UGR File #505
USGS
Abstract

UGR FILE # 505

DEPOSITIONAL ENVIRONMENTS AND DIAGENESIS OF SOME NONMARINE UPPER CRETACEOUS RESERVOIR ROCKS, UINTA BASIN, UTAH

By

C. W. Keighin and Thomas D. Fouch
U.S. Geological Survey, Box 25046, Federal Center, Lakewood, Colorado 80225

ABSTRACT

UGR File #505
USGS
Abstract

DEPOSITIONAL ENVIRONMENTS AND DIAGENESIS OF SOME NONMARINE UPPER CRETACEOUS RESERVOIR ROCKS, U INTA BASIN, UTAH,

by

C. W. Keighin and T. D. Fouch

U.S. Geological Survey, Federal Center, Box 25046, Lakewood, Colorado 80225

ABSTRACT

Natural gas is produced from diagenetically created pore space developed in stratigraphic traps in nonmarine sandstones of the Upper Cretaceous Neslen, Farrer, and Tuscher Formations of the Mesaverde Group in the eastern part of the Uinta Basin. Porosity and permeability in these rocks are quite low and highly variable. For this reason, the reservoir rocks are commonly termed "tight" or "unconventional."

Although core is limited, our comparison of the physical and biological constituents in the rocks in the subsurface with those in temporally equivalent beds exposed along the Book Cliffs at the southeast margin of the basin indicates the reservoir units were formed by subaerial streams. Channel-form beds in the Neslen were formed in small, meandering streams on a coastal plain, and those of the overlying lower part of the Farrer represent more numerous and larger meandering streams with common straight segments. The Tuscher and the upper part of the Farrer form the uppermost Cretaceous rocks in the eastern part of the basin, and they were formed as part of an anastamosing complex of mixed braided and meandering streams that combined to preserve a thick sequence of sandstone units. Boundaries between these formations are gradational, as are the boundaries between depositional settings.

The sandstones, studied in thin section and by X-ray diffraction and scanning electron microscopy (SEM), are predominantly moderately well sorted very fine to fine-grained sublitharenites and litharenites. Rock fragments, primarily of chert and fine-grained sedimentary rocks, are commonly abundant. Deformation of labile rock fragments occurred, but the effects of compaction are relatively minor. No fractures, either open or healed were seen in thin section, but mineralized fractures were seen in core.

Chemical diagenesis had a greater influence on the sandstones than did mechanical compaction. Intergranular carbonate cements, dolomite/ankerite and calcite, are common; fine-grained authigenic(?) siderite occurs only in deeper (i.e., Neslen Formation) samples. Calcite content appears to decrease (to zero?) in the deeper samples, but ankerite becomes more abundant. Authigenic kaolinite commonly fills pores, partially to completely, but evidently has not replaced feldspars. Authigenic illite usually lines micropores (5-10 µm) in partially leached chert grains; in some cases, it partially replaces kaolinite. Development of authigenic clays significantly modified pore geometry and fluid flow and retention characteristics of the sandstones. Probably more than one episode of leaching removed, partially to completely, carbonate cements, chert grains, and feldspars. Dissolution formed secondary porosity, which appears to be responsible for the favorable reservoir characteristics of some of the sandstones.

Sandstone units containing the coarsest grains and the largest scale of crossbedding are commonly preferentially and pervasively cemented with carbonate minerals. Therefore, porosity and permeability may be very low in units that would otherwise be preferred exploration targets.

We suggest that the principal hydrocarbon reservoir rocks in the nonmarine part of the Mesaverde Group are developed in diagenetically enhanced stratigraphic traps.

