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FOSSIL ENERGY

GEOLOGICAL AND PETROPHYSICAL CHARACTERIZATION OF THE FERRON SANDSTONE FOR 3-D SIMULATION OF A FLUVIAL-DELTAIC RESERVOIR

Annual Report for the Period
September 29, 1993 to September 29, 1994

By
M. Allison

July 1995

Performed Under Contract No. DE-AC22-93BC14896

Utah Geological Survey
Salt Lake City, Utah

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

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ABSTRACT

The objective of the Ferron Sandstone project is to develop a comprehensive, interdisciplinary, quantitative characterization of a fluvial-deltaic reservoir to allow realistic inter-well and reservoir-scale models to be developed for improved oil-field development in similar reservoirs world-wide. Quantitative geological and petrophysical information on the Cretaceous Ferron Sandstone in east-central Utah will be collected. Both new and existing data will be integrated into a three-dimensional model of spatial variations in porosity, storativity, and tensorial rock permeability at a scale appropriate for inter-well to regional-scale reservoir simulation. Simulation results could improve reservoir management through proper infill and extension drilling strategies, reduction of economic risks, increased recovery from existing oil fields, and more reliable reserve calculations. Transfer of the project results to the petroleum industry is an integral component of the project. This report covers research activities for fiscal year 1993-94, the first year of the project. Most work consisted of developing field methods and collecting large quantities of existing and new data. We also developed preliminary regional and case-study area interpretations.

The project is divided into four tasks: (1) regional stratigraphic analysis, (2) case studies, (3) development of reservoirs models, and (4) field-scale evaluation of exploration strategies. The primary objective of the regional stratigraphic analysis is to provide a more detailed interpretation of the stratigraphy and gross reservoir characteristics of the Ferron Sandstone as exposed in outcrop. The primary objective of the case-studies work is to develop a detailed geological and petrophysical characterization, at well-sweep scale or smaller, of the primary reservoir lithofacies typically found in a fluvial-dominated deltaic reservoir. Work on tasks 3 and 4, development of reservoir models and field-scale evaluation of exploration strategies, will be conducted primarily during the last year of the project, and will incorporate the data and results of the regional stratigraphic analysis and case-studies tasks.

Regionally, the Ferron Sandstone consists of up to seven delta-front sandstone bodies or parasequence sets. Our work focuses on two parasequence sets (No. 1 and No. 2) in the lower part of the Ferron. The No. 1 represents a river-dominated delta deposit which changes from proximal to distal (where the sandstone pinches out) from east to west across the Ivie Creek area. The No. 2 contains more and cleaner sand, indicating a more wave-influenced environment of deposition.

During fiscal year 1993-94, the Ferron Sandstone outcrop belt within the study area was obliquely photographed, the photos digitized and transferred to compact discs, and the images reproduced and assembled into photomosaics. Lithofacies, measured sections, vertical and horizontal scales, and other data were plotted on the photomosaics in the field for both the regional and case-study analyses. Published and unpublished maps, measured sections, well logs, core descriptions, reports, and other data were collected, compiled, interpreted, and entered into a database developed by the Utah Geological Survey. Three case-study sites for detailed analysis of the major reservoir types have been selected and approved by the project team: Muddy Creek Canyon, Ivie Creek, and Willow Springs Wash in the north, central, and southern parts respectively of the study area.

Forty-six sections were measured and described in the Ivie Creek and Willow Springs

Wash case-study areas. Sections were correlated to develop preliminary interpretations of the stratigraphy and lithofacies. Over 500 paleocurrent measurements were taken at these and other localities. Lithologic and paleocurrent data are being entered into the database for use in constructing statistical models, strip logs, and lithofacies maps. Drilling permits were obtained for several core-hole locations in the Ivie Creek area. The No. 1 and No. 2 parasequence sets will be cored in each hole. The spacing pattern of the core holes is similar to that typically used to develop an oil field. Fifteen gamma-ray traverses were undertaken (corresponding to measured sections), each consisting of 200 to 400 measurements. All traverses included the entire No. 1 parasequence set, and most also included all or part of the No. 2 parasequence set. Core plugging of the Ferron Sandstone was done along nine vertical or near-vertical traverses. In all, 283 plugs were taken from various lithofacies in both the No. 1 and No. 2 sandstones.

A total of seven permeability transects were made on the outcrop at the Ivie Creek case-study site. The transects span the proximal, middle, and distal portions of the delta-front rocks of the No. 1 sandstone. Transect locations were designed to encompass the majority of the lithofacies present in the delta-front sequence. Data from these transects will be used to determine the statistical structure of the spatially variable permeability field within the delta front, to investigate how geological processes control the spatial distribution of permeability, and to evaluate permeability measurement techniques.

EXECUTIVE SUMMARY

Understanding reservoir heterogeneity is the key to increasing oil recovery from existing fields in the United States. Fluvial-deltaic reservoirs have the largest developed oil reserves, and due to the high degree of reservoir heterogeneity, the largest amount of untapped and unrecovered oil within developed reservoirs. Reservoir heterogeneity is dramatically exposed in the fluvial-deltaic Ferron Sandstone Member of the Cretaceous Mancos Shale in east-central Utah.

The Utah Geological Survey (UGS) leads a multidisciplinary team to develop a comprehensive and quantitative characterization of the Ferron Sandstone as an example of a fluvial-deltaic reservoir which will allow realistic interwell and reservoir-scale modeling. These models may be used for improved oil-field development in similar reservoirs world-wide. The Ferron Sandstone project team consists of the UGS (prime contractor), University of Utah, Brigham Young University, Utah State University, Amoco Production Company, Mobil Exploration and Producing Company, and several geologic contractors. This research is performed under the Geoscience/Engineering Reservoir Characterization Program of the U.S. Department of Energy, Pittsburgh Energy Technology Center. This report covers research activities for fiscal year 1993-94, the first year of the project. Most work consisted of developing field methods and collecting large quantities of existing and new data. We also developed preliminary regional and case-study area interpretations.

The project is divided into four tasks: (1) regional stratigraphic analysis, (2) case studies, (3) development of reservoirs models, and (4) field-scale evaluation of exploration strategies. The primary objective of the regional stratigraphic analysis is to provide a more detailed interpretation of the stratigraphy and gross reservoir characteristics of the Ferron Sandstone as exposed in outcrop. This regional study will include determining the dimensions and depositional environment of important sandstone reservoir bodies and the nature of contacts with adjacent rocks. The primary objective of the case-studies work is to develop a detailed geological and petrophysical characterization of some of the primary reservoir lithofacies typically found in a fluvial-dominated deltaic reservoir. Work on tasks 3 and 4, development of reservoir models and field-scale evaluation of exploration strategies, will be conducted primarily during the last year of the project, and will incorporate the data and results of the regional stratigraphic analysis and case-studies tasks.

Regionally, the Ferron Sandstone consists of up to seven delta-front sandstone bodies or parasequence sets. The focus of our work is two parasequence sets in the lower part of the Ferron. Previous workers have designated these as the No. 1 and No. 2 sets. The No. 1 represents a river-dominated delta deposit which changes from proximal to distal (where the sandstone pinches out) from east to west across the Ivie Creek area. The No. 2 contains more and cleaner sand, indicating a more wave-influenced environment of deposition. Recognizable sequences within the sets have been designated with lower-case letters (for example, No. 1a). In some cases, the divisions may lack transgressive surfaces, yet are recognizable by changes in sedimentary styles. In the Ivie Creek area, the No. 1 a,b, and c parasequences are well exposed and we interpret them to be low-wave-energy subdelta deposits. The uppermost carbonaceous mudstone or ash-rich coal is the sub-A coal zone. A flooding surface has been identified at the top of the sub-A. The boundary with the overlying No. 2 parasequence set is drawn at this flooding surface. We have initially interpreted the No. 2 a, b, and c parasequences as low-wave-energy subdelta deposits.

The Ferron Sandstone outcrop belt within the study area was obliquely photographed. These photographs (a total of 1,823 depicting 80 miles [130 km] of outcrop) were digitized and transferred to compact discs. Using image-editing software, photographs are being assembled into reproducible photomosaics. Lithofacies, measured sections, vertical and horizontal scales, and other data are being plotted on the photomosaics in the field for both the regional and case-study analysis.

The UGS collected and compiled published and unpublished maps, measured sections, well logs, core descriptions, reports, and other data. There are 481 wells in the study area, of which 412 were cored. Information and interpretation (thickness, type of lithology, and geologic description) of these wells has been entered into the **INTEGRAL*gim** database developed by the UGS.

Three case-study sites for detailed analysis of the major reservoir types have been selected and approved by the project team: Muddy Creek Canyon, Ivie Creek, and Willow Springs Wash in the north, central, and southern parts respectively of the study area. The entire Ferron section will be analyzed at the Muddy Creek Canyon site. In this area, the Ferron Sandstone is composed of seven deltaic units. Some of these units are stratigraphically simple; others include a variety of facies and display abrupt lateral variations. The Ivie Creek site was selected to examine the abrupt facies changes in the No. 1 delta-front unit. The basal unit is a thick, sandy parasequence which pinches out to the west. This basal unit is overlain by a thin, silty parasequence which extends farther to the west. The Willow Springs Wash site is the largest of the study areas and was selected for the excellent three-dimensional aspect of exposures in the Willow Springs Wash and Indian Canyon areas. The focus of our work at this site will be to describe and map the parasequences of the No. 1 delta-front unit.

Forty-six sections were measured and described in the Ivie Creek and Willow Springs Wash case-study areas. Sections were correlated to develop preliminary interpretations of the stratigraphy and lithofacies. Over 500 paleocurrent measurements were made at these and other localities. Lithologic and paleocurrent data are being entered into the UGS **INTEGRAL*gim** database for use in constructing statistical models, strip logs, and lithofacies maps. Fifteen gamma-ray traverses were undertaken (corresponding to measured sections), each consisting of 200 to 400 measurements. All traverses included the entire No. 1 parasequence set, and most also included all or part of the No. 2 parasequence set. Core plugging of the Ferron Sandstone was done along nine vertical or near-vertical traverses. In all, 283 plugs were taken from various lithofacies in both the No. 1 and No. 2 sandstones.

A total of seven permeability transects, four vertical and three sub-horizontal (parallel to bedding), were made on the outcrop at the Ivie Creek case-study site. The transects span the proximal, middle, and distal portions of the delta-front rocks of the No. 1 sandstone. Transect locations, jointly established by the geological and engineering teams, were designed to encompass the majority of the lithofacies present in the delta-front sequence. Data from these transects will be used to determine the statistical structure of the spatially variable permeability field within the delta front, to investigate how geological processes control the spatial distribution of permeability, and to evaluate permeability measurement techniques.

Eleven core-hole locations were permitted by the Utah Division of Oil, Gas and Mining in the Ivie Creek area; five or six of these locations will be drilled. The total depth of each core hole will be approximately 550 feet (150 m). The No. 1 and No. 2 parasequence sets will be cored (approximately 160 feet [50 m] thick) in each hole. The spacing pattern of the core holes is similar to that typically used to develop an oil field.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Project Purpose

Nationwide, fluvial-deltaic reservoirs have the largest developed oil reserves, and due to the high degree of reservoir heterogeneity, the largest amount of untapped and unrecovered oil within developed reservoirs. Reservoir heterogeneity is dramatically exposed in the fluvial-deltaic Ferron Sandstone Member of the Cretaceous Mancos Shale in east-central Utah. To evaluate the Ferron Sandstone as a model for fluvial-deltaic reservoirs, the UGS, University of Utah, Brigham Young University, Utah State University, Amoco Production Company, Mobil Exploration/Producing Technical Center, The ARIES Group, and geologic consultant Paul B. Anderson entered into a cooperative agreement with the U.S. Department of Energy as part of its Geoscience/Engineering Reservoir Characterization program.

The purpose of this multi-year project is to develop a comprehensive, interdisciplinary, and quantitative characterization of a fluvial-deltaic reservoir which will allow realistic inter-well and reservoir-scale modeling to be used for improved oil-field development in similar reservoirs world-wide. The geological and petrophysical properties of the Cretaceous Ferron Sandstone in east-central Utah (Figure 1.1) will be quantitatively determined by a multidisciplinary team. Both new and existing data will be integrated into a three-dimensional representation of spatial variations in porosity, storativity, and tensorial rock permeability at a scale appropriate for inter-well to regional-scale reservoir simulation. Results could improve reservoir management through proper infill and extension drilling strategies, reduction of economic risks, increased recovery from existing oil fields, and more reliable reserve calculations. The project is divided into four tasks: (1) regional stratigraphic analysis, (2) case studies, (3) development of reservoirs models, and (4) field-scale evaluation of exploration strategies. Transfer of the project results to the petroleum industry is an integral component of the project.

This report is organized into four sections: Introduction, Regional Stratigraphy, Case Studies, and Technology Transfer. It is a progress report of on-going research and is not intended as a final report. Whenever possible, preliminary conclusions have been drawn based on available data and field observations.

1.2 Background

The Ferron Sandstone Member of the Cretaceous Mancos Shale is well exposed along the west flank of the San Rafael uplift of east-central Utah (Figure 1.1). The Ferron Sandstone is a fluvial-deltaic deposit with excellent exposures of a variety of delta architectures along the margins of a rapidly subsiding basin (Figure 1.2a). The Ferron Sandstone is an analogue for many of the highly productive reservoirs in the Alaskan North Slope, Gulf Coast, and Rocky Mountain regions. Fluvial-deltaic reservoirs nationwide have the largest reserves and the largest untapped moveable oil.

