge Creek", middle part of Wahoo	69	37.4	144	39.3	(ML) Mt. Michelson	C2	SW	12	3	N	30	E	ARCO Alaska Inc.
8.1	AK22M	APK88A - "eastern Sadlerochit Mountains - 'Sunset Pass'" - conodont sampling	69	38.6	144	34.7	(ML) Mt. Michelson	C1	SW	5	3	N	31	E	A. Krumhardt
8.11	AK109M	SKM91A - "eastern Sadlerochit Mountains - 'Sunset Pass'" = AK22M resampled	69	38.6	144	34.7	(ML) Mt. Michelson	C1	NW	5	3	N	31	E	S. Morgan
8.12	AK6M	ARCO Sadlerochit - "eastern Sadlerochit Mountains - 'Sunset Pass'" - upper Wahoo	69	38.2	144	34.8	(ML) Mt. Michelson	C1	NW	8	3	N	30	E	ARCO Alaska Inc
8.2	AK120M	SKM92A - "eastern Sadlerochit Mountains - 'Sunset Pass'"- below AK22M/AK109M	69	38.6	144	34.7	(ML) Mt. Michelson	C1	NW	5	3	S	31	E	S. Morgan
8.3	AK1M	86RC17 - "eastern Sadlerochit Mountains - 'Sunset Pass'" - Wahoo	69	37.95	144	36.75	(ML) Mt. Michelson	C1	NW	7	3	N	31	E	R. Carlson
8.41	AK79M	AK90D - "eastern Sadlerochit Mountains - 'Sunset Pass' - lower Wahoo, spot sampl	69	38.6	144	34.7	(ML) Mt. Michelson	C1	SW	5	3	S	31	E	A. Krumhardt
8.42	AK78M	AK90C - "eastern Sadlerochit Mountains - 'Sunset Pass'" - lower Wahoo, spot samp	69	38.6	144	34.7	(ML) Mt. Michelson	C1	SW	5	3	S	31	E	A. Krumhardt
8.5	AK2M	86RC16 - "eastern Sadlerochit Mountains - 'Sunset Pass'" - Alapah	69	38.3	144	37.2	(ML) Mt. Michelson	C2	NW	7	3	N	31	E	R. Carlson
9.1	AK17M	KW87V - "Leffingwell Ridge" - upper Wahoo, measured downsection	69	29.6	143	7.5	(DP) Demarcation Pt.	B4	NE	31	2	N	37	E	K. Watts & J. Dumoulin
9.2	AK95M	KW86X - "Leffingwell Ridge" - middle/upper Alapah to Wahoo	69	29.2	143	7.8	(DP) Demarcation Pt.	B4	NE	31	2	N	37	E	K. Watts & C. Hanks

Map #	Locality	Strat. Section Description	Lat. o	Lat. '	Long. o	Long. '	Map Quad	Map	1/4	Sec.	T.	N/S	R.	E/W	Collector
9.3	AK96M	KW86Y - "Leffingwell Ridge" - Kayak Shale to Alapah	69	28.8	143	9.7	(DP) Demarcation Pt.	B4	SE	36	2	N	36	E	K. Watts & C. Hanks
10.1	AK10M	87PG-A - "central Shublik Mountains" - upper Wahoo	69	30.9	145	41.75	(ML) Mt. Michelson	C3	SE	22	2	N	26	E	P. Gruzlovic
10.2	AK12M	PG87-C - "central Shublik Mountains." - Lower Wahoo to lowest upper Wahoo	69	31	145	41.4	(ML) Mt. Michelson	C3	NW	23	2	S	26	E	P. Gruzlovic
10.3	AK11M	87PG-B - " central Shublik Mountains" - Kayak to lower Wahoo	69	30.8	145	39.6	(ML) Mt. Michelson	C3	SE	0	2	S	26	E	P. Gruzlovic
11.1	AK14M	87PG-E - "Fourth Range" - upper Wahoo	69	20.9	145	37.2	(ML) Mt. Michelson	B3	NW	21	1	S	27	E	P. Gruzlovic
11.2	AK13M	87PG-D - "Fourth Range" - Endicott Group to lower upper Wahoo	69	21	145	38.4	(ML) Mt. Michelson	B3	SE	17	1	S	27	E	P. Gruzlovic
11.21	AK77M	AK90A - "Fourth Range" - AK13M and above to Echooka, conodont sampling	69	21	145	38.4	(ML) Mt. Michelson	B3	SE	17	1	S	27	E	A. Krumhardt
12.1	AK16M	87PG-F - "Plunge Creek" - upper Wahoo	69	15	146	10.3	(ML) Mt. Michelson	B4	SE	19	2	S	25	E	P. Gruzlovic
12.2	AK15M	87PG-G - "Plunge Creek" - Alapah Limestone	69	15	146	10.1	(ML) Mt. Michelson	A4	SE	19	2	S	25	E	P. Gruzlovic
13.1	AK19M	KW87Y - "Wahoo type section" - calcareous Echooka above bona fide Wahoo	69	1.5	146	56	(ML) Mt. Michelson	A5	NE	8	5	N	22	E	K. Watts
13.2	AK20M	KW87Z - "Wahoo type section" - upper part of Wahoo, measured downsection	69	1.5	146	56	(ML) Mt. Michelson	A5	NE	8	5	S	22	E	K. Watts
13.21	AK118M	SKM91E - "Wahoo type locality" - upper part of Wahoo, AK20M revisited	69	1.5	146	56.1	(ML) Mt. Michelson	A5	NE	8	5	S	22	E	S. Morgan
13.22	AK131M	SKM92E - "Wahoo type locality" = AK20M - uppermost Wahoo, resampled for conodont	69	1.5	146	56.1	(ML) Mt. Michelson	A5	NE	8	5	S	22	E	S. Morgan
13.3	AK112M	SKM91D - "Wahoo" - new Wahoo stratotype, conodont sampling	69	1.4	147	0.1	(SG) Saganavirktok	A1	SE	12	5	S	21	E	S. Morgan

Appendix A- Locality data

Map #	Locality	Strat. Section Description	Lat. o	Lat. '	Long. o	Long. '	Map Quad	Map	1/4	Sec.	T.	N/S	R.	E/W	Collector
13.31	AK130M	SKM92D - "Wahoo"- new Wahoo stratotype - uppermost AK112M resampled, conodont sa	69	1.4	147	0.1	(SG) Saganavirktok	A1	SE	12	5	S	21	E	S. Morgan
14.1	AK18M	KW87W - "Old Man Creek" - Wahoo, measured downsection	69	25.5	144	12.9	(ML) Mt. Michelson	B1	SW	23	1	N	32	E	K. Watts
14.2	KW87X	KW87X - "Old Man Creek" - Kekiktuk to lowest Alapah	69	26.1	144	13.4	(ML) Mt. Michelson	B1	SE	15	1	N	32	E	K. Watts
15.1	AK71M	KW88F - "Aichilik River wall" - Wahoo, measured downsection	69	23.2	143	2.7	(DP) Demarcation Pt.	B4	NW	6	1	S	38	E	K. Watts
15.2	AK123M	ME92A - "Aichilik River wall" - below AK71M, measured downsection	69	23.3	143	2.4	(DP) Demarcation Pt.	B4	NW	6	1	S	38	E	M. Eckstein
16.1	AK124M	ME92B - "Egaksrak wall"- upper Alapah, overlaps and overlies AK21M	69	23.9	142	51.2	(DP) Demarcation Pt.	B4	SW	32	1	N	38	E	M. Eckstein
16.2	AK21M	KW88C - "Egaksrak wall" - lower Lisburne - Alapah	69	24.1	142	50.7	(DP) Demarcation Pt.	B4	NE	32	1	S	38	E	M. Eckstein
17	AK23M	KW88D - "west Aichilik" - Itkilyariak or lower Lisburne (?).	69	23.1	143	7.7	(DP) Demarcation Pt.	B4	NW	2	1	S	37	E	K. Watts
18	AK24M	KW88E - "Jago River" - Itkilyariak or lower Lisburne(?)	69	19.1	143	27	(DP) Demarcation Pt.	B5	NW	33	3	S	36	E	K. Watts
19	AK98M	88KW7 - "Okpilak" - tectonically thinned overturned Lisburne, downsection	69	20.8	143	53.4	(ML) Mt. Michelson	B5	NW	22	1	S	34	E	K. Watts
20.1	AK111M	SKM91C - "Pogopuk Creek" - Wahoo, most complete section, conodont sampling	69	7.6	146	26	(ML) Mt. Michelson	A5	NW	23	3	S	23	E	S. Morgan
20.2	AK72M	KW89A - "Pogopuk Creek" - upper Wahoo	69	9.7	146	28.2	(ML) Mt. Michelson	A5	SW	24	3	S	23	E	K. Watts & P. Gruzlovic
20.3	AK73M	KW89B - "Pogopuk Creek" - lower upper Wahoo(?)	69	7.6	146	26.7	(ML) Mt. Michelson	A5	NE	1	3	S	23	E	K. Watts & P. Gruzlovic
20.4	AK74M	KW89C - "Pogopuk Creek" - lower Wahoo - upper Wahoo contact(?)	69	7.5	146	26.7	(ML) Mt. Michelson	A5	NE	1	3	S	23	E	K. Watts & P. Gruzlovic
21.1	AK76M	KW89D - "Okpilak - North" - lower Lisburne and/or Itkilyariak Formation (?)	69	22.35	143	56.1	(DP) Demarcation Pt.	B5	NW	9	1	S	34	E	K. Watts & P. Gruzlovic

Map #	Locality	Strat. Section Description	Lat. o	Lat. '	Long. o	Long. '	Map Quad	Map	1/4	Sec.	T.	N/S	R.	E/W	Collector
21.2	AK99M	KW89E - "Okpilak-North" - Itkilyariak Formation and/or Kekiktuk Conglomerate(?)	69	22.2	143	56.3	(DP) Demarcation Pt.	B5	NW	9	1	S	34	E	K. Watts & P. Gruzlovic
22.1	AK75M	KW89F - "North Bathtub Ridge" - entire Lisburne	69	8.7	142	18.2	(DP) Demarcation Pt.	A3	NE	31	3	S	41	E	K. Watts
22.12	AK125M	ME92C - "North Bathtub Ridge" - Locality AK75M revisited	69	8.7	142	18.2	(DP) Demarcation Pt.	A3	NE	31	4	S	41	E	M. Eckstein
23.1	AK113M	KW91A = 91S -"South Bathtub - Kongakut River"- Alapah to Wahoo, dip slope at top	69	0.3	142	23.9	(DP) Demarcation Pt.	A3	SW	16	5	S	41	E	K. Watts
23.2	AK100M	KW89G - "South Bathtub - Kongakut River", Kayak to Alapah	69	31.1	142	0.1	(DP) Demarcation Pt.	A3	SW	13	5	S	40	E	K. Watts
24	AK80M	KW90A - "Echooka Anticline" - upper Wahoo	69	9.5	146	56.9	(ML) Mt. Michelson	A5	NW	25	3	S	21	E	K. Watts & S. Morgan
25.1	AK82M	KW90C - "Near Wahoo Lake" - uppermost Wahoo	69	2	144	3.5	(SG) Saganavirktok	A1	SE	2	5	S	21	E	K. Watts & S. Morgan
25.2	AK81M	KW90B - "Near Wahoo Lake" - Wahoo, badly strained	69	2	147	3.5	(SG) Saganavirktok	A1	SE	2	5	S	21	E	Watts, Dumoulin, & Morgan
25.3	AK83M	KW90D - "Near Wahoo Lake" - part of Wahoo - incomplete	69	1	147	0.8	(SG) Saganavirktok	A1	SE	12	5	S	21	E	Watts, Dumoulin, & Morgan
25.4	AK84M	KW90E - "Near Wahoo Lake" - upper Alapah with speleothems	69	1.6	147	3.5	(SG) Saganavirktok	A1	NE	11	5	S	21	E	K. Watts & S. Morgan
26.1	AK110M	SKM91B - "Marsh Fork" - upper Wahoo to Echooka	69	8	145	50.1	(ML) Mt. Michelson	A4	SE	33	4	S	26	E	S. Morgan
26.2	AK114M	KW91Z - "Marsh Fork"- Kayak to upper Alapah (Wachsmuth?)	69	10	145	50	(ML) Mt. Michelson	A4	SW	22	3	S	26	E	K. Watts
27.1	AK122M	SKM92C - "Clarence River" - uppermost Wahoo to Echooka, conodont sampling	69	25.7	141	4.1	(DP) Demarcation Pt.	B1	SE	21	1	N	45	E	S. Morgan
27.2	AK107M	KW91Y - "Clarence River" - upper Alapah to Wahoo.	69	25.5	141	4.2	(DP) Demarcation Pt.	B1	SE	21	1	N	45	E	K. Watts & J. Dumoulin
27.21	AK121M	SKM92B - "Clarence River" - locality AK107M revisited, conodont sampling	69	25.5	141	4.2	(DP) Demarcation Pt.	B1	SE	21	1	S	45	E	K. Watts & J. Dumoulin
27.3	AK129M	KW92Z - "Clarence River" - lower to middle Alapah	69	25.8	141	5.6	(DP) Demarcation Pt.	B1	NW	21	1	N	45	E	K. Watts

Map #	Locality	Strat. Section Description	Lat. o	Lat. '	Long. o	Long. '	Map Quad	Map	1/4	Sec.	T.	N/S	R.	E/W	Collector
27.4	AK108M	KW91X - "Clarence River" - lower Alapah - (Egaksrak grainstone)	69	25.2	141	8.8	(DP) Demarcation Pt.	B1	NW	29	1	N	45	E	K. Watts & J. Dumoulin
28	AK128M	KW92Y- "Leffingwell Ridge East - Egaksrak River" - Alapah to Wahoo, w/ conodonts	69	31.1	142	43.2	(DP) Demarcation Pt.	C3	NE	23	21	S	38	E	K. Watts
29.1	AK132M	APK92A - "Northern Echooka" - lower Wahoo, conodont sampling	69	14.2	147	19.1	(SG) Saganavirktok	A1	SE	28	2	S	20	E	A. Krumhardt
29.2	AK133M	APK92B - "Northern Echooka" - upper Wahoo, conodont sampling	69	14.2	147	19.1	(SG) Saganavirktok	A1	SW	29	2	S	20	E	A. Krumhardt
100.1	AK116M	KW91V - "Shainin Lake"- Alapah type section - upper part	68	20.1	151	0.9	(CL) Chandler Lakes	B2	NE	8	13	S	5	E	K. Watts & J. Dumoulin
100.2	AK115M	KW91W - "Shainin Lake"- Alapah type section - lower part	68	19.65	151	0.7	(CL) Chandler Lakes	B2	SE	8	13	S	5	E	K. Watts & J. Dumoulin
100.3	AK94M	KW90K - "Shainin Lake" - upper Wachsmuth to lower Alapah type section	68	19.5	151	1.2	(CL) Chandler Lakes	B2	SE	8	13	S	5	E	K. Watts & J. Dumoulin
100.4	AK93M	KW90J - "Shainin Lake" - middle Wachsmuth type section	68	19.4	151	0.8	(CL) Chandler Lakes	B2	SE	8	13	S	5	E	K. Watts & J. Dumoulin
100.5	AK92M	KW90I - "Shainin Lake" - upper Kayak to lower Wachsmuth type section	68	19.5	150	59	(CL) Chandler Lakes	B2	SE	8	13	S	5	E	K. Watts & J. Dumoulin
100.6	AK117M	KW91T - "Shainin Lake"- Argillaceous limestone member - Wachsmuth Formation	68	19.35	150	59.4	(CL) Chandler Lakes	B2	NW	16	13	S	5	E	K. Watts & J. Dumoulin
101.1	KW92V	KW92V - "Sheenjek River" - lower to middle Alapah	68	57.7	143	39.7	(TB) Table Mountain	D5	SW	31	5	S	36	E	K. Watts
101.2	AK127M	KW92W - "Sheenjek River" - Kayak to lower Lisburne / Alapah	68	58	143	49.8	(TB) Table Mountain	D5	SE	32	5	S	35	E	K. Watts
101.3	AK126M	KW92X - "Sheenjek River" - garbage section, Kayak to lower Lisburne / Alapah	68	57.9	143	38.9	(TB) Table Mountain	D5	SE	31	5	S	36	E	K. Watts
102.1	AK88M	KW90F4 - "Atigun Gorge" - Wahoo to Echooka, above AK87M	68	29.35	149	9.7	(PS) Phillip Smith	B4	SW	17	11	S	13	E	Watts, Dumoulin, & Morgan

Map #	Locality	Strat. Section Description	Lat. o	Lat. '	Long. o	Long. '	Map Quad	Map	1/4	Sec.	T.	N/S	R.	E/W	Collector
102.2	AK87M	KW90F3 - "Atigun Gorge" - Wahoo, above AK86M, below AK88M	68	29.35	149	9.7	(PS) Phillip Smith	B4	SW	17	11	S	13	E	Watts, Dumoulin, & Morgan
102.3	AK86M	KW90F2 - "Atigun Gorge" - Wahoo above / overlaps AK85M, below AK87M	68	29.35	149	9.7	(PS) Phillip Smith	B4	SW	17	11	S	13	E	Watts, Dumoulin, & Morgan
102.4	AK85M	KW90F - "Atigun Gorge" - Wahoo below / overlaps AK86M	68	29.35	149	9.7	(PS) Phillip Smith	B4	SW	17	11	S	13	E	Watts, Dumoulin, & Morgan
103.1	AK90M	KW90G2 - "Atigun Gorge" - middle to upper Alapah (transitional unit.)	68	26.35	149	15.3	(PS) Phillip Smith	B4	NW	2	12	S	12	E	Watts, Dumoulin, & Morgan
103.2	AK89M	KW90G - "Atigun Gorge" - Kayak to Alapah	68	26.7	149	15.6	(PS) Phillip Smith	B4	SW	35	11	S	12	E	Watts, Dumoulin, & Morgan
104	AK91M	KW90H - "Itikmalak Creek" - uppermost Wahoo to Siksikpuk	68	22.9	149	41.7	(PS) Phillip Smith	B5	NE	26	12	S	10	E	K. Watts & S. Morgan
105	WELL	WELL is a cored well in the Lisburne oil field, no UAF Museum number	0	0	0	0		A1		0	0	S	0	E	S. Morgan

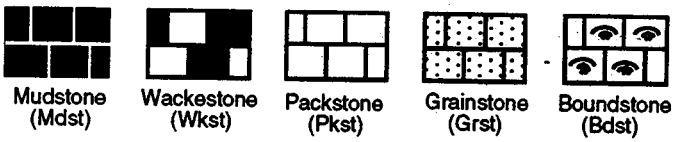
APPENDIX B

PETROGRAPHIC DATA FROM THE *WAHOO* COMPUTERIZED DATABASE

Appendix B summarizes some of the information contained in the *Petrographic* file in the *Wahoo* computerized database. It is listed in order of map index number keyed to specific stratigraphic sections as shown on a map of northeastern Alaska (see Appendix A) and by position within each successive stratigraphic section. The sample number is in two parts: the first part (AK_M) is the University of Alaska Museum number and refers to a specific stratigraphic section (see Appendix A); the second part of the number is in meters above base of section (negative numbers indicate that the section was measured downward). The locality "WELL" refers to a cored well in the Lisburne oil field and its depth is in feet (see Chapter 4). The symbols used to illustrate the carbonate texture (after Dunham, 1962) and the relative abundance of different grain types are explained on Figure B-1. The relative abundance of grain types are listed in columns as follows: Abundant = >50%; Common = 10-50%; Minor = 1-10%; and Rare = <1%. Paleoenvironmental interpretations are based on carbonate texture and grain types, together with position within a stratigraphic succession/parasequence and relationship to adjacent lithologies. These interpretations are **preliminary** and subject to change as additional analyses become available since the last data input (September 1993).

EXPLANATION

CARBONATE TEXTURAL CLASSIFICATION



SKELETAL GRAINS

- Pelmatozoan
- Bryozoan (undifferentiated)
- Bryozoan (full-frond fenestrate)
- Bryozoan (ramose, "stick")
- Brachiopod
- Bivalve
- Gastropod
- Foraminifer
- Trilobite
- Ostracod
- Sponge Spicule
- Coral (undifferentiated)
- Coral (colonial)
- Algae (undifferentiated)
- *Asphaltina sp.*
- *Archaeolithophyllum sp.*
- *Donezella sp.*
- *Calcisphaera sp.*
- Oncolite
- Bioclast (undifferentiated)

NON - SKELETAL GRAINS

- Ooid
- Superficial Ooid
- Peloid
- Intraclast
- Grapestone
- Detrital Quartz

Figure B-1. Key to symbols used in Appendix B.