INTRODUCTION

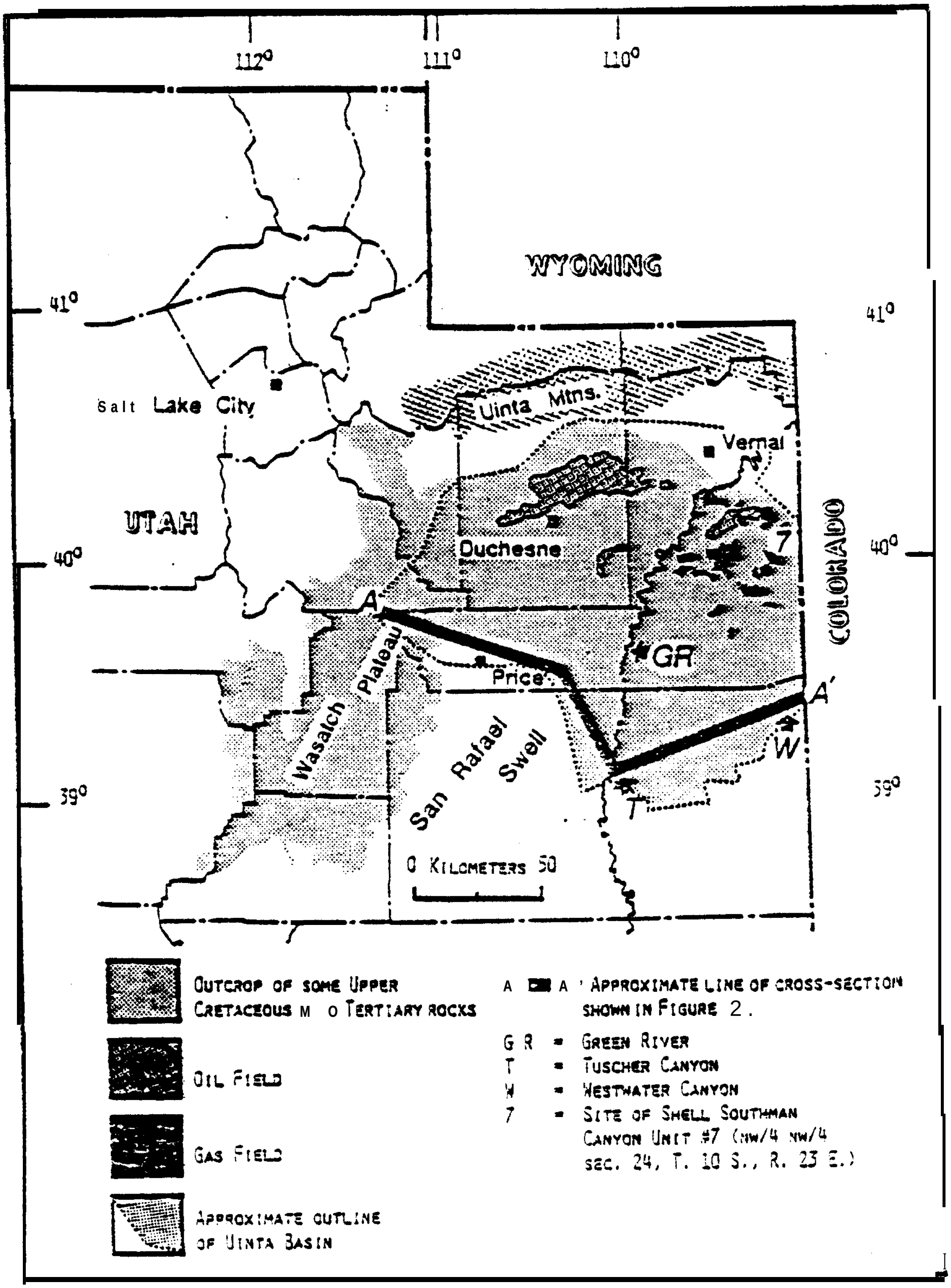
Nonmarine natural gas-bearing sandstone beds of the Upper Cretaceous Mesaverde Group in the Uinta Basin, Utah, are characterized by relatively low but variable values of porosity and permeability. For this reason, these reservoir rocks are frequently referred to as "tight" or "unconventional" reservoirs. Part of the Southman Canyon gas field (Fig. 1) (Campbell and

Figure 1.--NEAR HERE

Bacon, 1976) is developed in Eocene nonmarine rocks of the Wasatch Formation in addition to those of the Mesaverde Group. Temporally and depositionally similar rocks contain natural gas in much of the Piceance Creek basin, and they are productive at several fields (Johnson, 1979a-c; Johnson and others, 1979a-c, 1980).

Exploration for gas and/or oil in units that contain rocks whose porosity and permeability vary greatly has historically proven difficult and commonly unsuccessful in the absence of sufficient economic incentives. It has also often proven fruitless when a reasonably accurate analysis of the sedimentologic and mineralogic characteristics of the objective units was not utilized. In the absence of an understanding of the sedimentologic and mineralogic properties of the rocks, borehole geophysical logs are commonly misinterpreted and potential reservoirs are damaged during drilling, completion, or stimulation activites.

USGS
Abstract



The purpose of this paper is twofold: (1) to present new data on the sedimentology and mineralogy of the nonmarine part of the Mesaverde Group in the Southman Canyon gas field, Utah, and (2) to present our analysis of the data. We hope this will facilitate development of sedimentologic and diagenetic models that may prove useful in the exploration for hydrocarbons in continental rocks.

Our analysis is based upon the descriptions of four cores of the Mesaverde Group from the Shell Southman Canyon Unit no. 7. The cored intervals total 56 m and span the nonmarine section of beds, which is approximately 336 m thick.

We are somewhat restricted in interpreting the processes that operated during mineral diagenesis in these rocks because of the paucity of cored rock to analyze at Southman Canyon. Carefully documented published data and interpretations derived from similar studies of nonmarine rocks that had a similar sedimentologic and diagenetic history are scarce. There is no detailed published information for the nonmarine part of the Mesaverde Group of the study area; our studies of the mineralogy and sedimentology of these rocks are continuing. Our analysis of the sedimentologic origin of the rocks was further limited because of the great distance to exposures of the beds. The nearest outcrops of depositionally and temporally equivalent beds are more than 40 km to the south along the Book Cliffs. These factors serve to reduce the certainty of our interpretations, and many are very speculative in the absence of additional data that can be used to test our hypotheses.

Although many of the physical, biologic, and chemical properties of a potential reservoir rock are determined by the original composition of minerals and sedimentary structures established during sedimentation, the rocks formed are commonly modified by diagenetic processes.

STRATIGRAPHIC AND SEDIMENTOLOGIC SETTING

Figure 2 is a stratigraphic cross section of Cretaceous and some Tertiary units that extend from the Wasatch Plateau on the west across the southern part of the Uinta Basin to the boundary between the states of Utah and Colorado on the east (Fig. 1). Of general interest to this study is the part of the section between Woodside, Utah, and the Colorado-Utah boundary. Of special interest are nonmarine rocks of the Neslen and overlying Cretaceous units for they were cored at the Southman Canyon gas field and are the subject of this report.

Rock units designated as the Neslen Formation and undifferentiated Tuscher and Farrer Formations in Figure 2 are so assigned because these

Figure 2.--NEAR HERE

formational names has been historically applied to rocks of similar lithology and age exposed along the eastern Book Cliffs of Utah. However, the identification of formation boundaries by unique combinations of lithologies is commonly very difficult in continental rocks in the subsurface where determination of lithologic associations is commonly uncertain. Identification is especially difficult if surface boundaries are based on topographic expression. In addition, these lithologies are transitional, as are the boundaries between depositional environments.