The Ferron Sandstone is an eastward-thinning clastic wedge deposited during Upper Cretaceous time. The Ferron and equivalent portions of the Frontier Formation in northern Utah and Wyoming record a pronounced and widespread regression of the Cretaceous Western Interior seaway. In the study area, these deposits accumulated on a deltaic shoreline in a rapidly

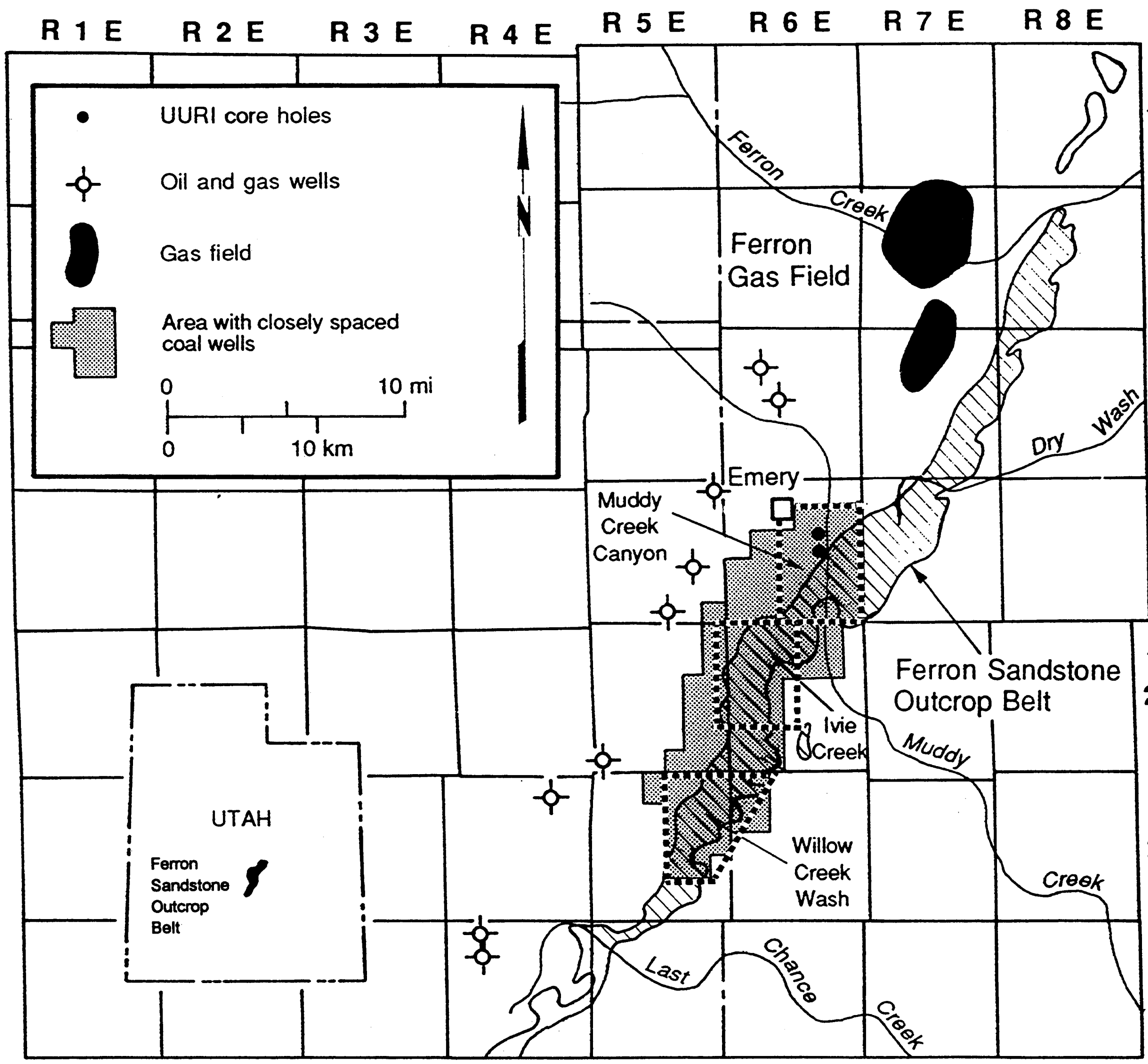


Figure 1.1. Location map of the Ferron Sandstone study area (cross-hatched) showing detailed case-study sites (outlined by heavy dashed lines).

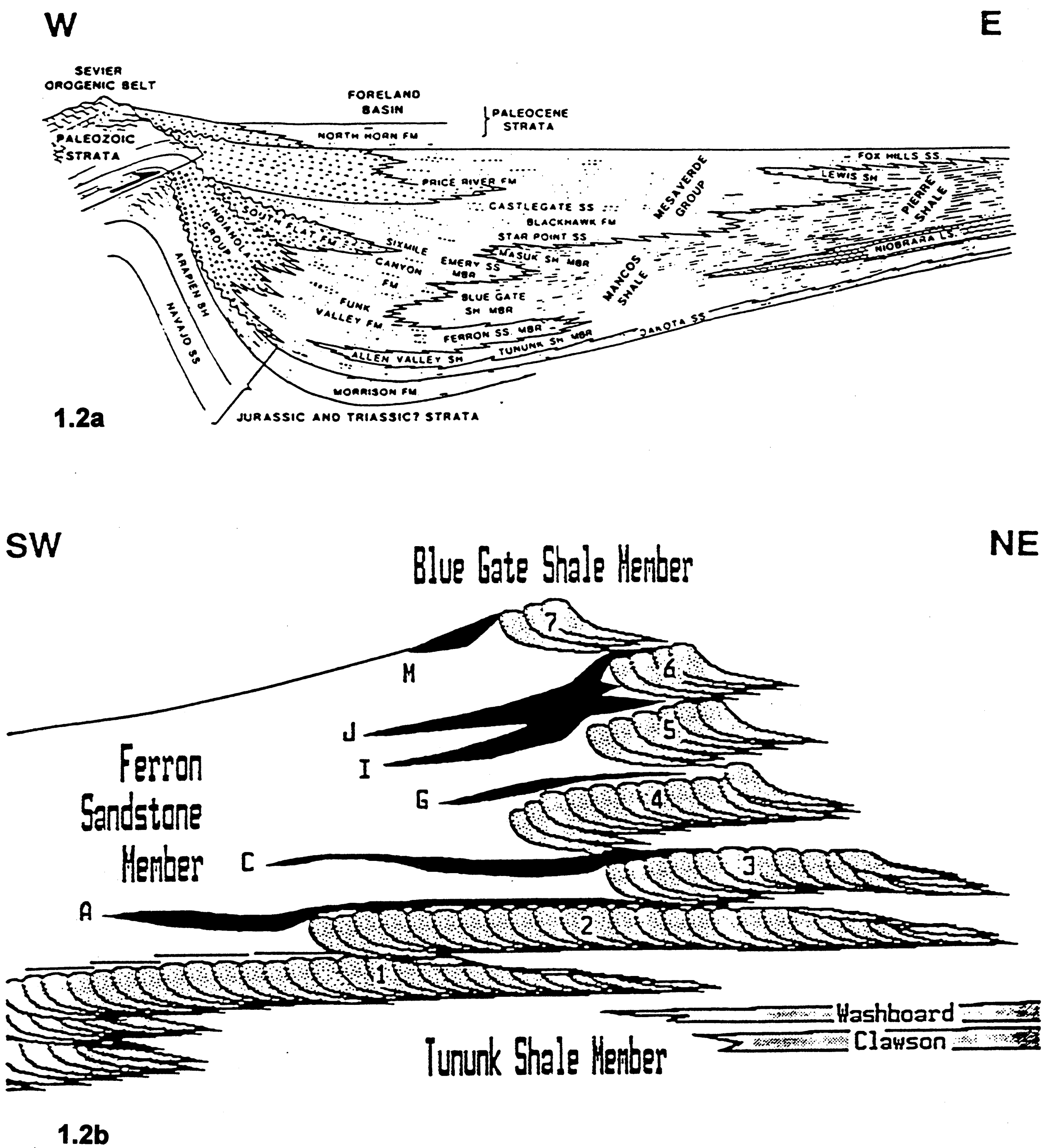


Figure 1.2. a) Cross section of the Cretaceous foreland basin across Utah (from Ryer, 1981a). b) Diagrammatic cross section of the Ferron Sandstone and adjacent members of the Mancos Shale showing the numbering and stacking of the deltaic cycles (parasequence sets (from Ryer, 1991). Coal horizons (black) designated by letters.

subsiding portion of the Cretaceous foreland basin. The Ferron consists of a series of stacked, transgressive-regressive cycles which are well displayed in outcrop. Seven deltaic cycles (parasequence sets), numbered 1 through 7 in ascending order have been mapped (Figure 1.2b). The various delta cycles define a hierarchical pattern of seaward-stepping, vertically-stacked and landward-stepping depositional geometries. This architecture indicates an initial strong supply of sediment relative to available space where sediment could accumulate, followed by near-balance and then a relative decrease in sediment supply. Each delta cycle displays in outcrop all, or portions of each of the complex depositional environments that make up a typical fluvial-dominated deltaic deposit. Such environments include meander channels, distributary channels, tidal channels, mouth-bar complexes, wave-modified strandlines, bar-finger sandstones, prodelta and delta-front deposits, transgressive sandstones, as well as bayfill, lagoonal, and floodplain deposits.

The excellent exposures and accessibility of the three-tiered hierarchical stacking pattern and associated complex depositional environments of the seven deltaic cycles make the Ferron Sandstone of Utah the best analogue for petroleum reservoirs in fluvial-dominated deltas throughout the world. The Ferron Sandstone is a good analogue for the Triassic Ivishak Formation, the principal reservoir at Prudhoe Bay field, Alaska, and for the Tertiary Wilcox and Frio Formations of south Texas. The Ferron Sandstone is also an excellent model for and is correlative to, the Cretaceous Frontier Formation which produces petroleum throughout Wyoming. In Utah, the Ferron lithofacies are a good analogue for the Tertiary Green River and Wasatch Formations, the major oil and gas producing reservoirs in the Uinta Basin. Sands and coalbeds of the Ferron Sandstone produce gas north of the study area in the Wasatch Plateau and along the west-northwest flank of the San Rafael uplift.

This project is motivated by the need to deal with complex reservoir heterogeneities on an interwell to field scale. These scales are difficult to resolve in reservoir exploration and development activities. Standard industry approaches to field development rely on generic depositional models constrained primarily by data obtained in petrophysical (logging and coring) evaluations of exploration and development wells. The quantity, quality, and distribution of these data are typically insufficient to adequately model the reservoir. Work on the Ferron Sandstone is predicated on the assumption that detailed outcrop mapping of petrophysical and geological properties of this analogue reservoir will provide an unusually comprehensive database and reservoir simulation. Simulation results can be used to guide exploration and development strategies in reservoirs found in similar depositional environments.

1.3 Approach

The primary approach of the study is to quantitatively determine geological and petrophysical properties of the Ferron Sandstone. This information should help to improve reserve estimates in fluvial-dominated deltaic reservoir systems and aid in designing more efficient production strategies. To reach this goal, existing and new data are being collected for integration into a three-dimensional representation of spatial variations in porosity, storativity, and tensorial character of rock permeability at a scale appropriate for interwell to regional scale reservoir simulation.

During the 1993-94 project year (the first year of the project), regional facies mapping was initiated to refine current models for the architecture, geometry, and distribution of lithofacies in the Ferron Sandstone (Table 1.1). Case-study sites were selected for more detailed mapping and analysis of specific facies important to reservoir production. Extensive vertical and lateral outcrops provided excellent opportunity for investigation. The existing database was augmented with additional detailed mapping of the three-dimensional geologic structure and determination of petrophysical properties of various lithofacies (Tables 1.1 and 1.2) at several case-study locations within the Ferron Sandstone outcrop belt to serve as reservoir analogues (Figure 1.3). Determining permeability anisotropy within each facies was an important consideration and is being accomplished by: (1) mapping lithofacies (clay content variations/sandstone to shale ratios) and sedimentary structures (orientations/dips of sediment fabrics/structures), (2) collecting core plugs for oriented permeability determinations in the laboratory, (3) producing gamma-ray profiles from outcrops, and (4) using a unique magnetic susceptibility technique to assess anisotropy in pore geometry (Table 1.2). Existing mini-permeameter survey on outcrop were augmented by adding complementary vertical and horizontal mini-permeameter traverses. Core holes were permitted through state and federal regulatory agencies. These core holes will be located near the outcrop to extend the permeability data lithofacies network into the third dimension.

This information will later be used to identify flow units within each case-study area at the scale of a single production well. Numerical simulations of reservoir response will be used to assess the scale at which flow units must be defined within each lithofacies. Once the appropriate scales are established, three-dimensional gridded databases will be developed that contain the best estimates of the three-dimensional distributions of both scalar (porosity, storativity) and tensorial (permeability) petrophysical properties of flow units found within the various lithofacies of the Ferron Sandstone (Figure 1.4). Architectural heterogeneities (e.g., texture and diagenesis) will be examined in thin sections and compared to flow units. Standard geostatistical approaches will be used to extrapolate between the detailed study areas and other observation points.

Reservoir modeling at the regional (field) scale will be performed to evaluate how a detailed understanding of the geological and petrophysical structure of the Ferron Sandstone will enhance exploration and development strategies in similar reservoir systems. Numerical simulations of reservoir response to multiple-well production strategies will be used to quantitatively assess the effectiveness of both standard and modified strategies.