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
6	AK4M184				Y★	⚘		open marine
6	AK4M182.5	limestone			≈♁•⊖	⊙	Y★	shoal
6	AK4M182	limestone			⊙•	≈♁YΣ⊖		shoal
6	AK4M181.5	limestone			♁⊖•	♣≈	⚷	shoal
6	AK4M181	limestone		⊙	⊖•	♁		shoal
6	AK4M180.5	limestone			⊙•	♁♣Σ	⚷	shoal
6	AK4M180	limestone			♁•	Y≈♣⚡⊙⊖★	Q	lagoonal
6	AK4M179	limestone			♁⊙Σ	⚘≈⚷•★Y	⚠	shoal
6	AK4M178	limestone			⚡Y⊖★	ϙ♁≈•⚘	⚠	shoal
6	AK4M177.5	limestone			Y•	♣♁≈⊖★		open marine
6	AK4M177	limestone			Y♁⚡•★	♣ϙ⚠≈	⚲	open marine
6	AK4M176.5	limestone			Y≈★⚡	⚘•	ϙ	open marine
6	AK4M176	limestone			Y⚡★	⚷≈	⚡•	open marine
6	AK4M175.5	limestone			Y⚡★	⚡⚘		open marine
6	AK4M175	limestone			Y≈★⚡	♣⚠•	ϙ⚘	open marine
6	AK4M171	limestone			Q⚲•	≈Y⚠	⚷	lagoonal
6	AK4M170.5	limestone			Y⚡★	Q		open marine
6	AK4M170	limestone			⚡Y•★	≈♣⚠⚘		open marine
6	AK4M169.5	limestone			⚡Y•★	⚡♣≈	♁	open marine
6	AK4M169	limestone			⚘♁Y★⚡	⚡ϙ⚠≈	♣	open marine
6	AK4M168.5	limestone			⚡Y•★	ϙ≈	⚠	open marine
6	AK4M166	limestone			Y♁⚡•★	♣Q≈⚷⚲	Σ	lagoonal
6	AK4M165.5	limestone			♁•	≈♣★Y		lagoonal
6	AK4M165							
6	AK4M164.5							
6	AK4M164							
6	AK4M163.5	limestone			⚡Y★•⊖	Qϙ⚷⊙≈	♣⚠Σ	lagoonal
6	AK4M163	limestone			⚡Y⊖★	ϙ≈•	⚷QΣ⚘	open marine
6	AK4M162.5	limestone			⊖•	≈⚷ϙ★⚡Y	Q⚡Σ⚠	shoal
6	AK4M162	limestone			YQ★⚡	♁⚡♣	ϙ⚘	open marine
6	AK4M161	limestone			Q⚡Y★⚡	ϙ≈		open marine
6	AK4M160.5	limestone			Y⚡★	ϙ⚡≈	⚘⚷•⊖	open marine
6	AK4M160	limestone			⚡ϙY★⚡	≈⚷⚠⚘		open marine
6	AK4M159				Y⚡★	⚡Q	⚘	open marine
6	AK4M157	limestone			⚡Y⚡	⚷Q⚘≈	ϙ⚠	open marine
6	AK4M156.5	limestone			Y≈★⚡	♁⚡⚘	⚷	open marine
6	AK4M156	limestone			Y⚡★⚡	⚷≈•	⚘⚠	open marine
6	AK4M155.5	limestone			≈⚡Y★⚡	♣⚘⚠	•	open marine
6	AK4M155	limestone			Y⚡★	⚡		open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
6	AK4M154.5	sandstone		Q				open marine
6	AK4M154		■		⚒	Q		open marine
6	AK4M153.5	limestone	▦		YY★ᗰ	⚱	♁≈ᗩ	open marine
6	AK4M153	limestone	▦					open marine
6	AK4M152.5	limestone	▦		Yᗰ★	⚱	Q≈	open marine
6	AK4M152	limestone	▦					open marine
6	AK4M151.5	limestone	▩		Yᗰ★	Y⚱		open marine
6	AK4M151	dolostone				★⚒		open marine
6	AK4M150.5		▦		Yᗰ★	QY⊙⚱	♀♁≈	open marine
6	AK4M150	limestone	▩		Yᗰ★	≈Y⚱⚱	ℬ	open marine
6	AK4M149.5	limestone	▦	Yᗰ	Q	Y⚱⊙		open marine
6	AK4M147.5	limestone	▩	⊙	Yᗰ★	♁≈	Y♀⚱⧗ᗩ	shoal
6	AK4M147	limestone	▩	⊙	Yᗰ★	♀≈	Yℬ⊛	shoal
6	AK4M146.5	limestone	▦		Yᗰ★		Y≈	open marine
6	AK4M146	limestone	▦		Yᗰ★	Y	♀≈	open marine
6	AK4M145.5	limestone	▩		Yᗰ★	≈Y⧗⚱	♁	open marine
6	AK4M143.5	limestone	▩	⊖	♁●			shoal
6	AK4M142.5	limestone	▩		♁≈●	Yᗰ★	♁⊖	lagoon
6	AK4M142	limestone	▩		Y♁●ᗰ	≈♁⊖⚱	♀★	lagoon
6	AK4M141.5	limestone	▩		♁●	♁≈⊖	ℬ⊙	lagoon
6	AK4M141	limestone	▩		♁●	≈ℬ★Y	⚱♁⊙⊖	lagoon
6	AK4M140.5	limestone	▩	⊙	●	≈Y⊛	♁ℬ⧗	shoal
6	AK4M140	limestone	▩	●	♁⊖	ℬ♁Y	Q★⊙	lagoon
6	AK4M139.5	limestone	▩	⊙	⊖	Y≈★ᗰ	ℬ♁⊛ℓ	shoal
6	AK4M139		▩		⊙●	≈	Y♁	shoal
6	AK4M138.5	limestone	▦		Qℓ●	♁≈Y	★	lagoon
6	AK4M138	limestone	▦		≈⊖●	♁YQℬ⊙⧗ᗰ★		lagoon
6	AK4M137.5	limestone	▦		⊖●	≈♁Q★ᗰY	⊙	lagoon
6	AK4M137	limestone	▦		⊙	♁♁●		lagoon
6	AK4M136.5	limestone	▦		⊙	Y♁Qℓ★	ᗩ♁⧗⊛	lagoon
6	AK4M136	limestone	▚			≈Qℓ●⊙	Y♁ℬ★⊛⚒ᗩ	lagoon
6	AK4M135.5	limestone	▩	⊙		Y♁ᗰ●★	Yℬ	shoal
6	AK4M135	limestone	▩	⊙	●	Y♁ᗰ⧗★	ℬᗩ	shoal
6	AK4M134.5	limestone	▩	Yᗰ	★	≈♁●ᗩ	ℬY⊛⊖	open marine
6	AK4M134	limestone	▩	Yᗰ	★	♁Y●≈	ℓ⚱ℬ⊛⊙⊖	open marine
6	AK4M133.5	limestone	▩		Yᗰ★	⚱≈♁ℓ●⊙⊖	⊛	open marine
6	AK4M133	limestone	■			Yℓ	≈★	lagoon
6	AK4M132.5	limestone	▩	⊙	⧗	ℬ≈★		shoal
6	AK4M132	limestone	▩	⊙	⧗	Y♁●	♁≈Y	shoal
6	AK4M131.5	limestone	▚		ℓ	♁✇	ᗰY⊖★	lagoon
6	AK4M131	limestone	▩	⊙	⧗	♁≈●	YYᗩ★	shoal
6	AK4M130.5	limestone	▩	⊙		⊖♁⧗⊛		shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
6	AK4M130	limestone		⊙		⅄Y⧖	⅃⦶	shoal
6	AK4M130	limestone			⌂⊖•	Y≈★⌘	⍳⅃⚘	lagoon
6	AK4M129.5	limestone			⚘⊖•	≈⅃⌂⊙⌘Y	★⅄⧖⍳	lagoon-above wave base
6	AK4M129	limestone			⊖•	⚘Q⌂≈★⌘Y	⅃⦶	lagoon
6	AK4M128.5	limestone			•	≈Q⌂Y⊖⍟⍳	★⚘⧖⊙	lagoon
6	AK4M128	limestone		•	⍳	Q≈Y	⚘	lagoon
6	AK4M127.5	limestone				⚘	⍳⧖	open marine
6	AK4M127	limestone			⍳Q•⍟	⚒	≈★	open marine
6	AK4M126.5	limestone			•	YQ⌂⍳★⌘	⚘⍟	open marine
6	AK4M126	limestone			Y⚘★⌘	⊖⊙•	⅃	open marine
6	AK4M125.5	limestone			Y⌘★	⅄⍳≈⍝⦶	⚘⌂⧖⊖	open marine
6	AK4M124.5	limestone		⊙		⧖	Y⅄★⌘	shoal
6	AK4M124	limestone			⌘Y⊖★	Q⅄⌂≈⧖•⊙	⚘	shoal
6	AK4M123.5	limestone			Y⌘★	≈Q•⦶		open marine
6	AK4M123	limestone			Y⌘★	⅄⌂Q⊙⍝	≈⚘•⍝	open marine
6	AK4M122.5	limestone		⊙		⚘⅄Y★⌘		lagoonal
6	AK4M122	limestone		⊙	⊖	⌘Y⚘⊛⍝★		shoal
6	AK4M121.5	limestone			⚘≈•	⌂Y⌘		lagoonal
6	AK4M121	limestone			≈⌂Y•⌘	★⚘⊖⧖⊙	⅄	lagoonal
6	AK4M120.5	limestone			Y≈⚘•★⌘	⌂	Q⦶	lagoonal
6	AK4M120	limestone		⊙	≈⊖	⚘⅃⌂Y⧖•⌘		shoal
6	AK4M119.5	limestone		⊙	⌂⊖•	⚘≈⅄⅃★⧖Y⌘		shoal
6	AK4M119	limestone			⚘⌂≈•⊖	⌘Y⊙★	⦶	lagoonal
6	AK4M118.5	limestone			⌘Y⚘•⊖★	⅃≈⊙		shoal
6	AK4M118	limestone		⊙	•	⅃⚘⧖	⅄	shoal
6	AK4M117.5	limestone		⊖	⊙			shoal
6	AK4M117	limestone		⊙	⊖			shoal
6	AK4M116.5	limestone		⊙	⌂	⚘⅃Y★⌘		shoal
6	AK4M116	limestone			Y≈⅄⊛★⌘	⚘⌂⧖⊙	⍝•	open marine
6	AK4M115.5	limestone			Y⌘★	⊙		open marine
6	AK4M115	limestone			⌘Y⌂•⊙★	⚘⅄⧖≈	⦶⍝	shoal
6	AK4M114.5	sandstone						beach
6	AK4M114	limestone		⊖	⌂•	≈⚘⍳Y⊙★⌘	⅃	shoal
6	AK4M113.5	limestone			Y⌘★	≈⌂⍝•⊙	⅃Q⅄⧖⍝⚘	open marine
6	AK4M113	limestone		⊖	⌂•	Y≈⌘⊙★	⅃	shoal
6	AK4M112.5	limestone		⊖	⌂•	≈⚘⅃Y⊙★⌘		shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
6	AK4M112	limestone			⊖♢•⊙	≈♣Y★ᗩY	ß⧗	shoal
6	AK4M111.5	limestone		⊙	⊖•	♣≈♢ß★⧗ YᗩY		shoal
6	AK4M110.5	limestone		⊖	•	ß♢⊙≈		shoal
6	AK4M110	limestone		⊖	♢•	Y≈ᗩ⊙★		shoal
6	AK4M109.5	limestone			♢⊖	≈YYßᗩ• ⧗★⊙		shoal
6	AK4M109	limestone			♢⊖•	Y≈★ᗩ		shoal
6	AK4M108.5	limestone			♢≈•	ᗩ♣⊖★		lagoonal
6	AK4M108	limestone			♢⊖•	≈♣ϒY⧗★ ᗩ		shoal
6	AK4M107.5	dolostone			★	⊍YᗩY		open marine
6	AK4M107	limestone			♢⊖•	ᗩY♣⧗⊙★	YQ⊍	shoal
6	AK4M106.5			•	♢⊖	≈♣Y★ᗩ		lagoonal
6	AK4M106	limestone		⊖	♢•	≈♣Y★ᗩ		shoal
6	AK4M105.5	limestone			★⊖•	♣ß≈ᗩY	Q	lagoonal
6	AK4M105	limestone			♢•	⊍≈♣⊖ᗩY		lagoonal
6	AK4M104.5	limestone			♢⊖•	≈♣ᗩY		shoal
6	AK4M104	limestone			Yᗩ★	Y♢ß⧗≈	ϒ⊍	open marine
6	AK4M103.5	limestone		⊖	Y♢ᗩ• ★	♣≈⊙	⊍	shoal
6	AK4M103	limestone			Y≈Q• ★ᗩ	♣⊖		lagoonal
6	AK4M102.5	dolostone				Qϒ★≈		lagoonal
6	AK4M102	limestone			Y≈ᗩ• ⊖	Q♣♢Y⊙⧗ ⊍★	ᗩ	shoal
6	AK4M101.5	limestone			≈♢Y• ᗩ	★♣⊛⊖		lagoonal
6	AK4M101	limestone			♢≈•	♣QY★ᗩ		lagoonal
6	AK4M100.5	limestone			≈•	♣Q♢★ᗩY		lagoonal
6	AK4M100	limestone			≈♣•Y	♢Q⊛		lagoonal
6	AK4M99.5	limestone			Q♢♣• ≈	Yᗩ★	⊍	lagoonal
6	AK4M99	limestone			≈Y•	Q♢♣⊖⊍		lagoonal
6	AK4M98.5	limestone			Q≈•	Y♣★ᗩ		lagoonal
6	AK4M98	limestone			Y≈★ᗩ	♣ß•⊍	Q	open marine
6	AK4M97	limestone			YYᗩᗩ ★	ß♢♣•⊍		open marine
6	AK4M96.5	limestone			≈YY★ ᗩ	ß♢⊍⧗ᗩ		open marine
6	AK4M95.5	limestone			YQ★ᗩ	ßYϒ♣⧗•≈		open marine
6	AK4M94	limestone			≈Q•ᗩ	♣		lagoonal
6	AK4M93.5	limestone			♣Q•≈	Yᗩ		lagoonal
6	AK4M92	limestone			≈QY• ᗩ	♣		lagoonal
6	AK4M88.5	limestone		★	Yᗩ	♣≈♢Q⊍• ⧗⊙		open marine
6	AK4M88	limestone		⊙	⊖	♣≈ß♢Y⊍ ᗩ★Yᗩ		shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
6	AK4M87.5	limestone		⊙	Y♣⧗	Y≈♢⚠★ ⚠		shoal
6	AK4M87	limestone		⊙	♢★⊖	♣ß Y≈⧗⚠ Y		shoal
6	AK4M86.5	limestone			♣ß♀⧗ ⊙⊖	Y♢Y★⚠		shoal
6	AK4M86	limestone		⊙	≈★⊖	Yß⧗	QY	shoal
6	AK4M85.5			≈	♣Q•★			lagoonal
6	AK4M85	limestone		•	♣QY≈ ⧗⊖★			lagoonal
6	AK4M84.5	limestone		Y	YQ★	≈♣♢⧗⊙ ⚠		open marine
6	AK4M84	limestone		•	Q♣≈			lower intertidal
6	AK4M83.5	limestone		≈	♣⊖•	Q		lower intertidal
6	AK4M83	limestone		•	Q≈⊖	♣		lagoon to lower intertidal
6	AK4M82.5	limestone		Y⚠	≈♣Y⊖ ⚠★	♢⊛⧗		open marine
6	AK4M76.5	limestone		Y⚠	⊖★•⊙	Y♀♢Q⧗≈ ß	⚠⊛	shoal
6	AK4M75.5	limestone		⊖	♣♀≈•★	Y♢⊙Q		shoal
6	AK4M74.5	limestone		Y⚠	★	≈♣•⊖		shoal
6	AK4M73	limestone		Y⚠	★⊖	ßQ♀♣		open marine
6	AK4M71.5	limestone		Y⚠	★	Q≈♢Y♀• ⧗⚠⊖	♣	open marine
6	AK4M71	limestone			Y⚠★	♀QY⚠⊛⊙ ⊖	⚠•	open marine
6	AK4M70.5	limestone		⊖	★⊙•	Q♣≈		shoal
6	AK4M70	limestone		⊖	Y★	ßQ♢♣⧗⊙ ≈		shoal
6	AK4M69.5	limestone		Y	★Q•⊖	♀♀⊙	♣≈⚠	open marine
6	AK4M68.5	limestone			Y⚠★	Q	Y♣	open marine
6	AK4M68	limestone		Y⚠	Q★	♀Y•	≈♣⚠♀	open marine
6	AK4M67.5	limestone		Y⚠	★⚠	QY♣⧗≈	•	open marine
6	AK4M67	limestone			Y⚠	Y≈★	Q⚠⧗	open marine
6	AK4M66.5	limestone				⚠Y★⊙⊖		open marine
6	AK4M66	limestone			⚠Y•★	Q♀⊖	ßO⚒⧗⊙	open marine
6	AK4M65	limestone				YQ⚠⚒★		open marine
6	AK4M64.5	limestone			Y⚠★	YQ	♀≈⚠♂	open marine
6	AK4M64	limestone		Y⚠	★	≈Y⧗⚠	♀Q⚠	open marine
6	AK4M63.5	limestone		Y⚠	★	♢Y⚠	♀♂•	open marine
6	AK4M63	limestone			Y⚠	Q★✇	♣♂	open marine
6	AK4M62.5	limestone			Y⚠	Q⚠	⚠	open marine
6	AK4M60.5	limestone			Y⚠	Q★	Yß⚠	open marine
6	AK4M59	limestone		Y⚠	★	≈♣Y♀⊛⊙ ⚠	Q♀♢•⚠ß	open marine
6	AK4M58.5	limestone		Y⚠	★	Y♀	Q	open marine
6	AK4M58	limestone		Y⚠	★	YQ♀		open marine
6	AK4M55	limestone		Y⚠	★	YQ♀		open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
6	AK4M53.5	limestone		Y	★	Y≈	♣Q⊗A	open marine
6	AK4M53	limestone		Y	★	≈YØΣA	•	open marine
6	AK4M52.5	limestone		Y	★	YØΣ	≈	open marine
6	AK4M52	limestone				YQ★	ℓ	open marine
6	AK4M51.5	limestone		Y	★	YØA	Q≈ℓ	open marine
6	AK4M51	limestone		Y	★	YØA	Q♣≈	open marine
6	AK4M50.5	limestone		Y	★	Y≈	Ø♣	open marine
6	AK4M50	limestone		Y	★	♣YØ≈		open marine
6	AK4M49.5	limestone		Y	★	ØA		open marine
6	AK4M49	limestone		Y	★	QYA♣		open marine
6	AK4M48.5	limestone		Y	★	≈ØA	YQ	open marine
6	AK4M48	limestone		Y	★			open marine
6	AK4M47.5	limestone		Y	★			open marine
6	AK4M47	limestone		Y	★	A	YØ	open marine
6	AK4M46.5	limestone		Y	★	YA		open marine
6	AK4M46	limestone		Y	★	Yβ	♣≈Ø	open marine
6	AK4M45.5	limestone		Y	★	Q≈		open marine
6	AK4M45	limestone		Y	★	Q		open marine
6	AK4M44.5	dolostone				Y★		open marine
6	AK4M44	limestone		Y	★			open marine
6	AK4M43.5	limestone		Y	★	A		open marine
6	AK4M42.5	limestone		Y	★	βA	♣≈Ø	open marine
6	AK4M42	limestone		Y	★	≈♣AØ		open marine
6	AK4M41	limestone		Y	★	A		open marine
6	AK4M40.5	limestone		Y	★	Q		open marine
6	AK4M40	limestone		Y	★			open marine
6	AK4M39.5	limestone		Y	★			open marine
6	AK4M39	dolostone				Y★		open marine
6	AK4M37.5	limestone			QY	★		open marine
6	AK4M37	limestone		Y	★	β≈	♣ØA	open marine
6	AK4M36.5	limestone		Y	★	βYA≈	QØ	open marine
6	AK4M36	limestone		Y	★	Y≈	Q⊙	open marine
6	AK4M35.5	limestone		Y	★			open marine
6	AK4M35	limestone		Y	★	Y≈Σ		open marine
6	AK4M34.5	limestone		Y	★	Q≈Ø	Q⊙	open marine
6	AK4M34	limestone		Y	★	≈		open marine
6	AK4M33.5	limestone		Y	★			open marine
6	AK4M33	limestone		Y	★	β≈		open marine
6	AK4M32.5	limestone		Y	★	ℓ		open marine
6	AK4M32	limestone		Y	★	β≈A	Σ	open marine
6	AK4M31	limestone		Y	★	A		open marine
6	AK4M30.5	limestone		Y	★			open marine
6	AK4M30	limestone			Y★			open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
6	AK4M29.5	limestone			Y ★	Y		open marine
6	AK4M29	limestone			Y ★		B	open marine
6	AK4M28.5	limestone			Y ★	Y Q A		open marine
6	AK4M28	limestone			Y ★			open marine
6	AK4M27.5	limestone			Y ★	A		open marine
6	AK4M27	limestone			Y ★			open marine
6	AK4M26.5	dolostone			Y ★	Q		open marine
6	AK4M26	dolostone					Y ★	open marine
6	AK4M25	dolostone				★		open marine
6	AK4M24.5	limestone			Y ★			open marine
6	AK4M24	dolostone			Y ★	Q		open marine
6	AK4M23.5	limestone			Y ★			open marine
6	AK4M23	limestone		Y	★			open marine shoal
6	AK4M22.5	dolostone			Y ★	Q	O	open marine
6	AK4M22	dolostone				Y ★		open marine
6	AK4M21.5	dolostone				Y ★		open marine
6	AK4M21	dolostone				Y ★		open marine
6	AK4M20.5	dolostone			Y ★			open marine
6	AK4M20	dolostone			Y ★	A		open marine
6	AK4M19.5	limestone			Y ★	A		open marine
6	AK4M19	dolostone				Y ★		open marine
6	AK4M18	dolostone				Y ★		open marine
6	AK4M17	limestone			Y ★	⚒		open marine
6	AK4M16	limestone			Y ★	Y A Q	O O	open marine
6	AK4M15.3	limestone				Q Y	★	intertidal
6	AK4M15	limestone			≈ Y Q			intertidal
6	AK4M14.5				Y ★	Q		open marine
6	AK4M13.8	limestone			Y ★	Q		open marine
6	AK4M13.5	limestone			Y ★	Q		open marine
6	AK4M13	dolostone		A	Y ★			open marine
6	AK4M12.5	limestone		≈	•			intertidal
6	AK4M12	limestone		≈	•			intertidal
6	AK4M11.5	limestone		≈				intertidal
6	AK4M11	limestone			≈ Y •	♣		intertidal
6	AK4M10.5	limestone			≈ Y			intertidal
6	AK4M10	limestone		≈				intertidal
6	AK4M9	limestone		≈	Y	♣		intertidal
6	AK4M8	limestone		≈	✇	♣		intertidal
6	AK4M7.5	limestone		≈				intertidal
6	AK4M7	limestone		≈		Y ✇	♣	intertidal
6	AK4M6.5	limestone		≈	•			intertidal
6	AK4M6	OTHER		≈	•	Y Q ★		intertidal
8.1	AK22M264.52	limestone			⚒			restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
8.1	AK22M264.52	limestone		•	⚒	★		restricted platform
8.1	AK22M264.51	limestone			◎◎≈• ⚒	Y♣	Q	restricted to open platform
8.1	AK22M263.5	limestone		•		⚒		restricted platform
8.1	AK22M262.5	limestone			◎•	Y★⧗⊖	♣	open platform
8.1	AK22M261.5	limestone			◎⚒•	Y★		restricted to open platform
8.1	AK22M260.5	limestone		Y	★	◎Y◎⊖⧗	≈Q⊙	open platform - moderate energy
8.1	AK22M260.5	limestone		Y	★		⧗	open marine shelf
8.1	AK22M259.4	limestone			Y◎★⧗ •	⊖	Q♣≈	open platform
8.1	AK22M258.3	limestone		◎		Y★⧗•		open platform
8.1	AK22M258	limestone			⚒•		Q	restricted platform
8.1	AK22M257	limestone		•	⚒		Q Y★	restricted platform
8.1	AK22M256	limestone		•	⚒	♣	Q⧗	restricted platform
8.1	AK22M254	limestone			◎Y★	♣⧗⧗•	⊙	open platform
8.1	AK22M253	dolomitic limestone					Q Y★	intertidal to restricted
8.1	AK22M251.7	limestone			•	Y♣⧗ ★	Q	tidal channel
8.1	AK22M251	limestone			Y◎⧗★	Y≈•		open platform
8.1	AK22M250	limestone			◎•	⧗		open platform
8.1	AK22M249	limestone		•	Q	★♣⚒	⊙	restricted to open platform
8.1	AK22M248.2	limestone			Y★	Y≈⧗		open platform behind shoal
8.1	AK22M247	limestone		Y	★			open marine - high energy
8.1	AK22M246	limestone		Y	★	Y	◎◎≈	open platform / marine
8.1	AK22M245	limestone			♣•	◎QY★		tidal channel to open platform
8.1	AK22M244	limestone			≈◎◎ Y	Y★⧗		open platform
8.1	AK22M243	limestone			Y★	Q		open platform
8.1	AK22M242	limestone		◎	•		Q	open platform
8.1	AK22M241	limestone			◎	Y•⊖★	Q	open platform
8.1	AK22M240	limestone			Y★		≈	open marine
8.1	AK22M239	limestone			◎⊙	♣Y•★		shoal to near shoal
8.1	AK22M238.5	dolomitic limestone				Q★Y		open to restricted platform
8.1	AK22M237.01	limestone			♣◎⊖• ⊙	Y★		shoal to near shoal
8.1	AK22M237	limestone			⊗•	♣Y⊙		open platform
8.1	AK22M236	limestone			≈◎•Y	♣⧗⧗★		open platform
8.1	AK22M235	limestone		Y	★	≈♣		open marine-above wave base
8.1	AK22M235	limestone		Y	★	◎◎≈ ♣	Q⊙	open / restricted platform
8.1	AK22M234	limestone		•		Q⊖	♣	restricted to open platform
8.1	AK22M232	limestone		•		Y Q⧗⚒	♣	restricted to open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
8.1	AK22M231	limestone				Y		open marine - high energy
8.1	AK22M230.5	limestone		Y				open marine - low energy
8.1	AK22M230	limestone				Y		open platform/shoal/tidal channel
8.1	AK22M228	limestone		Y				open marine - high energy
8.1	AK22M227.6	limestone						shoal
8.1	AK22M226	limestone		Y				open marine - high energy
8.1	AK22M225	limestone				Y		open platform to shoal
8.1	AK22M224	limestone						open platform to tidal
8.1	AK22M223	limestone			Y			restricted platform
8.1	AK22M222.5	limestone						shoal to open platform
8.1	AK22M222	limestone				Y		tidal channel
8.1	AK22M220.5	dolomitic limestone						open marine - low energy
8.1	AK22M218.7	limestone						open platform near shoal
8.1	AK22M216	limestone			Y			open platform
8.1	AK22M215	limestone				Y		open / restricted platform
8.1	AK22M213	limestone					Y	open platform to patch reef
8.1	AK22M211.7	limestone				Y		shoal to open platform
8.1	AK22M210	limestone		Y	Y			open marine near shoal
8.1	AK22M208.3	limestone				Y		open platform
8.1	AK22M206	limestone						open platform
8.1	AK22M201.5	limestone				Y		shoal
8.1	AK22M200.5	limestone		Y				open marine near shoal
8.1	AK22M199.1	dolomitic limestone						open platform
8.1	AK22M198	limestone						shoal to open platform
8.1	AK22M196	dolomitic limestone				Y		restricted platform
8.1	AK22M195.7	limestone				Y		shoal
8.1	AK22M194.75	limestone				Y	Y	open platform
8.1	AK22M194.5	limestone				Y		open platform
8.1	AK22M194	limestone				Y		shoal to open platform
8.1	AK22M193.65	limestone				Y		restricted platform
8.1	AK22M193	dolomitic limestone				Y		open platform
8.1	AK22M192	limestone						shoal to open platform
8.1	AK22M191.5	limestone						shoal
8.1	AK22M190.05	limestone						open platform
8.1	AK22M190	limestone		Y				open platform / marine mod energy
8.1	AK22M187.6	dolomitic limestone						restricted to open platform
8.1	AK22M186	limestone				Y		shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
8.1	AK22M185	limestone		≈	⊖	♣	Y★	open platform to shoal
8.1	AK22M184.02	limestone		≈	⊖	♣	⊕Y⊕⧗⊛•	open platform to shoal
8.1	AK22M184.01	limestone		⊙	•	⊛		shoal
8.1	AK22M183	limestone		⊙		≈⊖	★⊕Y⊕⊛⧗	shoal to open platform
8.1	AK22M182.02	dolomitic limestone		⊙		◎•	⊕★	shoal
8.1	AK22M182.01	limestone		⊙	•	⊛	≈	shoal
8.1	AK22M181	limestone			Y★	⊕Q⧗⧗⊙	♣	open platform to shoal
8.1	AK22M180.52	limestone		⊗⊗		★Y	⊕	patch reef/open platform
8.1	AK22M180.51	limestone		⊗⊗				patch reef
8.1	AK22M180	limestone			≈♣•Y⊕	★◎⊙⧗⊖	Q⊕	open platform/channel/near shoal
8.1	AK22M179	limestone			⊙	⊕◎⧗•	♣⊛	shoal
8.1	AK22M177.8	limestone			⊖•⊖	♣≈Y⊙⧗⊕Y		open platform
8.1	AK22M177	limestone			≈◎⧗⊙	♣⊕Y◎⊖•⊛★	QY⊕	open platform to shoal
8.1	AK22M176.2	dolomitic limestone				Q◎		intertidal to restricted
8.1	AK22M176	limestone		⊙		≈Y◎♣•⧗⊖	⊖⊕⊛	shoal
8.1	AK22M174.02	limestone		◎◎	⊙	•⊛	≈⊖⧗⊖	open platform to shoal
8.1	AK22M174.01	limestone		⊙	◎	•	⊕⊖⧗⊛⊖	shoal
8.1	AK22M172.02	limestone			≈⊖	Y⊕⊕♣★•⧗⊙⊕	Y◎	open platform to shoal
8.1	AK22M172.01	limestone		⊙		•	♣Y⊛	shoal
8.1	AK22M170.85	limestone			Y	⊕Q•⊕	≈⊕⊙	open platform
8.1	AK22M169.9	limestone			≈Q⊕⧗⧗Y	♣★Y⊖•⊕	⊕⊙	open platform
8.1	AK22M168	limestone			Y	QY⊕	⊕	open marine - low energy
8.1	AK22M166	limestone		Y	⊕	♣≈⊕Y•⧗⊙		open platform
8.1	AK22M165	calcareous dolostone			Y★	⊕Q•⊕	⊕⧗⊙	open marine - low energy
8.1	AK22M164	dolomitic limestone					⊕⊙	intertidal
8.1	AK22M162	limestone		⊙	•	⊛	≈	shoal
8.1	AK22M160	limestone			⊖⊙•	♣≈◎⊕Y⊕⧗⧗Y⊕	⊛	shoal / near platform
8.1	AK22M157	limestone		Y	⊕	⊕≈⊕⧗•	Q♣	open marine - high energy
8.1	AK22M156	limestone			Y	⊕≈Y⧗⊙	⊕	open platform
8.1	AK22M155	dolostone					★	open marine - low energy
8.1	AK22M154	dolomitic limestone			Y★	⊕	Q	open marine-mod/high energy
8.1	AK22M153.8	dolomitic limestone				Y★		open marine - low energy

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
8.1	AK22M152	limestone						open marine-mod/high energy
8.1	AK22M150	limestone						shoal to open platform
8.1	AK22M149	limestone						shale to open platform
8.1	AK22M147	dolomitic limestone						restricted platform
8.1	AK22M145	calcareous dolostone						open platform / marine - low energy
8.1	AK22M144.8	dolomitic limestone						open marine - low energy
8.1	AK22M143	dolomitic limestone						open marine - high energy
8.1	AK22M141.75	limestone						open platform
8.1	AK22M141	dolomitic limestone						restricted platform
8.1	AK22M140	limestone						open platform
8.1	AK22M138	dolomitic limestone						intertidal to restricted
8.1	AK22M136.5	limestone						open marine/platform/near shoal
8.1	AK22M131	limestone						open platform
8.1	AK22M130	limestone						open platform
8.1	AK22M128	limestone						open platform
8.1	AK22M126	limestone						tidal channel
8.1	AK22M125	limestone						open platform/near shoal/channel
8.1	AK22M124	limestone						open platform
8.1	AK22M122	limestone						open platform
8.1	AK22M121	limestone						open platform/marine/near shoal
8.1	AK22M116	limestone						open platform/marine/channel
8.1	AK22M114	limestone						open platform
8.1	AK22M112	limestone						open platform - near shoal to
8.1	AK22M111.5	limestone						open platform
8.1	AK22M111	dolomitic limestone						restricted platform
8.1	AK22M110	cherty limestone						open platform near shoal/hi energy
8.1	AK22M108	limestone						open platform
8.1	AK22M106	limestone						tidal channel
8.1	AK22M105	limestone						open marine/channel/near shoal
8.1	AK22M104	limestone						open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
8.1	AK22M103	limestone						near shoal
8.1	AK22M101.95	dolomitic limestone						open marine - low energy
8.1	AK22M100	limestone						shoal to tidal channel?
8.1	AK22M99	limestone						shoal
8.1	AK22M98	limestone						open platform to near shoal/channel
8.1	AK22M97.8	limestone						tidal channel
8.1	AK22M96	dolomitic limestone						restricted platform
8.1	AK22M94	limestone						open marine/near shoal/channel
8.1	AK22M93	limestone						tidal channel?
8.1	AK22M92.6	shale						open marine
8.1	AK22M92	dolomitic limestone						open to restricted platform
8.1	AK22M91	dolomitic limestone						open platform
8.1	AK22M90	limestone						restricted to open platform
8.1	AK22M88.9	dolomitic limestone						restricted platform
8.1	AK22M88	limestone						open marine
8.1	AK22M88	limestone						open platform to tidal
8.1	AK22M87	limestone						open platform-mod energy
8.1	AK22M86	dolomitic limestone						open platform
8.1	AK22M85	dolomitic limestone						open to restricted platform
8.1	AK22M83.8	limestone						restricted platform
8.1	AK22M83							intertidal to restricted
8.1	AK22M79.8	dolostone						intertidal to restricted
8.1	AK22M79.75	cherty limestone						open platform
8.1	AK22M79.7	cherty limestone						open platform
8.1	AK22M79.5	limestone						restricted to open platform
8.1	AK22M79	limestone						open platform
8.1	AK22M78	limestone						restricted platform
8.1	AK22M77	dolomitic limestone						open platform to restricted
8.1	AK22M73	dolomitic limestone						open marine - low energy
8.1	AK22M72	dolomitic limestone						open marine - low energy
8.1	AK22M70	limestone						open platform
8.1	AK22M69	limestone						open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
8.1	AK22M68	limestone		Y		Q		open and near restricted platform
8.1	AK22M67	limestone				Q Y		shoal
8.1	AK22M66	limestone				Y		shoal
8.1	AK22M65	limestone		Y	Y		Q	open platform
8.1	AK22M64	limestone		Y	Y	Q		open marine - low energy
8.1	AK22M63	limestone		Y			Q Y	open platform
8.1	AK22M62	limestone		Y			Y	open platform
8.1	AK22M61	limestone				Q		open platform
8.1	AK22M60	limestone		Y	Y			open platform to tidal
8.1	AK22M59	limestone			Y		Q	open to restricted platform
8.1	AK22M58	limestone				Y	Q Y	restricted to open platform
8.1	AK22M57	limestone		Y				open marine-mod/high energy
8.1	AK22M56	limestone		Y	Y	Q		open marine - low energy
8.1	AK22M54	limestone		Y		Y		open marine-mod/high energy
8.1	AK22M53.5	limestone, chert		Y				open marine - mod energy
8.1	AK22M52	limestone				Y Q		restricted to open platform
8.1	AK22M51	limestone		Y		Y		open platform
8.1	AK22M50	limestone		Y				open platform/marine/mod-hi energy
8.1	AK22M48	limestone		Y		Q		open marine-mod/high energy
8.1	AK22M46	limestone		Y		Y		open marine-mod/high energy
8.1	AK22M45	limestone		Y				open marine
8.1	AK22M45	limestone		Y			Q	open platform/marine/mod-hi energy
8.1	AK22M44	limestone			Y			open marine - low energy
8.1	AK22M42	limestone		Y		Q Y		open marine - low energy
8.1	AK22M40	limestone			Y			open platform / marine / mod energy
8.1	AK22M38	limestone			Y	Y		open marine-mod/high energy
8.1	AK22M36	limestone		Y		Y	Q	open marine-mod/high energy
8.1	AK22M35	limestone			Y		Q	open platform / marine / mod energy
8.1	AK22M34	limestone		Y		Y	Q	open marine-mod/high energy
8.1	AK22M32	limestone		Y	Y		Q	open marine-mod/high energy