UGR File #505
USGS
Abstract

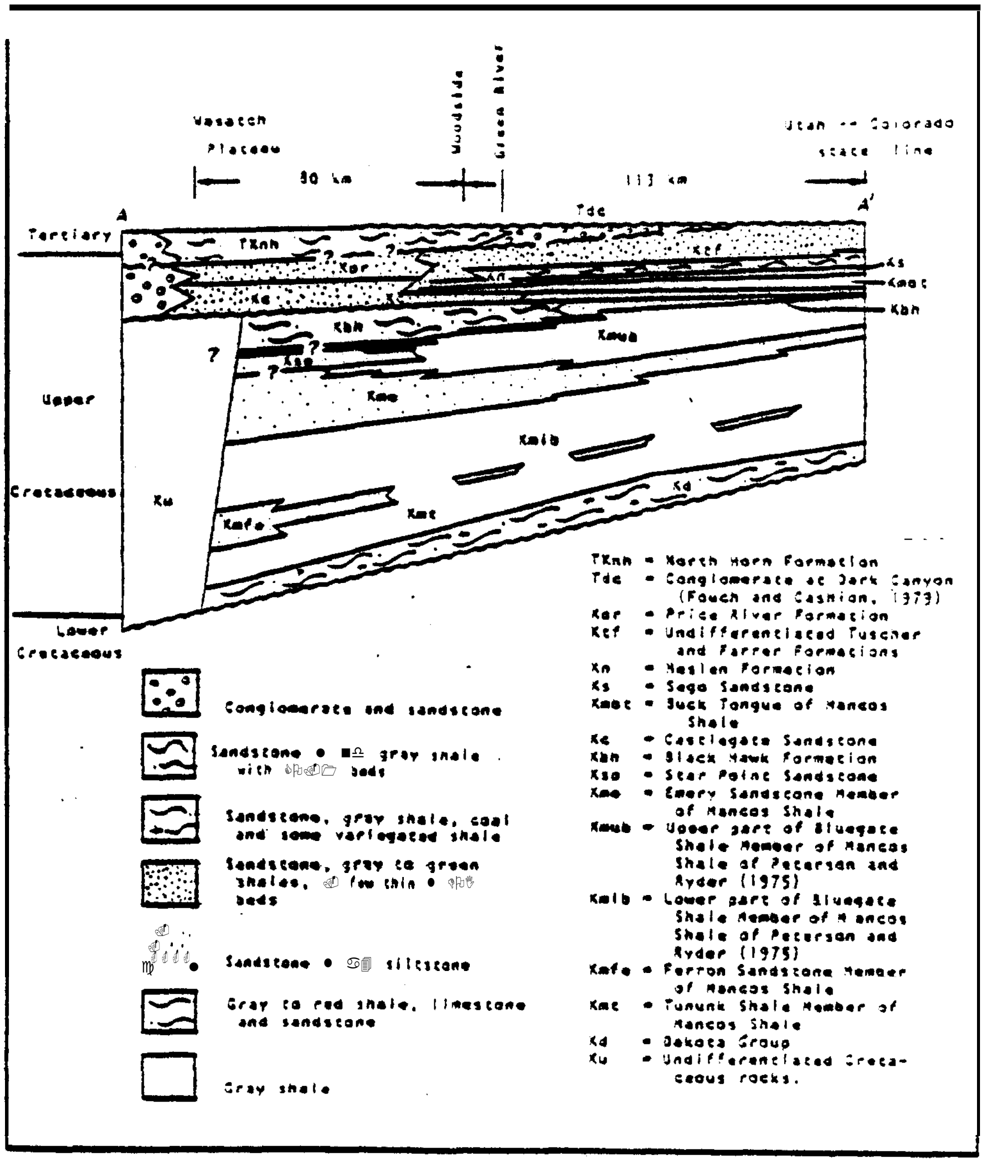


Fig 2

Nomenclature for stratigraphic units in the nonmarine part of the Mesaverde Group exposed east of the Green River in Utah was developed primarily by Fisher (1936) and by Fisher and others (1960). Fisher first applied the name Neslen to conspicuous coal-bearing beds in Neslen Canyon that also contained sandstone and carbonaceous gray shale. The unit is a slope-former and contai ns many horizontal and near-horizontal beds. East of the Green River, the Neslen grades upward into a sequence of resistant crossbedded lenticular sandstones and nonresistant carbonaceous medium-gray to olive-green shales that Fisher (1936) termed Farrer. Overlying the Farrer in part of the eastern Book Cliffs of Utah is a sequence of resistant cliff-forming sandstone beds that are locally altered white; they are locally medium to coarse grained and pebble-bearing. These beds were first termed Tuscher by Fisher (1936) for the exposures of the rocks in Tuscher--spelled Tusher on current maps--Canyon northeast of Green River, Utah. In 1960, Fisher and others placed the Tuscher in the Mesaverde Group The terms Nelsen and Farrer were elevated by them in 1960 in stratigraphic rank from member status (of the Price River Formation) to formational status of the Mesaverde Group and were considered to be of a Late Cretaceous age. The use of these formational names to designate mappable units of the nonmarine Mesaverde east of the Green River has been only slightly modified by most authors (Abbot and Liscomb, 1956; Young, 1966; Cashion, 1973; Fouch and Cashion, 1979; Keighin, 1979; Keighin and Fouch, 1979). In addition, this grouping of rocks can be traced to the subsurface of the eastern part of the Uinta Basin. Fouch and Cashion (1979) illustrated the borehole geophysical log signatures for these rocks and distinguished the coal-bearing Neslen from the undi fferentiated Tuscher and Farrer Formations. These terms are used for nonmarine Mesaverde rocks discussed in this paper, for the authors have traced the units from the Southman Canyon gas field to those drill holes illustrated by Fouch and Cashion (1979). In addition, this distinction emphasizes the basic contrast among mappable rock units, and, therefore, indirectly among their sedimentologic origins.