1.4 References

Ryer, T.A., 1981, Deltaic coals of Ferron Sandstone Member of Mancos Shale: predictive model for Cretaceous coal-bearing strata of western interior: American Association of Petroleum Geologists Bulletin, v. 65, no. 11, p. 2323-2340.

---1991, Stratigraphy, facies, and depositional history of the Ferron Sandstone in the canyon of Muddy Creek, east-central Utah: *in* Chidsey, T.C., Jr., editor, Geology of east-central Utah: Utah Geological Association Publication 19, p. 45-54.

Table 1.1 Characteristics of some sandstone facies within the Ferron Sandstone Member of the Mancos Shale.

Facies	Shape/Size	Features
meander/distributary channels		
a) multi-story (seaward stepping)	15-30 ft thick, W/T < 100	low bedform diversity, high interconnection
b) multi-lateral (landward stepping)	15-30 ft thick, W/T > 100	high bedform diversity, moderate interconnection
mouth-bar complex	≤ 10 ft thick	ball and pillow, bioturbated
wave-dominated delta front	80-130 ft thick	storm-generated bedforms
tidal channels	elongate pods, 10 ft W x 100 ft L	erosional base, imbricate structure, bioturbated
transgressive lags	≤ 8 ft thick	erosional base, lags, bioturbated

(W = width, T = thickness, and L = length)

Table 1.2. List of selected lithologic and petrophysical measurements to be made during field and laboratory studies of the Ferron Sandstone.

Measurement Type	Range	Precision
OUTCROP		
outcrop gamma ray	0 to > 200 API	± 10
in-situ mini-permeameter	10.0 to 3,000 md	± 5
WELL LOGGING		
density	1.0 to 3.0 g/cc	± 0.04
sonic	50 to 200 units/ft	± 3
neutron	0 to 100%	± 1%
resistivity	0.1 to 2000 ohm-m	± 3%
gamma ray	0 to > 200 API	± 10
spectral gamma: K	0 to ≥ 10%	± 0.5%
spectral gamma: Th	0 to ≥ 100 ppm	± 10%
spectral gamma: U	0 to ≥ 20%	± 15%
dipmeter	0 to ≥ 60°	± 1°
log-derived permeability	1.0 to 2,000 md	± 10%
CORE		
plug porosity, total	0 to ≥ 50%	± 0.5%
plug porosity, fracture	0 to ≥ 20%	± 0.5%
plug bulk density (dry)	1.5 to 3.0 g/cc	± 0.01
plug bulk density (saturated)	1.5 to 3.0 g/cc	± 0.01
plug grain density	2.0 to 3.0 g/cc	± 0.05
plug compressional velocity	1.5 to ≥ 4.0 km/s	± 1.0%
plug shear velocity	1.0 to ≥ 3.0 km/s	± 2.0%
plug mineralogy	1 to 5 dominant minerals	± 5% each
plug natural gamma	0 to ≥ 200 API	± 20
plug permeability	0.1 to 3000 md	± 30%
continuous core gamma ray	0 to ≥ 200 API	± 20
continuous core mini-permeability	0.1 to 3,000 md	± 5
magnetic susceptibility	10^{-6} to 10^{-2} SI	± 5%
pore anisotropy: axes	not applicable	± 5%
pore anisotropy: magnitude	0 to 100%	± 2%

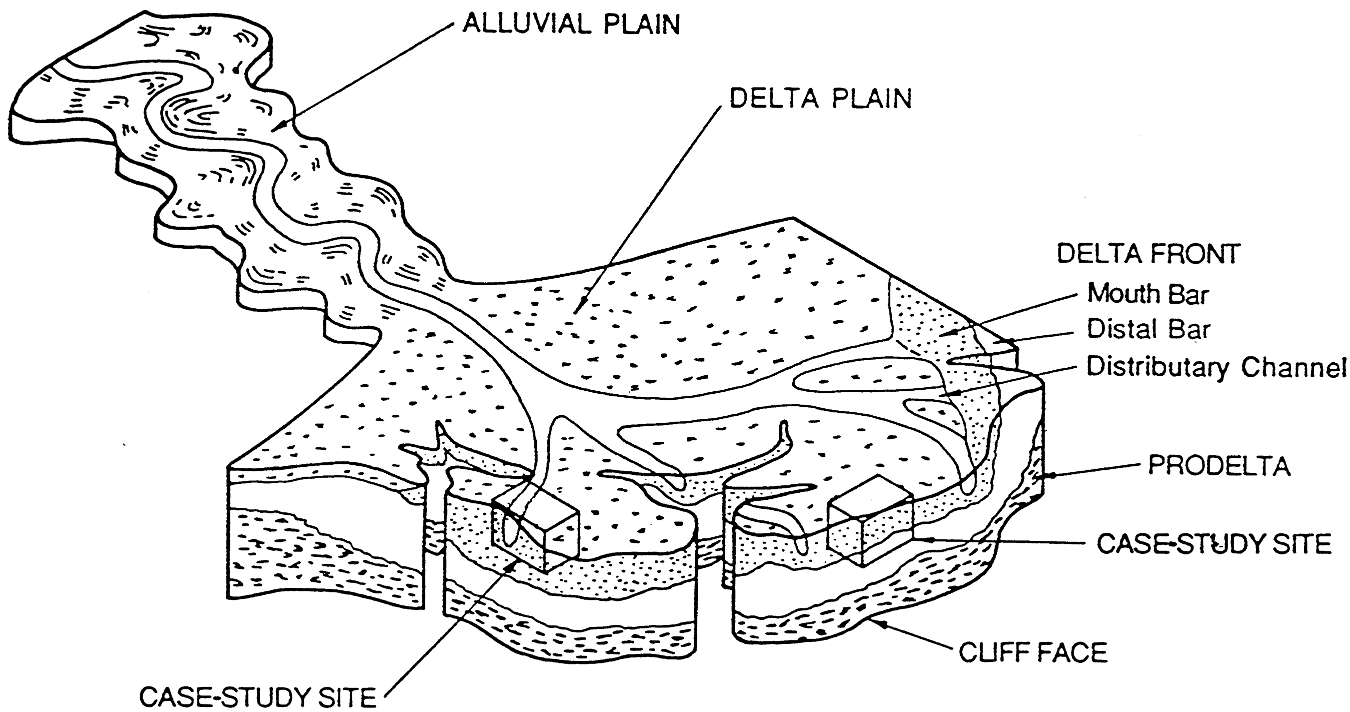


Figure 1.3. Schematic diagram illustrating relative scales and spatial relationships among vertical outcrops of the Ferron Sandstone (cliff face), possible case-study sites, and typical lithofacies of a fluvial-dominated deltaic reservoir system (modified from Ryer, 1981).

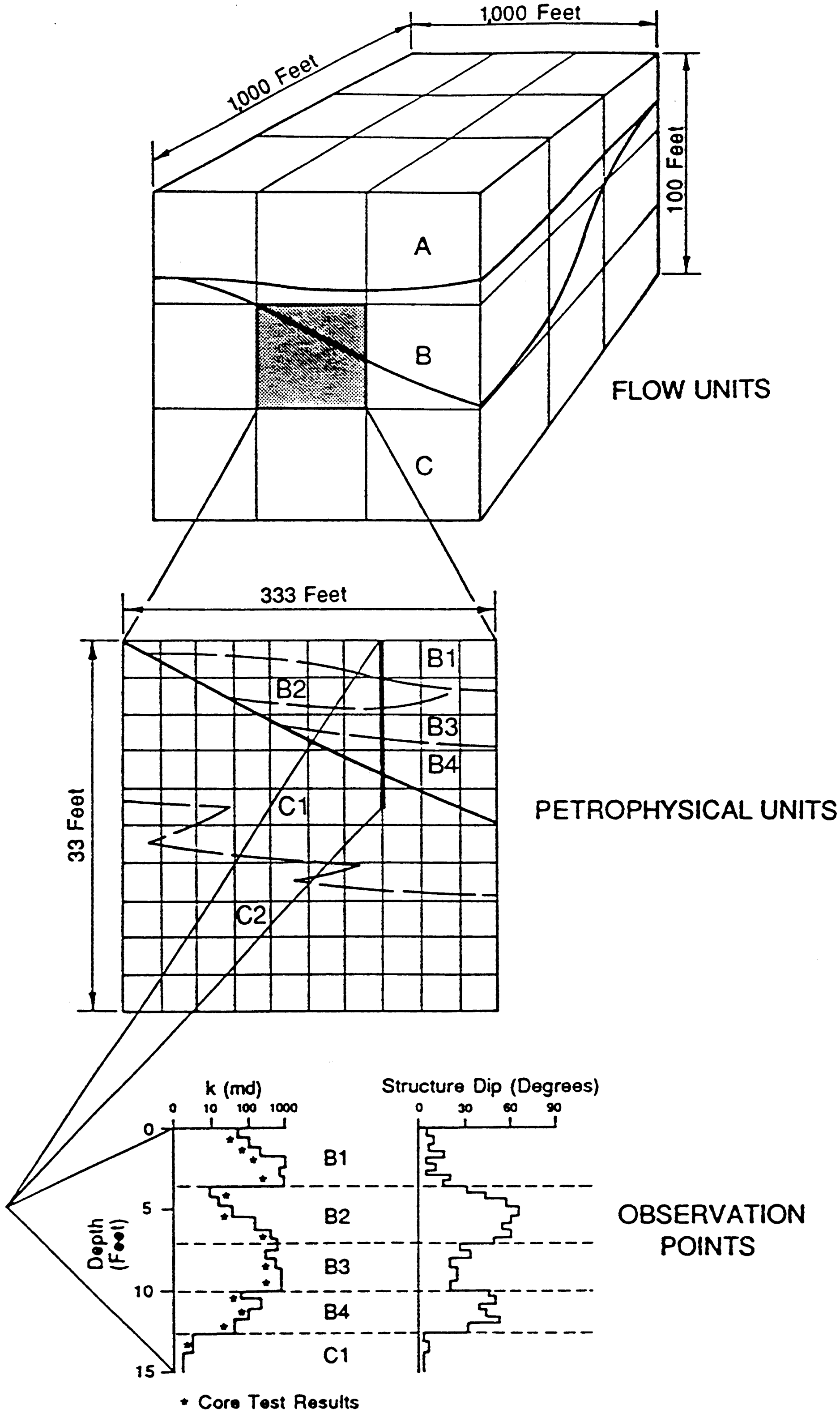


Figure 1.4. Hierarchy of scales involved in scaling up from observational data points obtained from transects and core-hole logs to the definition of petrophysical units (B1, B2, and others), and ultimately to define reservoir-scale flow units (A, B, and C).

2. REGIONAL STRATIGRAPHY

The regional stratigraphy of the Ferron Sandstone has been described by Anderson (1991), Barton and Tyler (1991), Cotter (1971, 1975a, 1975b, 1976), Davis (1954), Gardner (1991), and Ryer (1981a, 1981b, 1982a, 1981b, 1983, 1991). The primary objective of studying the regional stratigraphy is to provide a more detailed interpretation of the stratigraphy of the Ferron Sandstone outcrop belt from Last Chance Creek to Ferron Creek (Figure 1.1). This area is similar to the scale of a moderate to large oil reservoir. The regional study includes determining the dimensions and depositional environment of each sandstone body, and the nature of the contacts with adjacent rocks or flow units. Important bounding surfaces, geometries, and depositional environments are being mapped in the field on photomosaics to characterize the variability of fluvial-dominated deltaic reservoirs. The regional study provided a basis for selecting prime outcrops for detailed case studies of the major reservoir types (meander belt, mouth-bar complex, wave-modified delta front, bar-finger sands, distributary channel, and tidal channels). Toward the end of the project, the regional morphological framework will be incorporated into model simulations at the oil and gas field scale.

2.1 Aircraft-assisted and Ground-based Photography

Most of the near-vertical outcrop belt within the study area has been obliquely photographed in order to construct photomosaics. The Ferron Sandstone has excellent exposure along strike; numerous canyons that cut perpendicular to strike offer excellent exposures along the depositional dip direction. The main Ferron Sandstone cliff and its deeply incised canyons together provide a three-dimensional view of lithofacies variations and transitions. The area photographed is in Emery and Sevier Counties, Utah, and consists of about 80 miles (130 km) of outcrop (cliff face). Boundaries of the area photographed are from one mile (1.6 km) south of Last Chance Creek north to Ferron Creek (Figure 1.1). Images were digitized to develop a computer graphics database for interpretation and manipulation. Several techniques were evaluated for producing digital photomosaics using the most cost-effective method without significant resolution compromise.

2.1.1 Methods

Fixed-wing aircraft-assisted photographs were taken as close to a right angle to the vertical outcrops as possible. A successful test flight proved that the techniques worked. Canyon areas inaccessible by aircraft were photographed from stationary ground-based positions with the start and finish azimuths of the mosaic marked on topographic maps. Photographs have approximately 30 percent overlap to allow for combination into photomosaics. Photographic work was scheduled to minimize shadows on east- and west-facing sides of canyons.

A 35-mm auto-wind camera with a 200 - 300 mm telephoto lens was used with a fast color print film (400 ASA). Distortion is reduced because of the focal length of the lens. The camera was oriented with the widest field of view vertical. This orientation took in the entire thickness (or that portion exposed) of the Ferron outcrop belt.

The color print film of the outcrop was: (1) evaluated, (2) transferred from the negative images to a digitized format, and (3) copied to compact discs (CDs). Reproducible black-and-white prints were generated using image-editing software and laser printers.