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
8.1	AK22M30	limestone		Y			•	open platform / marine / mod energy
8.1	AK22M28.3	limestone			•	Q		open marine-mod/high energy
8.1	AK22M25	limestone		Y	★		Q	open marine
8.1	AK22M25	limestone		Y	★	Q		open platform / marine / mod energy
8.1	AK22M24.1	limestone		Y•			Q	open marine - low energy
8.1	AK22M22.6	limestone				Y	Q	open marine - low energy
8.1	AK22M22.1	limestone				•	Q	open marine - low energy
8.1	AK22M20.5	limestone		Y•		Q		open marine - low energy
8.1	AK22M20.1	limestone		★	Y	•		open marine - low energy
8.1	AK22M18	limestone		Y	•	★Q		open marine-mod/high energy
8.1	AK22M16.2	limestone		Y		Q★•		open platform / marine /high energy
8.1	AK22M13.7	limestone		Y				open marine-mod/high energy
8.1	AK22M10	limestone		Y	★	•	Q	open / near restricted platform
8.1	AK22M9.7	dolomitic limestone					Q	restricted platform
8.1	AK22M9	limestone		Y	★	•	Q	open / near restricted platform
8.1	AK22M8.9	dolostone				Q•		restricted
8.1	AK22M3.4	limestone		Y		★	Q	open platform / low energy
8.1	AK22M1.6	limestone			Y	Q		open marine - low energy
8.1	AK22M1.2	dolostone						restricted
10.1	AK10M128.5	sandstone		Q				
10.1	AK10M128	limestone			Y★	•	Q	open platform
10.1	AK10M127.5	limestone			Y★	•	Q	open platform
10.1	AK10M127	limestone		⊙		★Y		shoal
10.1	AK10M126.5	limestone			Y★			open marine
10.1	AK10M126	limestone		⊙			★	shoal
10.1	AK10M125.5	limestone		⊙			★	shoal
10.1	AK10M125	limestone		⊙				shoal
10.1	AK10M124.5	limestone				★Y•		open platform
10.1	AK10M124	limestone				★Y		open platform
10.1	AK10M123.5	limestone		⊙		★Y		shoal
10.1	AK10M123	limestone			Y★			open platform
10.1	AK10M122.5	limestone			Y★			open platform
10.1	AK10M122	limestone			⊙		Y★	shoal
10.1	AK10M121.5	limestone, OTHER				★		open platform
10.1	AK10M121	limestone			Y★			open platform
10.1	AK10M120.5	limestone			Y★			open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.1	AK10M120	limestone		⊙		★Y⊖⧸Q	⌂♣⚲	shoal
10.1	AK10M119.5	limestone, OTHER			♣⧸⊙	≈⚲⌂⧸⊖⧖Y★	⚲⚠	open platform
10.1	AK10M119	limestone			≈♣★⊙⊖	⧸⌂Y⧖⧸	⚙	shoal
10.1	AK10M118.5	limestone			Y★	⚲♣⚠⧖⊙	⚠	open platform
10.1	AK10M118	limestone		⊙		⊖⧖	♣Y★	shoal
10.1	AK10M117.5	limestone			♣⚙⧸	Y≈★•⚠		open platform
10.1	AK10M117	limestone		⧸	♣	★Y≈⚙⧖•⚠	⚠	open platform
10.1	AK10M116.5	limestone		⧸	♣	≈★•	⚲⚠⧖	open platform
10.1	AK10M116	limestone		⧸		Y≈♣•⚠★Q	⚲	open platform
10.1	AK10M115.7	limestone		⧸		Y♣★⚠⚲Q	≈⌂⚠⚲	open platform
10.1	AK10M115.5	limestone			Y★⊙	♣⧸≈⧖⧸	⌂⚠⚠	shoal
10.1	AK10M115	limestone, dolostone			Y★	♣⧸⚲⧖⧸⧸	⚠	open marine
10.1	AK10M114.5	limestone			Y★	≈⚲	♣⧸⚠	open marine
10.1	AK10M114	limestone		⊙		⊖⧖	⧸	shoal
10.1	AK10M113.5	limestone			Y★⧖	♣⧸≈⊙⧸	⚠⚲⚠⚲	open platform
10.1	AK10M113	limestone			Y≈⧖★	♣⧸⌂⚠•⊙⧸	Q⚠⚲	open platform
10.1	AK10M112.5	limestone			★Y⊙⊖	♣⧸⌂⧖⧸≈	⚲	shoal
10.1	AK10M112	limestone			Y★	♣⧸⧖⚲	≈⚠	open platform
10.1	AK10M111.5	limestone			≈Y★	⧸⌂⧖♣	⚠⚠	open platform
10.1	AK10M111	limestone		⊙		Y★⧖	⊛	shoal
10.1	AK10M110.5	limestone		⊙		⊖	≈♣Y⧖★	shoal
10.1	AK10M110	limestone		⧸	⊙	≈♣⧸⧖★Y	⚲Q⚠⚠	open platform
10.1	AK10M109.5	limestone			Y≈⊙★	⚲♣⧸⧖⊖⚠	⚠	shoal
10.1	AK10M109	limestone			★Y⊙⊖	♣≈⧖	Q⚲	shoal
10.1	AK10M108.5	limestone			Y★	♣⚲⧖	⧸	open marine
10.1	AK10M107.9	limestone			Y★	⚲⧸⧸	♣⚠	open marine
10.1	AK10M107.5	limestone			Y★		⧸⧸	open marine
10.1	AK10M107	limestone		⊙		⊖⧖	≈Y	shoal
10.1	AK10M106.5	limestone			⊙⧖	Y♣⊖★	⌂	shoal
10.1	AK10M106	limestone		⊙		♣Y⊖Q	⚲★⚠	shoal
10.1	AK10M105.5	limestone			Y★	⚲♣⚠⧖•	⧸Q⚠⧸⧸	open platform
10.1	AK10M105	limestone			⌂Y★	♣⧸⚲≈	⚠	open platform
10.1	AK10M104.5	limestone			Y★	⚲	♣⧸⚠⧖⚠	open platform
10.1	AK10M104	limestone		★	Y⊙⧖	♣⧸⌂⚠⚲≈	⚠	shoal
10.1	AK10M103.5	limestone			Y≈★⧖⊙	⧸⌂♣⚠⚲	⚠	shoal
10.1	AK10M103	limestone			Y≈★⧖⊙	♣⧸⚠⚲		shoal
10.1	AK10M102.5	limestone			Y≈⊙★	⚲♣⧸⧖⚠⚠	⌂	shoal
10.1	AK10M102	limestone			Y⧸⧸★	⚲	♣⚠	open marine
10.1	AK10M101.5	limestone			Y★	⚲⧸⧸	♣≈⚠	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.1	AK10M101	limestone			Y★	⚱⚒⚓	♣	open marine
10.1	AK10M100.52	limestone			Y★⊙	≈♣⚱⚒⚓Q		open marine
10.1	AK10M100.51	limestone, dolostone			Y★⊙	⚱⚒⧗	≈⚓	open marine
10.1	AK10M100	limestone			Y★	♂⚱⧗	♣⚒⚓	open marine
10.1	AK10M99.5	limestone, dolostone			Y⚒★	⚱⚒	♣	open marine
10.1	AK10M99.35	limestone, dolostone			Y★	⚱	Q⚒⚒	open marine
10.1	AK10M99	limestone			Y★	⚱	♣⚒⧗	open marine
10.1	AK10M98.5	limestone			•⧗	≈♣♢⊙★Y	⚱	shoal
10.1	AK10M98	limestone		⊙	⧗	⚱♣♢•★Y	⚒	shoal
10.1	AK10M97.5	limestone			⊙•⧗	≈♣♢♂★Y	⚱	shoal
10.1	AK10M97	limestone			⊙⧗	♣♢Y•★	≈⚱	shoal
10.1	AK10M96.5	limestone			⊙⧗	⚱♣♢•★Y		shoal
10.1	AK10M96	limestone			★Y⧗•	≈♣♂⚱⊙✇♂	♢Q⚒	open platform
10.1	AK10M95.5	limestone			★Y•⊙	♂♣✇⧗⚒	⚱	open platform
10.1	AK10M95	limestone			⊙•⧗	≈♣♢⊖★Y	♂✇	shoal
10.1	AK10M94.5	limestone			≈Y★	♣♢⚱⧗•	♂⚒✇	open marine
10.1	AK10M94	limestone			Y★	♣♂⚱⚓⚒	⚒⧗	open marine
10.1	AK10M93.5	limestone			Y★	♂⚱	♣♢⚒⚓	open marine
10.1	AK10M93	limestone			Y★	♣♂⚱⚒⚓	⚒⧗	open marine
10.1	AK10M92.5	limestone			Y★	⚱⚒⚒	♣⚓⧗	open marine
10.1	AK10M92	limestone			Y★	⚱♂⚒⚒	⧗	open marine
10.1	AK10M91.5	limestone, dolostone			Y⚒★	⚱	♣Q⚒⚓	open marine
10.1	AK10M91	limestone, dolostone			Y⚒★	⚱	⚓⚒	open marine
10.1	AK10M90.5	limestone			Y★	♣⚱⧗	≈⚒⚒	open marine
10.1	AK10M90	limestone			Y⚒★	⚱	Q	open marine
10.1	AK10M89.5	limestone			Y★	⚱	♣⚒⚒	open marine
10.1	AK10M89	limestone, dolostone			Y⚱⚒★	⚒	Q⚒	open marine
10.1	AK10M88.5	limestone, dolostone				⚒	Q	open marine
10.1	AK10M88.3	limestone			Y★	♣♂♢⧗•≈	⚓⚒⊙⚒	open marine
10.1	AK10M88	limestone			Y★	♣⚱⚒	⚓	open marine
10.1	AK10M87.5	limestone			Y★	⚱	♣⚒⚒	open marine
10.1	AK10M87	limestone			⊖⊙	♣≈♢♂★⧗ ⚱Y	♂⚒	shoal
10.1	AK10M86.5	limestone		⊙	⊖	♣≈♢♂★⧗ ⚱Y	♂	shoal
10.1	AK10M86	limestone			Y≈★⧗ ⊙	♣♂♢•⚒⚱		open platform
10.1	AK10M85.5	limestone			Y★	⚱≈⚓⧗⚒	⚒	open platform
10.1	AK10M85	limestone			Y★	♣⚱⧗	♂≈⚒	open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.1	AK10M84.5	limestone			★Y⊙⊖	♣ß≈⧗Ⓥ	Q✓Ⓐ	shoal
10.1	AK10M84	limestone			Y≈⊖★	♣ßⓈ⧗⊙Ⓥ	⅄Ⓐ	shoal
10.1	AK10M83.5	limestone			Y≈⊖★	Ⓥ♣ß⧗⊙Ⓐ	⅄	shoal
10.1	AK10M83	limestone			≈Y★	Ⓥ♣⅄⧗•	Ⓐ	open marine
10.1	AK10M82.5	limestone			Y★	Ⓥ⅄	ßⓀ	open marine
10.1	AK10M82	limestone			Y★	Ⓥ	⅄⅄Ⓐ	open marine
10.1	AK10M81.5	limestone			Y★	⅄Ⓥ	⅄Ⓐ	open marine
10.1	AK10M81	limestone			Y★⊙	Ⓥ♣ß⧗⊕ ⅄	Q⅄✓	open platform
10.1	AK10M80.5	limestone			Y★⊙	≈♣ß⧗⅄ ⅄Q	Ⓐ	shoal
10.1	AK10M80	limestone			Y★	♣ßⓈ⧗⅄	⅄≈Ⓐ✓	open marine
10.1	AK10M79.5	limestone			Y★	♣ßⓈ⧗⅄	≈✓	open marine
10.1	AK10M79	limestone			Y★	♣Ⓥ⧗	ß⅄⅄	open marine
10.1	AK10M78.5	limestone			Y★	⅄⅄	Ⓐ	open marine
10.1	AK10M78	limestone			Y★	⅄	Ⓥ≈ß⊙Ⓐ⅄	open marine
10.1	AK10M77.5	limestone		⊙		≈♢Ⓥ★Y	♣ß✓⅄	shoal
10.1	AK10M77	limestone			Y≈★⧗ ⊙	ß♣Ⓥ	♢	open platform
10.1	AK10M76.5	limestone			Y≈★⧗ ⊙	♣Ⓥ	⅄♢Ⓐ✓	open platform
10.1	AK10M76	limestone			Y≈★⧗ ⊙	ß♣Ⓥ	Q✓	open platform
10.1	AK10M75.5	limestone			Y≈⧗★	♣♢Ⓥ⊙✓		open platform
10.1	AK10M75	limestone			⊖⊙•	≈♣★Y	♢⅄	shoal
10.1	AK10M74.5	limestone			Y★	Ⓥ⧗	♣Ⓐ	open marine
10.1	AK10M74	limestone			Y⅄★	⅄Q	ßß⅄	open marine
10.1	AK10M73.5	limestone		⅄	★	⅄Y	Q⅄	open marine
10.1	AK10M72.5	limestone				⅄Q		open marine
10.1	AK10M72	limestone		⅄	Y	★⅄	♣♢✇Ⓥ	open marine
10.1	AK10M71.5	limestone			Y★		⅄⅄ßⓈ⧗⊙Ⓐ	open marine
10.1	AK10M71	limestone			Y⅄★	Q		open marine
10.1	AK10M70.5	limestone			Y★⊙	♣♢≈⧗Ⓥ	ßⒶ	open platform
10.1	AK10M69.5	limestone		⊙		Y≈⧗★	♢ßß	shoal
10.1	AK10M69	limestone		⊙		≈♣♢★YⒶ	✓	shoal
10.1	AK10M68	limestone			Y★⊙	ßß≈	✓⅄⧗✇	open platform
10.1	AK10M67.5	limestone		⊙	Y★	♣⊖⊕	ß≈⧗	shoal
10.1	AK10M67	limestone			Y⊙⊕	♣ß≈⧗★	♢	shoal
10.1	AK10M65.5	limestone			Y★	⅄Ⓥ	Ⓐ	open marine
10.1	AK10M65	limestone			★Y⧗⊖	≈♣♢•⊙Ⓥ	ß	shoal
10.1	AK10M64.5	limestone			★Y•⊖	♣ß♢≈⧗⊙ Ⓥ	⅄	shoal
10.1	AK10M64	limestone			★Y•⊖	≈ⒶⓈ♣⊙⧗ ⅄✓	⅄✇	shoal
10.1	AK10M63.5	limestone			★Y•⊖	≈♣♢⧗⊙Ⓥ	Qß✇	shoal
10.1	AK10M63	limestone		⊙	⊖	≈♢Y⧗★		shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.1	AK10M62.5	limestone		⊙	⊖	≈ᴑYΣ★	Q	shoal
10.1	AK10M62	limestone		⊙	⊖	Y≈ᴑΣ•★	⚘	shoal
10.1	AK10M61.5	limestone			⊖⊙	≈⚘ᴑ♣•Σ Y★	⍝	shoal
10.1	AK10M61	limestone			⊖⊙	≈⚘ᴑ♣•Σ Y★	⍰⍝	shoal
10.1	AK10M59.5	limestone			Y≈•★	⚘⍳ᴑ♣⊙Σ ⍟⊖	⍝	open marine
10.1	AK10M59	limestone			⍲★	⚘Y⍝	⍝	open marine
10.1	AK10M58	limestone				⚘Q	ᴑ★	open marine
10.1	AK10M57.5	limestone			Y★	♣⚘⊙	⍰ᴑ≈⍳⍝	open platform
10.1	AK10M57	limestone			≈⍰Y⊙ ★	♣ᴑΣ⚘		open platform
10.1	AK10M56.5	limestone			≈⍰Y⊙ ★	♣ᴑ⍝⚘		open platform
10.1	AK10M56	limestone			Y★⊙	♣≈ᴑ⍰⍟Σ ⚘⍝	⍳⍝	open platform
10.1	AK10M55.5	limestone			Y★⊙	♣⍰ᴑΣ⚘≈	⍝⍝	open platform
10.1	AK10M55	limestone			★YΣ⊙	⍰ᴑ♣⍝≈	⚘⍝	open platform
10.1	AK10M54.5	limestone			Y★	⚘♣⍳⍲	Q⍰⍝	open platform
10.1	AK10M54	limestone		⊖		≈⚘ᴑ♣⊙Σ Y★		shoal
10.1	AK10M53.5	limestone		⊖		≈⚘ᴑ♣⊙Σ Y★		shoal
10.1	AK10M53	limestone		⊖		≈⚘ᴑ♣⊙Σ Y★	Q	shoal
10.1	AK10M52	limestone			≈Y★	♣⍰⚘⍝⍝	⍳	open marine
10.1	AK10M51.5	limestone			Y★	≈♣⍰Σ⍝ ⚘	⍝	open marine
10.1	AK10M51	limestone			Y★	≈♣Σ⚘	ᴑ⍝⍝	open marine
10.1	AK10M50.5	limestone, chert			Y⍲★	⚘	Q	open marine
10.1	AK10M50	limestone			Y≈⊖★	♣ᴑΣ⚘	⍝⍝	shoal
10.1	AK10M49.5	limestone			Y★	⚘⍝	⍰⍳⍝	open marine
10.1	AK10M49	limestone			Y★	⚘	Q♣	open marine
10.1	AK10M48.5	limestone			Y★	⚘♣•⍝		open platform
10.1	AK10M48	limestone			Y★	≈♣⍰Σ⍝ ⚘	ᴑ	open platform
10.1	AK10M47.5	limestone			Y★	♣ᴑ⚘Σ•	≈⍰⍝⍝	open platform
10.1	AK10M47	limestone			⚘Y★	♣⍳•Q	⍝⍟	open platform
10.1	AK10M46.5	limestone			Y★	≈♣⍰⚘Σ⍳ ⍝	⍝	open platform
10.1	AK10M46	limestone			Y★	≈ᴑ⚘⍝⍲	Q♣Σ	open platform
10.1	AK10M45.5	limestone			Y★	⍝⍳	Q♣≈	open platform
10.1	AK10M44.5	limestone			Y★	♣⍰ᴑ⚘Σ⍝ ⍲	≈	open platform
10.1	AK10M44	limestone			Y≈•★	⚘♣ᴑ⍳Σ⊙ ⊖	Q⍰⍝	shoal
10.1	AK10M43.5	limestone			Y≈•★	⚘♣ᴑΣ⊖⍳ Q	⍰⍝	shoal
10.1	AK10M43	limestone			Y★	♣⍰≈•⚘	Q	open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.1	AK10M42.5	limestone			≈Y★	⊍♣♢⧗•⊙	Q𝓑	shoal
10.1	AK10M42	limestone			≈Y★	♣⊍♢𝓑•⧗𝓘⊙	Q	shoal
10.1	AK10M41.5	limestone			Y♢•★	≈♣⊍⧗⊙Q	𝓑✇	shoal
10.1	AK10M41	limestone			Y★•	♣♢⊍⊖Ⓐ Q	✇	shoal
10.1	AK10M40.5	limestone			Y★⊖	⊍♣♢⧗•⊙ Q	≈	shoal
10.1	AK10M40	limestone			★Y⧗• Q	≈♣⊙Ⓐ	𝓑Ⓐ	open platform
10.1	AK10M39.5	limestone			Y★	≈♣𝓑⊍⧗Ⓐ Ⓐ Q	𝓘⚒	restricted platform
10.1	AK10M39	limestone			⊍Y★	≈♣Ⓐ✇𝓘Q	Ⓐ	restricted platform
10.1	AK10M38.5	limestone			Y★𝓘	⊍♣𝓗•Ⓐ Q	♢✇	restricted platform
10.1	AK10M38	limestone			Y𝓗★	⊍≈♣Ⓐ𝓘Ⓐ	♢Q⊙	open platform
10.1	AK10M37.5	limestone			𝓗Y•★	⊍♣✇𝓘Q	≈Ⓐ	restricted platform
10.1	AK10M37	limestone			Y♣•★	Ⓐ⊍𝓘⧗✇Q	≈	open platform
10.1	AK10M36.5	limestone			Y★⧗	♣𝓑♢Ⓐ⊍≈	⊙	open platform
10.1	AK10M36	limestone			Y♣⊙★	𝓑♢≈⧗Ⓐ	Ⓐ✇	open platform
10.1	AK10M35.5	limestone			Y★	♣≈♢𝓑⊍• ⧗Ⓐ Ⓐ	Q✇	open platform
10.1	AK10M35	limestone			Y𝓗★	♣≈♢𝓑⊙⧗ ⊍✇Q	Ⓐ	open platform
10.1	AK10M34.5	limestone			Y★⊙	♣𝓑♢≈⧗ Ⓐ𝓗	✇	open platform
10.1	AK10M34	limestone			★Y•𝓘	♣⊍✇Q	𝓗	open platform
10.1	AK10M33.5	limestone			Y♣⊙★	𝓑♢≈⧗⊍	Ⓐ✇	open platform
10.1	AK10M33	limestone		⊙		Y♣★⧗⊖		shoal
10.1	AK10M32.5	limestone		⊙		Y⊍♣★⧗⊖ Ⓐ		shoal
10.1	AK10M32	limestone		⊙		★Y⧗⊖	♣≈	shoal
10.1	AK10M31.5	limestone		⊙		Y♢★⧗⊖	♣Ⓐ	shoal
10.1	AK10M31	limestone, chert			Y★			open platform
10.1	AK10M30.5	limestone			Y♣⧗★	≈𝓑⊍Ⓐ𝓘Q	♢✇	open platform
10.1	AK10M30	limestone			Y★	≈♣𝓑⊍⧗Ⓐ Ⓐ		open platform
10.1	AK10M29.5	limestone			Y𝓑⧗★	Ⓐ≈♣⊙Ⓐ𝓘	Q✇	lagoonal
10.1	AK10M29	chert			⚒	Q		restricted platform
10.1	AK10M28.5	limestone			★Y𝓘•⚒	♣⊍Ⓐ Q		restricted platform
10.1	AK10M28	limestone						restricted platform
10.1	AK10M27.5	chert				⚒		restricted platform
10.1	AK10M27	limestone				⚒	Q	restricted platform
10.1	AK10M26.5	limestone			Y★	≈♣♢⊍⧗Ⓐ 𝓘	𝓑Q✇Ⓐ	restricted platform
10.1	AK10M26	limestone			Y★𝓘	♣𝓑♢⊍⚒✇ Ⓐ	Q≈	open platform
10.1	AK10M25.5	limestone			Y★	⊍≈♣•Ⓐ𝓗 Q	♢Ⓐ	open platform
10.1	AK10M25	limestone			𝓗★⚒	YQ		restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.1	AK10M24.5	limestone			Y★	♣≈⚲Q	𝍸𝍝	open platform
10.1	AK10M24	limestone				𝍸Y⚒★	⚲	restricted platform
10.1	AK10M23.5	dolostone			Y𝍸	⚒		restricted platform
10.1	AK10M23	limestone			𝍸	⚲Y⚒	Q	deep
10.1	AK10M22.5	limestone			Y𝍸★	♣⚲𝍴Q		restricted platform
10.1	AK10M22	limestone			Y★	𝍸Q	𝍴	restricted platform
10.1	AK10M21.5	limestone			Y★⚒	𝍸		restricted platform
10.1	AK10M21	limestone			Y★	♣⚲𝍵Q	𝍰≈𝍝	open platform
10.1	AK10M20.5	limestone			Y★	♣⚲𝍴Q	𝍵	open platform
10.1	AK10M20	limestone			Y𝍸★	⚲⚒Q	♣	restricted platform
10.1	AK10M19.5	limestone			Y★	♣⚲⚒		open platform
10.1	AK10M19	chert			⚒	Y★Q		restricted platform
10.1	AK10M18.5	limestone			Y★⧗	≈♣⌂𝍝𝍵⚲Q	𝍰⊙	lagoonal
10.1	AK10M18	limestone			★Y•𝍵	Q♣⚲⊘𝍸		restricted platform
10.1	AK10M17.5	limestone			★Y•𝍵	Q♣⌂𝍴𝍸⚲	𝍰≈	restricted platform
10.1	AK10M17	limestone		⊙	Y★	♣𝍰⌂⧗𝍵⚲	Q⚒	open platform
10.1	AK10M16.5	limestone			★Y•𝍵	≈♣⚲⧗⊘	𝍴𝍝	restricted platform
10.1	AK10M16	limestone			Y≈•★	♣⚲⌂𝍰𝍝⧗𝍴𝍵Q	⊘	restricted platform
10.1	AK10M15.75	limestone			𝍸Y𝍵★	𝍰𝍴Q		restricted platform
10.1	AK10M15.5	limestone			Y⚲𝍴★	𝍰⌂𝍸𝍝𝍵	♣	open platform
10.1	AK10M15	limestone			Y⌂𝍴★	⚲𝍰𝍸⧗𝍝	Q♣	open platform
10.1	AK10M14.5	limestone			★Y•𝍵	⚲♣𝍴𝍸Q	𝍝	restricted platform
10.1	AK10M14	limestone			★Y•𝍵	♣⚲𝍸Q	𝍝⊘	restricted platform
10.1	AK10M13.5	limestone			★Y•𝍵	⚲𝍸𝍴	♣	restricted platform
10.1	AK10M13	limestone			𝍸Y•★	⚲≈♣⊘𝍵𝍴Q		restricted platform
10.1	AK10M12.5	limestone			⚲Y★	𝍵𝍴⧗𝍝Q	♣	open platform
10.1	AK10M12	limestone			★Y•𝍵	Q⚲𝍸	𝍴𝍝	restricted platform
10.1	AK10M11.5	limestone			Y≈𝍵★	♣𝍰⚲𝍝𝍸		open platform
10.1	AK10M11	limestone			★Y⧗•	≈♣⌂⚲𝍝𝍵𝍴	𝍰⊘	open platform
10.1	AK10M10	limestone			★Y⧗•	≈♣⚲𝍵𝍴	⌂𝍝⊙	open platform
10.1	AK10M9.5	limestone			★Y•𝍵	≈♣⚲⊘𝍸Q	𝍝	restricted platform
10.1	AK10M9	limestone			Y♣★⚒𝍵	⚲𝍸•	𝍰Q≈𝍝𝍴	restricted platform
10.1	AK10M8.5	limestone			𝍸★	YQ	⚲	restricted platform
10.1	AK10M8	limestone			Y★	≈⚲𝍸Q		restricted platform
10.1	AK10M7.5	limestone			𝍸★	⚲≈𝍴Y	Q♣𝍝	restricted platform
10.1	AK10M7	limestone			Y★	♣≈⚲Q	⌂𝍝	open platform
10.1	AK10M6.5	limestone			Y★	⚲♣𝍴𝍝𝍵Q	⌂𝍰	open platform
10.1	AK10M6	limestone			Y𝍸★	⚒Q		restricted platform
10.1	AK10M5	limestone			𝍸★	⚲♣𝍵YQ	⌂𝍝	restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.1	AK10M4.5	limestone			⊗Y★	⊗≈⊙⊼⧗ ⊛⊘	⊛	restricted platform
10.1	AK10M4	limestone			≈Y★	⊗⊛⊘⧗⊛Q	⊗	open platform
10.1	AK10M3.5	limestone			Y★•	Q⊗⊛⊘⊼	⊛	restricted platform
10.1	AK10M3	limestone			⊛Y•★	Q⊗⊘⊼	⊙	restricted platform
10.1	AK10M2.5	limestone			Y⊛★	⊗⊛Q	⊛⊼	restricted platform
10.1	AK10M2	limestone			Y★	≈⊗⊙⊗⧗⊛ ⊼	⊛	open platform
10.1	AK10M1.5	limestone			Y⊛⊘★	⊗⊼	Q⊙	restricted platform
10.1	AK10M1	limestone			Y★	≈⊗⧗⊼	⊗	open platform
10.1	AK10M0.5	limestone			Y★	⊗⊙⊼⧗⊛	⊗	open platform
10.1	AK10M0	limestone			Y★	⊗⊗⊛⊼Q	⧗	open platform
10.2	AK12M83	limestone			★Y•⊼	⊛⊘Q	⊛⊼⊙	restricted platform
10.2	AK12M81	limestone			Y⊛★	⊗⊘Q		open platform
10.2	AK12M79	limestone			★Y•⊘	Q≈⊛⊛⊼⊗		restricted platform
10.2	AK12M77.5	limestone, dolostone			⊛Y•★	Q⊼⊘	⊛⊗	restricted platform
10.2	AK12M77	limestone			⊗Y★	⊛⊛⊗⊛⊘⊼ Q	⊙	open platform
10.2	AK12M76	limestone			Y★	⊛⊗⊙⧗⊛⊗		open platform
10.2	AK12M74	limestone			⊗Y★	≈⊛⊙⊛⊼⊗		open platform
10.2	AK12M72	limestone			Y★	≈⊛⊗⧗⊼	Q⊗	open platform
10.2	AK12M70	limestone			Y★•	Q⊛⊗⊙⊘	≈⊛	restricted platform
10.2	AK12M69	limestone			⊗Y★	Q	⊛⊛	open platform
10.2	AK12M68	limestone		⊖		Y≈⊛★⧗• ⊙	⊗	shoal
10.2	AK12M66	limestone			Y★	⊗⊼⊘	≈⊗⊛	open marine
10.2	AK12M64	limestone			⊗⊛★	Y⊙⊼⊛⊘		open marine
10.2	AK12M62	limestone			⊛★	⊗Y⊼	≈	open marine
10.2	AK12M60	limestone		★	Y	⊗⊗⊼	⊛	open marine
10.2	AK12M58	limestone		★	Y	⊗⊼	⊛	open marine
10.2	AK12M56	limestone			Y⊛★	⊗⊼	⊗⊛	open marine
10.2	AK12M54	limestone			⊛Y⊼★	⊗⊘	⊛	open marine
10.2	AK12M50	limestone			⊛Y⊼★	⊛⊗⊼		open marine
10.2	AK12M46	limestone			Y⊛★	⊗	⊛	open marine
10.2	AK12M44	limestone			Y★	⊗⊛⊛⊛⊼		open marine
10.2	AK12M42	limestone		⊙		⊛≈⊙⊗⊛⊖ Y★		shoal
10.2	AK12M40	limestone, dolostone			Y★⊙	≈⊛⊗⊼⧗• ⊖	⊛	shoal
10.2	AK12M38	limestone		★	⊗Y	⊛⊼	≈	open marine
10.2	AK12M36	limestone			⊛Y⊼ ★	⊗⊘	⊛⊙	open marine
10.2	AK12M33	limestone, dolostone			Y⊛★	⊛⊗	Q	open marine
10.2	AK12M32	limestone			Y★	⊛⊗⊼	⊗⊘⧗	open marine
10.2	AK12M30	limestone			Y★	⊗⊛⊼⊛		open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.2	AK12M28	limestone			Y★	♣ß⚱⚔⚒		open marine
10.2	AK12M26	limestone			Y⚒★	♣⚱⚲	⚙⧗	open marine
10.2	AK12M24	limestone, dolostone			Y⚒★	⚱	♣	open marine
10.2	AK12M22	limestone			Y⚒★	♣	ß⚙	open marine
10.2	AK12M20	limestone			Y★	♣	⚔≈⧗⚙	open marine
10.2	AK12M16	limestone			Y★	⚔	♣⚱	open marine
10.2	AK12M14	limestone			Y★	⚔	♣ß⧗⚙	open marine
10.2	AK12M12	limestone			Y★	≈♣ß⚱⧗⊗⚔	⚙	open marine
10.2	AK12M8.5	limestone			★Y•⊖	≈⚱ß♣⚔⊙⧗⚲☮Q	⚙	shoal
10.2	AK12M6	limestone			Y≈⊖★	♣⚠⚔⧗⚲	ß	shoal
10.2	AK12M4.5	limestone			≈ß★Y	⚱♣⧗⚲	⚙	open platform
10.2	AK12M3	dolostone				⚒		restricted platform
10.3	AK11M389	limestone			♣Y★	⚱⚔	ß⚲	open platform
10.3	AK11M383	limestone, dolostone			⚒	★		restricted platform
10.3	AK11M380	limestone, OTHER				⚒Q		restricted platform
10.3	AK11M375	limestone, OTHER		⚒				restricted platform
10.3	AK11M374.5	limestone, OTHER			⚒	Q		restricted platform
10.3	AK11M351	OTHER			⚒	Q		restricted platform
10.3	AK11M345.5	OTHER			⚒			restricted platform
10.3	AK11M335	OTHER				⚒Q		restricted platform
10.3	AK11M325.5	limestone			★Y•⚲	♣Q		restricted platform
10.3	AK11M320	limestone			★•	⊗⊗⚒Q		restricted platform
10.3	AK11M315.5	limestone			⚱Y★	⚔⚲⚙Q		open platform
10.3	AK11M312	limestone		★	Y	⚱♣⚲⚔	ß⚙	open platform
10.3	AK11M297	limestone			Y★	⚱♣•⚲	☮	open platform
10.3	AK11M290	limestone			Y★	⚱⚲		open platform
10.3	AK11M285	limestone		★	Y	⚔ß⧗⚲	♣	open platform
10.3	AK11M279.5	limestone, OTHER			Y★⚒			open platform
10.3	AK11M274.5	limestone			Y★⧗	⚱		open platform
10.3	AK11M270	limestone			Y★	ß⚱⚒	♣⚔	open platform
10.3	AK11M264	limestone			Y★	⚱♣•⚲	≈☮	open platform
10.3	AK11M261	limestone			Y★	⚱≈⚲⚔	♣⚙	open platform
10.3	AK11M254.4	limestone			Y⚒★	⚱⚙	Q	open platform
10.3	AK11M250	limestone			Y★	⚒	≈	open platform
10.3	AK11M247.5	limestone			Y⚒★	♣⚱		open platform
10.3	AK11M241	limestone			Y⚒★	⚱⚲⚒		open platform
10.3	AK11M234.5	limestone			Y⚒★	⚱⚙	♣≈	open platform
10.3	AK11M229	limestone			Y★	⚱	♣	open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.3	AK11M223	limestone, OTHER			★			open platform
10.3	AK11M220.5	limestone			Y★•	≈♣⧗⦶	⊛	shoal
10.3	AK11M216.02	chert						
10.3	AK11M216	limestone			★Y•⊖	♣⦶⧗	◊	shoal
10.3	AK11M210	limestone			Y★	♣⦶⌘	⌓	open platform
10.3	AK11M205	limestone			≈♣⚷⦶ ⧗★Y		⌘⌓	open platform
10.3	AK11M200	limestone			⦶≈♣• ★Y	⌓		lagoonal
10.3	AK11M195	limestone			Y⦶◊★	♣≈⊛	⌓	lagoonal
10.3	AK11M190	limestone			★Y•⊖	◊♣⊛⧗⊙	⌂⦶	shoal
10.3	AK11M185	limestone			Y★•	⦶♣⊛◊		lagoonal
10.3	AK11M180.02	limestone, OTHER			Y★			lagoonal
10.3	AK11M180	limestone, OTHER			Y★			lagoonal
10.3	AK11M170	limestone, chert			Y★	⧗		shoal
10.3	AK11M166	limestone			Y★•	⦶♣◊⧗⊛	⌓	shoal
10.3	AK11M163	dolostone						intertidal
10.3	AK11M160.5	limestone			★Y•◊	⦶♣⧗⊛		lagoonal
10.3	AK11M157	limestone			★Y•◊	♣≈⦶	⌓	lagoonal
10.3	AK11M150	limestone			★Y•◊	≈♣⊛⦶		lagoonal
10.3	AK11M145.02	chert						
10.3	AK11M145	limestone			★Y•◊	♣		lagoonal
10.3	AK11M141	limestone			Y★	⦶◊		lagoonal
10.3	AK11M134	limestone			Y⌂★⊙ ⊖	♣≈⦶		shoal
10.3	AK11M131	limestone			Y★⊙	≈♣⦶•⊖	⌓	shoal
10.3	AK11M125	limestone			Y★⊖	≈♣⊙⦶	⌓	shoal
10.3	AK11M121.52	limestone, chert			◊•	♣⊛		lagoonal
10.3	AK11M121.5	limestone			★Y•◊	♣⊛		lagoonal
10.3	AK11M115	limestone			★Y•⊛	♣◊		lagoonal
10.3	AK11M110	limestone			Y★•	≈⦶◊	⊙	shoal
10.3	AK11M104	limestone			Y★•	⦶⊙		shoal
10.3	AK11M97	limestone			◊⚒	⌂★	⚷♣⦶	lagoonal
10.3	AK11M90	limestone			★Y•⊖	♣◊⊙	⊛	shoal
10.3	AK11M71.5	limestone			⌘★	◊⚒	♣	lagoonal
10.3	AK11M67.5	limestone			Y★•	◊♣⊙⊛	⌓	shoal
10.3	AK11M60	limestone			◊	★⊛	♣	lagoonal
10.3	AK11M55.7	limestone			Y★•	♣◊⊙	⌓⧗	shoal
10.3	AK11M50	limestone, dolostone			★◊⚒	♣Y		lagoonal
10.3	AK11M46.56	limestone			Y≈•★	◊♣⧗⌓		lagoonal
10.3	AK11M40.5	limestone			★Y•◊	♣⊛		lagoonal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
10.3	AK11M10	dolostone, OTHER						intertidal
10.3	AK11M6.5	limestone			≈★⚒	♣Y◐Q	⚒	lagoonal
10.3	AK11M5.7	limestone			Y★•	Q♣≈⊘◐	⚒	lagoonal
10.3	AK11M4.5	limestone			◐⚒•	⊘Q		lagoonal
10.3	AK11M0.5	OTHER			⚒			intertidal
10.3	AK11M0	dolostone				Q		intertidal
11.1	AK14M114.03	limestone			⊖⊙	♣⌂⧗★	◐	shoal
11.1	AK14M114	limestone			⊖⊙	♣⌂Y⧗★		shoal
11.1	AK14M113.5	limestone			⊖⊙	Y♣⧗★		shoal
11.1	AK14M113	limestone			♣⊖⊙	Y★⧗		shoal
11.1	AK14M112.5	limestone			⊖⊙	Y★⧗		shoal
11.1	AK14M112	limestone			⊖⊙	★⧗		shoal
11.1	AK14M111.5	limestone			⊖⊙	Y♣⧗★		shoal
11.1	AK14M111	limestone			≈⊖⊙	♣⌂Y⧗★	Q	shoal
11.1	AK14M109.5	limestone			⊖⊙⧗	≈♣⚷⚠★Y		shoal
11.1	AK14M108.5	limestone			★Y⧗⊙	♣⚷≈•⊖	⚒	lagoonal
11.1	AK14M108	limestone			⊖⊙	≈Y⌂♣•⧗★⚠		shoal
11.1	AK14M107.5	limestone			⊖⊙	Y≈♣★⧗•⚠		shoal
11.1	AK14M107	limestone			⊖⊙	★Y⚠⧗•	◐	shoal
11.1	AK14M106.5	limestone			⊖⊙	≈Y⌂♣•⧗★⚠	⚷	shoal
11.1	AK14M106	limestone			⊖⊙	≈Y⌂♣•⧗★⚠Q	⚒	shoal
11.1	AK14M105.5	limestone			⊖⊙	≈Y⌂♣•⧗★⚠	⚒	shoal
11.1	AK14M105	limestone			★Y⊙⊖	≈♣⌂⧗•⚠	⚘	shoal
11.1	AK14M104.5	limestone			★Y⊙⊖	≈♣⌂⧗•⚠		shoal
11.1	AK14M104	limestone			★Y⊙⊖	≈♣⌂⧗•⚠		shoal
11.1	AK14M103	limestone			Y⚒★	⚘	♣	open marine
11.1	AK14M102.5	limestone		⊙	⊖	Y♣⚠★		shoal
11.1	AK14M102.25	limestone			⊖⊙	≈♣⌂⧗★Y		shoal
11.1	AK14M101.5	limestone		⊙	⊖	Y♣⌂★⧗⊘⚠	≈	shoal
11.1	AK14M101	limestone		⊙		Y♣⌂★•⊖⚠	⚷	shoal
11.1	AK14M100	limestone			⊖⊙	♣★		shoal
11.1	AK14M99	limestone		⊙	Y★⧗	♣⌂•≈	⚷⚒⊘	shoal
11.1	AK14M98.5	limestone		⊙		≈♣⌂⧗★Y		shoal
11.1	AK14M98	limestone			Y⚒⊙	⚒⚘♣◐⚒★		open platform
11.1	AK14M97.5	limestone			⊖⊙	≈⌂Y⧗★Q	◐	shoal
11.1	AK14M96.5	limestone		⊙		Y≈★⧗•		shoal
11.1	AK14M96	limestone			Y★⊖	⚘≈•⊙Q	♣⚒⚒	shoal
11.1	AK14M95.5	limestone			Y★⧗	♣≈⚘	⚒	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.1	AK14M95	limestone			Y★	&BÔ◊•Λ ⌘	Ⓐ	open marine
11.1	AK14M94.5	limestone			Y★	&≈ÔBⓋ⧗ ◊Λ	ⒶⓅ	open marine
11.1	AK14M94	limestone			Y★	⌘◊⚒Λ	B	open marine
11.1	AK14M93	limestone			Y⌘★	◊Ⓐ	&Λ•	open marine
11.1	AK14M92.5	limestone			Y★	&BÔΛ⌘ ◊	ⒶQ•Ⓟ	open platform
11.1	AK14M92	limestone			Y★	Λ◊⊗⧗⊙	&BⓅⒶ	open platform
11.1	AK14M91.5	limestone		⊙	•	≈ÔY⊖★	B	shoal
11.1	AK14M91	limestone		⊙	•	YÔ⊖★	Q⧗	shoal
11.1	AK14M90.5	limestone			⊖⊙•	&ÔYⒷ★Q		shoal
11.1	AK14M90	OTHER		Q	•	&Ⓟ		restricted platform
11.1	AK14M89.5	limestone			⊗&•Ⓑ	★Y≈⧗ⓅⒷ	⊖	open platform
11.1	AK14M89	limestone			≈Y★	◊&B⧗•Λ	Ⓐ	open platform
11.1	AK14M88.5	limestone			Y★	Λ◊Ⓑ⧗•Q	BⒶ	open platform
11.1	AK14M88	limestone			Y★	◊Λ⧗Q	&ⒶⓅ	open platform
11.1	AK14M87.5	limestone			Y★	◊&⌘•ΛQ	BⒶ	open platform
11.1	AK14M87	limestone, dolostone			Y⌘★	◊	ΛQ•Ⓐ	open platform
11.1	AK14M83.5	limestone			★Y⧗⊙	BÔ&•≈Q	◊Ⓟ	lagoonal
11.1	AK14M83	limestone			≈Y★	◊&⧗ⒶQ	BⒷ	open marine
11.1	AK14M82.5	limestone			Y★	◊⌘	B&Ⓐ	open marine
11.1	AK14M82	limestone			Y★	⌘◊•Λ	BⒶ	open marine
11.1	AK14M81.5	limestone			⌘★⚒	Y		open marine
11.1	AK14M81	limestone			Y★	◊Ⓑ•	Λ⚒	open marine
11.1	AK14M80.5	limestone			≈Y★	◊⧗	Q⚒	open marine
11.1	AK14M80	limestone			Y≈⧗★	B&•	◊Ⓑ	open marine
11.1	AK14M79.5	limestone			Y≈⧗★	B&•	◊	open marine
11.1	AK14M79	limestone			Y★	◊⧗	B	open marine
11.1	AK14M78.5	limestone			Y⌘★	◊Q	&ΛⒶ	open marine
11.1	AK14M78	limestone, dolostone			Y⌘★	Q	◊ΛⒶ	open marine
11.1	AK14M77.65	limestone, shale			⌘★⚒	Y	Ⓐ	open marine
11.1	AK14M77.45	limestone			Y★	◊⌘	B&Λ	open marine
11.1	AK14M77	shale				QY	Ⓐ	open marine
11.1	AK14M76.5	limestone			Y★	⌘◊Λ⧗•	&BⒶⒷ	open marine
11.1	AK14M76	limestone			Y★	◊&ΛⒶⒷ		open marine
11.1	AK14M75.5	limestone, dolostone			Y★	⌘Ⓐ	B•	open marine
11.1	AK14M75	limestone			Y★	◊⌘Λ	Ⓐ	open marine
11.1	AK14M74.5	limestone			Y★	◊BⒶ⌘	Λ	open marine
11.1	AK14M74.15	limestone			⌘★⚒	QYⒷ		open marine
11.1	AK14M73.5	limestone, dolostone			⌘Y⚒★	Q	◊Ⓐ	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.1	AK14M73	limestone			Y≈⧗★	♣ß♢⚲•⊙⊖	Q⚠	shoal
11.1	AK14M72.5	limestone			Y★	⚒⚲⊗⚠	Q≈⧗	open marine
11.1	AK14M72	limestone			Y★	⚒⚲ß⚠⚠	♣≈⧗	open marine
11.1	AK14M71.5	limestone			Y★	⚒⚠	⚲•	open marine
11.1	AK14M71	limestone			Y★	⚲⚒⚠	♢Q	open marine
11.1	AK14M70.5	limestone			Y★	⚲⚒	♢ß	open marine
11.1	AK14M70	limestone			Y★	⚲⚒	⚠⚠	open marine
11.1	AK14M69	shale				Q		open marine
11.1	AK14M68.5	limestone		⊖		Y≈♢⧗⊙★	ß⚠	shoal
11.1	AK14M68	limestone			Y★	⚲≈⚠⚠	Q	open marine
11.1	AK14M67.5	limestone			Y★	≈♣•⚲	Q⚠⚠	open marine
11.1	AK14M67	limestone			Y★	⚲⧗	⚠⚠	open marine
11.1	AK14M66.5	limestone			Y★	⚲♣⚠•⊗	≈☮	open marine
11.1	AK14M66	limestone			Y★	⚠⧗	⚠•	open marine
11.1	AK14M65.5	limestone, chert			Y⚒★			open marine
11.1	AK14M65	limestone			⚲Y★	⚠⚒⧗•	Q♣⚠	open marine
11.1	AK14M64.5	limestone, dolostone			Y★	⚒⚠•	ß⚲⚠	open marine
11.1	AK14M64	limestone, dolostone			⚲Y★	⚠♣⚠⧗⚠	Q	open marine
11.1	AK14M63.5	limestone			★Y⧗⊙	≈♣ß⚲•⊖⚠Q	⚠	lagoonal
11.1	AK14M63	limestone			Y⚒★	♣ß♢⚲•⚒⚠	Q⚠	open platform
11.1	AK14M62.5	limestone			Y⚒★	⚲≈•⚠Q	⚠⚠	open platform
11.1	AK14M62	limestone			Y★	⚲♣⚒⧗•	≈Q♢⊙☮⚠	open platform
11.1	AK14M61.5	limestone			Y★	⚲⚠⚠	ßQ≈♣	open platform
11.1	AK14M61	limestone			Y★	⚲ß⚒⧗⚠	♣♢≈⊙⚠	open platform
11.1	AK14M60.5	limestone			Y★⊖	♣ß♢≈⧗•⊙	⚲Q⚠⚠	shoal
11.1	AK14M60	limestone			Y★	⚠⚲⚠⧗•	ß	open platform
11.1	AK14M59.5	limestone			Y★⊙	≈♣♢⧗•⚠	⚲	shoal
11.1	AK14M59	limestone			★Y⊙⊖	♣♢≈⧗•	Qß	shoal
11.1	AK14M58.5	limestone			★Y⊙⊖	≈♣⧗•	⚠	shoal
11.1	AK14M58	limestone			Y★⊖	≈♣♢⚲⧗•⊙	⚠	shoal
11.1	AK14M57.5	limestone			Y≈★⊙⊖	♣♢⧗•	ßQ⚠⚲	shoal
11.1	AK14M57	limestone			⊖≈⧗⊙	Y♣•★	⚠♢⊗⚠	shoal
11.1	AK14M56.3	chert			Y★			
11.1	AK14M56	limestone			≈Y★	♣ß⚠⧗•	⚠	open marine
11.1	AK14M55.5	limestone, dolostone			Y★	⚲	Q⚠	open marine
11.1	AK14M55	limestone, dolostone			Y★	≈♣ß⚠⚠⚲		open marine
11.1	AK14M54.5	limestone			★Y⧗⊙	♢ß≈	Q⚠	lagoonal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.1	AK14M54	limestone			≈Y★	ßÔ&ÞØ	QÞ⊙	open marine
11.1	AK14M53.5	limestone			Y★	ÔßØ	&Ⓐ	open marine
11.1	AK14M53	limestone			Y★	≈&ÔΣΛØ	ßⒶ✇	open marine
11.1	AK14M52.5	limestone, dolostone			Y★	ØÞQ	Σ	open marine
11.1	AK14M52.25	limestone, dolostone			Y★	Ø⊙	ΛⒶ	open marine
11.1	AK14M52.15	limestone, dolostone			Þ★	ØY		open marine
11.1	AK14M52	limestone			Y≈⊖★	Ø&ÔΣ•Ⓐ	Λ⊙	shoal
11.1	AK14M51.52	limestone			≈Y★	ØÞÔ&•Σ⊖	ΛⒶ	shoal
11.1	AK14M51	limestone			≈Y★	ØÞ&Ôß•Σ⊖Λ	Q⊙	shoal
11.1	AK14M50.5	limestone			Y≈•★	Ø&ÔΣ⊖	ΛⒶ✇	shoal
11.1	AK14M50	limestone			≈&Y•★	ØßΛΣ	Ô	open platform
11.1	AK14M49.5	limestone			Y★	ΛØ&Σ•Ⓐ	≈Þ	open platform
11.1	AK14M49	limestone			Y★	ØΛß&•ΣⒶ	≈⊙	open platform
11.1	AK14M48.5	limestone			Y≈★Σ⊖	&ßÔØ•ⒶΛ	Q	shoal
11.1	AK14M48	limestone			≈Y★	&ßÔΛØ	Ⓐ	open marine
11.1	AK14M47.5	limestone			≈Y★	ßΛ•		open marine
11.1	AK14M47	limestone			≈Y★	&ØÔß•ΣΛⒶ	⊙	open marine
11.1	AK14M46.5	limestone			Y≈Λ★	&ßQØΣⒶ⊙		open marine
11.1	AK14M46	limestone			Y★	Ø≈ßΣΛ⊙	Q	open marine
11.1	AK14M45.5	limestone			≈ß★Y	Ø&ÔΛΣⒶ⊙		open marine
11.1	AK14M45	limestone			⊖⊙	≈ØÔ&ΣY★	Ⓐ	shoal
11.1	AK14M44.5	limestone			⊖⊙	≈ØÔ&ΣY★	ß	shoal
11.1	AK14M44	limestone			⊖⊙	Ø≈&YΣ★		shoal
11.1	AK14M43.5	limestone			ÔÞ★	≈ßΛY	Ø⊙	open marine
11.1	AK14M43	limestone		≈	&Y★	ØÔΛΣ	Qß⊙	open marine
11.1	AK14M42.5	limestone			≈ß★Y	ÔΛ	&⊙	open marine
11.1	AK14M42	limestone			≈ß★Y	ØÔ⊙ΛQ		open marine
11.1	AK14M41.5	limestone			≈ß★Y	ÔΛ	QⒶ⊙	open marine
11.1	AK14M40.5	limestone			Y★	&ßΛØ	QⒶ	open marine
11.1	AK14M40	limestone			≈ßÔΣ★Y	&	QΛ	shoal
11.1	AK14M39.5	limestone			≈&ßΣ★Y	ÔΛQ		shoal
11.1	AK14M39	limestone			≈ßYΣ★	ÔΛ	&	shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.1	AK14M38.5	limestone			≈ƒY⧗★	♣ΛıQ		shoal
11.1	AK14M38	limestone			Y★	♣ƒ⊍⊕Λ		open marine
11.1	AK14M37.5	limestone			ƒ⌂★Y	⊍≈ıΛQ		open marine
11.1	AK14M37	limestone			≈Y★	ƒ⌂⊍⧗Λ	♣	open marine
11.1	AK14M36.5	limestone			⊍Y★	≈♣ƒΛ⧗•ı	⌂	open marine
11.1	AK14M36	limestone			ƒY★	⊍⌂⧗Λ	⊙	open marine
11.1	AK14M35.5	limestone			⌂Y★	ƒΛ⧗	Q⊕	shoal
11.1	AK14M35.1	limestone			Y★	ƒ⌂⊍⧗Λ	Q⊕	shoal
11.1	AK14M34.5	limestone			⌂⊞★	≈ƒ⊍⧗Λ	Q	shoal
11.1	AK14M34	limestone			⌂Y★	⊍ƒΛ⧗•≈	Q	shoal
11.1	AK14M33.5	limestone			Y★Λ	≈⊍	⌂Q⊕	shoal
11.1	AK14M33	limestone, dolostone			Y★	Λ⊍⧗ıQ	⊕	open platform
11.1	AK14M32.5	limestone, dolostone			Y★⧗	⊍Λıq	⊙	open platform
11.1	AK14M32	limestone			⊍Y★	Λ♣⧗ı	Q✇	open platform
11.1	AK14M31.5	limestone			≈Y★	♣⊍⌂ƒ•⧗Λıq	⊕⊙	open platform
11.1	AK14M31	limestone, dolostone			⊞★	⊍ƒ⌂⊕ıΛQ		open platform
11.1	AK14M30.3	limestone, dolostone			Y★	≈⊍ƒ♣ı⧗⊞Λ	Q	open platform
11.1	AK14M30	limestone			Y★	⊍≈ıΛ	⌂Qƒ	open platform
11.1	AK14M29.5	limestone			Y★	⊍≈•Λ	Q♣	open platform
11.1	AK14M29	limestone			Y⊞★	≈♣ƒ⧗Λ⊍	⊕⊙	open platform
11.1	AK14M28.5	limestone			Y≈•★	⊍♣ƒ⧗⊙Λ	Q	open platform
11.1	AK14M28	limestone		⊙	Y★	Qƒ⌂⧗⊍♣		shoal
11.1	AK14M27.5	limestone, dolostone				★Y⚒ıQ		restricted platform
11.1	AK14M27	limestone			≈Y★	ƒΛ⧗	Q♣⊍	open platform
11.1	AK14M26.75	limestone			★Y•ı	Q♣⊍	✇	restricted platform
11.1	AK14M26.5	limestone			Y★•	Q≈♣⧗ı⊍	ƒ	restricted platform
11.1	AK14M26.3	chert						
11.1	AK14M26	limestone			Y⊞★	⊍Λ♣≈ı⚒✇⊕⧗		restricted platform
11.1	AK14M25.5	limestone			Y★•	≈♣◎⊕ı⊍		open platform
11.1	AK14M25	limestone			Y★	♣ƒ⌂≈⧗Λ⊍	ı⊕	open platform
11.1	AK14M24.5	limestone			Y★⧗	≈⊍⌂♣Λ⊖⊙ı⊕		open platform
11.1	AK14M24	limestone			⊞Y⚒★	⊍≈♣Λ⧗⊙ı		open platform
11.1	AK14M23.5	limestone			Y★⊙	⧗	ƒQ⊕≈	open platform
11.1	AK14M23	limestone		⊙	⧗	♣⌂★Y	⊕	shoal
11.1	AK14M22.5	limestone			★Y⧗⊙	≈⊍♣⌂ƒ⊕⊖ı⊞Λ		shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.1	AK14M22.3	limestone						restricted platform
11.1	AK14M22	limestone						restricted platform
11.1	AK14M21.5	dolostone						restricted platform
11.1	AK14M21	limestone, dolostone						restricted platform
11.1	AK14M20.5	limestone, dolostone						restricted platform
11.1	AK14M20	dolostone						restricted platform
11.1	AK14M19.5	dolostone						restricted platform
11.1	AK14M19	dolostone						restricted platform
11.1	AK14M18.5	limestone, dolostone						restricted platform
11.1	AK14M18	limestone						open platform
11.1	AK14M17.5	limestone						restricted platform
11.1	AK14M17.01	limestone, dolostone						restricted platform
11.1	AK14M16.5	limestone						open platform
11.1	AK14M16	limestone						open platform
11.1	AK14M15.5	limestone, dolostone						restricted platform
11.1	AK14M15	limestone						restricted platform
11.1	AK14M14.5	dolostone						restricted platform
11.1	AK14M14	limestone		Q				open platform
11.1	AK14M13.5	limestone						open platform
11.1	AK14M13	dolostone						restricted platform
11.1	AK14M12.5	dolostone						restricted platform
11.1	AK14M12	dolostone						restricted platform
11.1	AK14M11.5	limestone, dolostone						open platform
11.1	AK14M11	limestone						open platform
11.1	AK14M10.5	limestone						open platform
11.1	AK14M10	limestone, dolostone						open platform
11.1	AK14M9.5	limestone						open platform
11.1	AK14M9	limestone						shoal
11.1	AK14M8.5	limestone						shoal
11.1	AK14M8	limestone						shoal
11.1	AK14M7.5	limestone						shoal
11.1	AK14M7	limestone, dolostone						restricted platform
11.1	AK14M6.5	dolostone						restricted platform
11.1	AK14M6	dolostone						restricted platform
11.1	AK14M5.5	dolostone						restricted platform
11.1	AK14M5	limestone, dolostone						restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.1	AK14M4.5	dolostone			⚒	⚠ Q	Y	restricted platform
11.1	AK14M4	dolostone			⚒	Q		restricted platform
11.1	AK14M3.5	dolostone			⚒	Q		restricted platform
11.1	AK14M3	dolostone				⚒ Q		restricted platform
11.1	AK14M2.5	dolostone			⚒	Q		restricted platform
11.1	AK14M2	limestone			⚠ ★ ⚒	Y ⚱ ⚙ ⚲	Q	restricted platform
11.1	AK14M1.5	limestone, dolostone			Y ★	≈ ⚗ ⚱ ⧗ ⚙ Q	⚲ ⚙	open platform
11.1	AK14M1	limestone, dolostone			⚠ Y ⚙ ★	⚲ ⚒ Q		restricted platform
11.1	AK14M0.5	limestone, dolostone			Y ⚠ ★	⚲ ⚒ Q	♣	restricted platform
11.1	AK14M0	limestone			Y ★	Q ⚗ ⚙ ♣	⚱	open platform
11.2	AK13M388.1	limestone		★	⚗ Y	⚙	⚙	restricted platform
11.2	AK13M387.7	dolostone			⚒	⚠		restricted platform
11.2	AK13M385.9	dolostone			⚒	Q		restricted platform
11.2	AK13M385.3	limestone			Y ★	⚱ ♣ ⚙ • ⚲	⚙	open platform
11.2	AK13M385	limestone			Y ★	⚙ ♣ • ⚲		open platform
11.2	AK13M384.5	limestone			Y ★	⚠ ⚱ ⚙ ⚙	⚗	open platform
11.2	AK13M384	limestone			Y ⚠ ★	⚱ Q		open platform
11.2	AK13M383	limestone			Y ★	⚱ ♣ ⧗ ⚙	⚗	open platform
11.2	AK13M381.5	limestone			Y ★	⚱ ⚙ Q	♣ ⚙ ⧗	open platform
11.2	AK13M380	limestone			Y ★	⚠ Q	⧗	open platform
11.2	AK13M378	dolostone				⚠ ⚒		restricted platform
11.2	AK13M375.9	dolostone			⚒	★		restricted platform
11.2	AK13M375	limestone			Y ⚠ ★	⚱	Q ⚙	restricted platform
11.2	AK13M373	limestone			Y ★	⚙	⚠ ⚙	open platform
11.2	AK13M371	limestone			Y ★	⚱	♣	open platform
11.2	AK13M369	limestone			Y ★	⚱ ⚙ Q	⚙	open platform
11.2	AK13M367	limestone			Y ★	⚙	⚗ ⚱ ⧗ ⚙	shoal
11.2	AK13M366	limestone			Y ★	⚙	⚙	shoal
11.2	AK13M365	limestone			Y ★			open marine
11.2	AK13M363.5	limestone			Y ★	⚗ ⚱ ⚙	⚠	open marine
11.2	AK13M358	dolostone			Y ★			open marine
11.2	AK13M356.5	dolostone			Y ★			open marine
11.2	AK13M355.3	limestone			Y ★	⚱	≈ ⚙	open marine
11.2	AK13M354	limestone			Y ★	≈ ⚠	Q ♣ ⚙	open marine
11.2	AK13M352	limestone			Y ★	≈ ⚱ ⚠	♣	open marine
11.2	AK13M350	limestone			Y ★	♣ ⚠	≈ ⚱	open marine
11.2	AK13M348	limestone			Y ★	⚠ ⚲	♣	open marine
11.2	AK13M346	limestone			Y ★	⚱	⧗	open marine
11.2	AK13M344	limestone			⚱ Y ★	♣ ⚙		open marine
11.2	AK13M342	limestone			Y ★	⚱ ⚠		open marine
11.2	AK13M340	limestone			⚗ Y ★	≈ ♣ ⚱ ⧗ ⚙	Q	open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.2	AK13M337.8	limestone			Y			open platform
11.2	AK13M336	limestone			Y		Q	shoal
11.2	AK13M334	limestone			Y		Q	open marine
11.2	AK13M332	limestone			Y		Q	open marine
11.2	AK13M330	limestone			Y			open marine
11.2	AK13M327.5	limestone			Y	Q		open platform
11.2	AK13M326	limestone			Y			open platform
11.2	AK13M324	limestone			Y		Q	shoal
11.2	AK13M322	limestone			Y			open marine
11.2	AK13M320	limestone			Y			open marine
11.2	AK13M318	limestone			Y			open marine
11.2	AK13M316	limestone			Y			open marine
11.2	AK13M314	limestone			Y			open marine
11.2	AK13M312	limestone			Y			open marine
11.2	AK13M310	limestone			Y	Q		open marine
11.2	AK13M307	limestone			Y			open marine
11.2	AK13M304.5	limestone				Y Q		open marine
11.2	AK13M302.5	dolostone						restricted platform
11.2	AK13M300.5	dolostone						restricted platform
11.2	AK13M298.5	limestone, dolostone						restricted platform
11.2	AK13M296	limestone, dolostone						restricted platform
11.2	AK13M294	dolostone						restricted platform
11.2	AK13M292	limestone			Y			restricted platform
11.2	AK13M290	limestone				Y	Q	restricted platform
11.2	AK13M288	dolostone						restricted platform
11.2	AK13M286	dolostone						restricted platform
11.2	AK13M285	limestone				Y	Q	restricted platform
11.2	AK13M280	limestone			Y			restricted platform
11.2	AK13M279	limestone, dolostone						restricted platform
11.2	AK13M278	limestone			Y			restricted platform
11.2	AK13M274	limestone			Y			restricted platform
11.2	AK13M268.5	dolostone						intertidal
11.2	AK13M262	dolostone						restricted platform
11.2	AK13M257	limestone			Y	Q		restricted platform
11.2	AK13M252	limestone			Y	Q		restricted platform
11.2	AK13M250.5	limestone			Y			restricted platform
11.2	AK13M249.5	limestone		★	Y			restricted platform
11.2	AK13M245	dolostone						restricted platform
11.2	AK13M240.5	dolostone						restricted platform
11.2	AK13M236	limestone, dolostone						intertidal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.2	AK13M231.5	limestone			Y★	⊘⌂	♣	restricted platform
11.2	AK13M226	limestone			⌘Y•★	⊘⊘⧗⚒		restricted platform
11.2	AK13M218	dolostone			⚒	★		restricted platform
11.2	AK13M208	dolostone			⚒	⊘Y★		restricted platform
11.2	AK13M204.7	limestone			⌘Y★	⊘≈♣⧗⊘⌂	✇⊙	restricted platform
11.2	AK13M204.4	limestone, dolostone				⚒		restricted platform
11.2	AK13M203.5	dolostone				⚒		restricted platform
11.2	AK13M202.8	limestone, dolostone			Y★	⊘⚒	⌂	restricted platform
11.2	AK13M202.3	limestone			Y★		⊘	restricted platform
11.2	AK13M200.5	dolostone			⌘★	Y⚒Q		restricted platform
11.2	AK13M184	limestone		★	Y	⧗		open platform
11.2	AK13M179	limestone			Y★	⊘⌘		open platform
11.2	AK13M174	limestone			⌘★	⊘⊘⚒	⌘♣⌂	open platform
11.2	AK13M171.5	chert			Y★	⊘		open platform
11.2	AK13M166	limestone			Y★	⊘⊘	♣⌂	open platform
11.2	AK13M160.5	limestone			Y★	⊘⊘⚒	Q⌂	open platform
11.2	AK13M155.5	limestone			Y★	⊘♣⊘⧗•		open platform
11.2	AK13M149.5	dolostone				★		open platform
11.2	AK13M143.5	limestone			Y★•	⊘	Q♣	lagoonal
11.2	AK13M138.5	limestone			Y★•	⊘♣⧗⊘		lagoonal
11.2	AK13M134.5	limestone			Y★	⊘⊘•Q	⌂	lagoonal
11.2	AK13M128.5	limestone			Y★•	⊘⊘⧗⊙	Q♣	shoal
11.2	AK13M124	limestone			⌘★	Y⊘⚒	♣	lagoonal
11.2	AK13M121	limestone			Y★⧗	⊘•	⌘Q⌂♣	shoal
11.2	AK13M116	limestone			Y★	⊘	Q	lagoonal
11.2	AK13M111	dolostone			Y★			lagoonal
11.2	AK13M107	limestone			Y★•	⊘♣⧗⊙Q		shoal
11.2	AK13M102	limestone			Y★•	♣	Q⌂✇	shoal
11.2	AK13M97.5	limestone			Y★•	♣⧗		lagoonal
11.2	AK13M92	limestone			★Y•⊙	♣⊘⧗	⌂✇	shoal
11.2	AK13M89	limestone			Y★•	Q		lagoonal
11.2	AK13M84	dolostone						intertidal
11.2	AK13M77.5	limestone, dolostone						intertidal
11.2	AK13M70.5	limestone			Y★	♣⊘⊘	⊗⊗	lagoonal
11.2	AK13M65	limestone			Y★•	⊘♣⧗⊘		shoal
11.2	AK13M62.5	dolostone						intertidal
11.2	AK13M59.5	limestone			≈★•	♣Y⊘	⌂	lagoonal
11.2	AK13M50.5	limestone			★≈⧗⊘	♣✇	Y	lagoonal
11.2	AK13M46.6	limestone				≈		intertidal
11.2	AK13M46.4	limestone, dolostone						intertidal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
11.2	AK13M45	dolostone						intertidal
11.2	AK13M43.5	dolostone						lagoonal
11.2	AK13M42.75	limestone, dolostone						intertidal
11.2	AK13M42.1	dolostone						intertidal
11.2	AK13M41.8	limestone						lagoonal
11.2	AK13M41.1	limestone						lagoonal
11.2	AK13M40.02	dolostone						intertidal
11.2	AK13M40.01	dolostone						lagoonal
11.2	AK13M26	dolostone						lagoonal
11.2	AK13M22.5	limestone						lagoonal
11.2	AK13M21.5	limestone						lagoonal
11.2	AK13M19	limestone						lagoonal
11.2	AK13M16.5	limestone						lagoonal
11.2	AK13M14.5	limestone						lagoonal
11.2	AK13M12	limestone						lagoonal
11.2	AK13M5	limestone						lagoonal
11.2	AK13M3	limestone						lagoonal
11.2	AK13M0	limestone						lagoonal
12.2	AK15M245.75	sandstone, OTHER						
12.2	AK15M245.5	limestone						open platform
12.2	AK15M245	limestone						open platform
12.2	AK15M244.5	limestone						open platform
12.2	AK15M244	limestone						open platform
12.2	AK15M243.5	limestone						open platform
12.2	AK15M243	limestone						open platform
12.2	AK15M242.5	limestone						open platform
12.2	AK15M242	limestone						shoal
12.2	AK15M241.5	limestone						shoal
12.2	AK15M241	limestone						open platform
12.2	AK15M240.5	limestone						open platform
12.2	AK15M240	limestone						open platform
12.2	AK15M239.5	limestone						open platform
12.2	AK15M239	limestone						open platform
12.2	AK15M238.5	limestone						open platform
12.2	AK15M237.5	limestone						shoal
12.2	AK15M237	limestone						open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
12.2	AK15M236.5	limestone			≈Y★	⊘&⧗●	Ⓐ	open marine
12.2	AK15M236	limestone			Y★	ß⌂&⊘≈	Ⓐ	open marine
12.2	AK15M234.5	limestone			⊘Y★	&ß⌂⊙ƒ≈ Q		open platform
12.2	AK15M234	limestone			⊖⊙⧗	ß⌂≈★Y	⊘	shoal
12.2	AK15M232.5	limestone			Y★	≈⊘ß&ƒ● ⧗Ⓐ⊙		open platform
12.2	AK15M232	limestone			Y★	⊘≈&⧗●ƒ	ßⒶ☮	open platform
12.2	AK15M231.5	limestone			Y★	⊘≈Ⓐ⧗●	&⌂ƒ⊙Ⓐ	open platform
12.2	AK15M231	limestone			⌂Y★	≈&ß⊘⧗● ƒ	⊙	open platform
12.2	AK15M230.5	limestone			≈Y★	ƒ⊘&⧗●⊙	Ⓐ	shoal
12.2	AK15M230	limestone			★⊙	≈&⌂⧗Y⊘	Ⓐ	shoal
12.2	AK15M229.5	limestone			Y★⊙	≈ß⧗⊘	&ƒ	shoal
12.2	AK15M229	limestone			Y★	⊘	ƒ●⧗	open marine
12.2	AK15M228.5	limestone			Y★	⊘Ⓐ	&Ⓐ	open marine
12.2	AK15M227	limestone, dolostone			Y★	⊘ⒶⒶ	Q	open marine
12.2	AK15M226.5	limestone			⊖★⧗⊙	&≈⌂ß⊘Ⓐ ●YⒶ		lagoonal
12.2	AK15M226	limestone			Y★●	≈&⊘⧗ƒ		open platform
12.2	AK15M225.5	limestone			Y&ƒ★	ß⌂≈●⊘		open platform
12.2	AK15M225.5	chert						open platform
12.2	AK15M225	limestone, dolostone			Y★	⊘&ß●✕Ⓐ	ƒ⧗	open platform
12.2	AK15M224.5	limestone			Y★	≈ß⧗Ⓐ	⌂	shoal
12.2	AK15M224	limestone			Y★	⊘≈⧗Ⓐ	&	open marine
12.2	AK15M223.5	limestone			Y★	≈&⊘⧗Ⓐ	ƒ	open marine
12.2	AK15M223	limestone			Yß⧗★	⌂⊘	≈Ⓐ	open marine
12.2	AK15M222.5	limestone			Y★	⊘ƒ	&⧗	open marine
12.2	AK15M222	limestone			Y★	⊘Ⓐ	Ⓐ	open marine
12.2	AK15M220.5	limestone			Y★	⊘⧗	ßⒶ●	open marine
12.2	AK15M220	limestone			Y★	&⊘Ⓐ	ƒ≈⧗Ⓐ	open platform
12.2	AK15M219.5	limestone		⊙		≈&ß⊖★Y	Ⓐ	shoal
12.2	AK15M219	limestone			Y★	&ß⌂⧗⊘≈	ƒⒶ	open marine
12.2	AK15M218.5	limestone			Y★	≈&ß⧗Ⓐ⊘		open marine
12.2	AK15M218	limestone			Y★	ß&⊘	≈	open marine
12.2	AK15M217.5	limestone			Y★	Ⓐ⊘&⧗●Ⓐ	⌂ƒ	open marine
12.2	AK15M217	limestone			Y★	&≈⌂ß●⧗ ⊘Ⓐ	Ⓐ	open marine
12.2	AK15M216.5	limestone			Y★	&ß⌂⧗⊘≈	Ⓐ⊙	shoal
12.2	AK15M216	limestone			Y★	ß⊘Ⓐ	⌂Ⓐ⧗	open marine
12.2	AK15M215	limestone, dolostone			Y★	⊘Ⓐ	Ⓐ●	open marine
12.2	AK15M214.5	limestone			Y★	⊘	Ⓐ●	open marine
12.2	AK15M214	limestone, dolostone			Y★	⊘		open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
12.2	AK15M213.3	limestone			Y★	⚘	♣⍝	open marine
12.2	AK15M212	limestone			Y★	⚘⍝⍝	⚷	open marine
12.2	AK15M211.5	limestone			★Y⧗⊙	≈♣⚷•⍝⚘	⍝	lagoonal
12.2	AK15M211	limestone			Y★	⚘≈•⍝	♣⍝	open marine
12.2	AK15M210.5	limestone			Y★	≈♣⚘•⍝	⍝	open marine
12.2	AK15M210	limestone			Y★	≈♣⚘•⍝		open marine
12.2	AK15M209.5	limestone			Y★	≈♣⚷⧗•⚘	⌂⍴⍝	open marine
12.2	AK15M208.5	limestone			Y★	⚘•	⍝	open marine
12.2	AK15M208	limestone, dolostone			Y★	♣⚘⍝	⍜	open marine
12.2	AK15M207	limestone			Y★	⚘≈♣⧗•⍝	⚷	open marine
12.2	AK15M206.5	limestone			Y★	⚘•	⍝⧗	open marine
12.2	AK15M206	limestone			Y★	♣⚘•	⌂⍝	open marine
12.2	AK15M205.5	limestone			Y★	⚘	⧗	open marine
12.2	AK15M204.5	limestone			Y★•	♣⚷≈⧗⚘		open platform
12.2	AK15M204	limestone			Y★•	⚘≈♣⍝⧗⊖⍴	⊗	open platform
12.2	AK15M203.5	limestone			Y★•	⚘♣⍝⧗⍴		shoal
12.2	AK15M203	limestone			Y★•	⚘≈♣⧗⍴⍝	⍟	shoal
12.2	AK15M202.5	limestone			Y★	♣≈⌂⚷•⧗⚘⍝	⍴⍝	shoal
12.2	AK15M202	limestone			★Y•⍴	⚘♣⍟⍝⍜	⍝	open platform
12.2	AK15M201.5	limestone			Y★	⚘≈♣⍝⧗•⍝		shoal
12.2	AK15M201	limestone			Y★	♣⚷≈⍝⚘	⍴⍝⧗	shoal
12.2	AK15M200.5	limestone			Y★	♣⚷⚘•⍝	≈⍴⍝	open marine
12.2	AK15M200.1	chert				⚒		open marine
12.2	AK15M200	chert			★	⚒		open marine
12.2	AK15M199.5	limestone			⌂Y★	⚘⚷⍝⧗•	♣⍴⍝	open marine
12.2	AK15M199.1	limestone			Y★	⚘⍝•	♣⍴⍝	open marine
12.2	AK15M198.5	OTHER			Y★			open marine
12.2	AK15M198	limestone			Y★	♣•⧗	⚘⍴⍝	open marine
12.2	AK15M197.25	limestone			⚘Y★	♣	⚷	open marine
12.2	AK15M196.5	limestone		★	⚷Y	≈♣⌂⚘⧗•⍝		open marine
12.2	AK15M196	limestone			Y★	⚘♣⧗⍝	⚷⍝	open marine
12.2	AK15M195.5	limestone			Y★	⚘♣•⍝		open marine
12.2	AK15M195	OTHER			★	Y		open marine
12.2	AK15M194.5	limestone			Y★	⚘	⍝⧗	open marine
12.2	AK15M194	limestone			Y★	⚘⍝		open marine
12.2	AK15M193.5	limestone			Y★	♣⚷⊗⚘		open marine
12.2	AK15M193	limestone			Y★	⚘♣⚷⧗⍴⍝	≈⍝	open marine
12.2	AK15M192.5	limestone			Y★	⚘♣⚷⧗•⍝	⍝⊖	open marine
12.2	AK15M192	limestone			⚘Y★	♣⚷⌂⍝⍴⍝	⊙	open marine
12.2	AK15M191.5	limestone			Y★	⚘•	⍝⧗	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
12.2	AK15M191	limestone			Y★	≈♣♢⊘⧗◎ ⋀		open marine
12.2	AK15M190.5	limestone			Y♢⧗★	≈ß⋀⊘	♣	shoal
12.2	AK15M190	limestone			Y★	♢ß⊘	≈	open marine
12.2	AK15M189.2	limestone			Y★	♢⊘⋀	◊	open marine
12.2	AK15M188.5	limestone			Y★	ß♢⧗⋀		open marine
12.2	AK15M188	limestone			Y★	ß♢⊘≈	♣◊⧗	open marine
12.2	AK15M187.5	limestone			Y★	♢⊘⋀	ß	open marine
12.2	AK15M186.5	limestone			Y★	ß♢⊘◎⋀	♣	open marine
12.2	AK15M186	limestone			ß♢★Y	≈♣◎⊘		open marine
12.2	AK15M184.25	limestone			♢Y★	⊘ß◎⋀		open marine
12.2	AK15M184	limestone			♢Y★	≈ß⊘◎⋀	♣	open marine
12.2	AK15M182.5	limestone			Y★	≈♣⊘◎⋀	♢◊⊙	open marine
12.2	AK15M182	limestone			Y★	⊘	ß	open marine
12.2	AK15M181.5	limestone			Y★⊙	≈♣ß⊘⧗• ⊖Q	◊	lagoonal
12.2	AK15M181	limestone			★⊖⊙	⊘♣ßY⧗ ⊗⊗⋀	◎	shoal
12.2	AK15M180.5	limestone			Y★⊙	♣ß♢≈⧗ ⋀⊘	◎	shoal
12.2	AK15M180	limestone			Y♣•★	⋀⊘◊✱◎	✇	open platform
12.2	AK15M179.5	limestone			Y♣•★	⊘≈⋀◎◊	✇⧗	open platform
12.2	AK15M179	limestone			≈Y★	ß♢⊘♣	⧗	shoal
12.2	AK15M178.5	limestone			Y★	⊘⋀	ß♣	open marine
12.2	AK15M177	limestone			Y★	⊘⋀		open marine
12.2	AK15M176.5	limestone			Y★	♣ß⋀⊘		open marine
12.2	AK15M176	limestone			⊘Y★	⋀ß⧗◊		open marine
12.2	AK15M175.5	limestone			⊘Y★	ß⋀◎	♣⧗	open marine
12.2	AK15M175	limestone			Y★	⊘⋀•	♣≈	open marine
12.2	AK15M174.5	limestone			Y★	ß⊘⋀	♣	open marine
12.2	AK15M174	limestone			Y★	⊘⋀	≈◎•	open marine
12.2	AK15M173.5	limestone			♢Y★	≈⊘⋀	ß◎	open marine
12.2	AK15M173	limestone			ßY★	♢⊘◊	♣◎	open marine
12.2	AK15M172.5	limestone			⊘Y★	ß♣◊	≈•	open marine
12.2	AK15M172	limestone			Y★	⊘♣•◊	✇⧗	open marine
12.2	AK15M170.4	limestone			Y★	ß⊘⋀	♢♣◊	open marine
12.2	AK15M169.5	limestone			Y★	⊘⋀	ß♣	open marine
12.2	AK15M169	limestone			⊘Y★	♢	♣	open marine
12.2	AK15M163.5	limestone			Y★	♣⊘	⋀⧗	open marine
12.2	AK15M163	limestone			Y★	♣⋀◊	⧗	open marine
12.2	AK15M162.5	limestone			⊘Y★	ß♢♣•◊		open marine
12.2	AK15M162	limestone			Y★	≈♢⋀⊘	ß	open marine
12.2	AK15M161.5	limestone			Y★	⊘⋀	ß♣⧗	open marine
12.2	AK15M161.2	limestone			Y★	⊘◊	♣⋀	open marine
12.2	AK15M160.5	limestone			Y★	⊘⋀	ß♣⧗	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
12.2	AK15M160	limestone			♢Y★	⊍ꞮⱯ	♣	open marine
12.2	AK15M159.5	limestone			Y★	⊍Ɪ⧗	•	open marine
12.2	AK15M159	limestone			Y★	⊍Ɐ		open marine
12.2	AK15M158.5	limestone			Y★	♣⊍Ɐ	Q⊙•	open marine
12.2	AK15M158	limestone		★	Y•	⊍Ɪ⧗ⱮQ	♢≈	open platform
12.2	AK15M157.5	limestone			Y★•	♣Ɪ⊍⧗⊙Q	≈	open platform
12.2	AK15M157	limestone			Y★	♢≈Ɐ	ꞮⱠ⧗	open platform
12.2	AK15M156	limestone			Y★	♣⊍	ⱮⱮ	open platform
12.2	AK15M155.5	limestone			Y★⊖	⊍≈♣Ɱ⧗• ⊙Q	Ɱ	shoal
12.2	AK15M155	limestone			Y★⊖	⊍≈♣⧗⊙ Ɱ	Ɱ	shoal
12.2	AK15M154.5	limestone			★Y⚒⧗ ⊙	≈♣ꞮⱮ⊍	QⱮ	open platform
12.2	AK15M154	limestone			⚒⊙•	Y♣★⧗Ⱡ	≈	open platform
12.2	AK15M153.5	limestone			⚒•	★⊍♣⧗⊙Ⱡ Q	≈	open platform
12.2	AK15M153	limestone			⊙	Y★⊍♣≈⊖ ⧗⚒ⱮⱮ	ꞮⱠ	open platform
12.2	AK15M152.51	limestone			★Y•⊙	≈♣Ɪ⊍ⱠⱮ ⱧⱠ	Ɱ	open platform
12.2	AK15M152	limestone			ꞮY★	♢≈⊍	Ɱ	open platform
12.2	AK15M149.02	limestone			Y★	≈Ɪ⧗Ɱ	Ɱ	open platform
12.2	AK15M149.01	limestone			Y★	⊍≈Ɪ⧗Ɱ Ɱ		open platform
12.2	AK15M148.5	limestone			ꞮY★	⊍≈⧗Ɱ	Ɱ	open platform
12.2	AK15M148	limestone			Y★	≈Ɪ⊍⧗Ɱ	Ɱ	open platform
12.2	AK15M147.5	limestone			Y★	≈Ɪ⊍⧗Ɱ	ⱧQⱮⱠ	open platform
12.2	AK15M147	limestone			Y★	≈Ɪ⧗Ɱ	Ɱ	open platform
12.2	AK15M146.5	limestone			Y★	ꞮⱮ⧗	≈⊍	open platform
12.2	AK15M146	limestone, dolostone			Y★	♣ꞮⱮ⊍	Ⱡ♢⚒Ɱ	open platform
12.2	AK15M145.5	limestone			Y★	≈♣ꞮⱮ•Ɱ⊍	Ⱡ	open platform
12.2	AK15M144.5	limestone			ⱧⱠ★	⊍Y⚒Q		restricted platform
12.2	AK15M144	limestone			Y★	♣≈♢Ɪ⊍⊙ ⧗ⱧⱠⱮ	ⱠⱠ	open platform
12.2	AK15M143.5	limestone			Y★	≈♣Ɪ⊍⧗⊙ Ɱ	♢Ⱡ	open platform
12.2	AK15M143	limestone			Y★	ꞮⱠ≈ⱧⱠ⊍	ⱮⱮ	open platform
12.2	AK15M142.5	limestone			Y★⧗	≈♣Ɪ⊙Ɱ⊍	Ɱ	open platform
12.2	AK15M142	limestone			Y★•	≈♣ⱧⱠⱮ	Q	open platform
12.2	AK15M141.5	limestone			YⱧⱠ★	♣⊍ⱮQ	≈	open platform
12.2	AK15M141	limestone			★Y⧗⊙	≈ꞮⱠ⊖Ɱ ⊍	Ɱ	lagoonal
12.2	AK15M140.5	limestone			Y★•	Ⱡ⚒		restricted platform
12.2	AK15M140	limestone			Ⱡ	Y★⚒Q	♣	restricted platform
12.2	AK15M139.5	limestone			•	Y★Q		restricted platform
12.2	AK15M139	limestone			YⱧⱠ★	Ⱡ•Q	≈	restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
12.2	AK15M138.5	limestone			Y★	⊘≈&•◊Λ Q	⋔ ß⧗Θ	restricted platform
12.2	AK15M138	limestone			⋔★•	⊘≈&Y⚒◊ ΛQ	✇	restricted platform
12.2	AK15M137.5	limestone			Y★◊	&⊘⚒	Θ	restricted platform
12.2	AK15M137	limestone			Y★◊	⊘&⋔⚒✇	≈	restricted platform
12.2	AK15M136.5	limestone			Y★◊	⊘≈&Λ⚒✇ Θ	Q⋔	restricted platform
12.2	AK15M136	limestone			Y★•	⊘&✇◊Q	Θ⚒	restricted platform
12.2	AK15M135.5	limestone, dolostone			Y⊘★⋔	&Λ⚒	Θ	restricted platform
12.2	AK15M135	limestone			Y★	≈&ß⧗Λ ⊘	⋔Θ	open platform
12.2	AK15M134.5	limestone			Y★	&ß≈⧗Λ	⊘Θ	open platform
12.2	AK15M134	limestone			Y★	≈&ß⊘⧗◊ Λ	✇	open platform
12.2	AK15M133.5	limestone			Y★	&ß⧗Λ	≈Θ	open platform
12.2	AK15M132.5	limestone			⋔Y⚒★	&⊘Λ	Θ	restricted platform
12.2	AK15M132	limestone			Y★Λ	⊘&Θ⋔		restricted platform
12.2	AK15M131.5	limestone			Y★	⊘ß⧗Λ	Θ	restricted platform
12.2	AK15M131	limestone			⋔★	⊘Y	Θ⚒⧗	restricted platform
12.2	AK15M130.5	limestone			Y★	Λ⊘⚒◊	⋔Θ	restricted platform
12.2	AK15M130	limestone			Y★⚒	⊘&ß•◊Λ		restricted platform
12.2	AK15M129.5	limestone			Y⋔★	⊘&⚒Λ	Θ	restricted platform
12.2	AK15M129	limestone			Y★	&ß⊘⚒Λ	⋔	restricted platform
12.2	AK15M128.5	limestone			Y★	⊘ßΘΛ	⧗	open platform
12.2	AK15M128	limestone			Y★	ß&Λ	Θ⧗	open platform
12.2	AK15M127.5	limestone			Y★	Λ&Θ◊	⊘	open platform
12.2	AK15M127	limestone			Y★	⊘&ß⧗ΘΛ		open marine
12.2	AK15M126.5	limestone			Y★	⊘ßO⚒◊Λ	Θ	open platform
12.2	AK15M126	limestone			Y★	ß⊘Λ	O⋔•	open platform
12.2	AK15M125.5	limestone			Y★	&⊘Λ	Θ	open platform
12.2	AK15M125	limestone			Y★	⊘ΛΘ	&≈⧗	open platform
12.2	AK15M124.5	limestone		⊙	⧗	⊘≈Y•★	&ß◊Λ	shoal
12.2	AK15M124	limestone		⊙	⧗	Y★•	O	shoal
12.2	AK15M123.5	limestone			⊙⧗	YO•★		shoal
12.2	AK15M123	limestone			⊙⧗	&OY•★	⊘ΛΘ	shoal
12.2	AK15M122.5	limestone			⊙⧗	YO•★	⊘Λ	shoal
12.2	AK15M122	limestone		⊙	•⧗	&O★Y	⊘	shoal
12.2	AK15M121.5	limestone		⊙	•⧗	OY★		shoal
12.2	AK15M120.8	limestone			⊙•	Y⊘&★⧗⚒ ◊		open platform
12.2	AK15M120.5	limestone			⊙•	Y⊘&★⧗⚒ ◊		open platform
12.2	AK15M120	limestone			⊙•⧗	&⊘OßΛ⚒ Y★	Θ	open platform
12.2	AK15M119.5	limestone			⊙•⧗	OY★	ß&Λ	shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
12.2	AK15M119	limestone			⊙•⧗	ⅇ♢♣★Y	⅄Ⓐ	shoal
12.2	AK15M118.5	limestone		⧗	⊙	♢Y★		shoal
12.2	AK15M118	limestone		⧗	⊙	Y♢•★		shoal
12.2	AK15M117.5	limestone			Y★	ⅈ⅊♣⧗ⅆ⅄	Q	open platform
12.2	AK15M117	limestone			Y★⅄	⅊ⅈⅆ		open platform
12.2	AK15M116.5	limestone			Y★⊙	ⅈⅇ♢⧗⅄ⅆ		open platform
12.2	AK15M116	limestone		⊙	Y★	⅄⊖⧗	ⅇ	shoal
12.2	AK15M115.5	limestone			Y★⊙	ⅈⅇ♢⧗⊖⅄	Q≈⅄	open platform
12.2	AK15M115	limestone			★Y⅄⧗⊙	ⅇ♢⅊ⅆⅈ	Q♣≈	open platform
12.2	AK15M114.5	limestone			ⅈ★⅄	Y⅊ⅇ⅄⧗Ⓐⅆ	♣≈	restricted platform
12.2	AK15M114	limestone			Y★⧗	⅊ⅈⅇ≈Ⓐ⅄ⅆ		restricted platform
12.2	AK15M113.5	limestone			Y★⧗	ⅈ⅊⅄⅄ⅆ	♢♣	restricted platform
12.2	AK15M113	limestone			Y★⧗	⅊≈ⅈⅆ⅄	Q	restricted platform
12.2	AK15M112.5	dolostone			Y★	⅊ⅆ		restricted platform
12.2	AK15M112	limestone			★Y⧗⊙	♣ⅇ♢•⅊≈	ⅈ	open platform
12.2	AK15M109	limestone			Y★⅄	≈♣⧗⅊	Ⓐ	open platform
12.2	AK15M107	OTHER			⅄	★		restricted platform
12.2	AK15M105	limestone			Y★	♣ⅇ⅊⧗⅄	ⅆⒶ✇	open platform
12.2	AK15M103	limestone		⊖	Y★	≈♣⊙⧗•	ⅇ♢ⅆ⅊	shoal
12.2	AK15M100	limestone			⅊ⅈ	★Yⅆ⅄		open platform
12.2	AK15M98	limestone			Y★	⅊♣ⅈ⧗•		open platform
12.2	AK15M95	limestone			Y⅊★ⅈ	♣ⅆ•		open platform
12.2	AK15M93	limestone, dolostone			Yⅈ★	♣⅊		open platform
12.2	AK15M89	limestone			Y★	ⅈ⅄		open platform
12.2	AK15M84.5	limestone			Y★	⅊♣⅄⧗•	✇	open platform
12.2	AK15M82	limestone			Y★•	⅊ⅈ⧗Q	ⅆ✇	open platform
12.2	AK15M80	limestone			Y★	≈♣⅄⅊	ⅇⒶ	open platform
12.2	AK15M78	limestone			Y★	⅊Q	ⅆⒶ	open platform
12.2	AK15M75.6	limestone			Y★	⅊♣ⅆ⧗•	ⅈ⅄⅄	open marine
12.2	AK15M74	limestone			Y★	⅄	⅊ⅈ	open marine
12.2	AK15M72	limestone, dolostone			Y★	⅊ⅈ⅄	Ⓐ	open marine
12.2	AK15M70	limestone			Y★	⅊ⅈ⅄		open marine
12.2	AK15M68	limestone			Y★	⅊	⅄Ⓐ	open marine
12.2	AK15M66	limestone			⅊Y★		Ⓐ	open marine
12.2	AK15M64.5	limestone, dolostone			Y★	⅊		open marine
12.2	AK15M62	limestone, OTHER			Y★	⅊		open marine
12.2	AK15M59	limestone			⅊Y★	♣	ⅈ⅄	
12.2	AK15M56	limestone			Y★	⅊♣⅄ⅈ	Ⓐ	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
12.2	AK15M54	limestone			Y★			open marine
12.2	AK15M52	limestone			Y★			open marine
12.2	AK15M50	limestone			Y★			open marine
12.2	AK15M48	limestone			Y★			open marine
12.2	AK15M46	limestone, dolostone			Y★			open marine
12.2	AK15M44	limestone			Y★			open marine
12.2	AK15M42	limestone			Y★			open marine
12.2	AK15M40	limestone			Y★			open marine
12.2	AK15M38.4	limestone			Y★			
12.2	AK15M36	limestone			Y★			open marine
12.2	AK15M34	limestone			Y★			open marine
12.2	AK15M32.8	limestone			Y★			open marine
12.2	AK15M32	limestone			Y★			open marine
12.2	AK15M30	limestone			Y★			open marine
12.2	AK15M28	limestone			Y★			open marine
12.2	AK15M26	limestone		★	Y			open marine
12.2	AK15M24	limestone			Y★			open marine
12.2	AK15M20.1	limestone, chert				Y		
12.2	AK15M20.02	limestone, dolostone, chert				Y★		
12.2	AK15M18	chert			Y★			
12.2	AK15M16.5	limestone, chert			Y★			open marine
12.2	AK15M15	limestone			Y★			open marine
12.2	AK15M14	limestone			Y★			open marine
12.2	AK15M12	limestone			Y★			open marine
12.2	AK15M10	limestone			Y★			open marine
12.2	AK15M8	limestone			Y★			open marine
12.2	AK15M5	limestone			Y★			open marine
12.2	AK15M4	limestone			Y★			open marine
12.2	AK15M0	limestone			Y★			open marine
12.1	AK16M42.5	limestone			Y★			open platform
12.1	AK16M41	limestone			Y★			open platform
12.1	AK16M39.5	limestone			Y★			open platform
12.1	AK16M36	limestone			Y★			open platform
12.1	AK16M33.1	limestone			Y★			open platform
12.1	AK16M33	limestone			Y★			open platform
12.1	AK16M32.8	limestone			Y★			open platform
12.1	AK16M30	dolostone				Y★		restricted platform
12.1	AK16M27	limestone			Y★			open platform
12.1	AK16M24	limestone			Y★			open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
12.1	AK16M21.6	limestone			Y★	⊘ƀ⋀⧗•Q	♣≈ϑ	open platform
12.1	AK16M18	dolostone			Y★⚒	Q		restricted platform
12.1	AK16M17	limestone			Y★	ƀ	⋀Qϑ⧗•	open platform
12.1	AK16M15	limestone			Y★	ƀ⋀⧗	⊘	open platform
12.1	AK16M14	limestone			Y★	ƀ⧗	♣	open platform
12.1	AK16M12	limestone			⋔Y⋀★	⊘ϑ	≈⋀	open platform
12.1	AK16M9	limestone			Y★⚒	⋔ϑ		open platform
12.1	AK16M6	limestone			Y⋔★	⊘ϑ•		open platform
12.1	AK16M3	limestone			Y★	⊘ϑ•	♣⋔	open platform
12.1	AK16M0.01	limestone, dolostone			⚒	⋔★		restricted platform
13.3	AK112M192	limestone			⚒			restricted BWB
13.3	AK112M191	limestone						open platform OWB
13.3	AK112M190	limestone						open platform OWB
13.3	AK112M189	limestone						shoal OWB
13.3	AK112M188	limestone			Y			near shoal BWB
13.3	AK112M186	limestone				⚒		restricted BWB
13.3	AK112M185	limestone			⚒	Y⋔		restricted BWB
13.3	AK112M184	limestone, chert			⚒			restricted BWB
13.3	AK112M183	limestone		★		≈YY⧗⋀		near shoal OWB
13.3	AK112M181	limestone						open marine OWB
13.3	AK112M180	limestone						open marine BWB
13.3	AK112M179	dolostone						open marine BWB
13.3	AK112M178	dolostone						BWB
13.3	AK112M177	cherty limestone			Y★	ƀ	⧗	open platform OWB
13.3	AK112M176	limestone						open platform OWB
13.3	AK112M175	limestone			YY★	⊘⋀⋀	ƀ⧗	near shoal OWB
13.3	AK112M174	limestone			YY	≈		near shoal OWB
13.3	AK112M173	limestone			YY★	ƀ⊘⋔		open platform OWB
13.3	AK112M172	dolomitic limestone				⧗		open platform OWB
13.3	AK112M171	limestone						open platform OWB
13.3	AK112M170	limestone		★		YY		shoal OWB
13.3	AK112M169	limestone						near shoal OWB
13.3	AK112M168	dolomitic limestone						open platform OWB
13.3	AK112M167	dolomitic limestone						restricted BWB
13.3	AK112M166	limestone			Y★	⚒		open platform OWB
13.3	AK112M165	limestone						shoal? OWB
13.3	AK112M164	limestone						open platform OWB
13.3	AK112M163	dolomitic limestone		★				near shoal - OWB