As previously noted, Fisher and others (1960) considered the Tuscher Formation to be of a Late Cretaceous age although originally Fisher (1936, p. 20) had arbitrarily, and tentatively, assigned the unit to the Tertiary. Resolution of the uncertainty of the age of the Tuscher and of its proper usage as a mappable unit (and, therfore, its sedimentologic origin) on surface exposures and in the subsurface is difficult, for Fisher (1936) did not designate a type section or provide a detailed description of the rocks in Tuscher Canyon.

Fisher and others (1960, p. 50) presented a detailed description of beds in Tuscher Canyon they believed to be temporally equivalent to Upper Cretaceous rocks in western Colorado (Fisher and others, 1960 p. 7). Fouch and Cashion (1979) identified a conglomeratic sequence of sandstones in Dark Canyon (Fig. 2) that they have traced to the subsurface in part of the Uinta Basin. These conglomeratic beds are reservoirs for natural gas in parts of the basin. They have also noted what are believed to be temporally equivalent conglomerates sandstones in the right fork of Tuscher Canyon where the beds form the conspicuous conglomerates at the base of the Wasatch Formation. They believe the conglomeratic sandstone sequence is the basal conglomerate of the Wasatch Formation as used by Fisher (1936, p. 21) and is the uppermost part of the Tuscher Formation of Fisher and others (1960, p. 50). In Dark Canyon, a carbonaceous shale in the basal part of the conglomeratic sandstones yielded palynomorphs of a Paleocene age (Fouch and Cashion, 1979). It, therefore, seems reasonable to believe that the conglomeratic part of the Tuscher Formation of Fisher and others (1960, p. 50) in Tuscher Canyon is of a Paleocene, age although underlying rocks of the formation may be of Late Cretaceous age.

UGR File #505
USGS
Abstract

Near Westwater Canyon in the Book Cliffs (Fig. 1), the Neslen Formation consists of coal interbedded with horizontally thin-bedded fine-grained sandstones and carbonaceous shale. Relatively small and sparse channel-form sandstone units that contain well-developed large-scale low-angle crossbeds are locally abundant. The channel-form units are fine grained at their scoured bases and very fine grained at unit tops. We believe the large-scale low-angle crossbeds to be accretion beds of point bars formed in meandering streams. In much of the eastern Book Cliffs of Utah, the Neslen represents swampy coastal-plain depositional environments that have a few small meandering streams. The Neslen grades downward into littoral marine sandstone of the Sego Sandstone.

In Westwater Canyon, the Neslen grades upward into the Farrer Formation, a sequence of fine- to medium-grained sandstone, carbonaceous gray and olive-green claystone, and sparse thin coal beds. Sandstone content generally increases upward in the unit at the expense of claystone and coal. Near its transitional boundary with the underlying Neslen, the Farrer contains many isolated channel-form sandstone units that contain claystone and siltstone clasts (rip-ups) and the coarsest grains are located along a scoured base. These same channel-form sandstone beds grade upward from large-scale low-angle accretion beds at the bases to small-scale assymetric cross-stratified very fine grained sandstone at the top. We interpret the beds near the basal part of the Farrer to have formed on an alluvial flood plain that contained numerous small- and medium-size meandering streams. These streams flowed across a flood plain with many swamps that locally contained abundant herbaceous organic matter. This organic matter was subsequently transformed into small and discontinuous coal and carbonaceous shale units.

Where the upper part of the Farrer contains many sandstones, few claystones and sparse coals, and is principally a cliff-former, cycles of grain size and cross-stratification *are* not as well developed in individual units. Moreover, the beds commonly form complexes of apparently flatbedded units that, when viewed from a distance, can be traced for several tens of meters. However, close inspection of the units indicates the sandstone complexes are composed of anastomosing channel-form beds that apparently formed in braided streams flowing on surfaces of very low relief. Where such thick and resistant channel complexes comprise most of the uppermost Mesaverde Group beds, the rocks have been commonly included in the Tuscher Formation (Fisher, 1960).

The rocks of the Neslen and undifferentiated Farrer and Tuscher Formations can be reasonably interpreted to represent a vertical transition from coastal plain sedimentation (Neslen) to an alluvial plain with numerous small- and medium-size meandering streams (lower part of the Farrer) to the most landward depositional facies in which deposition was principally in anastomosing medium- and large-braided streams with local meandering courses (upper part of Farrer and Tuscher Formations).

Data derived from core examination are insufficient to precisely interpret the sedimentologic origin of the cored rocks at Southman Canyon field. However, as previously indicated, we have established the relation of cored rocks to the exposure of temporally and depositionally equivalent rocks along the Book Cliffs to supplement our subsurface studies.

Figure 3 (Neslen Formation) and Figures 4, 5, and 6 (undifferentiated Tuscher and Farrer Formations) are graphical representations of the