No scaling devices were used during the photography. Scale of the photos was determined in the field by measuring between locatable points on the photograph and those same points on the ground. During field mapping, coverage of each photomosaic was plotted on a 7.5-minute topographic quadrangle map with the aid of aerial photos.

The photomosaics were annotated with parasequences, parasequence sets, and lithofacies. Parasequence sets generally correlate to the existing stratigraphy of the seven delta-front sandstones or genetic sequences. Parasequences names were based on case-study locations and an A-, B-, C-type nomenclature. This allowed for adding parasequences identified later without disrupting the entire numbering system.

2.1.2 Results

The Ferron Sandstone outcrop belt within the study area (Figure 1.1) has been obliquely photographed. The resulting images were sharply focused, and changes in scale were minimal. These photographs (a total of 1,823 images of most of the 80-mile-[130-km-] long outcrop belt) have been digitized and transferred to CDs. Using image-editing software, photographs from the CDs are being assembled into reproducible photomosaics. Parasequences, parasequence sets, lithofacies, measured sections, vertical and horizontal scales, and other data are being plotted on the photomosaics in the field for both the regional and case-study analyses.

2.2 Collection of Existing Surface and Subsurface Data

Existing geophysical and core logs from the study area are being collected and interpreted to complement the lithofacies identification, depositional environment interpretation, and sandstone body geometries determined from the interpreted photomosaics. These data and other geologic information are being compiled in a database developed by the UGS, **INTEGRAL*gim**. This database is a geologic-information manager that links a diverse set of geologic data to records through a common, nongraphical user interface. **INTEGRAL*gim** contains much of the geologic data managed by the UGS and Utah Division of Oil, Gas and Mining (DOGM). The database includes petroleum, coal, mining, and stratigraphic data.

2.2.1 Methods

Published and unpublished maps, measured sections, well logs, core descriptions, mini-permeameter data, reports, and other data are being collected by the UGS. **INTEGRAL*gim** has been modified for this study to link various geologic attributes of the Ferron Sandstone to point-source locations. Formats for lithologic, paleocurrent, and core descriptions have been developed to standardize data collection. The database is designed so that geologic information, such as types and percentages of lithologies and sedimentary structures, can be incorporated into statistical models and exported into software programs to produce strip logs and lithofacies maps, percentage of lithofacies maps, and reservoir maps showing percentage of texture/fabric.

The database will also include well, core, and outcrop locations, lithology, porosity, mini-permeameter values, core plug permeability data, and unit tops, as well as other information.

Assigned stratigraphic rank of the various units measured in the field is included in the database and the thicknesses of these units calculated.

The **INTEGRAL*gim** database containing information from the Ferron Sandstone will be available at the conclusion of the project.

2.2.2 Results

Nine sources of basic geological and geophysical drill data on the Ferron Sandstone were identified (Table 2.1). The largest data holder is the Bureau of Land Management (BLM), which has hundreds of drill records from coal exploration holes drilled by Consolidation Coal Company (CONSOL). These records indicate that 357 wells were drilled on the unleased federal lands in the study area. Data were obtained for two core holes in the study area drilled by the University of Utah Research Institute (UURI). BP Exploration (BP) has donated core and geophysical logs from five stratigraphic test holes in the study area. The UGS has compiled published records (Edson and Barnosky, 1977; Edson, 1978; Hodder and Jewell, 1979; Ellis, 1980; and Ryer, 1981b) from 39 wells drilled by the federal government (BLM and U.S. Geological Survey [USGS]) in the study area. The study area contains 58 oil and gas exploratory and development wells. Most records of the wells which penetrate the Ferron Sandstone have been obtained.

By September 30, 1994, the UGS had acquired 138 geophysical logs and 1,800 feet (550 m) of core or core descriptions from these wells (Table 2.1). Information from 232 wells has been entered into ASCII files; data for 305 of the 481 total wells was also entered into the UGS **INTEGRAL*gim** database for the Ferron project (Table 2.1). Interpretations (thickness, type of lithology, and geologic description) have been completed for 343 wells.

Base maps have been digitized for the Willow Springs, Short Canyon, Johns Peak, Mesa Butte, Walker Flat, and Geyser Peak quadrangles. These base maps show drill-hole locations (petroleum exploratory and development wells, and coal core-holes), measured sections, coal outcrops, coal mined-out areas, drainages, and the top and base of the Ferron Sandstone.

2.3 Case-study Site Selection

The types of dominantly sandstone lithofacies that characterize the Ferron reservoir types were tentatively identified before the project began. These reservoir types were defined and mapped at the regional scale and will be the subject of the detailed, highly focused case studies.

2.3.1 Methods

Various geologic studies of the Ferron Sandstone (Anderson, 1991a, 1991b; Barton and Tyler, 1991; Cotter, 1971, 1975a, 1975b, 1976; Gardner, 1991; Ryer, 1981a, 1981b, 1982a, 1982b, 1983, 1991) were reviewed to compile a list of locations and types of lithofacies in the Ferron Sandstone to be examined in greater detail as part of the subsequent case studies. Preliminary regional interpretations were also used to help select the type and location of lithofacies for case studies. Potential case-study sites were delineated during several reconnaissance field trips by the geologic team.

Table 2.1. **Summary of well, geophysical log, and core data collected for the Ferron Sandstone study area.**

Source of wells	No. of wells with geophysical logs	No. of logs obtained by the UGS[1]	No. of wells cored/ footage cored	Core obtained by the UGS[1] (in feet)	No. of wells recorded in ASCII files[1]	No. of wells recorded in INTEGRAL*gim[1]
OIL AND GAS						
UURI[2]	2	2	2/800	800	0	0
ARCO[3]	7	7	7/3,527	descriptions only	0	0
BP[4]	5	5	5/1,000	1,000	0	0
other	58	41	0	0	0	0
COAL						
CONSOL[5]	357	62	356/unknown	descriptions only	232	305
USGS[6]	33	15	29/1,402	descriptions only	0	0
BLM[7]	0	0	6/1,156	descriptions only	0	0
WSMC[8]	12	0	0	0	0	0
HVCC[9]	7	6	7/463	descriptions only	0	0
TOTAL	481	138	412/8,348	1,800	232	305

[1] as of September 30, 1994
[2] University of Utah Research Institute
[3] ARCO Oil and Gas Company
[4] British Petroleum Exploration Inc.
[5] Consolidation Coal Company
[6] U.S. Geological Survey
[7] U.S. Bureau of Land Management
[8] Western States Mineral Corporation
[9] Hidden Valley Coal Company

2.3.2 Results

Three potential case-study sites were delineated during reconnaissance field trips: **Muddy Creek Canyon, Ivie Creek,** and **Willow Springs Wash,** in the north, central, and southern parts respectively of the study area (Figure 1.1).

Muddy Creek Canyon site -- Unlike the other potential study sites, where we will focus entirely on delta-front units in the basal part of the Ferron, the Muddy Creek site will involve analyses of the entire Ferron section. The nearly continuous outcrops, the three-dimensional aspect of the exposures, and the relative abundance of subsurface control facilitate three-dimensional mapping of individual reservoir types in the Ferron Sandstone in this area. Initial plans are to create a three-dimensional field-scale reservoir model of several sandstone units representing an area of about 3 miles (4.8 km) in the north-south direction, 2 miles (3.2 km) in the east-west direction, and 450 to 500 feet (140-150 m) vertically. The Ferron Sandstone is composed of seven deltaic units in the Muddy Creek Canyon area. Some of these units are stratigraphically simple; others include a variety of facies and display abrupt lateral facies variations.

Ivie Creek site -- The Ivie Creek site was selected to examine the abrupt facies changes in the No. 1 delta-front unit in outcrops north of Ivie Creek, east of the mouth of Ivie Creek Canyon. The basal unit is a thick, sandy, river-dominated parasequence tentatively designated the No. 1a which pinches out to the west. Overlying the No. 1a and extending beyond it to the west is a thin, presumable river-dominated parasequence of very low-energy, tentatively designated No. 1b. Of particular interest is the interrelationship among high-angle foreset beds, hummocky cross bedding, and planar-laminated sandstones. Modeling will focus on the effects the various bounding surfaces would have on fluid flow in these units. Recommendations will be made on how bounding surfaces can be identified from core and well-log data and, ultimately, how such features should be considered in field development and secondary or enhanced recovery programs.

Willow Springs Wash site -- The Willow Springs Wash site is the largest of the potential study areas. It covers an area 3.5 miles (5.6 km) long and 4 miles (6.4 km) wide (Figure 1.1). The site was selected because of the excellent three-dimensional aspect of exposures in the Willow Springs Wash and Indian Canyon areas. The focus of the work at this site will be parasequences of the No. 1 delta-front unit (Figure 2.1). Reservoir modeling will concentrate on variations in fluid flow between the parasequence types and on the amount of communication between each parasequence set.

2.4 Preliminary Regional Stratigraphic Interpretations

Regionally, the Ferron Sandstone consists of up to seven delta-front sandstone bodies or parasequence sets. The focus of our work is two parasequence sets in the lower part of the Ferron. Previous workers have designated these as the No. 1 and No. 2 sets. Recognizable sequences within the sets have been designated with lower-case letters (for example, No. 1a). Most fit the definition of a parasequence, being bounded above and below by transgressive surfaces ("flooding surfaces" in sequence-stratigraphic terminology). In some cases, the divisions may lack transgressive surfaces, yet are recognizable by changes in sedimentary styles.

The details of the parasequence-level stratigraphy in the No. 1 parasequence set are

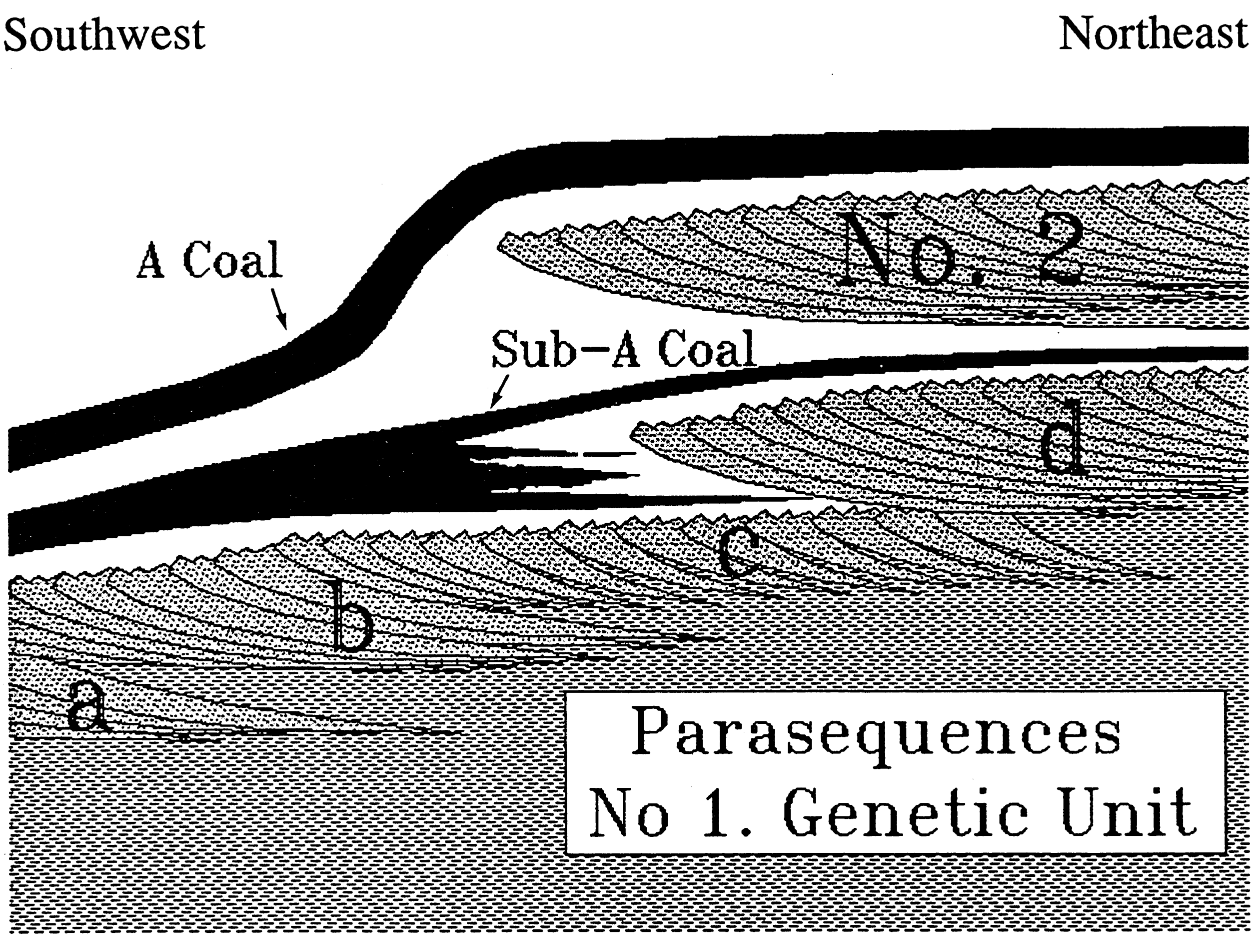


Figure 2.1. Diagrammatic cross section showing arrangement of parasequences (a, b, c, and d) of the Ferron Sandstone No. 1 delta-front sandstone unit at the Willow Springs Wash case-study area.

apparent along the outcrop from Last Chance Creek to the southern part of the Ivie Creek area, a case-study area in the center of the project study area (Figure 1.1). The No. 1a and b parasequences constitute a thick interval of sandstone at the base of the Ferron at Last Chance Creek and pinch out rapidly northward. In Indian Canyon of the Willow Springs Wash area, the No. 1 a, b, c, and d parasequences are well exposed. The No. 1d is differentiated from the preceding sequences based on a change from wave-dominated to low-wave-energy, river-dominated depositional style. It records northwestward progradation of a low-energy subdelta. The channels that supplied the sediment are apparent at several locations on both sides of Indian Canyon. In the Ivie Creek area, the No. 1 a,b, and c parasequences are well exposed and are interpreted as a low-wave-energy subdelta. From its landward pinch-out at the mouth of Willow Springs Wash, the No. 2 parasequence set thickens dramatically northward. Separating the No. 2 into parasequence-level units is difficult; possibly no divisions can be made in the Willow Springs Wash area. In the Ivie Creek area, the No. 2 can be divided and is interpreted as a low-wave-energy subdelta.