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
13.3	AK112M162	limestone						shoal OWB
13.3	AK112M161	dolomitic limestone			Y★	⊘⌒	⌂	OWB
13.3	AK112M160	limestone						shoal OWB
13.3	AK112M159	dolostone						BWB
13.3	AK112M158	limestone						shoal OWB
13.3	AK112M157	limestone			Y★	⊘⊘⌒		shoal OWB
13.3	AK112M156	limestone						OWB
13.3	AK112M155	limestone						BWB - OWB
13.3	AK112M154	cherty limestone					⚒	restricted (?) or BWB
13.3	AK112M153	chert						open/shoal OWB ?
13.3	AK112M152	limestone			Y	⊘★⌒		BWB ?
13.3	AK112M151	limestone			Y	Q⊘★		restricted or BWB
13.3	AK112M150	limestone				Y⊘⚒★		restricted (?) or BWB
13.3	AK112M149	limestone			Y	⊘		restricted (?) or BWB
13.3	AK112M148	limestone, chert			Y★			restricted or BWB
13.3	AK112M147	limestone, chert			Y⚒			restricted or BWB
13.3	AK112M146	chert						OWB
13.3	AK112M145	limestone			≈★	Y		OWB
13.3	AK112M144	limestone, chert			★	Y		BWB ?
13.3	AK112M143	limestone			Y★	⊘⌂		restricted or BWB
13.3	AK112M142	cherty limestone						restricted (?) or BWB
13.3	AK112M141	limestone			Y	★		restricted (?) or BWB
13.3	AK112M140	limestone, chert				Y★		restricted (?) or BWB
13.3	AK112M139	dolostone						
13.3	AK112M138	dolomitic limestone			Y★	⊘	Q	open marine OWB
13.3	AK112M137	limestone, dolostone			Y	★		restricted (?)
13.3	AK112M136	limestone			⚒Y★	≈⊘⌒	⌂⊙	open marine OWB
13.3	AK112M135	limestone			Y★	≈⚒⌒⊘	Q⌂⌂⌂	shoal or open marine DWB
13.3	AK112M134	dolomitic limestone				Y⊘⚒★	⌂Q⌂	restricted platform
13.3	AK112M132	limestone			Y★	⊘	Y⌂≈⌂⌒	open marine OWB
13.3	AK112M131	limestone			Y	≈Y⊘⌒★	Q	open marine below wave base
13.3	AK112M130	limestone			Y★	Y⊘	Q≈	open marine OWB
13.3	AK112M129	limestone			Y★	⊘⌂	⌂	shoal ?
13.3	AK112M128	limestone			Y★	Y	Q⊘⌂	open marine OWB
13.3	AK112M127	limestone			Y★		⊘	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
13.3	AK112M126	limestone, chert				Y	Q	open marine BWB
13.3	AK112M125	limestone				Y Y	Q	open marine OWB
13.3	AK112M124	limestone, chert				Y		open marine ?
13.3	AK112M123				Y	Y	Q	open marine
13.3	AK112M122	chert, OTHER					Y	?
13.3	AK112M121	dolomitic limestone					Q	?
13.3	AK112M120	dolostone, chert				Y		
13.3	AK112M119	dolomitic limestone, chert			Y Y			open marine?
13.3	AK112M118	limestone, chert			Y		Q	open marine
13.3	AK112M117	limestone, dolostone					Q	open marine
13.3	AK112M116	dolostone, chert				Y		shoal ? -
13.3	AK112M115	dolostone, chert				Y Y		restricted platform
13.3	AK112M114	limestone, chert				Y		restricted platform
13.3	AK112M112	dolostone, chert			Y			shoal
13.3	AK112M111	limestone, chert			Y	Y		open platform
13.3	AK112M110	limestone			Y Y	Q		open platform
13.3	AK112M109	limestone, dolostone			Y	Y	Q	open platform
13.3	AK112M107	cherty dolostone						restricted (?)
13.3	AK112M106	cherty limestone			Y		Q	restricted (?)
13.3	AK112M105	dolomitic limestone			Y	Y	Q	open platform
13.3	AK112M104	dolomitic limestone			Y	Y		open platform
13.3	AK112M103	limestone			Y	Y	Q	near shoal
13.3	AK112M102	limestone			Y	Q		open platform
13.3	AK112M101	limestone			Y	Y	Q	open platform
13.3	AK112M100	limestone, chert						
13.3	AK112M99	calcareous dolostone		•				restricted platform
13.3	AK112M98	dolostone		•			Q	restricted platform
13.3	AK112M97	dolomitic limestone				Y	Q	restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
13.3	AK112M95	calcareous dolostone						restricted
13.3	AK112M94	calcareous dolostone				Y	★⚒	restricted
13.3	AK112M93	dolostone		•			✐	restricted
13.3	AK112M92	dolostone				Y	Q★	restricted
13.3	AK112M91	cherty dolostone					≈★	restricted
13.3	AK112M90	dolostone				★		restricted
13.3	AK112M89	dolostone						restricted marine
13.3	AK112M88	dolostone			Y𝓐			open platform
13.3	AK112M87	cherty dolostone				Y𝓐★		open platform
13.3	AK112M86	dolostone			Y𝓐	★	⚱	open platform
13.3	AK112M85	dolostone			Y𝓐			open platform
13.3	AK112M84	dolomitic limestone			Y★	⚱		open platform
13.3	AK112M83	limestone			Y	Q★⚒	✐⚱✇Ⓐ	open platform
13.3	AK112M82	limestone			Y★	⚱	≈QΣⒶ	near shoal
13.3	AK112M81	limestone			Y★	≈♣YΣ𝓐⚱		near shoal
13.3	AK112M79	limestone				Y★	Q	
13.3	AK112M78	limestone			Y	★	Q⚱Ⓐ	open marine
13.3	AK112M77	limestone				Y⚱Q•⚒★		restricted platform
13.3	AK112M76	chert						
13.3	AK112M75	limestone			Y★	⚱	QⒶ	
13.3	AK112M74	cherty limestone			Y𝓐★	⚱⚒	Q	restricted platform
13.3	AK112M73	dolomitic limestone			Y★	Y𝓐	Q⚱	open marine
13.3	AK112M72	dolomitic limestone			Y★		♣	open marine
13.3	AK112M71	limestone, dolostone			★	Y		open marine
13.3	AK112M70	limestone, dolostone			★	Y	Q	open platform/shoal
13.3	AK112M69	limestone, dolostone			★			open platform/shoal
13.3	AK112M68	dolostone				⚱		
13.3	AK112M67	dolostone				★	Q	
13.3	AK112M66	dolostone					Q	
13.3	AK112M64	limestone, chert				★		open platform
13.3	AK112M63	limestone			Y★	⚱		open platform
13.3	AK112M62	limestone			•	⚱Q★Y		open / restricted platform
13.3	AK112M61	limestone			•	★✐	Q⚱✇	restricted platform
13.3	AK112M60	limestone				𝓐Y⚱•⚒★	✐Ⓐ	restricted platform
13.3	AK112M59	dolostone				Y★		open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
13.3	AK112M57	dolostone						
13.3	AK112M56	limestone			Y★	⚘	Q	open platform
13.3	AK112M55	cherty limestone			Y⌘	Y⚘★	Q⚒	open platform
13.3	AK112M54	limestone, chert			Y	⚘Y★⌘	Q⍝	
13.3	AK112M53	cherty limestone				Q⚒	⚘	restricted marine
13.3	AK112M52	limestone, chert				•	⚘Y	restricted?
13.3	AK112M51	cherty limestone			Y	⌘⚘Y⚒⍝★	Q	restricted
13.3	AK112M50	dolostone, chert				⚘Y★		
13.3	AK112M49	limestone, dolostone				YY★	⚘	
13.3	AK112M47	cherty dolostone				★		
13.3	AK112M46	chert				Y		
13.3	AK112M45	cherty dolostone				Y★	⚘	
13.3	AK112M44	dolostone				Y★	Q	
13.3	AK112M43	cherty dolostone				⚘Y★		
13.3	AK112M41	dolostone						
13.3	AK112M40	cherty dolostone					Y★	
13.3	AK112M39	cherty dolostone				⊗		
13.3	AK112M38	dolomitic limestone			Y	⚘★	Q⍝⚒	
13.3	AK112M37	dolostone				Y⌘★	⚘	
13.3	AK112M35	limestone			Y	⚘★	Q⍝	
13.3	AK112M34	limestone			⚒		⚘YⱰY	restricted marine
13.3	AK112M33	limestone			Y★	Y⚘⌘	⍝⍟⍟⚒⊗⍝	
13.3	AK112M32	limestone			Y⌘	⚘★	⍝	
13.3	AK112M31	limestone			★•		Q⚘	
13.3	AK112M30	chert			⚒			
13.3	AK112M29	limestone			Y⌘★	Ɒ⚒		
13.3	AK112M28	limestone, chert			Y⌘	⚘Y⚒★		
13.3	AK112M27	dolostone				⚘Y★		
13.3	AK112M26	cherty limestone			Y	⚘★		
13.3	AK112M25	limestone, chert			Y	Y⌘	★	
13.3	AK112M24	limestone			Y	★		
13.3	AK112M23	limestone, chert				Y★	⚘	