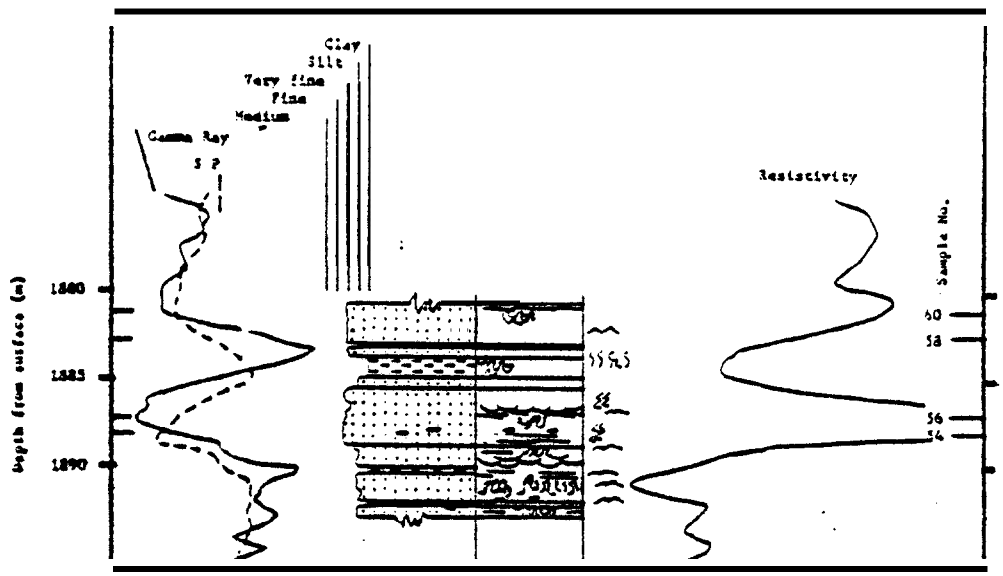
---

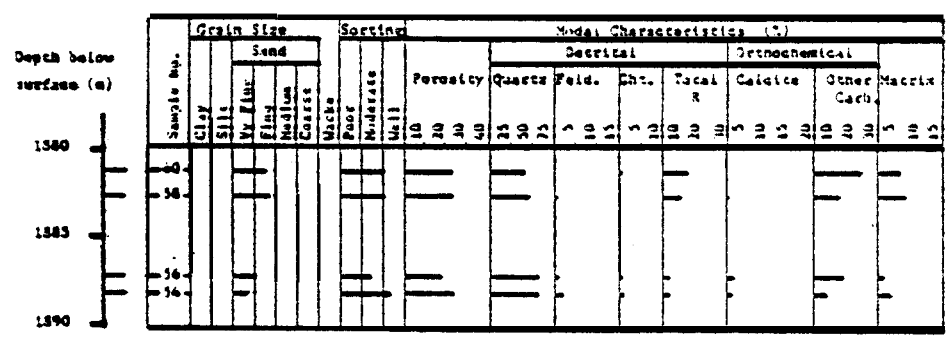
Figures 3, 4, 5, 6.--NEAR HERE

---

lithologies of cores of the Neslen and their geophysical log responses at the Southman Canyon gas field in the Shell Southman Canyon Unit, no. 7. The cores consist of fine- to very fine grained sandstones and thin silty and sandy, gray carbonaceous claystones. Variations in grains size are not striking, but claystone and siltstone clasts and a few medium-size grains occur near the base of some units. The sandstone units commonly contain higher-angle cross-strata near their bases, and they grade upward into horizontally thin-bedded units that are commonly very contorted and rich in silt and clay. Root traces are common in the contorted and convoluted rocks, and they almost everywhere contain coal fragments and other carbonaceous organic matter.