Our regional work in the northern part of the Ivie Creek area (Figure 1.1) has identified a marine sand formed in the brackish water lithofacies found to the south in the Ivie Creek case-study area. Stratigraphically, this sand is between the No. 1c and the top of the sub-A coal zone and has been tentatively designated the No. 1d parasequence. This parasequence may be exposed to the northeast of Ivie Creek. In the No. 2c, a large channel system is exposed with a predominantly west-to-southwest-directed paleoflow. We have tentatively interpreted this system to be a tidal channel complex, which flooded back into the bay deposits that are well defined in the Ivie Creek case-study area. We interpreted the marine sands found proximal to the channel system as deposits of the flood-tidal delta.

2.5 References

Anderson, P.B., 1991a, Landward pinch-out of Cretaceous marine nearshore clastics in the Ferron Sandstone Member of the Mancos Shale and Blackhawk Formation, east-central Utah; potential stratigraphic traps: Utah Geological Survey Contract Report 91-12, 110 p.

---1991b, Comparison of Cretaceous landward pinch-outs of nearshore sandstones: wave- *versus* river-dominated deltas, east-central Utah, *in* Chidsey, T.C., Jr., editor, Geology of east-central Utah: Utah Geological Association Publication 19, p. 283-298.

Barton, M.D. and Tyler, Noel, 1991, Quantification of permeability structure in distributary channel deposits Ferron Sandstone, Utah, *in* Chidsey, T.C., Jr., editor, Geology of east-central Utah: Utah Geological Association Publication 19, p. 273-282.

Cotter, Edward, 1971, Paleoflow characteristics of a Late Cretaceous river in Utah from analysis of sedimentary structures in the Ferron Sandstone: Journal of Sedimentary Petrology, v. 41, no. 1, p. 129-138.

---1975a, Deltaic deposits in the Upper Cretaceous Ferron Sandstone, Utah, *in* Broussard, M.L.S., editor, Deltas, models for exploration: Houston Geological Society, p. 471-484.

---1975b, Late Cretaceous sedimentation in a low-energy coastal zone: the Ferron Sandstone of Utah: Journal of Sedimentary Petrology, v. 45, p. 15-41.

---1976, The role of deltas in the evolution of the Ferron Sandstone and its coals: Brigham Young University Geology Studies, v. 22, pt. 3, p. 15-41.

Davis, L.J., 1954, Stratigraphy of the Ferron Sandstone, *in* Grier, A.W., editor, Geology of portions of the high plateaus and adjacent canyon lands, central and south-central Utah: Intermountain Association of Petroleum Geologists, Fifth Annual Field Conference Guidebook, p. 55-58.

Edson, G.M., 1978, Core drilling in 1978 - Willow Springs quadrangle, Emery and Sevier Counties, Utah: U.S. Geological Survey Open-File Report 78-1049, 21 p.

Edson, G.M., and Barnosky, C.L., 1977, Lithologic and geophysical logs of holes drilled in the Willow Springs, quadrangle, Emery and Sevier Counties, Utah: U.S. Geological Survey Open-File Report 77-866, 31 p.

Ellis, E.G., 1980, Geophysical logs and coal sections for four holes drilled in the Emery East quadrangle, Emery County, Utah: U.S. Geological Survey Open-File Report 80-1027, 5 p.

Gardner, M.H., 1991, Siliciclastic facies architecture in foreland basin clastic wedges - field guide to the Ferron Sandstone Member of the Mancos Shale, east-central Utah: Colorado School of Mines, unpublished report, 35 p.

Hodder, D.T., and Jewell, R.C., editors, 1979, Reclaimability analysis of the Emery coal field. Emery County, Utah: U.S. Bureau of Land Management EMRI Report No. 16, 408 p.

Ryer, T.A., 1981a, Deltaic coals of Ferron Sandstone Member of Mancos Shale: predictive model for Cretaceous coal-bearing strata of western interior: American Association of Petroleum Geologists Bulletin, v. 65, no. 11, p. 2323-2340.

---1981b, The Muddy and Quitchupah Projects: a project report with descriptions of cores of the I, J, and C coal beds from the Emery coal field, central Utah: U.S. Geological Survey Open-File Report 81-460, 34 p.

---1982a, Possible eustatic control on the location of Utah Cretaceous coal fields, *in* Gurgel, K.D., editor, Proceedings of the 5th Symposium on the Geology of Rocky Mountain Coal: Utah Geological and Mineralogical Survey Bulletin 118, p. 89-93.

---1982b, Cross section of the Ferron Sandstone Member of the Mancos Shale in the Emery coal field, Emery and Sevier Counties, central Utah: U.S. Geological Survey Map MF-1357.

---1983, Transgressive-regressive cycles and the occurrence of coal in some Upper Cretaceous strata of Utah: Geology, v. 11, p. 207-210.

---1991, Stratigraphy, facies, and depositional history of the Ferron Sandstone in the canyon of Muddy Creek, east-central Utah: *in* Chidsey, T.C., Jr., editor, Geology of east-central Utah: Utah Geological Association Publication 19, p. 45-54.

3. CASE STUDIES

The primary objective of the case studies is to develop a detailed geological and petrophysical characterization, at well-sweep scale or smaller, of the primary reservoir lithofacies typically found in a fluvial-dominated deltaic reservoir. Sedimentary structures, lithofacies, bounding surfaces, and permeabilities measured along closely spaced traverses (both vertical and horizontal) will be combined with data from core drilling to develop a three-dimensional view of the reservoirs within each case-study area. In developing the characterization, an evaluation will be conducted on how variations in sedimentary structures and lithofacies influence both compartmentalization and anisotropy of permeability.

A secondary objective of the case studies involves developing empirical relationships between mini-permeameter measurements made in the field and laboratory-determined permeabilities at both irreducible water saturation and residual oil saturation. The resulting transforms will be used to estimate the relative permeability values to be used as parameters in single-phase reservoir models.

3.1 Field Work

Field work during 1994 field season consisted of measuring stratigraphic sections, measuring paleocurrents, and interpreting photomosaics in Ivie Creek and Willow Springs Wash case-study areas. Core holes in the Ivie Creek area were planned, permitted, and staked. Closely spaced stratigraphic sections within a specific study site were measured in order to: (1) map variations in lithofacies, sedimentary structures (size, geometry, orientation/dip, and percent of sedimentary structures), and bedding types; and (2) characterize bounding surfaces both between and within sandstone bodies. Core holes will help provide a three-dimensional geometry of reservoir lithofacies. Core holes will be logged with sonic, density, neutron, focused resistivity, spectral gamma ray, and dipmeter tools.

3.1.1 Methods

Description of the individual units in the measured sections include the following information: (1) primary and secondary lithologies, composition, color, grain size of the rocks; (2) size, shape, and degree of induration of the beds; (3) sedimentary structures, biologic structures, and fossils in the rocks; and (4) bounding surfaces and depositional environment of the unit. Sections were correlated to develop preliminary interpretations of the stratigraphy and lithofacies. Field forms and codes were developed so lithologic and paleocurrent data could easily be entered into the UGS **INTEGRAL*gim** database.

Core holes are planned in the Ivie Creek area (Figure 1.1). These wells will be drilled downdip 200 to 1,200 feet (60-265 m) from the Ferron outcrop. Cores and geophysical logs from these wells will provide data for three-dimensional morphologic interpretation of individual lithofacies. Surface right-of-ways from Utah School and Institutional Trust Lands Administration and the U.S. Bureau of Land Management (BLM) were obtained. A survey of current mineral-lease ownership showed no active coal lessees or other mineral-rights holders. Staking and permitting procedures through the Utah Division of Oil, Gas and Mining (DOGM), the oil and gas regulatory agency for Utah, were initiated in order to drill and complete the core holes by the end of November 1994. Core-hole locations were surveyed using the global-positioning system. Permitting involved filing a DOGM "application to drill" (APD) which included: (1) an eight-point drilling program and a pre-site inspection, (2) obtaining clearance by the Utah Division of Wildlife Resources, (3) an on-site archeological inspection by Utah Division of State History, (4) obtaining a monitor-well construction permit (requires identification and notification of any significant encounter of water), and (5) obtaining a water-use permit (allows use of water from sources other than municipal sources) from the Utah Division of Water Rights, and an on-site surface right-of-way inspection by the BLM.

3.1.2 Results

Forty-six sections were measured and described in the Ivie Creek and Willow Springs Wash case-study areas. Over 500 paleocurrent measurements were made at these and other localities. Lithologic and paleocurrent data are being entered into the UGS **INTEGRAL*gim** database for use in constructing statistical models, strip logs, and lithofacies maps.

Eleven core-hole locations were permitted from DOGM in the Ivie Creek area (Figure 3.1) but only five or six core holes will be drilled. Water-use and right-of-way permits were also obtained. The total depths of the core holes will be approximately 550 feet (150 m). The Ferron No. 1 and No. 2 parasequence sets will be cored (approximately 160 feet [50 m]) in each hole. The proposed spacing pattern of the core holes will be similar to that typically used to develop an oil field.

A large-diameter core (7 7/8 inch [20 cm]) from a UURI Ferron core hole (the UURI No. 1) was logged and important core segments photographed. The core hole was drilled in the Muddy Creek case-study area (Figure 1.1) in 1991. The tops of lithologic and genetic units were noted and the principal facies boundaries were interpreted. The geophysical log of the UURI No. 1 was interpreted and compared to the core description. This information and data from the cores to be drilled later in the project will be used to prepare strip logs, and facies maps, and to define "type" logs for the principal reservoir(s) in the case-study area.

3.2 Outcrop Gamma-ray Measurements

Objectives for collecting outcrop gamma-ray measurements for the Ferron Sandstone in the Ivie Creek case-study area are: (1) to determine variations in clay-mineral content (or sand/shale ratios), (2) to permit detailed correlation among and between outcrop traverses and core-hole gamma-ray logs, and (3) to detect possible diagenetic changes associated with precipitation of uranium. Variations in the gamma-ray signal are related to clay content in shaly sandstones which, in turn, influences the compartmentalization of flow units.

3.2.1 Methods

Field measurements were taken using a portable 256-channel gamma-ray spectrometer capable of determining total natural gamma counts as well as concentrations of potassium, thorium, and uranium (Figure 3.2). The spectrometer was tested in the lab and field to determine its vertical resolution and replicability. Test measurements in the field were found to

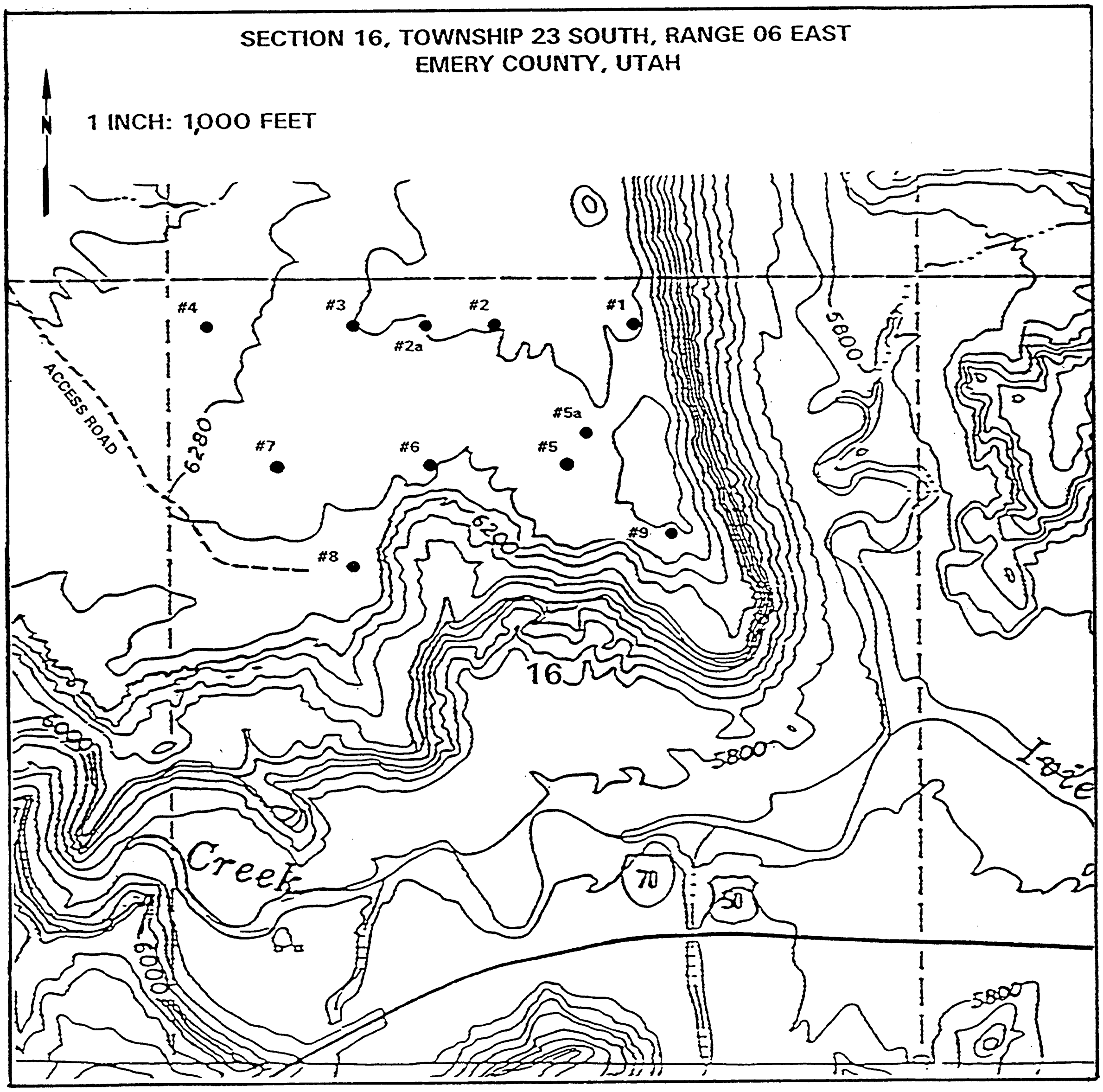


Figure 3.1. Locations of 11 proposed core holes permitted in the Ivie Creek case-study area, section 16, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah to core the No. 1 and No. 2 sandstones. Base map from U.S. Geological Survey Mesa Butte and Walker Flat 7.5' topographic maps; contour interval is 40 feet (12 m).