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
13.3	AK112M22	cherty limestone			Y	★		
13.3	AK112M21	limestone			Y	★	≈	
13.3	AK112M20	dolostone				Y★		
13.3	AK112M19	limestone			YY	★		
13.3	AK112M14	cherty limestone			Y	★		
13.3	AK112M12	cherty limestone			Y	★		
13.3	AK112M10	dolostone				Y★		
13.3	AK112M8	dolostone				Y★		
13.3	AK112M6	dolostone				Y★		
13.3	AK112M4.02	dolostone						
13.3	AK112M0	dolostone, chert				Y	★	
15.1	AK71M0	limestone				★⊙	Y	shoal
15.1	AK71M-0.5	cherty limestone			★			shoal
15.1	AK71M-1	cherty limestone			★	⊙		shoal
15.1	AK71M-1.5	limestone		•		YY★⊙		shoal
15.1	AK71M-2	cherty limestone			•	★⊙		shoal
15.1	AK71M-2.5	cherty limestone		•		YY⊖★		open marine above wave base
15.1	AK71M-3	cherty limestone					★	
15.1	AK71M-3.5	cherty limestone			★	Y		
15.1	AK71M-4	cherty limestone				★		
15.1	AK71M-4.5	cherty limestone		Y	★•		⊙	open marine above wave base
15.1	AK71M-5	cherty limestone		⊖	⊙	★•		shoal
15.1	AK71M-5.5	cherty limestone		⊙	•	Y★		shoal
15.1	AK71M-16	limestone			⊖⊙•	Y★		shoal
15.1	AK71M-16.5	limestone		⊖	⊙•	Y★		shoal
15.1	AK71M-17	limestone		★	Y	Y•		open marine above wave base
15.1	AK71M-17.5	limestone		Y	★	•		open marine above wave base
15.1	AK71M-18	cherty limestone			Y★			open marine above wave base
15.1	AK71M-18.5	limestone			Y★			open marine above wave base
15.1	AK71M-18.8	cherty limestone			★	Y		open marine above wave base
15.1	AK71M-19	limestone			⊖⊙•	Y★		open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.1	AK71M-19.5	limestone			⊖⊙•	♣Y★	⋀	shoal
15.1	AK71M-20.5	limestone		⊖	•	Y♣⊙★	⁄	shoal
15.1	AK71M-21	limestone		Y		★		
15.1	AK71M-21.5	limestone			Y⋀⋀★			open marine above wave base
15.1	AK71M-22.01	limestone		Y	★			open marine above wave base
15.1	AK71M-22.02	limestone		Y	★	⋀⋀		open marine above wave base
15.1	AK71M-22.5	limestone		•	★	⊕Y⧗	♣⊛	
15.1	AK71M-23	limestone			★	Y		open marine above wave base
15.1	AK71M-23.5	limestone		⊖	•	⊘⊙		shoal
15.1	AK71M-24	cherty limestone		•		★⊖		open marine above wave base
15.1	AK71M-24.5	cherty limestone			★•		⊖	
15.1	AK71M-25	limestone		•		★⊖	⊛	shoal
15.1	AK71M-25.5	limestone		⊖	•	★⊙		shoal
15.1	AK71M-27.5	limestone			•	♣⊖★Y		open marine below wave base
15.1	AK71M-28.5	limestone		Y	⋎★	⋀•		open marine above wave base
15.1	AK71M-29	limestone		★	⋎Y	•⧗		open marine above wave base
15.1	AK71M-30	limestone			♣⊖⊙	Y★•	⁄	shoal
15.1	AK71M-30.51	limestone			♣⊙	★Y⊖⧗•		shoal
15.1	AK71M-30.52	limestone			⊖♣⊙⧗•	Y★	⊘	shoal
15.1	AK71M-31	cherty limestone			⊖⊙•	♣≈★	Y⁄	open marine below wave base
15.1	AK71M-31.5	cherty limestone			Y	♣★⊖⊘⋀•⧗⊖⊙	⋀⊛	open marine above wave base
15.1	AK71M-33	limestone		•	♣⊖		Y	open platform / shoal
15.1	AK71M-33.5	limestone			♣•⧗	★Y⊖⁄		open marine above water base
15.1	AK71M-34	cherty limestone		•		♣★		open platform
15.1	AK71M-34.5	limestone		•	⊖	Y♣⊙★	⊘⧗	open platform / shoal
15.1	AK71M-35	limestone			Y★•	⊖		shoal
15.1	AK71M-35.5	limestone		Y	★	⋀⊖⧗•	⊙	open marine above wave base
15.1	AK71M-36	limestone			•	Y★		
15.1	AK71M-36.5	limestone			•	Y★		open marine above wave base
15.1	AK71M-37	limestone				Y★•	⊛	
15.1	AK71M-37.5	limestone			★			
15.1	AK71M-38	limestone		Y	★	⋀•		open marine above wave base

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.1	AK71M-38.5	limestone		★	Y			open marine above wave base
15.1	AK71M-39	cherty limestone				Y★		
15.1	AK71M-39.5	cherty limestone					★	
15.1	AK71M-40	limestone		⊙	•	Y★⧗		shoal
15.1	AK71M-40.5	cherty limestone			Y★	•	♀	open platform
15.1	AK71M-41	limestone			★•	Y		open platform
15.1	AK71M-41.5	limestone			★•	Y		open marine above wave base
15.1	AK71M-42	limestone				Y★		
15.1	AK71M-42.5	cherty limestone			★•	Y		open marine below wave base
15.1	AK71M-43.51	limestone			★			
15.1	AK71M-43.52	limestone			★	Y		
15.1	AK71M-44	limestone			★	Y		
15.1	AK71M-44.5	limestone			★•	≈♀Y⊙⊖		open marine above wave base
15.1	AK71M-45	cherty limestone			★			
15.1	AK71M-45.5	limestone				Y★		
15.1	AK71M-46	limestone			•	★		
15.1	AK71M-46.5	limestone			•	★		
15.1	AK71M-47	limestone			★•	≈Y		open marine below wave base
15.1	AK71M-47.5	limestone			★•	Y	♂	open marine below wave base
15.1	AK71M-48	limestone		Y	•	≈♂♀★		open marine above wave base
15.1	AK71M-49.5	limestone		Y	★	Y♂♂		open marine above wave base
15.1	AK71M-50	limestone			Y	♂♂★		
15.1	AK71M-50.5	cherty limestone			Y★			
15.1	AK71M-51	limestone		⊖		Y♀★•⊙		shoal / open marine above wave base
15.1	AK71M-51.5	limestone		•		Y★		
15.1	AK71M-51.8	cherty limestone			★	⚒		
15.1	AK71M-52	limestone			Y	♂♂★•		
15.1	AK71M-52.5	cherty limestone			Y★	♀•⧗	♣	open marine above wave base
15.1	AK71M-53	limestone		Y	★•			open marine above wave base
15.1	AK71M-53.5	cherty limestone		Y	★			open marine above wave base
15.1	AK71M-54	limestone		★	Y	⊖Y⧗•		open marine above wave base

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.1	AK71M-54.5	cherty limestone		Y	★			open marine above wave base
15.1	AK71M-55.1	limestone		•		★		
15.1	AK71M-55.5	cherty limestone		Y	★			open marine below wave base
15.1	AK71M-56	cherty limestone		Y	★			open marine below wave base
15.1	AK71M-56.5	cherty limestone		Y	★			open marine above wave base
15.1	AK71M-57	cherty limestone			Y★			open marine above wave base
15.1	AK71M-57.5	cherty limestone		Y		Y★		open marine above wave base
15.1	AK71M-58	limestone		Y	★•			open marine above wave base
15.1	AK71M-58.5	limestone		Y	★•	Y		
15.1	AK71M-59	limestone			Y•	★		open marine above wave base
15.1	AK71M-59.5	limestone		•	Y	★		shoal
15.1	AK71M-60	cherty limestone		★	Y			open marine above wave base
15.1	AK71M-60.5	limestone		Y	★			open marine above wave base
15.1	AK71M-60.9	cherty limestone				★		
15.1	AK71M-61	limestone		Y	★			open marine below wave base
15.1	AK71M-61.1	cherty limestone			YY★			open marine below - above wave base
15.1	AK71M-61.5	cherty limestone		★	Y			open marine below - above wave base
15.1	AK71M-62	cherty limestone		Y	★	Y•		open marine below - above wave base
15.1	AK71M-62.5	cherty limestone		Y	★			open marine above wave base
15.1	AK71M-63	cherty limestone		Y	★			open marine above wave base
15.1	AK71M-63.5	cherty limestone		Y	★			open marine above wave base
15.1	AK71M-64	limestone		Y	★			open marine above wave base
15.1	AK71M-64.5	cherty limestone			Y★			open marine above wave base
15.1	AK71M-65	cherty limestone		★	Y			open marine above wave base
15.1	AK71M-65.5	limestone		★	Y			open marine above wave base
15.1	AK71M-66	cherty limestone			Y★			open marine above wave base
15.1	AK71M-66.5	limestone		★	Y			open marine above wave base

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.1	AK71M-67	cherty limestone		★	Y	⧗		open marine above wave base
15.1	AK71M-67.5	cherty limestone		•	⚒			restricted platform
15.1	AK71M-68	cherty limestone		•	⚡Y	★⚠⧗	♣⚠	open platform
15.1	AK71M-68.5	limestone		•		⚠ Y⚡★⚒⚠ ⚡	♣	restricted platform
15.1	AK71M-69	cherty limestone			Y•	★⚒	⚡	open platform
15.1	AK71M-69.5	cherty limestone			Y	⚠★⚡⧗•⚠	♣	open platform
15.1	AK71M-70	cherty limestone			Y	⚠⚡★•⚠	⚡	open platform
15.1	AK71M-71	limestone		•		⚡	★	restricted platform
15.1	AK71M-71.5	cherty limestone			•			
15.1	AK71M-72	limestone		•		★⚡	Y⚠	restricted platform
15.1	AK71M-72.5	cherty limestone		•		⚡⚒	★⚠	restricted platform
15.1	AK71M-73	cherty limestone				Y♣★•⚡	⚠	open platform
15.1	AK71M-73.5	cherty limestone		•	⚒		Y★	restricted platform
15.1	AK71M-74	cherty limestone		•	⚒	Y★		open platform
15.1	AK71M-74.5	cherty limestone		Y	★	⚠⚠ ⚷⧗• ⚠		open platform
15.1	AK71M-75	cherty limestone		•		Y⚠★	⚡	restricted platform
15.1	AK71M-75.5	cherty limestone		•		⚠ Y⚒★		restricted platform
15.1	AK71M-76	cherty limestone		•	★	Y⚠⚠		open platform
15.1	AK71M-76.5	cherty limestone		Y	★•	⚡⚠⚠	⚠	open platform
15.1	AK71M-77	limestone		Y	★•	⚠⚠	⚡⚠	open platform
15.1	AK71M-77.5	cherty limestone		★	Y	⚠•⧗		open platform
15.1	AK71M-78.5	cherty limestone			★⊙⧗	Y⚠		shoal
15.1	AK71M-79	limestone			⊙	★•		shoal
15.1	AK71M-79.5	limestone		•		Y⚡⚠⚒★	⚡	restricted platform
15.1	AK71M-80	limestone		•	Y⚠	⚡★⚒		restricted platform
15.1	AK71M-81	limestone			Y★	⚡⚠⧗		open marine above wave base
15.1	AK71M-81.5	cherty limestone			Y•	⚠⚠⚡★⚠⚡ ⚠		open / restricted platform
15.1	AK71M-82	cherty limestone			Y★•	⚷⚡⚠⚠		open marine above wave base
15.1	AK71M-82.5	limestone			★	⚠♣⧗⊖		shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.1	AK71M-83	limestone				Y♣★⧗⊖		shoal
15.1	AK71M-83.5	limestone		•	⚒	♣★		restricted platform
15.1	AK71M-84	limestone		•		★⚒	♣	open platform
15.1	AK71M-84.5	limestone		Y	⚡★•		⋀⊙	open platform
15.1	AK71M-85	cherty limestone		•				restricted platform
15.1	AK71M-85.5	limestone			•	Y★	⋀	open platform
15.1	AK71M-86	limestone		•	Y	⚡★⚒	⁄	open platform
15.1	AK71M-86.5	cherty limestone		•	⋀	Y⚡★	⁄	open platform
15.1	AK71M-87	cherty limestone			Y★	⋎⋀		open platform
15.1	AK71M-87.5	cherty limestone		Y•		⚡⋎⋀★		open platform
15.1	AK71M-88	cherty limestone		•	★	Y		open platform
15.1	AK71M-88.5	cherty limestone			Y★•	⚡		open platform
15.1	AK71M-89	limestone			Y★•	⧗	⚡	open marine above wave base
15.1	AK71M-89.5	limestone		Y	★	⋀⧗		open marine above wave base
15.1	AK71M-90	cherty limestone		Y	★	⚡⋀⧗		open marine above wave base
15.1	AK71M-90.5	limestone			Y★			open marine above wave base
15.1	AK71M-91	limestone		Y	★	⋀⧗		shoal
15.1	AK71M-91.5	cherty limestone			Y★	⋀⧗		open marine above wave base
15.1	AK71M-92	limestone		Y	★	⋀⧗		open marine above wave base
15.1	AK71M-92.5	limestone			Y★	⚡⋎⧗⋀		open marine above wave base
15.1	AK71M-93	cherty limestone		Y	★	⚡⋎⧗⋀		open marine above wave base
15.1	AK71M-96	cherty limestone		•	Y★	⋎	⚡	open platform
15.1	AK71M-98	cherty limestone		•	Y★	⋀	⚡⋀⚒	open platform
15.1	AK71M-98.5	cherty limestone			Y★•	⋀⧗		open marine above wave base
15.1	AK71M-99	cherty limestone			Y★	⋀⧗		open marine above wave base
15.1	AK71M-99.5	cherty limestone		Y	★	⋎⧗	⚡⋀	open marine above wave base
15.1	AK71M-100	cherty limestone		Y	★	⚡⋎⋀•⋀	⧗	open marine above wave base
15.1	AK71M-100.5	cherty limestone		•	Y⚡		★	open marine below wave base
15.1	AK71M-101	cherty limestone		•	Y⚡	⋎★		open marine below wave base