UGR File #505
USGS
Abstract





USGS
Abstract

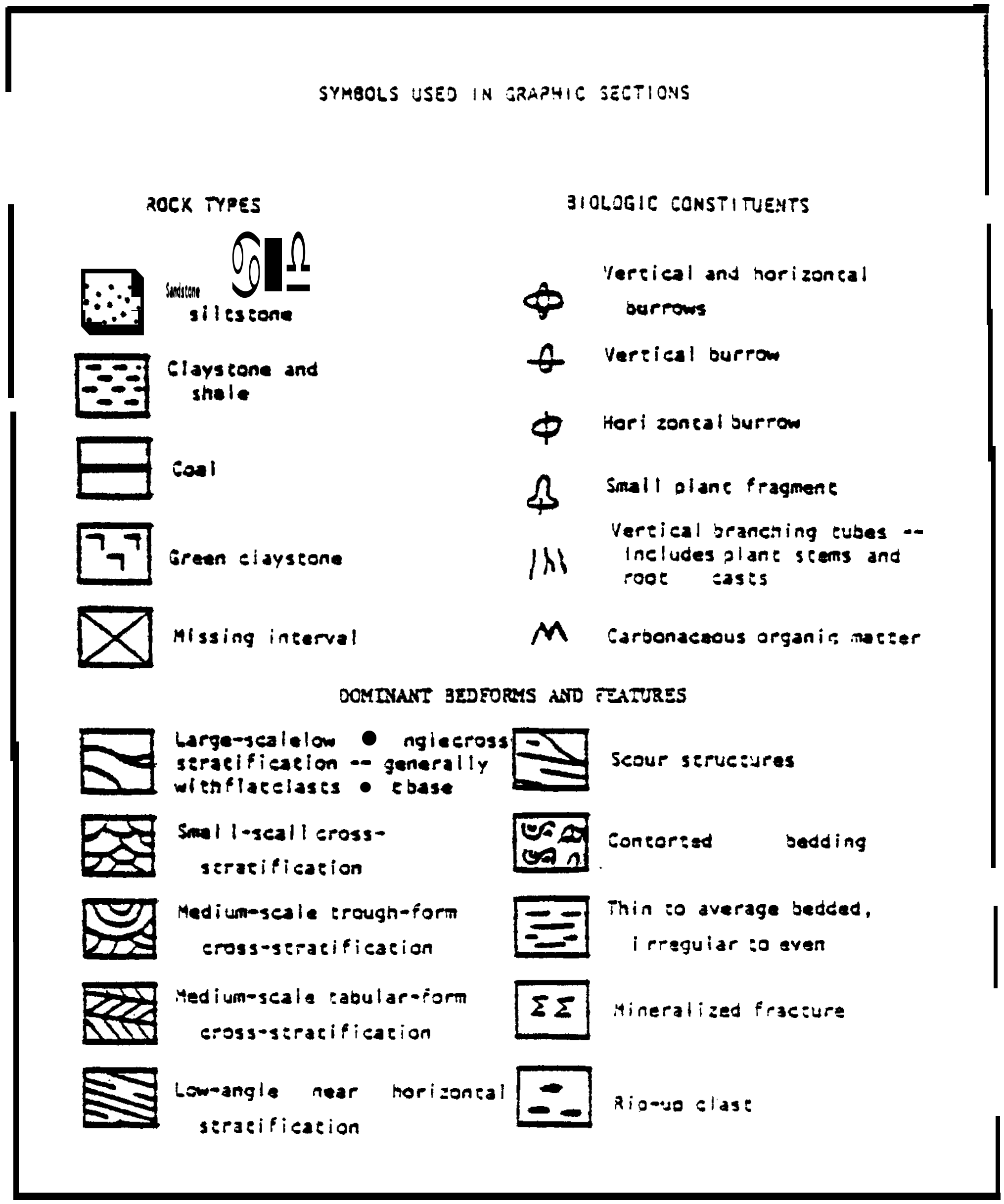


Fig 3A

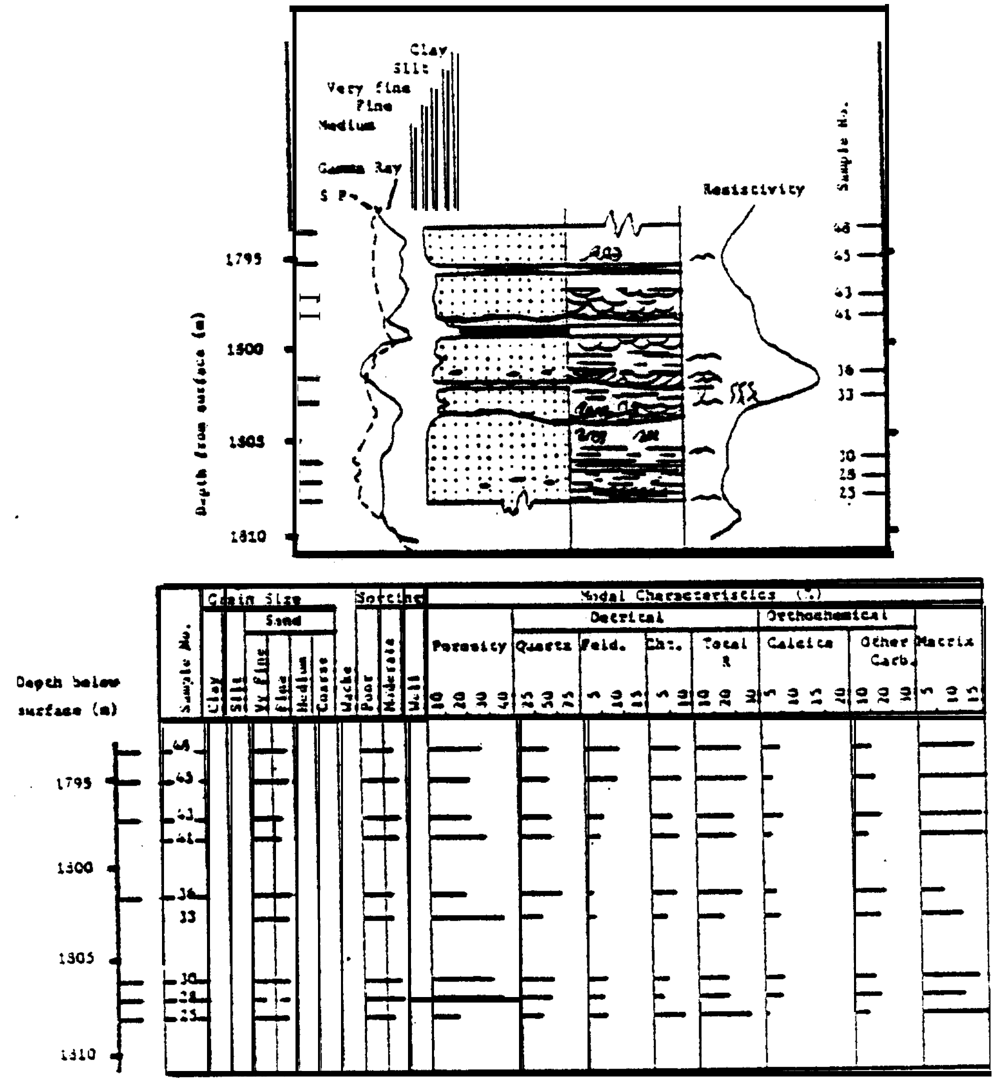

Clay
Silt
Very fine
Fine
Medium
Gamma Ray
S P
Resistivity
Sample No.
Depth from surface (m)
1795
1800
1805
1810
Depth below surface (m)
Sample No.
Grain Size
Sand
Clay
Silt
Vy fine
Fine
Medium
Coarse
Wacke
Sorting
Poor
Moderate
Well
Modal Characteristics (%)
Detrital
Orthochemical
Porosity
Quartz
Feld.
Chr.
Total R
Calcite
Other Carb.
Matrix