Figure 3.2. Gamma-ray spectrometer measures natural gamma counts and concentrations of potassium, thorium, and uranium along a measured section in the Ivie Creek case-study area. Photo by T.C. Chidsey, Jr., Utah Geological Survey.

be unreliable in rough topography because gamma rays entered the sides of the detector. This problem was corrected by covering the sides with lead shielding.

Field measurements showed that the total gamma-ray count is not always a reliable indicator of clay content. Potassium and thorium co-vary, probably because they are present primarily in clays. Uranium, however, is not commonly correlated with potassium and thorium. This indicates that uranium is present in minerals other than clays. Consequently, for reliable determination of clay content, potassium and thorium must be measured rather than just total gamma rays. One-minute measurements were made, almost five times the duration needed for good total-gamma values but barely sufficient for reliable potassium, thorium, and uranium measurements. Gamma-ray measurements were run along the same transects as the mini-permeameter sampling and measured sections.

3.2.2 Results

All gamma-ray logging was done along vertical or near-vertical (depending on access) traverses. Fifteen gamma-ray traverses were undertaken, each consisting of 200 to 400 measurements at 0.5 to 1.0 foot (0.15-0.3 m) intervals. All traverses included the entire No. 1 parasequence set, and most also included all or part of the No. 2 parasequence set. Most traverses corresponded to measured sections. The gamma-ray profiles are being used for correlation (Figure 3.3) and quantitative determination of sand/shale percentage.

3.3 Outcrop Core-plug Sampling

The objective of core-plug sampling in the Ivie Creek case-study area was to characterize vertical and lateral variations of a number of petrophysical properties (velocity, density, porosity, permeability, and mineralogy) in the types reservoir rocks found in the Ferron Sandstone and to determine the interrelations among these properties.

3.3.1 Methods

The core-plug sampling technique involved drilling a 1- to 4-inch- (2.5-10-cm-) long core plug, 1 inch (2.5 cm) in diameter, with a portable gas-powered motor and water-cooled diamond bit. The geographic orientation of each sample was determined and the sedimentary structure of the drilled bed was noted or photographed.

3.3.2 Results

All core plugging was done along vertical or near-vertical (depending on access) traverses. A total of 283 samples were taken from nine traverses. Most traverses corresponded to measured sections. Various lithofacies from both the No. 1 and No. 2 sandstones were sampled.

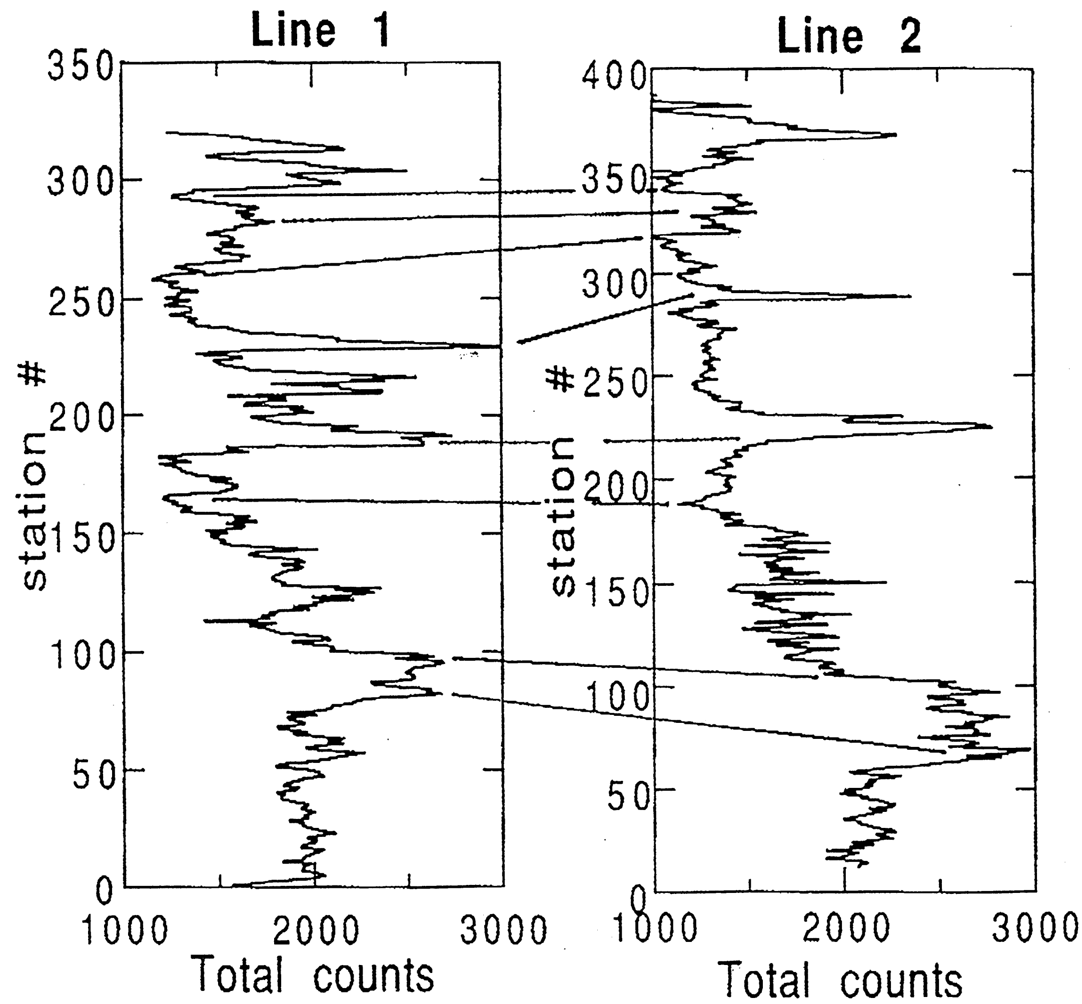


Figure 3.3. Typical gamma-ray profiles from traverses in the Ivie Creek case-study area. Preliminary correlations between sandstone and shale units are shown.

3.4 Mini-permeameter Measurements

A large quantity of permeability data was collected from outcrop exposures in the Ivie Creek case-study area. These data can be integrated into a complete reservoir characterization product that can assist in subsequent reservoir-simulation work. Two activities make the Ivie Creek case-study site important as a reservoir analog. First, five to six core holes will be drilled in a five-spot pattern, with 40 acre spacing, in close proximity to the cliff exposures extensively studied earlier in the field season. These wells will provide core and geophysical logs through the sedimentary sections of primary interest. Most importantly, the data from the cores and logs will provide a sound basis for determining the detailed vertical variation in reservoir properties that cannot easily be determined in outcrop work. Second, an associated surface seismic study by the University of Utah will be conducted, and will also make it easier to interpret the outcrop. The resulting interpretation will aid in inferring lateral variations in reservoir properties in reservoirs without good outcrops.

Outcrop permeability testing, when combined with detailed geologic mapping, will improve understanding of the lateral variability in permeability for specific bedform types. Vertical permeability transects provide a coarse map of vertical permeability variations. These variations can be used, along with outcrop gamma-ray mapping, to match the lateral permeability transects and geological mapping. Additional detailed data will be provided from the nearby core holes.

3.4.1 Methods

Seven permeability transects, four vertical and three sub-horizontal (parallel to bedding), were made on the outcrop at the Ivie Creek case-study site (Figure 3.4). The transects span the proximal, middle, and distal portions of the delta-front rocks of the No. 1 sandstone. Transect locations were jointly chosen by the geological and engineering teams to include the majority of the lithofacies present in the delta-front sequence. Data from these transects will be used to determine the statistical structure of the spatially variable permeability field within the delta front, to investigate how geological processes control the spatial distribution of permeability, and to evaluate permeability measurement techniques.

The four vertical transects are approximately 600 feet (200 m) apart and 100 to 200 feet (30-60 m) long. Measurement intervals (station spacing) on all of the vertical transects are 0.3 feet (0.1 m). From west to east (distal to proximal), the transects are: T-2, T-1, T-3, and T-4. The three sub-horizontal, bed-parallel transects are approximately 50 feet (15 m) long. From west to east the transects are: T-7, T-6, and T-5. Station spacing on the bed-parallel transects is 0.5 feet (0.2 m).

After general sedimentologic and stratigraphic interpretation of the area encompassing the vertical transects, a "window" approximately 300 feet (90 m) wide was selected for detailed geologic description. The window extends across the middle and distal portions of several clinoforms (deltaic foresets). Three stratigraphic sections (at the center and two ends of the window) were measured in detail noting lithologies and grain size, primary and secondary sedimentary structures, and bed thicknesses. Lateral and vertical variations of these parameters within units were also described. Units as thin as 0.01 feet (0.2 cm) were described. Within the window, a representative succession of several adjacent clinoforms in the No. 1a was chosen to

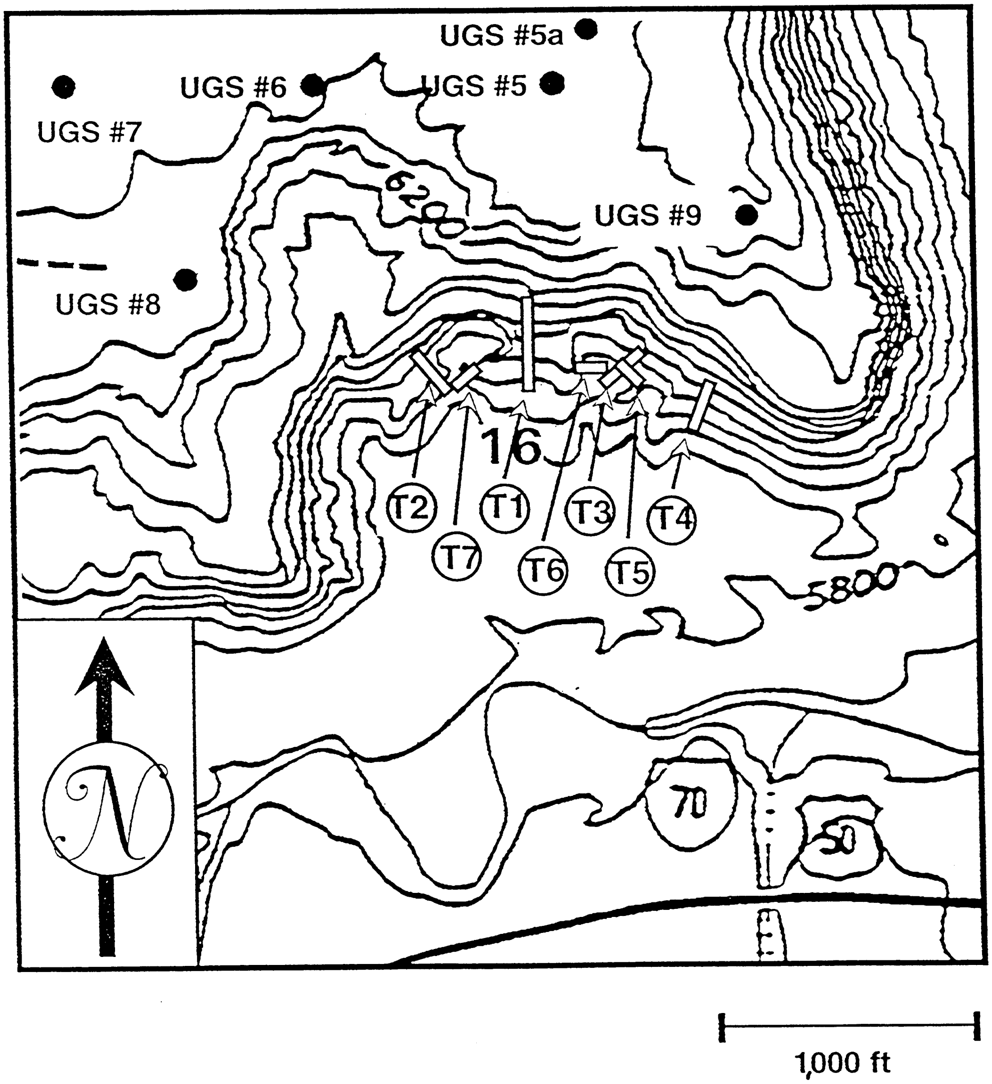


Figure 3.4. Location of seven permeability transects (vertical and parallel to bedding) in the Ivie Creek case-study area, section 16, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah. Proposed core-hole sites are shown by heavy dots. Base map from U.S. Geological Survey Mesa Butte and Walker Flat 7.5' topographic maps ; contour interval is 40 feet (12 m).