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.1	AK71M-101.5	cherty limestone		•	Y ★			open marine above wave base
15.1	AK71M-102	cherty limestone			★ Y •	Y		open marine below wave base
15.1	AK71M-102.5	cherty limestone		•	Y	Y ★		open marine below wave base
15.1	AK71M-103	cherty limestone		•		Y Y ★		open marine below wave base
15.1	AK71M-103.5	cherty limestone		•	Y	Y ★		open marine below wave base
15.1	AK71M-104	cherty limestone			Y ★ •			open marine below wave base
15.1	AK71M-104.5	cherty limestone				Y Y ★		open marine above wave base
15.1	AK71M-105	cherty limestone		Y	★	Y		open marine above wave base
15.1	AK71M-105.5	cherty limestone		★	Y •			open marine above wave base
15.1	AK71M-106	cherty limestone		Y	★			open marine above wave base
15.1	AK71M-106.5	limestone			Y ★			open marine above wave base
15.1	AK71M-107	cherty limestone		★	•	Y Y		open marine above wave base
15.1	AK71M-107.5	cherty limestone		★	Y	Y •		open marine above wave base
15.1	AK71M-108	cherty limestone			★	Y	Y	open marine above wave base
15.1	AK71M-108.5	cherty limestone		•	★		Y	open marine below wave base
15.1	AK71M-109	cherty limestone		•		Y ★		open marine below wave base
15.1	AK71M-109.5	cherty limestone		•		Y Y ★		open marine below wave base
15.1	AK71M-110	cherty limestone		★	Y	Y		open marine above wave base
15.1	AK71M-110.5	cherty limestone			★	Y		
15.1	AK71M-111	cherty limestone			★	Y •	Y	
15.1	AK71M-111.5	cherty limestone			•	Y ★	Y	open marine below wave base
15.1	AK71M-112	cherty limestone			•	Y ★		open marine below wave base
15.1	AK71M-112.5	cherty limestone			Y ★ •			open marine below wave base
15.1	AK71M-113	cherty limestone			★	Y •		open marine below wave base
15.1	AK71M-113.5	cherty limestone			•	Y ★	Y	open marine below wave base
15.1	AK71M-114	cherty limestone			★ •	Y		open marine below wave base

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.1	AK71M-114.5	cherty limestone		•	★	Y		open marine below wave base
15.1	AK71M-115	cherty limestone		•	★	YY		open marine below wave base
15.1	AK71M-115.5	cherty limestone		★	•	YY		open marine below wave base
15.1	AK71M-116	cherty limestone		•		Y★	Y	open marine below wave base
15.1	AK71M-116.5	cherty limestone		•		Y★		restricted platform
15.1	AK71M-117	limestone			•	★Y		restricted platform
15.1	AK71M-117.5	dolostone				Y★•A	Y	open marine below wave base
15.1	AK71M-118	cherty dolostone			Y★	Y•A		open marine below wave base
15.1	AK71M-118.5	limestone			★•	YYA		
15.1	AK71M-119	limestone			★Y•	YA		open marine above wave base
15.1	AK71M-120	cherty dolostone		•		Y★	Y	restricted platform
15.1	AK71M-120.5	dolomitic limestone		•		Y★	Y	restricted platform
15.1	AK71M-121	calcareous dolostone		•		★	Y	restricted platform
15.1	AK71M-121.5	limestone		•	★			
15.1	AK71M-122	cherty dolostone			Y•	Y★		restricted platform
15.1	AK71M-122.5	cherty dolostone			★•	YA		restricted platform
15.1	AK71M-123	cherty limestone			★•	YA		shoal / open platform
15.1	AK71M-123.5	cherty limestone			Y★	Y		open platform
15.1	AK71M-124	cherty limestone			★	Y		open platform
15.1	AK71M-124.5	cherty limestone			★•	Y		open platform
15.1	AK71M-125	cherty limestone		Y	★			open platform
15.1	AK71M-125.5	cherty limestone			Y	★•		open / restricted platform
15.1	AK71M-126	cherty limestone		★	Y	YA•		open platform
15.1	AK71M-126.5	limestone			Y★•	YA		open platform
15.1	AK71M-127	limestone			•	Y★		open platform
15.1	AK71M-127.5	cherty dolostone		•	Y★	Y		open / restricted platform
15.1	AK71M-128	cherty limestone			Y★	YA		open platform
15.1	AK71M-128.5	cherty limestone			Y★•	Y		open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.1	AK71M-129	cherty limestone		★		Y		open platform
15.1	AK71M-129.5	cherty limestone		★	Y	Y●		open platform
15.1	AK71M-130	limestone		●	★	YY		open platform
15.1	AK71M-130.5	limestone			★●			
15.1	AK71M-131	cherty limestone			★●	⊘Y	Y⌗	restricted platform
15.1	AK71M-131.5	limestone			★●	Y		restricted platform
15.1	AK71M-132	limestone		●	★	YY◖	⌗	restricted platform
15.1	AK71M-132.5	limestone			★●			open platform
15.1	AK71M-133	limestone			★●	Y		open platform
15.2	AK123M88	cherty limestone			Y★	Y		open platform
15.2	AK123M7	cherty limestone		●	★	Y⌗◖		open platform
15.2	AK123M0	limestone			★	Y		
15.2	AK123M-2.5	limestone			★	YA●		
15.2	AK123M-6	limestone		★	Y	YAΣ		open marine above wave base
15.2	AK123M-7	cherty limestone		●	★	Y⌗◖		open platform
15.2	AK123M-8.1	cherty limestone		★	Y	●		open platform
15.2	AK123M-9.8	cherty limestone		★	Y	●		open marine above wave base
15.2	AK123M-11.8	cherty limestone			★●	YY◖⌗		open platform
15.2	AK123M-12.3	limestone		●		⌗Y⚒★		restricted platform
15.2	AK123M-15.3	cherty limestone		Y	Y★Σ	⌗		open platform
15.2	AK123M-16.4	limestone		●	⚒			restricted platform
15.2	AK123M-19.4	limestone		★	Y	⚓YΣ≈		open platform
15.2	AK123M-22	cherty dolostone			Y★●	Y⊘⌗		restricted platform
15.2	AK123M-22.2	cherty dolostone		●		★		
15.2	AK123M-24	cherty dolostone		●		⚒		restricted platform
15.2	AK123M-26.4	cherty limestone		●		★◖⚒		restricted platform
15.2	AK123M-27.01	cherty limestone		●		⌗Y⚒★		restricted platform
15.2	AK123M-27.02	cherty limestone		●	★	YΣ		open / restricted platform
15.2	AK123M-29.6	cherty limestone		●		★Y⚒◖		restricted platform
15.2	AK123M-30	cherty limestone		●		★⚒		restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.2	AK123M-31.1	cherty limestone		•		★	Y	restricted platform
15.2	AK123M-38.4	limestone		•		★		restricted platform
15.2	AK123M-39	cherty limestone			Y★•			open platform
15.2	AK123M-41	dolomitic limestone		•				restricted platform
15.2	AK123M-44	cherty dolostone			•	Y★		restricted platform
15.2	AK123M-45	limestone		•				restricted platform
15.2	AK123M-45.5	limestone		•				restricted platform
15.2	AK123M-46	limestone		•				restricted platform
15.2	AK123M-47.5	limestone		≈	•			intertidal
15.2	AK123M-49.2	cherty limestone		•	★			restricted platform
15.2	AK123M-51	limestone		•				restricted platform
15.2	AK123M-53	cherty limestone			★•			open platform
15.2	AK123M-53.6	limestone		•				intertidal
15.2	AK123M-55.6	limestone		•				restricted platform
15.2	AK123M-58	cherty limestone		•				restricted platform
15.2	AK123M-66	cherty limestone		•				restricted platform
15.2	AK123M-67	cherty limestone				•		restricted platform
15.2	AK123M-67.5	limestone		★		Y		open platform
15.2	AK123M-73	cherty limestone			★•	Y		open platform
15.2	AK123M-88	cherty limestone			Y★	Y		open platform
15.2	AK123M-92	cherty limestone				Y★•		open platform
15.2	AK123M-93	cherty limestone			Y•	★		open platform
15.2	AK123M-103	limestone			★•	Y		open platform
15.2	AK123M-105	cherty limestone			★•	Y		open platform
15.2	AK123M-106	cherty limestone			★			
15.2	AK123M-107	cherty limestone			Y•	≈★		open platform
15.2	AK123M-110.5	cherty dolostone				★		
15.2	AK123M-115	cherty limestone		Y		★•		open marine above wave base
15.2	AK123M-116	cherty limestone			Y•	≈Y★		open platform
15.2	AK123M-117.5	cherty limestone			•	Y≈★		open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
15.2	AK123M-118.4	cherty limestone		•				restricted platform
15.2	AK123M-119.5	cherty dolostone			•			open platform
15.2	AK123M-120.5	cherty dolostone			★•	Y		open platform
15.2	AK123M-121	cherty dolostone				★•		
15.2	AK123M-122.01	cherty limestone			★			shoal
15.2	AK123M-122.02	limestone		•	★	Y		shoal
15.2	AK123M-123	limestone		•	★	Y		shoal
16.1	AK124M697	limestone		•	Y★			open marine below wave base
16.1	AK124M692	cherty limestone		Y	★	•		open marine below wave base
16.1	AK124M688	cherty limestone		Y	★	•		open marine below wave base
16.1	AK124M685	dolomitic limestone			Y	Y★•		open marine below-above wave base
16.1	AK124M681	dolomitic limestone		•		★		restricted platform
16.1	AK124M680	cherty limestone			Y★	•		open marine above wave base
16.1	AK124M674	limestone			Y★	•		shoal
16.1	AK124M669.5	cherty limestone		•				restricted platform
16.1	AK124M667	cherty limestone		•				restricted platform
16.1	AK124M663	cherty dolostone						
16.1	AK124M657.5	cherty limestone		•		★Y		restricted platform
16.1	AK124M655	cherty limestone		•				restricted platform
16.1	AK124M653	cherty limestone		•		★		restricted platform
16.1	AK124M651	dolomitic limestone			•			restricted platform
16.1	AK124M648	dolostone			•			restricted / open platform
16.1	AK124M640.5	limestone		•		★		open / restricted platform
16.1	AK124M639	cherty limestone		•		Y★		restricted platform
16.1	AK124M637	cherty limestone			Y★	Y•		open platform
16.1	AK124M 637	cherty limestone			Y★	Y•		open platform
16.1	AK124M636	cherty dolostone			•	Y★		restricted platform
16.1	AK124M633	limestone			Y★•	Y		open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
16.1	AK124M627	cherty limestone		•		★⚒		open / restricted platform
16.1	AK124M623	cherty dolostone		•		★ß⚒ᛁ		open / restricted platform
16.1	AK124M621	cherty dolostone			•	⚒	★	restricted platform
16.1	AK124M618	cherty dolostone		•		⚒		restricted platform
16.1	AK124M613	limestone		•		★⚒	ᛁ	restricted platform
16.1	AK124M611	cherty limestone			•	Y♣ᛁ★		shoal
16.1	AK124M605	cherty limestone			•	★ᛁ⚒		restricted platform
16.1	AK124M598.8	cherty limestone		•	★	♣Yᛁ		open / restricted platform
16.1	AK124M594	cherty limestone		•		★ᛁ⚒		restricted platform
16.1	AK124M589	dolomitic limestone		•	≈	⚒	Y⋔	intertidal
16.1	AK124M588	cherty limestone		•	≈	⚒		intertidal
16.1	AK124M587.6	cherty dolostone		•	≈	⚒⧗		intertidal
16.1	AK124M587	limestone		•		★ᛁ⚒	⚘	open / restricted platform
16.1	AK124M578.5	limestone			Y★	⋀⋔Y•⚒ᛁ		open / restricted platform
16.1	AK124M576	dolomitic limestone			Y★	⋔ᛁ⚒	⧗	open to restricted platform
16.1	AK124M571	cherty dolostone			Y•	⋔Y★⚒⋀		restricted platform
16.1	AK124M569	limestone			★•	⚘♣ᛁY		open / restricted platform
16.1	AK124M567.5	limestone			Y★•	♣⚒	ᛁ	shoal
16.1	AK124M566.5	dolomitic limestone		⊗⊗		★•		open platform
16.1	AK124M566	cherty limestone			★	Yᛁ•		open platform
16.1	AK124M562.5	cherty limestone			Y★	≈Yᛁ⋀	⋔	open platform
16.1	AK124M560	limestone			Y★	♣ᛋ•≈	ᛁ⊙	shoal
16.1	AK124M557	calcareous dolostone			•	⋔Y⚒★	⊛	restricted platform
16.1	AK124M556	cherty limestone			Y★	♣⚒•	ᛁ	restricted platform / near shoal
16.1	AK124M551	cherty dolostone		•	⚒		★	restricted platform
16.1	AK124M548	cherty dolostone				★•	⋀⚒	restricted platform
16.1	AK124M542	calcareous dolostone			•	⋔Y⚒★		restricted platform
16.1	AK124M538.5	cherty dolostone				YY⚒★	•	restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
16.1	AK124M537	calcareous dolostone			•	★⚒		restricted platform
16.1	AK124M535	calcareous dolostone						
16.1	AK124M534	cherty dolostone				★		
16.1	AK124M533	cherty dolostone				⌘ Y Y • ⚒ ★		restricted platform
16.1	AK124M532	cherty dolostone			Y ★	Y ⌘ ⊘	◊	open platform
16.1	AK124M528.5	calcareous dolostone			★	Y ⌘		
16.1	AK124M527.5	dolomitic limestone			•	Y ⌘		restricted platform
16.1	AK124M526.5	calcareous dolostone				★ Y ⚒ ◊	⌘ ⊘	open platform
16.1	AK124M525	limestone			⚒	★ •		restricted platform
16.1	AK124M524	limestone			⚒	Y ♣ • ★	⌘ ◊ ⊘	restricted platform
16.1	AK124M522	limestone		•		★ ⌘ Y ⚒ ⊘ ◊		restricted platform
16.1	AK124M521	cherty limestone			Y •	★ Y ⚒ ◊		restricted platform
16.1	AK124M520	cherty limestone			Y •	♣ ★ ⊙	◊ ⧗	shoal
16.1	AK124M518	cherty limestone		★	Y	Y ⚒		open platform
16.1	AK124M517.5	dolostone, chert			Y	◊ ⌘ • ⚒	⌒	restricted platform
16.1	AK124M516	dolostone, chert			Y	★ ◊		open platform
16.1	AK124M514	calcareous dolostone			Y ★	Y ⌘		open platform
16.1	AK124M513.5	dolomitic limestone		Y	★	⊘ Y ⌒ ⌒	♣ ⌘	open platform
16.1	AK124M513.2	dolostone, chert				⌘ Y ⚒ ★		open platform
16.1	AK124M512	cherty limestone		★	Y Y	≈ ⌒	♣ ⊘	open platform
16.1	AK124M447	dolostone, chert			Y ⌘	Y ★ ⌒	⊘	open platform
16.1	AK124M416	limestone		•		♣ ★	⌒ ⊘	open platform
16.1	AK124M412	cherty limestone		★ •		Y		restricted platform
16.1	AK124M409	limestone		•		★	⚡ ♣ Y	restricted platform
16.1	AK124M383	dolostone				★		
16.1	AK124M340	cherty limestone			•	Y ★		shoal
16.1	AK124M281	limestone			•	Y ⌘ ◊	★	restricted platform
16.1	AK124M205	cherty limestone				⊘ ★	Y	shoal
16.1	AK124M125	limestone		⧗	◊ •	♣ ⚡ ≈ ⊘ Y	⌒	open / restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
16.2	AK21M514	cherty dolostone			•	Y★⚒		restricted platform
16.2	AK21M510	cherty limestone		Y	Y★	⚘⚒•	⚐	open platform
16.2	AK21M505	dolostone						
16.2	AK21M489	cherty dolostone						
16.2	AK21M486	dolostone				★		
16.2	AK21M484	dolostone				★		
16.2	AK21M481	dolostone			★	Y⚒•	⚐	restricted platform
16.2	AK21M477	limestone		★	Y⚒	≈⚘	♣⚐	open platform
16.2	AK21M472	cherty limestone		Y	★	Y⚒	⚐	open platform
16.2	AK21M470.7	dolostone		•		★		restricted platform
16.2	AK21M469	calcareous dolostone				⚒Y•★	⚘⚐	open-restricted platform
16.2	AK21M465	limestone			Y	★	♣⚇	shoal
16.2	AK21M461	limestone			Y	★	♣	shoal
16.2	AK21M458	limestone			Y★	♣⚇		shoal
16.2	AK21M454	limestone			★	Y⧗	♣	shoal
16.2	AK21M449	limestone			⚒Y•★	Y⚘⚇	⚐	open platform
16.2	AK21M447	limestone		★	Y⚒	≈⚘	♣⚐	open marine above wave base
16.2	AK21M444	calcareous dolostone			Y★			open / restricted platform
16.2	AK21M439.9	dolostone				⚒•		restricted platform
16.2	AK21M439	dolostone			•	⚒		restricted platform
16.2	AK21M435	dolostone				★		
16.2	AK21M431	dolostone		★		Y⚒		open platform
16.2	AK21M429	limestone			★•		♣Y⚇	shoal
16.2	AK21M424	limestone			Y⚒★	♣	⚇	shoal
16.2	AK21M422	limestone		•	⚒			restricted platform
16.2	AK21M419	limestone		★	Y•	⚘⚒	⚘	open / restricted platform
16.2	AK21M415	dolomitic limestone			•	★Q⚒⚘	♣⚇	restricted platform
16.2	AK21M410	limestone			⚒Y•★	⚘	♣	open platform
16.2	AK21M407	limestone		★	Y			shoal
16.2	AK21M402	dolostone						
16.2	AK21M398	dolomitic limestone		Y	Y★		⚇	open platform
16.2	AK21M390	limestone		•	⚒	⚘	⚇⚇	restricted platform
16.2	AK21M386	cherty limestone			•		★	shoal
16.2	AK21M384	limestone		•	★	⚇Y⚘	♣	open / restricted platform
16.2	AK21M380	cherty dolostone				★		
16.2	AK21M377	limestone		•		⚒Y⚇★	⚇⚘	restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
16.2	AK21M374	limestone			Y★	•⧗	♣⊛	shoal
16.2	AK21M368	limestone			Y★		♣⊛	shoal
16.2	AK21M362	limestone				Y♣★⧗⊛	⚘	shoal
16.2	AK21M361	limestone			•	★Y♣⚒⊛⚡		open platform
16.2	AK21M359	limestone			⚡Y	⚡⌂★•⚒		open / restricted platform
16.2	AK21M357	cherty dolostone					⚒	
16.2	AK21M352	dolomitic limestone					★	
16.2	AK21M346	limestone			Y★		⚠	shoal
16.2	AK21M340	limestone				★	Y⚘⧗⊛	shoal
16.2	AK21M336	limestone			★	Y	⊛	shoal
16.2	AK21M335	limestone		•		⚡Y⌂⚒⊛★	⚘⚘	restricted platform
16.2	AK21M333	cherty dolostone		⚒		★⊛•		restricted platform
16.2	AK21M330	dolomitic limestone				⚡Y⚡•⚒★		open / restricted platform
16.2	AK21M326	limestone			Y★	⧗	⚠	shoal
16.2	AK21M319	limestone		★	Y	⧗	♣⚘⊛	shoal
16.2	AK21M315.5	limestone				Y★•	♣⊛⧗	shoal
16.2	AK21M314	limestone		Y	★	⚘⚡	♣⊛⊖	open platform
16.2	AK21M310	dolostone				Y⚡		
16.2	AK21M305	dolostone						
16.2	AK21M300	dolostone				Y⚡		
16.2	AK21M298	calcareous dolostone					★	
16.2	AK21M295	dolostone					★	
16.2	AK21M294.5	limestone		•	⧗	⚒	Y♣⊛★	restricted platform
16.2	AK21M289.5	limestone			Y★		⊛	shoal
16.2	AK21M285	limestone			Y	⚘★	♣⊛	shoal
16.2	AK21M279	limestone			•	⚘♣Y★⚡	⚡⚡⊛⧗⊙	open / restricted platform
16.2	AK21M277	limestone			•	≈♣⌂⚘⚡★ Y	⚡⚠	open / restricted platform
16.2	AK21M268	limestone			•	Y♣⊛★	⊙	shoal
16.2	AK21M265	limestone				★≈♣⚡⧗• ⊛	Y	open platform / near shoal
16.2	AK21M262	limestone			•	♣⊛	★⚡	restricted platform
16.2	AK21M258	limestone			★	⚡Y⧗	♣⚠	shoal
16.2	AK21M253	limestone			★		Y	shoal
16.2	AK21M245	dolostone		★			Y	open platform
16.2	AK21M241	dolostone				★		
16.2	AK21M237	limestone			★	Y	≈⊙	shoal
16.2	AK21M 234	limestone				★		open platform
16.2	AK21M234	limestone			•	★		open / restricted platform
16.2	AK21M227	calcareous dolostone			★	⚡	♣Y	open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
16.2	AK21M218	limestone			YY★	≈		open platform
16.2	AK21M215	limestone		★		Y		shoal
16.2	AK21M211.5	limestone			★	Y≈		open / restricted platform
16.2	AK21M207.5	limestone			•	★		restricted platform
16.2	AK21M204	limestone			★	≈	Y	shoal
16.2	AK21M200	limestone			•	≈★	⊙	open / restricted platform
16.2	AK21M191	limestone			•⧗	Y★		shoal
16.2	AK21M188.5	calcareous dolostone				★⧗	Y	open platform
16.2	AK21M186	limestone			★⧗	Y		shoal
16.2	AK21M183	limestone				≈★•		restricted platform
16.2	AK21M178.8	limestone		≈		•		intertidal
16.2	AK21M175	limestone			•		★	restricted platform
16.2	AK21M169.9	limestone			≈•			intertidal
16.2	AK21M168	limestone			⊖•	YY⧗⊙		restricted platform / near shoal
16.2	AK21M166	limestone		⊙		⧗		shoal
16.2	AK21M161.7	limestone		•	⧗			restricted platform
16.2	AK21M161	limestone			•			restricted platform
16.2	AK21M156	limestone		•				restricted platform
16.2	AK21M154.5	limestone, sandstone		•		≈★		open platform
16.2	AK21M149.5	limestone			•	★	Y	open / restricted platform
16.2	AK21M145.5	limestone			YY⧗•			restricted platform
16.2	AK21M143	limestone				≈⧗•	Y Y	restricted platform
16.2	AK21M139.7	cherty limestone			•			restricted platform
16.2	AK21M137	limestone			•⧗		≈	restricted platform
16.2	AK21M135	limestone		•				intertidal
16.2	AK21M132.5	dolostone						restricted platform
16.2	AK21M131	limestone			⊚⧗			restricted platform
16.2	AK21M127.5	limestone		⊚		⧗.		restricted platform
16.2	AK21M126.8	limestone			⧗	≈	★	restricted platform
16.2	AK21M126.6	limestone			⧗			intertidal
16.2	AK21M123.7	limestone			≈⧗			open platform
16.2	AK21M123	limestone		⧗		≈		restricted platform
16.2	AK21M10	dolostone						
16.2	AK21M7	dolostone						
16.2	AK21M3.3	dolostone				★		
16.2	AK21M0.3	dolostone						
20.2	AK72M114	limestone			⊙	⧗★		shoal
20.2	AK72M113	limestone				Y		shoal
20.2	AK72M112	limestone				Y★⧗⊖		shoal
20.2	AK72M111	limestone			Y	★	Y	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
20.2	AK72M110	limestone			⊖	Q⊙	♢⊘Y	shoal
20.2	AK72M109	limestone			⊖	YQ⊙★	⊘♢⧗•	shoal
20.2	AK72M108	limestone			Y★	ƱY♢⚒ƱƱ⊘	Q✇⧗	restricted platform
20.2	AK72M107	limestone			Y★	Y⊘ƱƱ	♣Q⧗Ⓐ	open marine
20.2	AK72M106	limestone			YƱƱ★	ƱY⧗⊘	♣QⒶ≈	open marine
20.2	AK72M105	limestone				Y♣Ƴ★⧗⊙ ⊖	Q≈⊘	shoal
20.2	AK72M104	limestone			♢Y★	⊘⊘⊙	ƳQ♣⧗Ⓐ	shoal
20.2	AK72M103	limestone			★	Q♢⊘ƱY	⚒YⒶ⧗•	open platform
20.2	AK72M102	limestone			•	⊘♢Y⊖★	⊘♣	restricted platform
20.2	AK72M101	limestone			Y★	QYƱ•⚒	⊘⊘⊘⧗⚒	open platform
20.2	AK72M99	cherty limestone				♣⊘⊘ƳⒶ⧗ Y★	Q	open platform
20.2	AK72M98	limestone				♣⊘♢⊘Ⓐ⊙ Y★	Ƴ≈	shoal
20.2	AK72M97	cherty limestone			Y★	YƱ	ƳQ⊘⧗⊘≈	open marine
20.2	AK72M96	cherty limestone			Y★	Q⊘	⚒	open marine
20.2	AK72M95	limestone			YƱ★		Q⊘	open marine
20.2	AK72M94	cherty limestone			★	YƱ⧗	Ⓐ	open marine
20.2	AK72M93	limestone			YƱ	⊘★	Q⧗	open marine
20.2	AK72M92	cherty limestone			Y★	Y⊘ƱƱ	Q♣	open marine
20.2	AK72M90.7	cherty limestone				Y★	Q	shoal
20.2	AK72M90	limestone			⊖	YƱƱ⊙★	♣Q♢⧗Ⓐ⊘	shoal
20.2	AK72M89	limestone			YƱ	⊘★	QⒶ	open platform
20.2	AK72M88	limestone			YƱ	★⧗	QƱ♢≈⊙Ⓐ ⊘	open platform
20.2	AK72M87	limestone			YƱ	♢★⧗	Q⊘	open platform
20.2	AK72M86	limestone			YƱ	♢★	⊘Y	open platform
20.2	AK72M85	limestone			YƱ★	♢	QƱƳⒶ♣	open platform
20.2	AK72M84	limestone			Y★	Q⧗	♣⊘	
20.2	AK72M83	limestone			Y	♢⊘★	Ƴ♣Ⓐ	shoal
20.2	AK72M82	limestone			YƱ	♣Y★⊘	♢QⒶ	open platform
20.2	AK72M81	limestone			YƱ★	Y	ƳQ⊘Ⓐ⚒	open platform
20.2	AK72M80	limestone			Y★	Q	⚒Q⧗⊖	shoal
20.2	AK72M79	limestone			YƱ★	Y⊘	QⒶ	open platform
20.2	AK72M78	limestone			YƱ	★	Q⊘	open platform
20.2	AK72M77	limestone			YƱ	Y⊘★	QƳ⚒	open platform
20.2	AK72M76	limestone			YƱ⊙	⊘★⧗	ƳQ⚒♣	shoal
20.2	AK72M75	limestone			⚒	♣	⊘Q★•⊘	restricted platform
20.2	AK72M74	cherty limestone				Y★	⊘	
20.2	AK72M73	limestone				Q	★	restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
20.2	AK72M71.1	limestone			Y	⊘&★⊞	QY⊼≈	
20.2	AK72M71	limestone			⚒	⊞Y◊★	⊙⌂Y⊘&	open marine
20.2	AK72M70	limestone			Y★	⊘⊞⧗	Q&⊼	open marine
20.2	AK72M69	limestone			Y⊞★	QY&⧗⊘	ß⊼⊕	open marine
20.2	AK72M67	limestone			Y⊞	★⧗	YQ	open marine
20.2	AK72M66	limestone			Y⊞	Y★⧗	&Q⊼⊘	open marine
20.2	AK72M65	limestone			Y⊞★		Q&	open marine
20.2	AK72M64	limestone			Y	★	&Q⊕⊘	open marine
20.2	AK72M63	limestone			Y⊞★	Y⧗	Q	open marine
20.2	AK72M62	limestone			Y	Y⊞★	Q⊘⊕	open marine
20.2	AK72M61	limestone			Y⊞	Y★⧗	Q&	open marine
20.2	AK72M60	limestone			Y★	Y⊞⧗	ßQ⊙⊕&	open marine
20.2	AK72M59	limestone			YY⊞	⊘★	Q	open platform
20.2	AK72M58	limestone			⊘⚒	◊	Q★	restricted platform
20.2	AK72M57	limestone			⚒	⊘★◊	⌂Q	restricted platform
20.2	AK72M56	limestone			⚒	⊘Q★Y	◊	restricted platform
20.2	AK72M55	limestone			⚒	⊘Q★Y	◊	restricted platform
20.2	AK72M54	limestone			⚒	⊘Q⊞Y	★⌂⧗◊	restricted platform
20.2	AK72M49				⊙	⊞Y⌂•⊖★	Q⊙⧗&	shoal
20.2	AK72M48	limestone			⊙	⌂⊖	&ß★⊘	shoal
20.2	AK72M47	limestone		•		★	ßQ⌂&⊙Y⊘	restricted platform
20.2	AK72M46	dolostone			⚒		Q★	restricted lagoon
20.2	AK72M45	dolostone				Y★⚒	Q	restricted platform
20.2	AK72M44	limestone			Y	⊙⌂Y★⊞	≈&Q⧗⊙⊘	shoal
20.2	AK72M43	limestone			Y	Q⌂★⊘		open marine
20.2	AK72M41	limestone			Y⊞	⌂Q★	⊘&⊙⊼	open marine
20.2	AK72M40	limestone			Y	Y⌂⊞⧗★	&ßQ⊙⊼⊘	open marine
20.2	AK72M39	limestone			Y	⊘Y⌂⧗★⊞	ßQ&⊕≈	open marine
20.2	AK72M38	limestone			Y⊞	Y★	Q⌂&⊕⊘	open marine
20.2	AK72M37	limestone				YQ⊞⧗★	Y⌂⊘•⊕	open marine
20.2	AK72M32	limestone			⊖	⊘⊙⌂Y⧗★⊞	&Q⊼⊙⊕	shoal
20.2	AK72M31	limestone			⊖	Y⊙⌂⧗★⊞	ßQ&⊙⊕	shoal
20.2	AK72M30	limestone			⊖	⊘&⊙•⊙★	YQ⌂⧗⊕◊	shoal
20.2	AK72M29	limestone				Y&⊞•★	QYß⚒⊘	restricted lagoon
20.2	AK72M28	limestone			⚒	◊•	&QY⊘★	restricted platform
20.2	AK72M26.8	limestone				★YQ•⚒◊	&⌂⊘⊘	restricted platform
20.2	AK72M26	limestone			Y⊞	Y★	⊙⌂Q⧗⊼	open platform
20.2	AK72M22.8	limestone				Y⊘Y⊕★⊞	Q&	open platform
20.2	AK72M22	limestone			⊖⊙	&⊘⊙Y★⧗Y⊞	Q⌂⊕ß	shoal
20.2	AK72M21	limestone			★	ß&⊙YY⊙⧗⊞⊖	Q≈⊼	shoal
20.2	AK72M20	limestone			Y⊞★	Y	ßQ⌂⊕⊼⊘	open marine

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.1	AK75M1120	limestone			Y•	⌘⌀♣⧗⊙★		open marine AWB / BWB
22.1	AK75M1111	cherty limestone			⌘Y•★	⚒	♣⌂	open marine below wave base
22.1	AK75M1102	limestone		Y	★		⌀	open marine above wave base
22.1	AK75M1071	cherty limestone			Y•	⚒⌘★	⌀⊙	open marine below wave base
22.1	AK75M1064	limestone			Y	★⌘⧗•	⊙	open marine above wave base
22.1	AK75M1031	limestone		Y	⚒	★⌂		open marine awb
22.1	AK75M1009	limestone			Y⌘•	⚒★		open marine below wave base
22.1	AK75M1005	limestone		★	Y	⊖⊙		open marine above wave base
22.1	AK75M992	limestone		Y		★⌀⌂		open marine awb
22.1	AK75M976	dolomitic limestone			⌘Y•★			open marine below wave base
22.1	AK75M758.5	cherty dolostone			⚒•	Y⌘★		open marine below wave base
22.1	AK75M744	limestone		⚒Y	•	⌀★⚒⌂		open marine below wave base
22.1	AK75M739	limestone		•	★	Y	⊘	shoal
22.1	AK75M732.5	limestone			Y⌘•	⚒★	♣	open / restricted platform
22.1	AK75M704	limestone		Y⌘	•	★⌂⊗⌀	⊘	open / restricted platform
22.1	AK75M692.5	limestone		★				
22.1	AK75M683	dolostone		•			Y★⊘	restricted platform
22.1	AK75M664	limestone		•		Y⌀⌀★	⌂	open / restricted platform
22.1	AK75M598	cherty limestone		•		Y★		shoal
22.1	AK75M593	limestone			⚒Y★	•		open platform
22.1	AK75M576	dolostone		•		⚒		restricted platform
22.1	AK75M557	cherty limestone			★	Y•		shoal
22.1	AK75M534	limestone				★♣⊘•⊖	Y	shoal
22.1	AK75M520.5	limestone			•⧗	≈⌂⌀⌀⌂	⌀	restricted / open platform
22.1	AK75M488.2	argillaceous limestone		•	⧗			intertidal / restricted / subaerial
22.1	AK75M479.5	cherty dolostone						
22.1	AK75M462	limestone			•	★Y⌀⧗⚒⌀	⌀⊘	restricted platform
22.1	AK75M444.5	limestone			⊘•	⌀♣⌀⚒★Y		restricted / open platform
22.1	AK75M427.5	limestone			♣⌀	⊗⊗★⌀•⊘		open / restricted platform
22.1	AK75M392.5	limestone		•	♣⊘	⌀		restricted platform
22.1	AK75M377.3	limestone		⊗⊗		⌀≈♣Y⚒⊘★	⌀	restricted / open platform
22.1	AK75M353	limestone			•	★♣⌀⚒⊘		open / restricted platform
22.1	AK75M317.5	limestone			•	♣★		open / restricted platform
22.1	AK75M293	limestone				Y♣•★		open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.1	AK75M281	limestone				Y♣●★		open platform
22.1	AK75M250	calcareous dolostone			●	★	♣	
22.1	AK75M245	limestone				Y♣●★	𝒮	open platform
22.1	AK75M236.5	limestone				Y𝒴●★	☮	open platform
22.1	AK75M205.5	limestone			●	≈♣Y𝒥★	☮	restricted platform
22.1	AK75M184.5	limestone			♣	𝒥★●☮		restricted / open platform
22.1	AK75M167	limestone		●		𝒥𝒜	♣★	restricted platform
22.1	AK75M163.9	limestone				Y♣𝒲●★	☮	open platform
22.1	AK75M160	limestone			★	♣Y𝒥	𝒲☮	open platform
22.1	AK75M152	limestone		●		Y♣⚒★	☯♁☮𝒥	restricted platform
22.1	AK75M128	cherty dolostone				★	♣	
22.1	AK75M123	limestone				Y♣𝒥★	☮	restricted / open platform
22.1	AK75M120.5	dolostone				★		
22.1	AK75M109	dolostone				●		
22.1	AK75M101	cherty dolostone			●	⚒		restricted platform
22.1	AK75M70	dolostone						
22.1	AK75M52	dolostone						
22.1	AK75M42.5	dolostone						
22.1	AK75M6	limestone			⚒	Y♣𝒮●𝒥★		restricted platform
22.1	AK75M3	cherty limestone			⚒	★Y●𝒥		restricted platform
22.1	AK75M1.5	cherty limestone			⚒	★Y●𝒥	⊙⧗	restricted platform
22.1	AK75M0.5	cherty limestone			⚒●	𝒮𝒥	☮	restricted platform
22.12	AK125M1219	cherty limestone		Y	★	☯♣𝒴𝒲●𝒜 𝒜		open marine above wave base
22.12	AK125M1177	cherty limestone		Y	★	𝒲𝒴⧗●		open marine above wave base
22.12	AK125M1166	cherty limestone			★	Y𝒜●	☯	open marine above wave base
22.12	AK125M1156	cherty limestone			★	Y●		open marine below wave base
22.12	AK125M1150	limestone			Y●	★𝒲𝒥⚒𝒥𝒜		open marine below wave base
22.12	AK125M1147	cherty limestone			Y★	𝒴𝒲𝒜		open marine above wave base
22.12	AK125M1144	cherty limestone		Y		𝒲★𝒴≈𝒜● ⧗𝒥𝒜		open marine above wave base
22.12	AK125M1143	cherty limestone			Y●	★𝒲𝒴⚒𝒥𝒜		open marine below wave base
22.12	AK125M1137	cherty limestone			Y●	♣𝒮𝒴𝒥★𝒲		open marine below wave base
22.12	AK125M1136	cherty limestone			Y●	☯𝒲♣𝒴𝒮𝒜 ⚒𝒥★𝒜		open marine below wave base