Fig 3

USGS
Abstract

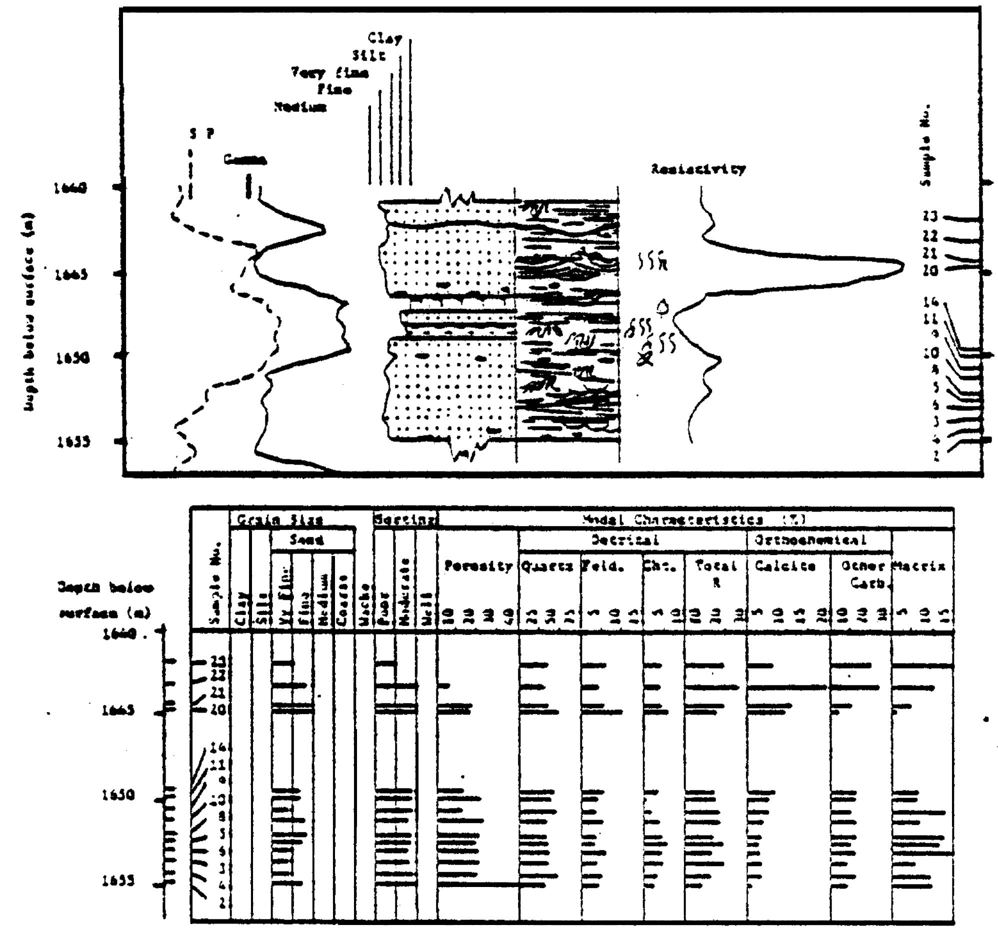


Fig 6

PETROGRAPHY

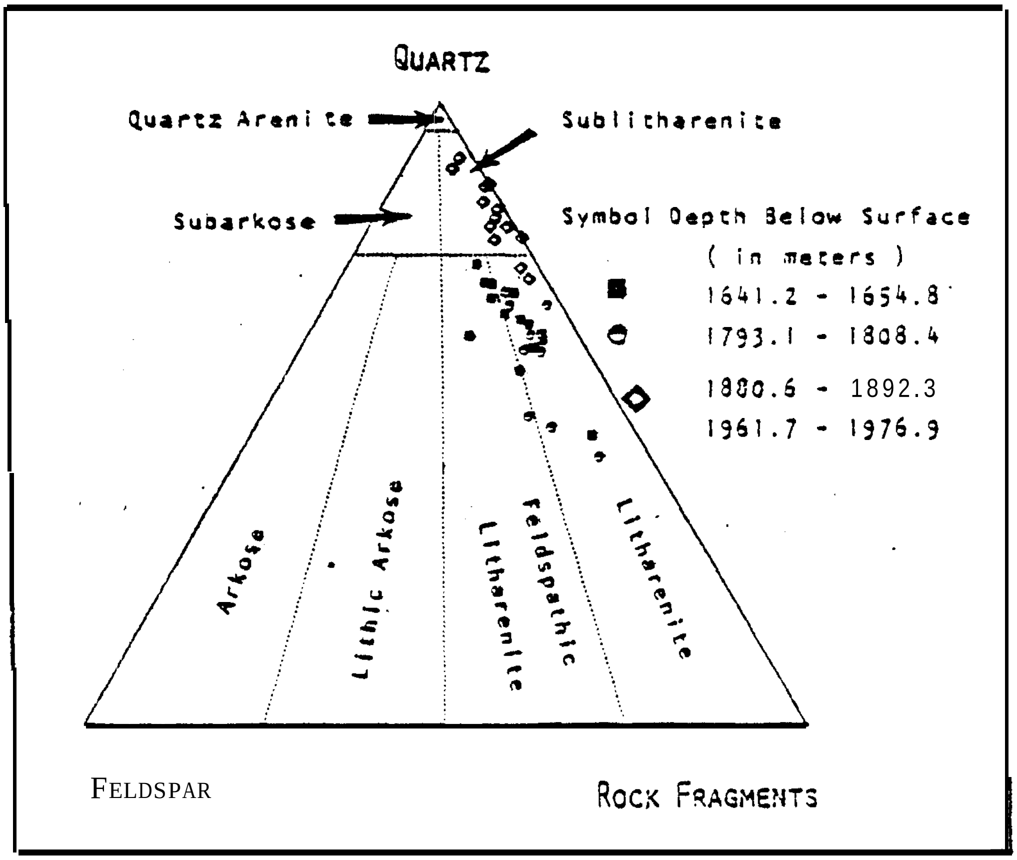
Thirty-eight samples of sandstones and siltstones were taken from cores cut between gas-producing intervals in the Mesaverde Group (Campbell and Bacon, 1976, pl. 1). Two thin sections were prepared from each sample; one section was impregnated with blue-dyed epoxy to aid in definition of porosity. One-half of this section was stained with Alizarin Red S to distinguish calcite. The other section was stained for potassium and plagioclase feldspars. Modal analyses were made by counting 300 points on one thin section for each sample. The results of the modal analyses are summarized in Table 1; results for each cored interval are given in Figures 3-6. One siltstone was examined, but its modal analysis is not included in the Table or Figures. Using Folk's classification scheme (Folk, 1974, p. 129), the sandstones are primarily litharenites and sublitharenites (Fig. 7).