expand documentation of lateral variation of these parameters within individual clinoforms. Locations along the clinoforms, termed "mini-windows", at approximate 50-foot (15-m) intervals were photographed to document the lateral variations in lithology, bed thickness, and sedimentary structures (Figure 3.5). Several mini-windows outside the main window were also interpreted. These are in a more proximal position and allow documentation of additional change in clinoforms. The dimensions of the mini-windows are about 4 feet (1 m) high by 6 feet (2 m) wide at the distal end of the clinoform and thicken to approximately 10 feet (3 m) high by 6 feet (2 m) wide at the proximal end of the clinoforms. This detailed geologic information will allow the reservoir modeler to develop rules and constraints on lateral variation within the delta front. From an evaluation of this work, the following procedure for window characteristics in future case-study areas was developed:

1. Take a photomosaic of the area in which the window is to be chosen.
2. Interpret and annotate the photomosaic noting parasequences, architecture between and within parasequences, and lithofacies and sedimentary structures. This will allow the detailed description of the window to be placed within the context of the parasequence.
3. Pick the location of the window.
4. Measure three very detailed stratigraphic sections (at center and two ends of the window) noting lithologies and grain size, primary and secondary sedimentary structures, thicknesses, and lateral and vertical variation within units. Units that are described may be as thin as 0.01 feet (0.2 cm). Make each unit a single lithology, for example, "lump" as little as possible. These detailed vertical transects will be used by the reservoir modeler to develop rules governing the vertical succession of permeability units within the window. The modeler may decide to lump several described units into one permeability unit. However, units can not easily be separated for modeling once they have been lumped in the field.
5. Pick a representative clinoform, or a succession of several adjacent clinoforms, and choose locations at approximate 50-foot (15-m) intervals at which photographs (mini-windows) will be taken. These mini-windows will document the lateral variations in lithology, bed thickness, and sedimentary structures that occur along clinoforms. The reservoir modeler will use this information to develop rules and constraints on lateral variations. The mini-windows are approximately 4 feet (1 m) high by 6 feet (2 m) wide at the distal ends of the window and clinoforms and thicken to approximately 10 feet (3 m) high by 6 feet (2 m) wide at the proximal ends.
6. Annotate the mini-windows by drawing bed boundaries and noting lithologies and sedimentary structures.

Core plugs roughly 0.75 inches (0.3 cm) in diameter and 1 to 3 inches (2.5-7.5 cm) long were drilled from the outcrop at each transect station (where possible) to ensure that permeability measurements could be made on fresh, unweathered rock surfaces. Drilling experience and examination of the core plugs indicate that chemical weathering extends into the rock less than 0.5 inches (1.3 cm). Whole plugs were typically recovered only from sandstone beds greater than 2 inches (5 cm) thick. Useful plugs could usually not be obtained from thinner sandstone beds or from thinly bedded sandstones, siltstones, and mudstones. Core-recovery rates range from 50 to nearly 100 percent. Where core plugs could not be recovered, small rock samples were taken, except where the outcrop was buried under colluvium.

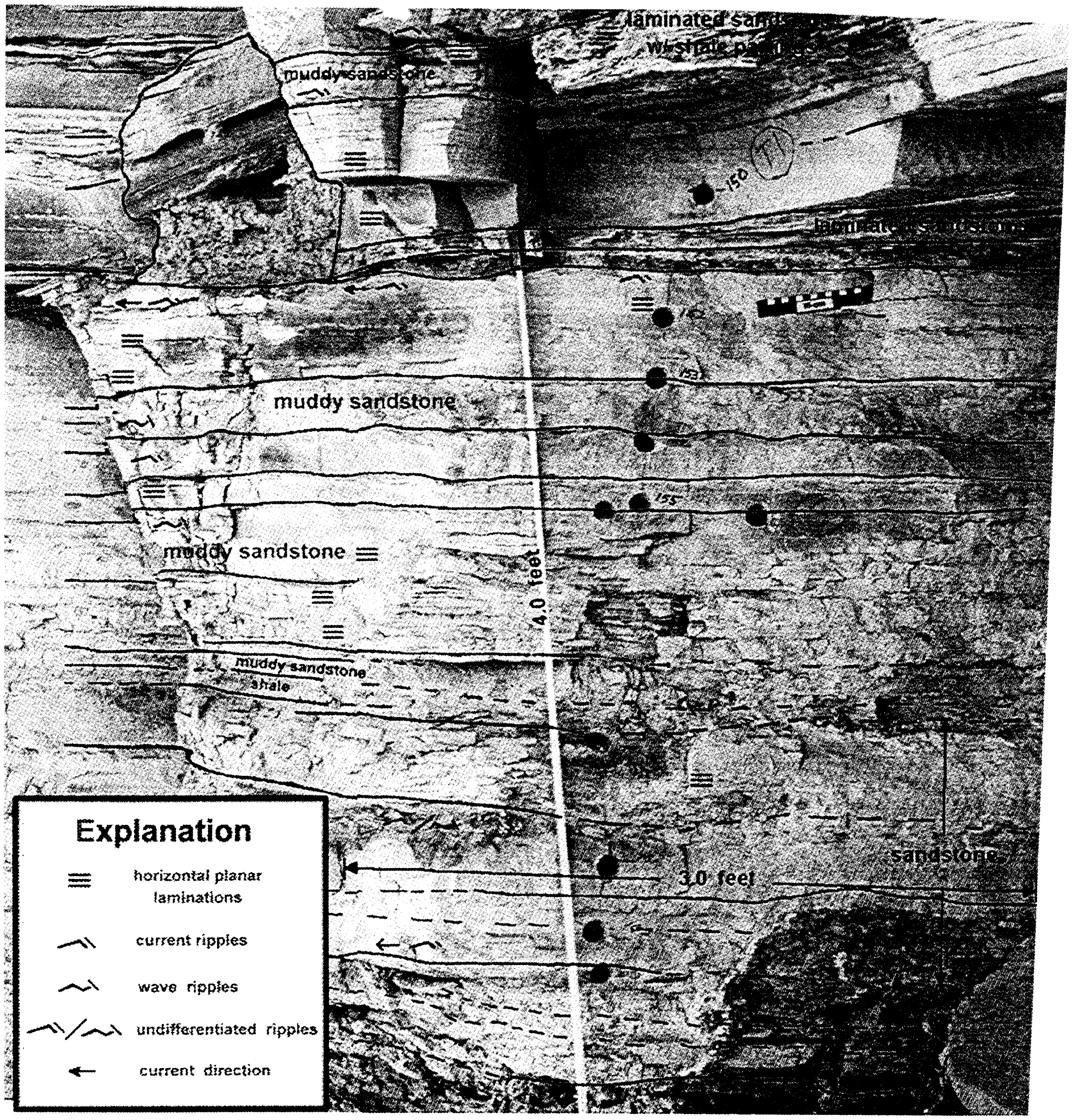


Figure 3.5. Portion of mini-window and geologic interpretation of the Ferron Sandstone No. 1a along permeability transect (vertical and parallel to bedding) in the Ivie Creek case-study area. Photo by R.D. Adams, Utah Geological Survey.

Permeability was measured in the laboratory on the unweathered end of the core plugs after the unweathered end was trimmed flat with a rock saw. The thin disks trimmed from the plug ends were saved for possible future petrographic analysis. At those stations where a good hole was drilled but a broken core was recovered, permeability was measured in the hole. Prior to measuring field permeability in a core hole, the back of the hole was prepared using a screwdriver and a rock hammer to chip away rough spots, providing a flat surface for the mini-permeameter probe tip. The hole was rinsed out with water and allowed to dry for at least 24 hours prior to permeability testing. The hole was also "cleaned" by a blast of compressed gas immediately before testing.

An electronic miniprobe permeameter (EMP) supplied by the Mobil Exploration/Producing Technical Center was used to make laboratory permeability measurements on the trimmed, whole core plugs and to make field measurements in core holes (Figure 3.6). This instrument has an accuracy of 1 to 12 percent and a precision of 1 to 3 percent on homogenous core plugs with permeabilities ranging from 1 to 4,500 millidarcies (md) (J.R. Garrison, Jr., Mobil, verbal communication, 1994). A rack was used to secure the probe in the laboratory; an expansion packer was used to secure the probe in a core hole in the field. In both cases, an air-actuated piston pushes the probe tip against the center of the sample, providing a air-tight couplingbetween the probe tip and the rock.

3.4.2 Results

The seven transects contained a total of 1,236 stations; of these, 1,000 were drilled and 900 whole core plugs were recovered for laboratory permeability testing. Permeability measurements made as of October, 1994 are too sparse to make any definitive statements about the spatial pattern of permeability in the delta front of the No. 1 sandstone. The early data suggest that a substantial fraction of the rocks are low permeability, less than 10 md. This holds true for both the mudstones and siltstones as well as the sandstones. However, the majority of the permeabilities obtained thus far are field measurements made in transects T-1 and T-2, situated in the middle and distal portions of the delta front, where siltstones and mudstones are common and lower permeabilities are expected. As of October, 1994 less than 50 permeability measurements had been made in the laboratory. The majority of these samples are more proximally located, fine-grained, well-cemented sandstones; permeability of these sandstones is usually less than 10 md. At a few stations, however, permeabilities greater than 100 md have been measured in coarser grained, poorly cemented sandstones.

Several stations were occupied multiple times in the field in order to obtain statistics to verify the precision of the mini-permeameter. In addition, several stations from which good whole core plugs were recovered were also field tested in the core hole to provide a comparison between field and laboratory measurements of permeability. The permeability of these core plugs will also be measured using conventional Hassler sleeve techniques to evaluate the accuracy of the mini-permeameter.

The strategy developed during the 1994 field season differs from previous outcrop work performed in the Ferron Sandstone (Barton and Tyler, 1991) because a much larger sequence type - a delta-front sequence - is being characterized rather than the more often studied and much smaller distributary channels. It is clear that distal portions of the delta front comprise an alternating set of thin sandstone and shale units. The relatively low permeability of the shales

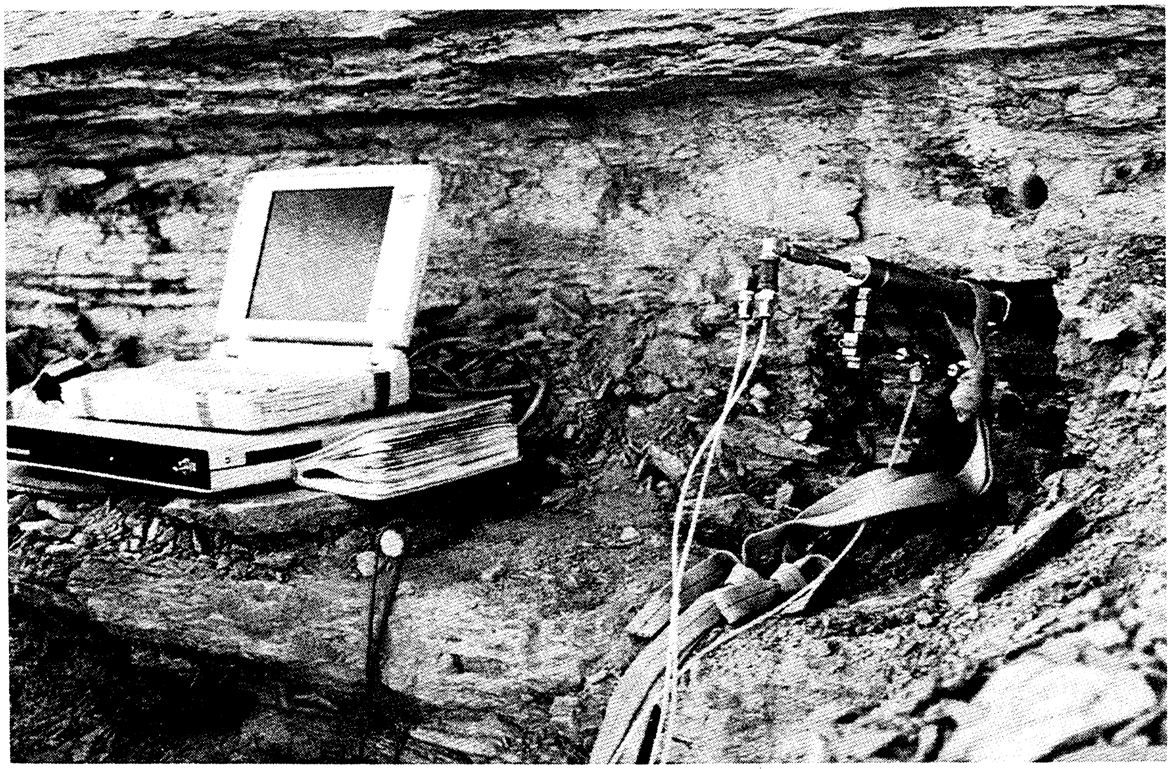


Figure 3.6. The electronic miniprobe permeameter measuring permeability in a core hole in the Ivie Creek case-study area. Photo by R.D. Adams, Utah Geological Survey.

suggests that developing appropriate lumped permeability averages will largely depend on the ability to capture the geometry of the sandstone and shale units. Although the data have been collected to characterize the internal variation of permeability within the distal sandstone layers, the juxtaposition of sandstone and shale is expected to play a dominant role in controlling the bulk permeability of distal regions of the delta front. In contrast, the more proximal regions of the delta front contain only small amounts of shale. Detailed permeability variations within the sandstone must be studied in order to compute realistic lumped average permeability values for this area of the delta-front sequence. Detailed mapping of bedform geometries provides an important basis for assessing how the scaling up and averaging should be carried out.