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.12	AK125M1130	limestone			Y			open marine above wave base
22.12	AK125M1123	limestone		Y				open marine above wave base
22.12	AK125M1120	cherty limestone		Y				open marine above wave base
22.12	AK125M1117	cherty limestone			Y			open marine above wave base
22.12	AK125M1114.5	cherty limestone		•	Y			open marine below wave base
22.12	AK125M1113	cherty limestone		Y				open marine above wave base
22.12	AK125M1109	limestone		Y				open marine above wave base
22.12	AK125M1105	limestone		Y				open marine above wave base
22.12	AK125M1101	cherty limestone		Y				open marine below /above wave base
22.12	AK125M1093	cherty limestone		Y				open marine above wave base
22.12	AK125M1092.7	limestone		Y				open marine above - below wave base
22.12	AK125M1087.2	limestone			Y			open marine above - below wave base
22.12	AK125M1080	limestone		Y				open marine above wave base
22.12	AK125M1076.5	cherty limestone		Y				open marine below - above wave base
22.12	AK125M1073	cherty limestone						open marine above - below wave base
22.12	AK125M1072	cherty limestone		•				open marine below wave base
22.12	AK125M1071.5	cherty limestone						open marine below wave base
22.12	AK125M1071	cherty limestone						open marine above - below wave base
22.12	AK125M1067.5	cherty limestone		Y				open marine above wave base
22.12	AK125M1066	cherty limestone						open marine above wave base
22.12	AK125M1058	cherty limestone		Y				open marine above wave base
22.12	AK125M1048	cherty limestone		Y				open marine above wave base
22.12	AK125M1047	cherty limestone			Y			open marine above wave base
22.12	AK125M1042	limestone			Y			open marine above wave base
22.12	AK125M1040	cherty limestone						open marine above wave base
22.12	AK125M1038	limestone		Y				open marine above - below wave base

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.12	AK125M1035	cherty limestone		Y				open marine above wave base
22.12	AK125M1027	cherty limestone			Y			open marine below wave base
22.12	AK125M1026	limestone		Y				open marine below wave base
22.12	AK125M1020	cherty limestone		Y				open marine above wave base
22.12	AK125M1014	cherty limestone			Y			open marine above wave base
22.12	AK125M1008.02	cherty limestone			Y			open marine below wave base
22.12	AK125M1008.01	cherty dolostone			Y			open marine below wave base
22.12	AK125M1007.5	cherty limestone			Y			open marine below wave base
22.12	AK125M1005	limestone						shoal
22.12	AK125M996	limestone		Y				open marine above / below wave base
22.12	AK125M994	limestone		Y				open marine above - below wave base
22.12	AK125M990	limestone		Y				open marine below wave base
22.12	AK125M986	cherty limestone		Y				open marine below wave base
22.12	AK125M981.5	cherty limestone		Y				open marine below wave base
22.12	AK125M976	cherty dolostone						open marine below wave base
22.12	AK125M974.5	cherty limestone						open marine below wave base
22.12	AK125M973	limestone		Y				open marine above wave base
22.12	AK125M957.5	limestone		Y				open marine below wave base
22.12	AK125M954	limestone		Y				open marine above wave base
22.12	AK125M950	cherty limestone						
22.12	AK125M949	cherty limestone						restricted platform
22.12	AK125M944	limestone						restricted platform / near shoal
22.12	AK125M943.5	limestone						shoal
22.12	AK125M938	cherty limestone					Y	restricted platform
22.12	AK125M933	cherty limestone						open / restricted platform
22.12	AK125M930	limestone						restricted platform
22.12	AK125M929.5	cherty limestone						restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.12	AK125M928	cherty limestone		•		Y		restricted platform
22.12	AK125M920	cherty limestone		•	Y			open / restricted platform
22.12	AK125M917.5	cherty limestone			•	Y		open / restricted platform
22.12	AK125M916	cherty dolostone		•		Y		restricted platform
22.12	AK125M914	limestone		•		Y		restricted platform
22.12	AK125M912.5	limestone		•		Y		open / restricted platform
22.12	AK125M909	cherty limestone		Y		•		open marine above wave base
22.12	AK125M906	cherty limestone			Y			open marine above wave base
22.12	AK125M906	cherty limestone			Y			open marine above wave base
22.12	AK125M904	cherty dolostone		•				
22.12	AK125M900	limestone			Y	•		shoal
22.12	AK125M897	cherty limestone		•		Y		open / restricted platform
22.12	AK125M896	limestone		•		Y		restricted platform
22.12	AK125M888.5	cherty limestone			•			restricted platform
22.12	AK125M887	cherty limestone			•			open platform
22.12	AK125M885	cherty limestone			•			restricted platform
22.12	AK125M882	cherty limestone			•	Y		restricted platform
22.12	AK125M877	cherty limestone				Y •		open / restricted platform
22.12	AK125M874	cherty limestone		•		Y		open / restricted platform
22.12	AK125M873	limestone		•				restricted platform
22.12	AK125M868	cherty limestone		•		Y		open / restricted platform
22.12	AK125M864	cherty limestone			•	Y		open / restricted platform
22.12	AK125M861	cherty limestone			Y •			open marine below wave base
22.12	AK125M859	limestone			Y •			open marine below wave base
22.12	AK125M855	cherty limestone		Y				open marine above wave base
22.12	AK125M852.5	limestone		Y	Y			open marine above wave base
22.12	AK125M845	limestone			Y	•		shoal
22.12	AK125M838	limestone			Y			open marine above wave base

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.12	AK125M835	cherty limestone			Y			open marine above wave base
22.12	AK125M825	limestone			Y			open marine above wave base
22.12	AK125M817.5	limestone				Y		open marine below wave base
22.12	AK125M815	limestone			Y			open marine below wave base
22.12	AK125M811	dolomitic limestone				Y		open marine below wave base
22.12	AK125M807	cherty limestone				Y		open marine above wave base
22.12	AK125M806	limestone		•				open marine below - above wave base
22.12	AK125M803.5	limestone			Y			open / restricted platform
22.12	AK125M802	limestone		•				open marine below wave base
22.12	AK125M799	cherty limestone			Y			open marine above wave base
22.12	AK125M796	dolostone						
22.12	AK125M791	cherty limestone			Y			open / restricted platform
22.12	AK125M790	limestone		•				restricted platform
22.12	AK125M786.3	cherty limestone			Y			open / restricted platform
22.12	AK125M785.5	cherty limestone		•		Y		restricted platform
22.12	AK125M784	cherty limestone			Y•			open / restricted platform
22.12	AK125M 784	cherty limestone			Y•			restricted to open platform
22.12	AK125M783.5	cherty limestone			Y•			open / restricted platform
22.12	AK125M782.5	cherty limestone			Y			open marine below wave base
22.12	AK125M779.5	cherty limestone			Y			open marine above wave base
22.12	AK125M776	limestone			Y			open marine below wave base
22.12	AK125M773.5	cherty limestone						open marine below wave base
22.12	AK125M770	limestone			•			open marine below/above wave base
22.12	AK125M769	limestone			Y			open marine awb
22.12	AK125M768.5	limestone			Y			open marine awb
22.12	AK125M768	limestone			Y			open marine below wave base
22.12	AK125M767	limestone		•				open marine below wave base
22.12	AK125M766	cherty limestone		•				restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.12	AK125M762.5	cherty limestone				★⚘⚡●⚒		
22.12	AK125M761	limestone			Y★	⚒⚘●⚓		open marine below - above wave base
22.12	AK125M754	limestone		●		★	⚘	shoal
22.12	AK125M752	limestone			★●	Y⚓		shoal
22.12	AK125M748	limestone			⚡Y●	⚘★⚡		open marine below wave base
22.12	AK125M743	limestone			Y●	⚘⚡⚒⚡★		open / restricted platform
22.12	AK125M740	limestone			Y	★⚒⚡⚓●⚠⚡		open / restricted platform
22.12	AK125M738	limestone			★●	Y⧗		shoal
22.12	AK125M717	limestone		●		★⚡		restricted platform
22.12	AK125M712	limestone			Y★	≈⚡⚒●⚡	⧗	open platform
22.12	AK125M710	cherty dolostone		●		Y⚡★⚒	⚠	restricted platform
22.12	AK125M707	cherty limestone			●	Y⚡⚒⚡★		open platform
22.12	AK125M700	limestone				Y★●		open platform
22.12	AK125M689	cherty limestone			★●	Y⚒		shoal
22.12	AK125M686	limestone		●	★	Y⚡		shoal
22.12	AK125M685	cherty limestone		●		⚡⚒		restricted platform
22.12	AK125M675	cherty dolostone		●		⚒Y★⚒⚡		restricted platform
22.12	AK125M666	limestone		●	⚒	⚡⚠		open / restricted platform
22.12	AK125M663.5	cherty limestone			⧗	Y♣⚡★	⊙	open platform
22.12	AK125M652	limestone		★	Y	⚘⚡⚓⚒		open platform
22.12	AK125M601	limestone			★	⚘♣⧗●	⚠	open platform
22.12	AK125M600	limestone			●	⚘♣★⚠⚡		open / restricted platform
22.12	AK125M597.5	cherty limestone			★	⚘Y●		shoal
22.12	AK125M597	limestone			★	⚡Y⧗●		shoal
22.12	AK125M589	cherty limestone		●		⚒Y★⚒⚡		restricted platform
22.12	AK125M584	cherty limestone		●		⚘≈♣⚡★Y		open / restricted platform
22.12	AK125M571	cherty limestone			★	⚘♣Y●⚡	⚠	open platform
22.12	AK125M557	cherty limestone				★♣●⊙		shoal
22.12	AK125M544	cherty limestone		●		⚘≈♣⚡★Y		open / restricted platform
22.12	AK125M523.5	limestone			●	⚘≈⚓⚠⚡★		open / restricted platform
22.12	AK125M517	limestone			●	⚘≈⚠⚡		restricted platform
22.12	AK125M498	limestone			⊙●	⚡★⚠⧗⊖		restricted platform / near shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.12	AK125M492	limestone		•		✇⌀★⧗⊙⚒		restricted platform
22.12	AK125M490	limestone		•		✇⌀⧗⚒		restricted platform
22.12	AK125M474.5	cherty limestone		•		⌀★⧗⚒		restricted platform
22.12	AK125M473	limestone		•		⌀★♣⧗⚒✇		restricted platform
22.12	AK125M471.2			•		★⌀		restricted platform
22.12	AK125M470	limestone		•		≈★⌀		restricted platform
22.12	AK125M467.5	cherty limestone		•		⌀⚒		restricted platform
22.12	AK125M466	limestone		•		⌀⚒		restricted platform
22.12	AK125M460	limestone		•		★⌀⚒		restricted platform
22.12	AK125M457.5	limestone		•		⌀⊖	⊙	restricted platform / near shoal
22.12	AK125M452	limestone		•		★⚷⌀⚒✇		restricted platform
22.12	AK125M447	limestone		•	⚒	⧗	✇	restricted platform
22.12	AK125M446	limestone		•		≈♣⚷⚱⚒✇⌀		restricted platform
22.12	AK125M445	limestone		•		★⚱⚷⚒✇⌀		restricted platform
22.12	AK125M439	limestone		•		⌀⚱♣✇⊙⊖⚒		restricted platform / near shoal
22.12	AK125M435	limestone			•	★♣⌀⚒✇		open / restricted platform
22.12	AK125M432	limestone				⚱≈♣★•✇⌀		open / restricted platform
22.12	AK125M400	limestone			✇•	≈♣⚷⚒⌀★	⚱	open / restricted platform
22.12	AK125M395	limestone			✇•	⚱♣⌀★		open / restricted platform
22.12	AK125M 395	limestone			✇•	⚱♣⌀★		open / restricted platform
22.12	AK125M388	limestone			•	⚱≈♣★⚒✇⌀		open / restricted platform
22.12	AK125M385	limestone			✇•	⚱♣⌀★		restricted platform
22.12	AK125M370	cherty limestone			⊗⊗•	⚱≈♣⚒✇⌀		open / restricted platform
22.12	AK125M363.5	limestone		⊗⊗				
22.12	AK125M357.5	limestone				Y⚱♣★•✇⌀		open platform
22.12	AK125M355.5	limestone			•	⚱≈♣Y⚒⌀★	✇	open / restricted platform
22.12	AK125M349.5	limestone			•	⚱Y⚷♣✇⚒★⌀		open / restricted platform
22.12	AK125M348.5	cherty limestone			•	♣⚱⚲⚷Y✇⚒★⌀		open / restricted platform
22.12	AK125M345	limestone			•	Y⚱♣★⚒✇⌀		open / restricted platform
22.12	AK125M339	cherty limestone			•	Y⚱♣⚒⌀★		open / restricted platform
22.12	AK125M336	cherty limestone			•	★⚱♣⚒✇⌀		open / restricted platform
22.12	AK125M326	limestone		⊗⊗		•		
22.12	AK125M322	cherty limestone				★♣•⚒		open / restricted platform
22.12	AK125M313	limestone		•		★Y♣⚒✇⌀		restricted platform
22.12	AK125M311	limestone		•		★Y♣⚒✇⌀		restricted platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
22.12	AK125M302	limestone			•	Y♣♀★⚒✇✓		open / restricted platform
22.12	AK125M290	cherty limestone				♣Y★		
22.12	AK125M285	limestone			•	Y♣★✇✓		open platform
22.12	AK125M283.5	limestone			★	Y♣•✓		open platform
22.12	AK125M282	limestone			★	Y✇		open platform
22.12	AK125M278	limestone			★	♣Y✇		open platform
22.12	AK125M276	limestone			★	Y✇•		open platform
22.12	AK125M275	cherty limestone			•	★Y✓⚒✇		restricted platform
22.12	AK125M274	limestone			★	Y•		open platform
22.12	AK125M271.5	limestone				Y♣♀⧗•★		open platform
22.12	AK125M269	limestone			★	♣⚒•		open platform
22.12	AK125M262	limestone				★Y•✇		open / restricted platform
22.12	AK125M 262	limestone				★Y•✇		open /restricted platform
22.12	AK125M215	limestone				Y♣★•✓		open platform
22.12	AK125M200	limestone		•		♣★✓		open / restricted platform
22.12	AK125M175	limestone				★Y♣✓•✇⚒		open / restricted platform
22.12	AK125M 175	limestone				★Y♣✓•✇⚒		open / restricted platform
22.12	AK125M172.4	limestone			•	Y✋♣★✇⚒✓		open /restricted platform
22.12	AK125M170	limestone		•		Y♣★⚒✓		open / restriction platform
22.12	AK125M162	limestone			★	≈♣•Y		open platform
22.12	AK125M157	cherty limestone		•		Y★		restricted platform
22.12	AK125M139	cherty limestone				✋♣Y•★		open platform
22.12	AK125M136	limestone				✋♣★•✓		open platform
22.12	AK125M123	cherty limestone			•	Y✓		open platform
22.12	AK125M108	limestone				★		
22.12	AK125M96	limestone						
22.12	AK125M92.5	cherty limestone				★		
22.12	AK125M87.5	cherty limestone				★		
22.12	AK125M70	limestone				★		
22.12	AK125M60	cherty limestone				★•		
22.12	AK125M35.02	cherty limestone						
22.12	AK125M35.01	cherty limestone						
22.12	AK125M31.5	cherty limestone				★		
22.12	AK125M21	cherty limestone						
100.1	AK116M156.5	limestone			★	Y✓✓•	♣✋	

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
100.1	AK116M154	limestone		Y	★	Y⌀	♣	
100.1	AK116M152	limestone			Y★	⌀	♣	
100.1	AK116M148.2	limestone			Y★	⌀		
100.1	AK116M146.5	limestone			Y★	⌀		
100.1	AK116M139.3	limestone			Y★	Y⌀	♣	
100.1	AK116M133.8	limestone			Y★	⌀		
100.1	AK116M131	limestone		Y		⌀★	⚒	
100.1	AK116M129.8	limestone			Y	♣Y⌀★		
100.1	AK116M127.02	limestone				Y⌀●⚒	☮	
100.1	AK116M127.01	limestone			●	Y⌀★	☮⚒	
100.1	AK116M124.5	limestone		⊗⊗				
100.1	AK116M124	limestone			Y★●	⌀♣		
100.1	AK116M120.3	limestone			Y★	⌀	♣	
100.1	AK116M118.5	limestone		★		Y	♣☮	
100.1	AK116M113.5	chert		★		⌀YY	♣	
100.1	AK116M111	limestone		Y	★	Y	♣♣☮	
100.1	AK116M108.7	cherty limestone			⌀	Y★		
100.1	AK116M106.3	chert			⌀	Y★⚒		
100.1	AK116M105.6	limestone		★		⌀	Y	
100.1	AK116M103.8	limestone			●	Y⌀★	♣	
100.1	AK116M99.1	limestone			●	★	☮	
100.1	AK116M97.5	limestone			Y●★	♣⌀		
100.1	AK116M95.7	limestone			★●	♣☮☮		
100.1	AK116M94.8	limestone			Y★	⌀●ᗡ	♣☮	
100.1	AK116M90.5	limestone			Y★	⌀♣●	☮	
100.1	AK116M89.5	limestone			★●		⌀Y	
100.1	AK116M88	limestone			★	⌀♣Y●	☮	
100.1	AK116M84	limestone			●	★		
100.1	AK116M82.5	limestone			●	⌀★		
100.1	AK116M79	limestone			●	YY★		
100.1	AK116M76	limestone		★	Y	≈⌀	♣	
100.1	AK116M74	limestone			★	Y⌀●⚒	♣	
100.1	AK116M65	limestone			Y●★	⌀☮	♣≈	
100.1	AK116M62	limestone			★	⌀♣Y●		
100.1	AK116M57.7	limestone			Y★●	⌀⚒		
100.1	AK116M57.3	limestone		★	Y	⌀♣●	☮	
100.1	AK116M56	limestone			Y★	♣Y⌀		
100.1	AK116M53.5			★	Y	♣Y⌀		
100.1	AK116M50.5	limestone			Y★	♣●		
100.1	AK116M45.5	cherty limestone		★	Y	♣⌀		

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
100.1	AK116M44.3	limestone			Y★	⬇	♣	
100.1	AK116M43	limestone			⌂Y•★		♣◎≈⧗⊛	
100.1	AK116M38.7	limestone		★	Y⌂	♣Y⊛⊛⬇		
100.1	AK116M32	limestone		★	Y	⬇	♣⌂	
100.1	AK116M20.7	dolomitic limestone			Y★	≈⬇•	♣⊛	
100.1	AK116M18	limestone			Y⌂★	♣⬇⌀		
100.1	AK116M11	limestone			Y⌂★	Y⬇⌀	⧗	
100.1	AK116M1	limestone		★	Y	⬇⌀⧗	⌃⌂	
100.2	AK115M167	limestone		•		★⊛⚒	♣	
100.2	AK115M162.6	limestone		★	•	⬇Y	♣⌀⊛	
100.2	AK115M160.5	limestone			Y★•	⬇⌀	♣	
100.2	AK115M158.3	limestone		•		Y★⚒	♣⊛	
100.2	AK115M153.7	limestone			Y★	♣⌀•		
100.2	AK115M153	limestone			⌂Y•★	♣⬇	⚒	
100.2	AK115M149.4	limestone		★		⬇♣YY•⌀⌂		
100.2	AK115M146.8	limestone		•		Y⌂★	♣⊛	
100.2	AK115M140.7	limestone			Y★•	♣⬇⌀	⊛	
100.2	AK115M137	limestone			⌂Y•★	⬇⌀	♣⊛	
100.2	AK115M136.5	limestone			★•	Y⬇♣⧗⌀⌃		
100.2	AK115M133.5	limestone		★	Y⌂•	♣⬇⌀	⊛	
100.2	AK115M133	limestone, cherty limestone			★•	⬇Y⌂Y	♣⊛	
100.2	AK115M125.8	limestone			⌂Y⊛★	♣Y⬇⧗⌀	⚕	
100.2	AK115M123.5	limestone			Y★	⬇⌀		
100.2	AK115M117.8				Y★	⧗	⬇⌀	
100.2	AK115M117.8	limestone			Y★	⧗	⬇⌀	
100.2	AK115M114.5	limestone			Y★	⧗	♣⬇	
100.2	AK115M113.3	limestone			Y★	⌀		
100.2	AK115M107.3	limestone		★	Y⌂	⬇		
100.2	AK115M101.5	limestone		★	Y	♣⬇	⧗	
100.2	AK115M96	limestone			Y⌂★	Y⬇	♣	
100.2	AK115M91.7	limestone			Y⌂★	⬇⌀⧗	♣	
100.2	AK115M89	limestone		★	Y	⧗	♣	
100.2	AK115M86	limestone			Y⌂★	♣Y≈⌀⬇		
100.2	AK115M83.5	limestone		★	Y	⬇⌀	♣	
100.2	AK115M79.5				Y⌂★	Y⬇⌀	♣	
100.2	AK115M77.5	limestone			★•	Y⬇⌂⚒⌀	⊛	
100.2	AK115M76.8				Y⌂★	⚕⌀⊙⧗⌀⬇	⌂	
100.2	AK115M74.5	limestone			Y★	≈⌀⬇⧗⌀.	⚕♣⌂	
100.2	AK115M71	limestone		★	♣	⌀⧗	⚕⌂	
100.2	AK115M70.3	limestone			Y⌂★	♣⬇	⚕	
100.2	AK115M66.5	limestone			♣★	⌀≈	⬇Y⌀	

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
100.2	AK115M64				♣★	⊘♡Y♂⚒	ß	
100.2	AK115M60.5	limestone			♣★	♡≈♂	Y⚒	
100.2	AK115M59.4	limestone			♣★	⊘≈♡•♂Y		
100.2	AK115M57.5	limestone			♣Y★	⚒⊘♡⧗⊙♂		
100.2	AK115M50.3	dolomitic limestone			★	Y⊘♣•♂⚒		
100.2	AK115M49.3	limestone			Y★	⊘♂	♣	
100.2	AK115M46.5	limestone			♣★	Y⊘⧗♂		
100.2	AK115M45	limestone				★⊘♣•⚒♂	✇⧗	
100.2	AK115M40.5	limestone			♣★	YY♂⚒	⚒⧗	
100.2	AK115M39.7	limestone			★	≈Y♡♣•⧗♂ ✇		
100.2	AK115M38.5	limestone			★	≈⊘♣♡◎⊛ ⧗•♂⊙	✇	
100.2	AK115M28	limestone			★	♣Y♂	Q⊘✇	
100.2	AK115M21.5	limestone			★	⊘♣♂Y		
100.2	AK115M18	dolostone				Y⊘⚒⚒★		
100.2	AK115M10.2	dolostone			★	Y⊘♣⚒♂⚒	ß✇	
100.2	AK115M7.2	dolomitic limestone				⊘YY⚒★.		
100.2	AK115M3	limestone			Y★	⊘Y♂⚒	♣✇	
100.2	AK115M0.5	limestone			Y★	⊘⚒♂	♣	
100.3	AK94M433.5	limestone			★	Y♂•	♣✇	
100.3	AK94M374.5	limestone			★	⊘♣♡⧗♂Y	✇	
100.3	AK94M373.5	limestone			★	⊘♣♂Y		
100.3	AK94M347	chert			⚒	♂	♣Y	
100.3	AK94M343	limestone, chert			⚒	Y★	✇	
100.3	AK94M332	dolomitic limestone, chert			⚒	Y★♂	✇	
100.3	AK94M327.5	dolomitic limestone		★	Y⚒	Y⊘♂	♣⚒	
100.3	AK94M324.5	limestone			Y★⚒	♂•	⚒✇	
100.3	AK94M322.5	limestone		★		Y♂		
100.3	AK94M315	dolomitic limestone			Y⚒★	Y♂		
100.3	AK94M311	dolomitic limestone				★⚒•		
100.3	AK94M310	dolomitic limestone				♂★✇•⚒		
100.3	AK94M305	limestone		★		♣Y⊘♂Y		
100.3	AK94M299	limestone		★		⊘Y♂	✇•	
100.3	AK94M295.5	limestone			★	⊘♣♡•⚒♂	✇	
100.3	AK94M287.5	limestone			★	♂⊘♣•⚒✇	♡	
100.3	AK94M285.5	limestone			★	♂♣•⚒	✇	
100.3	AK94M279.3	limestone			★	⊘Y♡♣⚒•♂ ✇		

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
100.3	AK94M277	limestone		★		⊘ ⊘ •	Y ♣ ⚒ ✇	
100.3	AK94M273.5	limestone			Y ⚠ ★	⊘ ♣ Y ⊘ • ⚒ ✇		
100.3	AK94M270	limestone			Y ⚠ ⚒	♣ ★ •	✇	
100.3	AK94M266	limestone			Y ⚠ ★	⊘ ⊘ ⚒ ✇	♣	
100.3	AK94M257.5	limestone			★ •	Y ⚒	✇	
100.3	AK94M255	dolomitic limestone		★		⊘		
100.3	AK94M252.5	limestone		★	Y	⊘ ⊘ ⧗	♣ ♣	
100.3	AK94M246	limestone		★		Y		
100.3	AK94M243	dolomitic limestone		★		⊘	Y ⧗	
100.3	AK94M238.5	limestone			•	⊘ ★ ⚒ ✇	⊘ Y	
100.3	AK94M236	dolomitic limestone			•	★ ⊘	✇	
100.3	AK94M233.5	dolostone				★		
100.3	AK94M231	dolostone			★			
100.3	AK94M227	limestone		•	★	Y ⊘ ⚠ ⚒ ⊘	✇	
100.3	AK94M223	cherty limestone				★		
100.3	AK94M215.5	limestone		★		⊘ Y		
100.3	AK94M214.5	limestone		★		Y ⊘	⚠ ✇	
100.3	AK94M207.5	dolomitic limestone, cherty limestone				★	♣ ✇	
100.3	AK94M201	limestone				★ ⚒		
100.3	AK94M200	dolomitic limestone			★	⊘ •		
100.3	AK94M199	dolomitic limestone		★		⊘ Y ⊘		
100.3	AK94M196	dolomitic limestone		★	Y	♣		
100.3	AK94M192.5	limestone		★		⊘ ♣ Y ⊘ ⚠		
100.3	AK94M184	dolostone			★	Y		
100.3	AK94M181	dolomitic limestone			Y ⚠	★ ⊘ • ⊘	⚒	
100.3	AK94M178	limestone			Y ★	⊘		
100.3	AK94M175	limestone		★		⊘ ♣ ⊘ Y		
100.3	AK94M170	dolomitic limestone			★	⊘ Y ⊘	Q	
100.3	AK94M168	dolostone						
100.3	AK94M164.3	dolostone, chert				★ ⚒		
100.3	AK94M157	limestone		★		⊘ Y ⊘		
100.3	AK94M155	dolomitic limestone			★	♣ Y ⊘	Q ⚠	
100.3	AK94M153	limestone		★		Y	⊘	

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
100.3	AK94M151	dolomitic limestone		★		⊘Y		
100.3	AK94M149.2	limestone			Y★	⊘⊘●		
100.3	AK94M145.8	limestone			Y★	⊘⊘	♣	
100.3	AK94M145	limestone			⊗⊗	Y⊘●★	♣	
100.3	AK94M144	dolomitic limestone			★●	⊘⊘⚒	♣	
100.3	AK94M142	limestone			Y⚠★	⊘⊘		
100.3	AK94M140.5	limestone			Y⚠★	⊘	Q	
100.3	AK94M138	dolostone				★		
100.3	AK94M137	dolostone				Y★		
100.3	AK94M134.5	dolostone				★	⊘	
100.3	AK94M132.5	dolostone				Y★	Q	
100.3	AK94M126.5	dolostone				★		
100.3	AK94M121.6	dolostone					★	
100.3	AK94M118.5	dolostone						
100.3	AK94M112.5	dolostone					★	
100.3	AK94M109.8	dolostone						
100.3	AK94M106.5	dolostone						
100.3	AK94M103	dolostone						
100.3	AK94M101	dolostone						
100.3	AK94M95.5	limestone			Y⚠★	⊘●	⊘	
100.3	AK94M94.62	OTHER			⚒	⊘Y★		
100.3	AK94M94.61	limestone		★	Y⚠⚒	⊘⊘		
100.3	AK94M94	dolomitic limestone		★			⊘Y	
100.3	AK94M62.02	OTHER				⊘Y★		
100.3	AK94M62.01	limestone			Y⚒	★⊘⊘⊘	♣⧗	
100.3	AK94M60	OTHER			⚒	★		
100.3	AK94M57.7	dolomitic limestone, chert			★	♣⊘		
100.3	AK94M57	dolostone			★			
100.3	AK94M48.5	OTHER				⚒		
100.3	AK94M46.5	limestone			Y⚠	⊘♣★⊗⊘	●	
100.3	AK94M46	limestone		★		♣⊘Y	♂	
100.3	AK94M43.5	limestone			★	Y⊘●	♣⊗	
100.3	AK94M40	dolostone				★		
100.3	AK94M38	dolomitic limestone		★		Y⊘⊘⚠		
100.3	AK94M36.5	dolostone				★		
100.3	AK94M34	limestone			★	⊘♂Y⚒⊘		
100.3	AK94M25	limestone		★		⊘Y	♣⊘	
100.3	AK94M22	cherty dolostone				Y★⚒		

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
100.3	AK94M20	limestone		★	Y			
100.3	AK94M16	limestone, dolostone			★	Y		
100.3	AK94M5	limestone		★		Y		
100.3	AK94M1	limestone		★			Y	
100.3	AK94M0	dolostone				★		
100.4	AK93M137	dolostone				Y★		
100.4	AK93M109.5	limestone			Y★			
100.4	AK93M108	limestone			★	Y		
100.4	AK93M107	dolostone					★	
100.4	AK93M100.5	dolostone				★		
100.4	AK93M92.5	dolostone				★		
100.4	AK93M91	dolostone				★		
100.4	AK93M86.5	dolostone				★		
100.4	AK93M83	dolostone				★		
100.4	AK93M82	dolostone				★		
100.4	AK93M68	dolostone						
100.4	AK93M65.5	dolostone				★		
100.4	AK93M61.5	limestone			★	Y		
100.4	AK93M57	limestone		★		Y		
100.4	AK93M53.2	limestone		★		Y		
100.4	AK93M51.2	limestone			Y★			
100.4	AK93M47	limestone		★	Y			
100.4	AK93M44.5	limestone			•	★		
100.4	AK93M42	limestone, dolostone						
100.4	AK93M39.5	limestone			Y★			
100.4	AK93M34	dolostone					Y★	
100.4	AK93M30.5	dolostone					★	
100.4	AK93M25	dolostone						
100.4	AK93M24	dolostone				Y★		
100.4	AK93M23.5	dolostone					★	
100.4	AK93M20.5	dolostone				Y★		
100.4	AK93M17.5	dolostone				★		
100.4	AK93M15	dolostone				★		
100.4	AK93M9.5	dolostone				★		
100.4	AK93M6	dolostone				Y★		
100.4	AK93M5.5	dolostone						
100.4	AK93M4	limestone		Y	★			
100.4	AK93M0	limestone			Y★			
100.5	AK92M59	limestone			Y★			
100.5	AK92M51.5	limestone		★	Y			
100.5	AK92M50	limestone, dolostone			Y	★		

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
100.5	AK92M48.6	limestone		Y				
100.5	AK92M45.8	limestone		★	Y			
100.5	AK92M44	limestone			Y ★	Q		
100.5	AK92M43	limestone				Y Q ★		
100.5	AK92M36.8	dolomitic limestone			Y ★			
100.5	AK92M35.5	limestone, dolostone		★	Y			
100.5	AK92M34.5	limestone			Y ★			
100.5	AK92M33.5	limestone, dolostone			Y ★			
100.5	AK92M31.5	limestone		★		Y Q	Y	Hardground??
100.5	AK92M1.7	limestone			★	Q Y		
100.5	AK92M1	limestone			Y ★			
100.6	AK117M11	limestone			Y ★	Y		
100.6	AK117M9	limestone		Y	★	Y		
100.6	AK117M5.5	limestone, dolostone				Y ★		
100.6	AK117M5.3	dolostone, chert				Y ★		
100.6	AK117M4.5	dolomitic limestone				Y Y • ★		
100.6	AK117M1.5	dolomitic limestone			Y ★	Y		
100.6	AK117M0.6	dolomitic limestone			Y ★			
100.6	AK117M0.5	limestone			Y	Y ★	Q	
105	WELL-9284	limestone			Y ★		Y Q	near shoal
105	WELL-9285.01	cherty limestone			Y ★	•		lagoon near shoal
105	WELL-9285.02	limestone				Y • ★ Y	Q	shoal/channel
105	WELL-9286	limestone			Y	Y ★		lagoon near shoal
105	WELL-9287	limestone			Y ★	•		open platform, near shoal
105	WELL-9288	limestone			Y ★		Q	open platform
105	WELL-9290	limestone			•	Y ★	Q	shoal
105	WELL-9291	limestone			•	★		shoal
105	WELL-9292	limestone			•	Y ★	Q	shoal
105	WELL-9293	limestone				Y ★ •		shoal
105	WELL-9294	limestone			Y Y ★	• ★		near lagoon/storm/channel
105	WELL-9295	limestone		•		Q		lagoon
105	WELL-9296	cherty limestone					Q	lagoon
105	WELL-9297	limestone				Q		lagoon

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9298	dolomitic limestone				Q⚒		lagoon
105	WELL-9299	limestone				Q𝒸⚒		lagoon
105	WELL-9300	limestone			⚒	Q𝒸		lagoon
105	WELL-9301	chert		⚒				lagoon
105	WELL-9302	limestone			Y★	◎◎♣𝓜𝒱	♀≈	open platform
105	WELL-9303	limestone			◎◎	Y𝒱★𝓜	𝒸⧗	shoal
105	WELL-9304	limestone			Y𝓜	◎◎♢★𝒱♣		open platform/near shoal
105	WELL-9305	limestone			◎◎★Y	♣𝒱	♢	open platform
105	WELL-9306	limestone			◎◎	𝒱♢Y⧗★	𝓑	shoal/platform
105	WELL-9307	dolomitic limestone			𝒱Y★		♢𝓑	open platform
105	WELL-9308	dolomitic limestone			Y★	♣𝒱		open platform
105	WELL-9309	chert				𝒱Q★Y		lagoon
105	WELL-9310	sandy or silty dolostone				Q		lagoon
105	WELL-9311	sandy or silty dolostone			Q			lagoon
105	WELL-9312	sandy or silty dolostone			Q	Y𝒱★𝓜		near open platform
105	WELL-9314	dolomitic limestone			𝒱Y★	♢	𝓑≈⊙	open platform
105	WELL-9315	limestone			Y★	♢♣𝒱	◎𝒸	open platform
105	WELL-9316	limestone			YY★	◎♣◎♢♀𝒱 ⊙⧗𝒜𝓜Λ	𝒸	open platform OWB
105	WELL-9317	dolomitic limestone			Y𝒱★𝓜	♣♢⊙≈	𝒸𝓑⧗	near shoal
105	WELL-9318	limestone			◎◎⊖	𝒱Y♀♣⊙⧗ 𝓜★	𝓑	shoal
105	WELL-9319	limestone			◎◎𝓜Y	♣♢𝒱⊖★	♀⧗	near shoal
105	WELL-9320	limestone			Y𝓜★	♣𝒱◎◎•⧗ Λ⊙	𝒸𝒜	open platform OWB
105	WELL-9321	dolomitic limestone			Y★	Λ𝒱⧗•	𝓑	near lagoon BWB
105	WELL-9322	limestone			◎◎•	Y♣♀𝓜⧗𝒸 ★	𝓑Q𝒜𝒱	lagoon/shoal
105	WELL-9323	limestone			◎◎	𝒱≈𝓑Y⧗★ 𝓜	♣Λ	shoal
105	WELL-9324	limestone	◎◎			Y𝒱𝓑⧗•★		shoal
105	WELL-9325	limestone			◎◎⊖	𝓑♀♢𝒱⧗★ Y	⊙	shoal
105	WELL-9326	limestone			◎◎⊖	♣♀♢★Y𝒱	𝓑⊙	shoal
105	WELL-9327	limestone			◎◎	𝒱𝓑♢Y⧗⊖ ★		shoal
105	WELL-9328	limestone			◎◎	𝓑𝒱♢♀⊖⧗ Y★		shoal
105	WELL-9329	limestone			Y𝓜	♣𝒱★	♀𝒜⧗	open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9330	dolomitic limestone			Y	Q		open platform BWB
105	WELL-9331	dolomitic limestone				Q		open platform BWB
105	WELL-9332	dolomitic limestone			Y			open platform BWB
105	WELL-9333	dolomitic limestone			Y		Q	near lagoon BWB
105	WELL-9334	limestone			Y			near shoal
105	WELL-9335	limestone			Y			shoal
105	WELL-9336	dolomitic limestone			Y			open platform/NWB
105	WELL-9337	limestone			Y			open platform OWB
105	WELL-9338	limestone			Y			open platform/NWB
105	WELL-9339	dolomitic limestone, sandy or silty limestone			Q			shallow intertidal
105	WELL-9340	sandy or silty limestone, cherty limestone			Q			shallow intertidal
105	WELL-9341	limestone						shallow intertidal
105	WELL-9342	limestone						open platform OWB
105	WELL-9343	dolostone					Q Y	
105	WELL-9344	sandy or silty limestone			Q			
105	WELL-9345	limestone			Y	Q		?
105	WELL-9346	limestone, dolostone, chert				Y		BWB or protected
105	WELL-9347	limestone, dolostone			Y		Q	near open platform
105	WELL-9348	limestone			Y			open platform OWB
105	WELL-9349	limestone, chert			Y			open platform OWB
105	WELL-9350	limestone			Y			open platform/NWB
105	WELL-9351.01	dolostone				Y		lagoon
105	WELL-9352	limestone			Y			open platform
105	WELL-9353	limestone			Y			open platform OWB
105	WELL-9354	limestone			Y			open platform OWB/BWB
105	WELL-9355	limestone			Y			open platform OWB
105	WELL-9356	limestone				Q		lagoon
105	WELL-9357	limestone				Q		lagoon

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9358	limestone				Q		lagoon
105	WELL-9359	limestone				Q	★	lagoon
105	WELL-9360	limestone				⚘QY⚡★		lagoon
105	WELL-9361	limestone, chert			Q	⚘♣•★	Y⚡	lagoon
105	WELL-9362	sandy or silty limestone			Q	★•	⚘Y	lagoon
105	WELL-9363	chert			⚘Y★			?
105	WELL-9364	limestone, dolostone				⚘Y♁◎⚡•⚒★	≈♣⚒⚒	lagoon
105	WELL-9365	limestone, dolostone				◎◎⚲⚘⚡★Y	⚷≈⚷	lagoon
105	WELL-9366	limestone, dolostone				≈⚘◎⚲◎⚒•★Y⚒		lagoon/with wave influence
105	WELL-9367	limestone		◎◎		Y★	⚷	lagoon/shoal
105	WELL-9368	limestone		◎◎		Y★		shoal
105	WELL-9369	limestone		◎◎		Y★	⚷⚘⚒	shoal
105	WELL-9370	limestone		◎◎		⚘≈♁⚒★Y	♣⚡	shoal
105	WELL-9371	dolomitic limestone			◎◎	≈♁⚘★Y		lagoon
105	WELL-9372.01	limestone			⚒	Q⚘•	Y★	lagoon
105	WELL-9372.02	limestone				⚘≈♣Y⧖⚡★	◎	lagoon
105	WELL-9373	limestone			⊙	⊖		shoal
105	WELL-9374	limestone			⊖⊙			shoal
105	WELL-9375.01	limestone		⊙		⚘•⧖	Q	shoal
105	WELL-9375.02	sandstone		Q				shallow - near shore
105	WELL-9376	dolostone, chert				Q		?
105	WELL-9377	limestone			★•	♣◎◎Y⚘≈	⚒	shoal/near shoal
105	WELL-9378	limestone			Y★	≈♣•⚘		shoal/near shoal
105	WELL-9379	limestone			Y⚒★	◎⚷♁◎≈•⧖⚘⚒	⚡⚒⊛	shoal
105	WELL-9380	chert						shoal
105	WELL-9381	limestone			◎Y★	◎♁•⚘	⚒	shoal
105	WELL-9382	limestone		⊙	⊖			shoal
105	WELL-9383	limestone		⊙	⊖	♁⚘★	QY	shoal
105	WELL-9384	limestone			⊖⊙	★		shoal
105	WELL-9385	limestone			⊖•	⚘Q♁⊙★Y		shoal
105	WELL-9386	limestone			•	⚘★♁Q⚡⊙⧖⚠⊖		lagoon
105	WELL-9387	sandstone		Q				shallow water
105	WELL-9388	sandstone		Q				shallow water
105	WELL-9389	limestone			⚘★	♣QY•⚒	≈	open platform/skeletal OWB

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9391	chert			Y★			?
105	WELL-9392	limestone			Y★	♣◎♢≈•ᗰ ⊍	ℬ𝒻⊙	open platform
105	WELL-9393	limestone			Yᗰ★	♣Y≈•⊍	♀◎	open platform OWB
105	WELL-9394	limestone			Yᗰ★	◎♀♢♣⊙⊍ ≈	𝒻	open platform OWB
105	WELL-9395	limestone			⊙	≈◎Y⊖★		shoal
105	WELL-9396	limestone			⊙	ℬY♢⊍⊖★ Y	◎◎ᗰ⧗ᗩ	shoal
105	WELL-9397	limestone			⊖⊙	Y◎♢♀≈ᗰ ★⊍Y	ℬ𝒻	shoal
105	WELL-9398	limestone			◎◎⊙	♣⊍♢YY⊖ ⊕ᗰ★	ᗩ	lagoon/shoal
105	WELL-9399	limestone		⊙		⊖	♣Y★	shoal
105	WELL-9400	limestone			⊖⊙	⊍Y★	𝒻ᗩ	shoal
105	WELL-9401	limestone			⊖⊙	⊍≈Y⧗★	♣	shoal
105	WELL-9402	limestone			⊖⊙	⊍★	QY	shoal
105	WELL-9403	limestone			⊖⊙		⊍★	shoal
105	WELL-9404	limestone			⊙•	♣⊍⊖	ℬQ★Y	shoal-near lagoon
105	WELL-9405	limestone			•	★⊍✇𝒻	♢Q	lagoon
105	WELL-9406	limestone				★	⊍Q𝒻⊙ᗩ	lagoon
105	WELL-9407	chert			⊙	⊍Y★	♣	shoal
105	WELL-9408	limestone			♣★•	⊍≈♢⊙✇Y	Q	near lagoon
105	WELL-9409	limestone			♣★•	⊍≈Y⊙✇	Q𝒻	near lagoon
105	WELL-9410	limestone			♣★•	⊍≈Y⊙✇	𝒻	near lagoon
105	WELL-9411	limestone			♣★•	⊍≈Y⊙✇	♢Q𝒻	near lagoon
105	WELL-9412	limestone			♣★•	⊍≈♢⊙✇Y	𝒻	near lagoon
105	WELL-9413	limestone			♣★•	⊍≈♢⊙✇𝒻	Y	near lagoon
105	WELL-9414	limestone			♣★•	⊍≈𝒻⊙✇	Q	near lagoon
105	WELL-9415	limestone			♣★•	Y⊍≈⊙✇𝒻	Q	near lagoon
105	WELL-9416	limestone			♣★•	⊍≈⊙𝒻	QYᗩ	near lagoon
105	WELL-9417	limestone			YY★	≈⊍♢♣𝒻• ᗰᗩ	♀Q	open platform
105	WELL-9418	limestone			YY★	♣≈♢ℬ⊍• ⧗ᗰᗩ	◎Q◎ᗩ𝒻	open platform
105	WELL-9419	limestone			◎◎★Y	♣≈♢♀⊍⊙ •𝒻⊖	ᗩℬ⧗✇	near shoal-washed in ooids
105	WELL-9420	dolomitic limestone			⊍YY★ ᗰ	◎◎♢♀𝒻ᗩℬ ♣	ᗩ•	open platform BWB
105	WELL-9421	dolomitic limestone, chert			Y★	♣⊍𝒻	♢Qᗩ	open platform BWB
105	WELL-9422	limestone, dolostone			Y★	♢⊍	Q≈⧗	open platform BWB
105	WELL-9423	dolomitic limestone			YY★ᗰ	ℬ♀♢⊍≈♣	𝒻⧗	open platform BWB
105	WELL-9424.01	dolostone				Yᗰ	Q	lagoon/deep water BWB

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Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9424.02	dolomitic limestone			◎Y	★⊖	ϑQ	lagoon/near shoal
105	WELL-9425	dolomitic limestone			⚠Y⊖★	◎ϒϑΛϑ♣	♁ℬ⚠	open platform-near shoal
105	WELL-9426	dolostone				♣Y★	♁	shallow/deep
105	WELL-9427	dolomitic limestone			Y⚠★	ϒ♣ϑ	⚠	open platform BWB
105	WELL-9428	cherty dolostone				Q		shallow/deep
105	WELL-9431	dolostone				Q		lagoon/quiet water
105	WELL-9432	dolostone				Q		lagoon/quiet water
105	WELL-9433	dolomitic limestone				Yϑ•★	Q	lagoon/quiet water
105	WELL-9434	limestone				★⚒	Q♣ϑ	lagoon/quiet water
105	WELL-9436	limestone				Yϑ⚒★	Q	lagoon/quiet water
105	WELL-9438	limestone		•		ϑ♁★✇ℓ	♣⚒⊙	lagoonal
105	WELL-9439	limestone		•		ϑ≈⊙★	Q♣ℓ	lagoonal
105	WELL-9440	limestone		•		ϑ≈Y⚒★	♣Q⊙ℓ	lagoonal
105	WELL-9441	limestone		•		ϑY★	Q	lagoonal
105	WELL-9442	limestone		•		ϑ♣Yℓ★	Q✇⊙	lagoonal
105	WELL-9443	limestone			⊖•	Yϑ≈⊙ℓ★	ϑ	shoal
105	WELL-9444	limestone			•	Yϑ♣★⊙⊖ℓ	ϑQ✇	shoal
105	WELL-9445	limestone			⊖•	♣≈♁ϑϑℓ⊙Y★	ℬ⚠⧗	near shoal
105	WELL-9446	limestone			ϑ•	Y♣ϑ★⊙⊖ℓ	⧗	near shoal
105	WELL-9447	limestone			•	ϑY♣≈⊖⊙★ℓ	⚠	near shoal
105	WELL-9448	limestone			YY•★	≈♣ϑϑ⧗⚠⚠	Qℓ⊙	lagoon channel
105	WELL-9449	limestone		•		ϑ≈♣Y⊖ℓ★	Q⚠	lagoonal
105	WELL-9451	limestone		•		ϑ≈♣ℓ★Y	♁Q✇	lagoonal
105	WELL-9452	limestone			Y★	≈♣ϑϑ•⊙ℓ	⚠✇	open platform NWB
105	WELL-9453	dolostone, chert				≈Yϑ★Y		open platform w/storm deposits
105	WELL-9454	dolostone				Y★•	Q♣ϑ	lagoon/quiet water
105	WELL-9455	dolomitic limestone			Y★			open platform BWB
105	WELL-9456	limestone		•		ϑ≈♣ℓ★Y	Q	lagoonal
105	WELL-9457	limestone			•	ϑ≈♣Y⊖ℓ★	⊙	near shoal/OWB
105	WELL-9458	limestone			Y•⧗	≈♣★ϑ		lag deposit/channel/storm
105	WELL-9459	limestone			•⧗	ϑ≈♣ℓ★Y	✇	lag deposit/channel/storm
105	WELL-9460	limestone			⚒	Q		lagoonal
105	WELL-9461	dolomitic limestone			⚒	≈Qϑℓ★		lagoonal
105	WELL-9462	limestone			★⚒	Qϑ	≈	lagoonal
105	WELL-9463	limestone			YY★	♣ϑϑ≈	ℬQ⧗⚠	open platform NWB

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9464	limestone			•			lag deposit/channel/storm
105	WELL-9465	limestone						near lagoon - storm sediment?
105	WELL-9467	limestone		⊖	Y			shoal
105	WELL 9468	limestone				Y		lagoonal
105	WELL-9468	limestone				Y		lagoonal
105	WELL 9469	dolomitic limestone						lagoonal
105	WELL-9469	dolomitic limestone						lagoonal
105	WELL-9470	limestone						shoal/storm
105	WELL-9471	limestone						open platform NWB
105	WELL-9472	limestone						channel deposit ?-
105	WELL-9473	dolomitic limestone			Y			open platform NWB
105	WELL-9474	limestone, dolostone					Y	open platform BWB
105	WELL-9475	sandstone		Q				shallow water
105	WELL-9476	limestone, sandstone		Q				shallow water
105	WELL-9477	sandy or silty dolostone		Q				shallow water
105	WELL-9478							?
105	WELL 9482	limestone			Y			open platform OWB
105	WELL-9482	limestone			Y			open platform OWB
105	WELL-9483	limestone			Y			open platform / near shoal
105	WELL-9484	limestone			Y			open platform / near shoal
105	WELL-9485	limestone			Y			open platform OWB
105	WELL-9486	limestone			Y			open platform OWB /near shoal?
105	WELL-9487	limestone						shoal
105	WELL-9488	limestone			⊖			near lagoon
105	WELL-9489	limestone			⊖			near lagoon
105	WELL 9489	limestone			⊖			near lagoon
105	WELL-9490	limestone						open platform NWB
105	WELL-9491	limestone						near lagoon
105	WELL-9492	limestone			Y			open platform / near shoal
105	WELL-9493	limestone			Y			open platform / near shoal
105	WELL-9494	limestone			Y			open platform / near shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9495	limestone			Y★	◎ƀ⅂◎Ⓐ⊖ ♣≈	Ⓥ⌂ƒ⧗Ⓐ	open platform / near shoal
105	WELL-9496	limestone			Y★	◎ƀ◎⌂⅂ƒ ⧗Ⓐ≈Ⓥ		open platform NWB
105	WELL-9497	limestone			Y★⊖	ƀ⅂♣Ⓥ≈	◎◎⊙Ⓐ	open platform / near shoal
105	WELL-9499	chert				≈♣•☮		lagoonal
105	WELL-9500	limestone, chert			≈	Q		lagoonal
105	WELL-9501	limestone			♣≈	★Ⓥƒ•☮	Q	lagoonal
105	WELL-9502	limestone			♣	◎ƀ⅂◎≈☮ ⧗Ⓥ★	Q	near lagoon
105	WELL-9503	limestone			♣Y	◎◎⅂Qƀ★ƒ ≈Ⓥ		channel?
105	WELL-9504	limestone			♣Y★	Q⅂⌂Ⓥ≈ƀ	◎◎⊙Ⓐ	open platform NWB
105	WELL-9505	limestone			Y	♣⅂⌂≈Ⓐ★ Ⓥ	QⒶ	open platform
105	WELL-9506	limestone			Y	Ⓥ♣⅂★•Ⓐ Ⓐ	ƒ	open platform NWB/OWB
105	WELL-9507	dolostone				ⓋQ⚒Y		lagoonal/quiet water
105	WELL-9508	dolomitic limestone			ⓋY★	♣	•	open platform BWB
105	WELL-9509	dolostone				ⓋY◎Q◎★ ⚒•ⒶⒶƒ	♣	near lagoon
105	WELL-9510	dolomitic limestone			Y★	◎♣◎⅂Y⊖⊙ Ⓐ≈Ⓥ	ƒ	open platform near shoal BWB
105	WELL-9511	dolomitic limestone				♣≈Ⓥ⅂◎◎ƒ ⊙•Y★Ⓐ	Q	open platform NWB/near shoal
105	WELL-9512	limestone			⊙	ⓋY⌂♣★• ⧗Ⓐ⊖	ƀƒⒶ	near shoal
105	WELL-9514	dolomitic limestone			Y	Ⓥ★♣≈⚒•ƒ ☮		near shoal (lagoon)
105	WELL-9515	sandy or silty limestone, chert						shallow water
105	WELL-9516	limestone				Ⓥ≈♣★•⊙ ☮		lagoonal
105	WELL-9517	limestone			ƀ⊙	♣Ⓥ◎⅂◎• ⧗Ⓐ Y★		near shoal
105	WELL-9518	limestone			Y◎⊖Ⓗ	◎ƀ⅂Y♣⊙ ⧗★Ⓐ		shoal
105	WELL-9519	limestone			◎⊖	◎♣⌂⅂Y⊙ ⧗★Ⓐ		near shoal
105	WELL-9520	limestone			◎	ƀ♣◎⅂YⒶ ⊙★ⓋY	⌂	shoal
105	WELL-9521	limestone			◎	♣Ⓥ◎⌂YY ⊙⧗ⒶⒽ★	ƀƒƀ	open platform / near shoal
105	WELL-9522	limestone			ƀ	≈♣⅂⊖★Ⓥ	ƒ•	open platform
105	WELL-9523	limestone				♣≈⌂⅂Ⓥƀ ⊖Y★	Ⓐƒ⊙☮	open platform / near shoal
105	WELL-9524	limestone			ƀ	Ⓥ≈♣★•⊖ƒ		open platform
105	WELL-9525	dolomitic limestone			Y★	≈♣Q⧗Ⓐ Ⓥ	⅂ƀⒶ	open platform BWB
105	WELL-9526	limestone			★ƀ	Ⓥ♣⌂⊙⊖Y	◎≈ƒ	open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9527	dolomitic limestone			Y★			open platform BWB
105	WELL-9528	limestone, dolostone				★	Q	lagoonal / deep water
105	WELL-9529	dolostone				★		lagoonal / deep water
105	WELL-9530	limestone, dolostone				★Y●	Q	lagoonal / open platform
105	WELL-9531	limestone				★		open platform
105	WELL-9532	limestone				★		open platform
105	WELL-9533	limestone				★		open platform
105	WELL-9534	limestone				★		open platform
105	WELL-9535	limestone				★		open platform
105	WELL-9536	limestone				★		open platform
105	WELL-9537	limestone, dolostone					★	lagoonal/deep water
105	WELL-9538	limestone				Y★		open platform / near shoal
105	WELL-9539	limestone				★Y		open platform / near shoal
105	WELL-9540	limestone			★	Y		channel deposit
105	WELL-9541	limestone, dolostone			Y★	Y		open platform BWB
105	WELL-9542	dolomitic limestone			Y	★		open platform BWB
105	WELL-9543	limestone			Y	★		near shoal
105	WELL-9544	limestone			Y	★	●	open platform
105	WELL-9545	limestone			Y★		Q	open platform NWB
105	WELL-9546	dolomitic limestone			Y	★		open platform BWB
105	WELL-9547	dolomitic limestone			Y★			open platform BWB
105	WELL-9549	sandy or silty limestone		Q				shallow water
105	WELL-9551	limestone				★		open platform
105	WELL-9553	limestone				★		open platform
105	WELL-9554	limestone				★	★	open platform
105	WELL-9555	limestone			Y	★		open platform BWB
105	WELL-9556	limestone				★Y		shoal
105	WELL-9557	limestone			Y	★	Q	open marine OWB / storm
105	WELL-9558	limestone			Y	★		open platform
105	WELL-9559	limestone, dolostone				Y●★	Q	shallow / deep / quiet water
105	WELL-9560	dolomitic limestone, chert				★●★		near lagoon

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9561	limestone			•	⚘≈♣⚇⚡★		lagoonal
105	WELL-9562	limestone		•		≈⚡⚒	Q	lagoonal
105	WELL-9563	limestone		•		⚘♣Q⚡★Y	⚇	lagoonal
105	WELL-9564	limestone			•	⚘≈♣⚒⚡★	Y	lagoonal
105	WELL-9565	dolomitic limestone		Y		♣≈♢◎⚘•⧗★⚠		open platform BWB
105	WELL-9566	dolomitic limestone				Y	Q⚡	lagoonal or deep / quiet water
105	WELL-9567	dolomitic limestone			⊖⧗	♣⚡⚐★Y⚘	≈⚠⚠	open platform NWB / storm?
105	WELL-9568	limestone			⊖⧗	⚡♢★Y		shoal / near shoal
105	WELL-9569	limestone			⊖	◎⚡⚐◎♣Y★≈⚘	⚡⊙	shoal
105	WELL-9571	chert				Q		shallow water
105	WELL-9573	dolostone				Q•		shallow water / quiet water
105	WELL-9574	dolostone				Q		shallow water / quiet water
105	WELL-9575	limestone				Q		quiet water / shallow
105	WELL-9587	limestone			⊖	•	♣⚘★	shoal
105	WELL-9588	limestone		⊖			⚘Y★	shoal
105	WELL-9590	limestone		⊖	•		≈⚘★	shoal
105	WELL-9592	limestone			⊖•	♣⚘★	⚡	shoal
105	WELL-9593	limestone			⊖•	⚘♣★Y		shoal
105	WELL-9594	limestone			⊖•	♣≈⚡	Q⚘	shoal / lagoonal
105	WELL-9595	limestone			♣★	⚘≈⚡•⚇	Q	lagoonal / channel
105	WELL-9596	limestone			⊖⊙	⚠◎♢⚐Y★⚡♣	◎⚡⧗	shoal
105	WELL-9597	limestone		⊙		⚡♣Y	⚐⚡	shoal
105	WELL-9598	limestone			⊙	◎◎♢⚐⚡⊖⧗♣Y		near shoal
105	WELL-9599	limestone			⊖⊙	◎♢♣★Y	⚠⚠	near shoal
105	WELL-9600	limestone			⊙	⚡◎♢♣⊖★≈	⧗	shoal
105	WELL-9601	limestone			⊙	◎♣⚠♢⚐⊖⧗★Y⚡⚡	⚠⚡	shoal
105	WELL-9602	limestone			♣★	≈⚘♢◎⊙•Y⚡	◎Q⚡⚇⚠	near shoal (behind it?)
105	WELL-9603	limestone			⊖	Y⚐♢•⊙★	⚡⚘	shoal
105	WELL-9604	limestone			♢Y⊖	◎⚐≈★⚘	Q⚠	near shoal
105	WELL-9605	limestone			Y	≈⚠♢⊖★⚘	⚡⚠•	open platform / near shoal
105	WELL-9606	limestone			♢Y	◎★⊖	⚠⊙	open platform
105	WELL-9607	limestone			•	≈♣Q⚘⚡★Y		near lagoon
105	WELL-9608	sandy or silty limestone			Q			shallow water
105	WELL-9609	limestone				Q		shallow water
105	WELL-9610	limestone				Q	⚘★	shallow water - deep?
105	WELL-9611	limestone			♣★	⚘≈♢Y⚇⚡⚡	⊙	near lagoon / channel / deep water

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9612	limestone						open platform
105	WELL-9613	dolomitic limestone						lagoonal / shallow water
105	WELL-9614	limestone						near shoal
105	WELL-9616	limestone						open platform
105	WELL-9617	dolomitic limestone						open platform OWB
105	WELL-9618	limestone						shoal
105	WELL-9619	limestone						near shoal
105	WELL-9620	limestone						shoal
105	WELL-9621	limestone						shoal
105	WELL-9622	dolomitic limestone						open platform BWB
105	WELL-9623	limestone						near shoal
105	WELL-9624	limestone						near shoal / channel
105	WELL-9625	limestone						open platform
105	WELL-9626	limestone						open platform
105	WELL-9627	dolomitic limestone						open platform
105	WELL-9628	dolomitic limestone						open platform
105	WELL-9629	dolomitic limestone						open platform
105	WELL-9630	dolostone						open platform BWB
105	WELL-9631	dolostone, chert						quiet water / shallow or deep
105	WELL-9632	limestone						shallow water
105	WELL-9633	limestone						open platform
105	WELL-9634	limestone, argillaceous dolostone						open platform / near shoal
105	WELL-9635	limestone						open platform
105	WELL-9636	limestone						open platform
105	WELL-9638	dolostone						quiet water / shallow or deep
105	WELL-9639	dolomitic limestone						lagoonal
105	WELL-9640	limestone						lagoonal
105	WELL-9641	limestone						lagoonal
105	WELL-9642	limestone						shoal
105	WELL-9643	limestone						shoal
105	WELL-9644	limestone						shoal

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9645	limestone			⊙	•		shoal
105	WELL-9647	limestone			⊖•		♣⊙	lagoonal?
105	WELL-9648	limestone			⊖•	★Y♣⧗⊙⚲	⚲	near shoal
105	WELL-9649	limestone			⚡⊖	Y⚘♣⧗⊙★	⚲	shoal
105	WELL-9650.01	limestone			⊖	Y★⚘⚲♣⚠•⧗⊙⚠⚡	⚲	near shoal
105	WELL-9651	limestone				⚘♣Q⚲•⚒⚡	⚠	lagoonal / deep water ?
105	WELL-9652	limestone			•	⚘♣Y⚲★	⚡Q⊙⚠	lagoonal
105	WELL-9653	limestone			•	≈♣Q⚘⊙⚠Y	★⚠⚠⚡	lagoonal
105	WELL-9654	limestone			•	Y★⚘♣≈⚒⊖⚠⚠⚡	Q⚲⊙	lagoonal?
105	WELL-9655	limestone			⚡	≈♣⚠★	Q	
105	WELL-9656	limestone			⚡	⚘♣⚠★	Q⚠•	
105	WELL-9657	limestone			⚡	≈♣⚠★	⚘⚲•	lagoonal??
105	WELL-9658	limestone			★⚡	♣≈	Q⚲⚠	open platform
105	WELL-9659	limestone			★⚡	♣≈	⚲	open platform
105	WELL-9660	limestone			★⚡	♣	⚘⚲⊙	open platform
105	WELL-9661	limestone			⚡⊙	≈⚘⚠♣★⚠Y⚡⚡	Q⚡	shoal
105	WELL-9662	limestone			Y	♣≈⚠⚲⊖⊙⚘★	⚲Q⧗⚠	open platform / near shoal
105	WELL-9663	limestone			Y★	♣⚲⚠⊖⚘≈	⚲⚡	open platform
105	WELL-9664	dolostone				Q⚒		quiet water
105	WELL-9666	limestone, dolostone			★	≈♣Q⚘•⚲Y	⚠	lagoonal
105	WELL-9667	dolomitic limestone			★	⚘≈♣•⚲Y		lagoonal?
105	WELL-9668	limestone			♣★•	≈⚲⚠	⚠	lagoonal
105	WELL-9669	limestone			⊙	⚘♣⚲Y⧗⊖★		shoal
105	WELL-9670	limestone		⊙		⚡•⧗	⚘◎★Y	shoal
105	WELL-9671	limestone		⊖⊙		♣⚡•	⚘≈⧗★	shoal
105	WELL-9672	limestone			⚡⊖	♣★•	⚲⊙	shoal deepening
105	WELL-9673	limestone			⚡⊖	♣⚲•		shoal
105	WELL-9674	limestone			⚡⊖	★⚘♣•⚠⚲		near shoal / open platform
105	WELL-9675	limestone			⚡⊖	♣★•	⚲⊙⧗	near shoal
105	WELL-9676	limestone			⚡	⚘♣⚠Y•⊖★		near shoal
105	WELL-9678	dolomitic limestone			⚡	⚘Y♣≈⊖•★⚲	◎⧗	lagoonal?
105	WELL-9679	limestone			•	⚘≈♣⚒⚲★	Q	lagoonal
105	WELL-9680							
105	WELL-9681	limestone			⚒•		⚠	quiet water - deep / shallow
105	WELL-9682	limestone			•	⚘♣★⚠⚲	Q≈⚡	lagoonal
105	WELL-9683	limestone			•	♣⚘⚲	⚠	lagoonal
105	WELL-9685	sandstone		Q				very shallow water

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9686	sandstone		Q				very shallow water
105	WELL-9687	sandstone		Q				very shallow water
105	WELL-9688	sandy or silty limestone			Q●	♣⚡⚠	⚒	lagoonal / shallow
105	WELL-9689	sandy or silty limestone, chert			Q	⚠⚒		lagoonal / shallow water
105	WELL-9690	sandy or silty limestone			Q★●	≈♣⚱⚠⚡	⚡	lagoonal
105	WELL-9691	limestone			Q★●	⚱♣⚠⚡	≈⚡	lagoonal / near shoal
105	WELL-9692	limestone			★●	≈♣Q⚠⚡⚱	⚡	lagoonal / near shoal
105	WELL-9699	dolomitic limestone			Y★●	⌂⚱⧗		open platform BWB
105	WELL-9700	dolomitic limestone			Y★●	⚠		open platform
105	WELL-9701	limestone, dolostone, chert			Y★●	⚱		open platform NWB
105	WELL-9702	dolostone			●			
105	WELL-9703	cherty limestone, dolostone			●			quiet water
105	WELL-9704	cherty limestone				●		quiet water
105	WELL-9705	cherty limestone				⚱Y⚒		quiet water
105	WELL-9707	limestone			★●	≈♣Q⚠⚡⚱		lagoonal
105	WELL-9708	chert						
105	WELL-9709	dolomitic limestone				≈⚱Q♣⚡● ★⚡		lagoonal
105	WELL-9710	limestone						quiet water
105	WELL-9711	limestone					Q	quiet water
105	WELL-9712	dolostone					Q	quiet water
105	WELL-9713	dolostone, chert				Y	Q	quiet water
105	WELL-9714	dolomitic limestone			Y	♣⚱★	⊙⧗	open platform BWB
105	WELL-9715	limestone			⚡	≈♣⚱⊖★		open platform
105	WELL-9716	limestone			♣★⚡	⚱≈⊖⚡		open platform
105	WELL-9717	limestone			⚡	⚱♣⚠★		open platform
105	WELL-9718	limestone			⚡	⚱≈♣⊖⚡★		open platform
105	WELL-9719	limestone			⚡	≈♣⌂⚱⊖⚡ ★		open platform OWB
105	WELL-9720	limestone			⚡	≈♣★⚱	Q⚠	open platform OWB
105	WELL-9721	limestone			⚡	⚱★♣≈⊖⊙ ⚡⚠		open platform
105	WELL-9722	limestone			⚡	⚱♣★⊙⚡	⚠	open platform

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9723	limestone						open platform
105	WELL-9724	limestone						shoal
105	WELL-9725	limestone						open platform - shoal / storm?
105	WELL-9727	dolostone, chert						quiet water
105	WELL-9728	limestone						open platform - shoal / storm
105	WELL-9729	limestone						shoal
105	WELL-9730	limestone						shoal / storm
105	WELL-9731	limestone						shoal
105	WELL-9732	dolomitic limestone						shoal
105	WELL-9733	limestone						shoal
105	WELL-9735	limestone						lagoonal
105	WELL-9736	limestone						lagoonal
105	WELL-9737	limestone						lagoonal
105	WELL-9738	limestone						lagoonal
105	WELL-9739	chert						lagoonal
105	WELL-9740	dolomitic limestone						lagoonal
105	WELL-9741	dolomitic limestone						lagoonal
105	WELL-9742	limestone						shoal
105	WELL-9743	limestone						open platform / near shoal
105	WELL-9744	dolomitic limestone						open platform
105	WELL-9745	dolomitic limestone						open platform
105	WELL-9747	limestone						open platform / shoal
105	WELL-9748	dolomitic limestone			Y			open platform BWB
105	WELL-9749	dolomitic limestone			Y			open platform BWB
105	WELL-9750	sandy or silty limestone						quiet water
105	WELL-9752	limestone						quiet water
105	WELL-9753	sandy or silty limestone						shallow water
105	WELL-9754	chert						shallow water

Map #	Sample	Rock Types	Carb. Text.	abundant	common	minor	rare	Depositional Environment
105	WELL-9755	limestone						quiet to turbulent water
105	WELL-9756	limestone						shoal
105	WELL-9757	limestone						shoal
105	WELL-9758	dolomitic limestone			Y		Q	open platform BWB
105	WELL-9759	limestone						shoal
105	WELL-9760	limestone						open platform / shoal
105	WELL-9761	dolomitic limestone						open platform
105	WELL-9762	dolostone			Y			open platform BWB
105	WELL-9763	dolostone			Y			open marine
0	0							

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