3.5 Preliminary Case-Study Interpretations

The Ferron Sandstone in the Ivie Creek area consists of two regional scale parasequence sets, the No. 1 and No. 2. Locally, each parasequence set is divided into three mappable, coarsening-upward, stratigraphic sequences (a, b, and c) which may or may not represent parasequences.

The lowest sequence in the No. 1 is the 1a and represents a river-dominated delta deposit which changes from proximal to distal (where the sandstone pinches out) or east to west across the Ivie Creek area. These changes can be documented at two locations along the outcrop belt. Steeply inclined beds (the clinoforms) of sandstone that accumulated on the prograding delta front are prominently displayed on the north side of Ivie Creek. Assuming a lobate shape for the deposits, the subsurface pinch-out location of these deposits has been approximated. The core-hole sites were chosen to help characterize the sequence from proximal to beyond the pinch-out.

The No. 1b sequence laps onto the more distal parts of the No. 1a sequence in the western part of the study area and represents the distal portion of another delta lobe, probably originating from the southwest. This sequence includes a channel sandstone body, lenticular in cross section, deposited by a northwesterly flowing stream.

The No. 1c sequence, the uppermost, is continuous across the entire Ivie Creek area and represents a wave-modified delta. The sequence is capped by unidirectional, trough-cross-bedded sandstone. The No. 1c contains loading features near the mouth of Ivie Creek and thickens to the north as the No. 1a pinches out.

Above the cross-bedded sandstone are 10 to 15 feet (3-6 m) of bay-fill deposits. These deposits consist of carbonaceous mudstone; thin, rippled-to-bioturbated sandstone and siltstone; fossiliferous mudstone to sandstone; oyster coquina; and ash-rich coal. The uppermost carbonaceous mudstone or ash-rich coal is the sub-A coal zone. A flooding surface has been identified at the top of the sub-A. The boundary with the overlying No. 2 parasequence set is drawn at this flooding surface.

The lowest sequence of the No. 2 parasequence set is the 2a. The 2a begins as interbedded sand and shale in a prodelta to lower shoreface environment. These deposits are thin, typically less than 10 feet (3 m) thick. They are overlain by a 0.5-to 1-foot-(0.2-0.3-m-) zone of highly carbonaceous to coaly sandstone which grades into 20 to 30 feet (6-9 m) of very-fine-grained, silty, and slightly carbonaceous sandstone. The unit is intensely bioturbated and was deposited in the middle-shoreface environment.

The No. 2b sequence consists of horizontally bedded, silty sandstone at the base and unidirectional, trough-cross-bedded sandstone toward the top. In a road cut along I-70 this unit displays trough sets which become horizontally bedded in a downdip direction. These deposits are interpreted as mouth-bar deposits.

The No. 2c sequence is separated from the underlying 2b sequence by a siltstone to shale interval which varies in thickness across the case-study area. Generally the entire unit fines from west to east. In the east, the No. 2c is interpreted as a bay-fill sequence (although it is devoid of fossils). At the top of the sequence is a thin, medium-grained carbonaceous sandstone which may represent the migration of a beach (foreshore deposits) across the bay fill prior to capping by coastal-plain deposits and deposition of the overlying A coal.

Deposition of sandstones in the No. 1 parasequence set was from the south to southeast, whereas the general coarsening of the No. 2 parasequence set to the west suggests that this unit was deposited from west to east. The No. 2 contains more and cleaner sand, indicating a more wave-influenced environment of deposition.

The Ferron Sandstone in Indian Canyon of the Willow Springs Wash area consists of excellent exposures of the No. 1 parasequence set. The set is divided into five mappable stratigraphic sequences (a through e). Three are considered parasequences. The parasequences are displayed in a forward-stepping arrangement similar to many delta-front reservoirs. The transgressive (or "flooding") surfaces that separate the parasequences are overlain, at least in part, by mudstone units that may act as permeability barriers between sandstone bodies. Rocks in these sequences contain prodeltaic; lower, middle, and upper shoreface; foreshore; and fluvial-dominated delta-front deposits.

The Nos. 1a through 1c represent non-deltaic coastal deposits; in contrast, the No. 1d represents deposits from a subdelta of a river-dominated deltaic complex. Paleocurrent measurements on large-scale, trough-cross-stratification in the delta-front sandstone at the top of the No. 1d indicate flow to the north (Figure 3.7). Several distributary channels cut the No. 1d in this area. Paleocurrent measurement taken from these channels indicate north to northeast flow (Figure 3.8). A bay-fill sequence caps the top of the No. 1 parasequence set.

The No. 2 parasequence set in Indian Canyon of the Willow Springs Wash area is thin and consists coastal-plain deposits containing little sandstone.

3.6 References

Barton, M.D. and Tyler, Noel, 1991, Quantification of permeability structure in distributary channel deposits Ferron Sandstone, Utah, *in* Chidsey, T.C., Jr., editor, Geology of east-central Utah: Utah Geological Association Publication 19, p. 273-282.

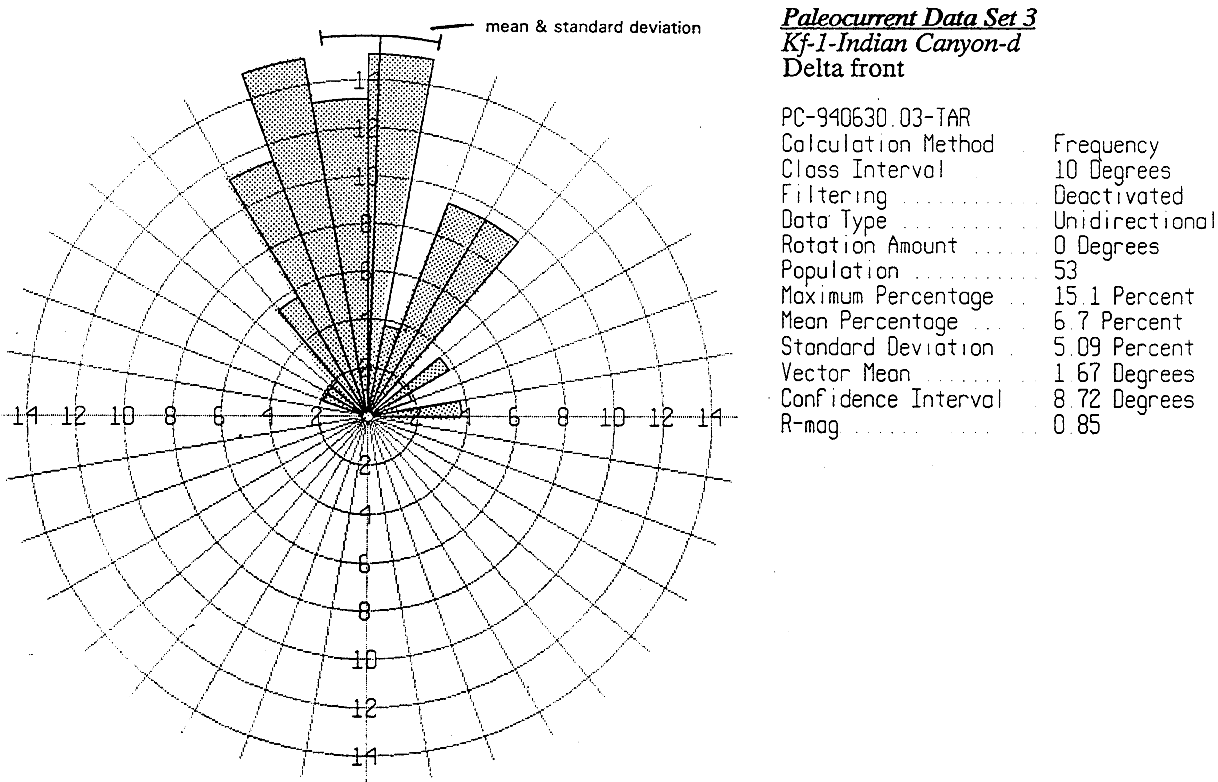
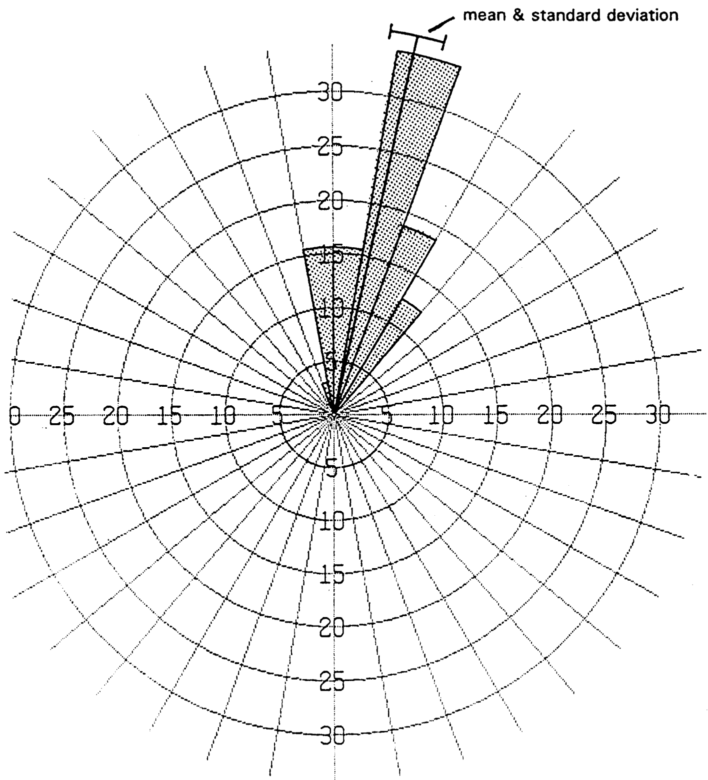


Figure 3.7. Rose diagram of paleocurrent data from a delta-front sandstone in the Ferron Sandstone No. 1d parasequence, Indian Canyon, Willow Springs Wash case-study area.



Paleocurrent Data Set 2
(Kf-1-Indian Canyon-d)
Distriburary channel

PC-940630.04-TAR All Measurements

Calculation Method	Frequency
Class Interval	10 Degrees
Filtering	Deactivated
Data Type	Unidirectional
Rotation Amount	0 Degrees
Population	32
Maximum Percentage ..	34.4 Percent
Mean Percentage	16.7 Percent
Standard Deviation .	10.21 Percent
Vector Mean	12.47 Degrees
Confidence Interval ..	4 Degrees
R-mag	0.98

Figure 3.8. Rose diagram of paleocurrent data from a distributary channel sandstone in the Ferron Sandstone No. 1d parasequence, Indian Canyon, Willow Springs Wash case-study area.

4. TECHNOLOGY TRANSFER

The UGS is the Principal Investigator for three government-industry cooperative petroleum-research projects including the Ferron Sandstone project. The projects are designed to improve recovery, development, and exploration of the nation's oil and gas resources through use of better and more efficient technologies. The projects involve detailed geologic and engineering characterization of several complex heterogeneous reservoirs. Two of the projects will include practical oil-field demonstrations of selected technologies. The U.S. Department of Energy and multidisciplinary teams from petroleum companies, petroleum service companies, universities, and state and federal governments are co-funding the three projects.

The UGS will release all products of the Ferron Sandstone project in a series of formal publications. These will include all the data as well as the results and interpretations. Syntheses and highlights will be submitted to refereed journals as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*, as well as the UGS *Petroleum News*.

The UGS has displayed the Ferron Sandstone project plans and objectives at all recent AAPG regional and national conventions and at the Society of Petroleum Engineers national convention throughout the year with three to four UGS scientists staffing the display booth. Abstracts have been submitted for technical presentations at future meetings.

4.1 Utah Geological Survey *Petroleum News*

The purpose of the UGS *Petroleum News* newsletter is to keep petroleum companies, researchers, and other parties involved in exploring and developing Utah energy resources, informed of the progress on various energy-related projects of the Utah Geological Survey. The UGS *Petroleum News* is published semi-annually and contains articles on: (1) DOE-funded and other UGS petroleum projects activities, progress, and results, (2) current drilling activity in Utah including coalbed methane, (3) new acquisitions of well cuttings, core, and crude oil at the UGS Sample Library, and (4) new UGS petroleum publications.

4.2 Technical Presentations and Publications

Adams, R.D., and Stapor, F.W., 1994, Response of delta morphology and progradational style to changes in accommodation, sedimentation, and basin topography: Ferron Sandstone, east-central Utah: Geologic Society of America Abstracts with Programs, v. 26, no. 7, p. 158.

Forster, C.D., and Best, Don, 1994, The Ferron Sandstone: outcrop studies of a fluvial-deltaic reservoir analog: Technical Presentation to Los Alamos National Laboratory.

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