Figure 7.--NEAR HERE

Detrital Mineralogy.--Monocrystalline quartz is the dominant mineral in most samples, comprising 25 to 55 percent of the framework grains; quartz is most abundant in the Neslen Formation. Polycrystalline quartz grains are uncommon, and extinction is fairly straight. Few grains show sign of strain.

Detrital feldspars comprise only 1 to 5 percent of the framework grains; potassium feldspar is slightly more common than plagioclase. Feldspars are less abundant in the Neslen Formation than in the overlying Tuscher and Farrer Formations.

USGS
Abstract



UGR File #505
USGS
Abstract

Formation	Depth below surface (m)	Number of samples	Quartz (Q)	Feldspar (F)	Rock Fragments (R) Chert	Other[3]	Total R	Carbonates Calcite	Other[4]	Matrix[5]
Tuscher	1641 - 1655	14	[1]35.2 [2](5.8)	4.5 (2.1)	3.4 (1.5)	11.9 (4.0)	15.4 (4.0)	5.5 (4.6)	11.3 (4.1)	9.8 (5.3)
Farrer	1793 - 1801	9	29.3 (5.3)	3.9 (1.9)	4.7 (2.0)	12.3 (4.0)	17.4 (5.7)	2.4 (1.2)	9.6 (2.6)	13.1 (4.4)
Neslen	1881 - 1890	4	50.4 (9.0)	1.1 (1.1)	0.7 (0.6)	6.8 (4.0)	7.4 (3.4)	0.7 (0.9)	13.6 (6.3)	4.1 (2.4)
Neslen	1962 1977	9	45.4 (6.7)	1.2 (0.8)	2.1 (1.6)	8.4 (2.5)	10.4 (3.0)	0.0 (0.0)	13.7 (10.9)	8.5 (1.9)

1: Mean value based on count of 300 points in thin section
2: Standard deviation from the mean
3: Fine grained sedimentary rock fragments
4: Dolomite, ankerite and, in the lower Neslen, siderite
5: Includes both mechanical and diagenetically produced material < 30 μm.

Igneous and fine-grained sedimentary rock fragments account for as much as 20 percent of the material in the samples examined. Up to 5 percent chert is present in some samples; it is slightly more abundant in the Tuscher and Farrer Formations. Only trace amounts of volcanic rock fragments were identified in the Tuscher Formation; none was identified in the other formations.

Biotite and muscovite are sparse; heavy minerals--rutile, zircon, tourmaline, and apatite--are rare.

Organic matter, probably coal, is present through the interval studied, but is more common in the Neslen Formation. Relatively undisturbed plant fragments are rare.

Mechanical Deformation.--The depth of the samples ranges from 1,641 to 1,977 m. The types and distribution of grain contacts are very similar to those described by Taylor (1950). There is no evidence to suggest that the rocks were buried significantly deeper in the past. There appears to have been more intense deformation in the deeper Neslen samples, although the types of grain contacts do not change, nor does apparent porosity. Post-depositional mechanical deformation was relatively minor. Mica shards are commonly bent, and a few plagioclase grains are broken. Some quartz grains show strain shadows thought to be induced by compaction (Fig. 8A). Most

---

Figure 8.--NEAR HERE

---

significant, in terms of porosity reduction and therefore, of reservoir quality, is the squeezing of soft rock fragments between more resistant detrital framework grains (Figs. 8B, C).

Diagenetic Mineralogy.--Evidence of chemical and physical diagenesis is found throughout the entire sequence of samples examined. Chemical diagenesis is more widespread and includes silica overgrowths on quartz (Figs. 9A, 10D), carbonate and clay cements, partial to complete replacement

Figures 9 and 10.--NEAR HERE

of quartz, feldspars, and rock fragments by clays and carbonates, and pore linings and fillings of kaolinite and illite. Quartz overgrowths are commonly euhedral, indicating growth into open space. Recognition of the overgrowths is sometimes facilitated by the presence of very thin "dust rings," formed by chlorite or other clay minerals. Partial to extensive leaching of feldspars, especially of plagioclase, is fairly common (Fig. 9B). The leaching, in addition to creating porosity, may provide small quantities of elements in solution, which may subsequently be incorporated in other diagenetic reactions. Rock fragments, especially chert, are generally extensively leached or altered to illitic clay (Fig. 9C). Some of the volcanic rock fragments (Fig. 8B) seen in the upper part of the section appear to have devitrified, at least to some extent.

Dolomite and ankerite are found in roughly constant amounts throughout the interval studied. Calcite is less abundant, and its abundance decreases with depth; none was identified, either in thin section or by X-ray diffraction, in the deeper Neslen samples. The carbonate minerals occur as void fillings, generally euhedral (Figs. 10A,C), and as replacements of some quartz, feldspar, and rock fragments.

Petrographic exami nation reveals distinctly zoned carbonates (Fig. 8A); in addition, study of selected samples with the electron microprobe shows distinct, usually abrupt, variations in chemical composition in carbonate mineral grains. Calcite is relatively pure; it contains small amounts (1-2 percent) of iron and magnesium (less than 1 percent). Dolomite and ankerite are commonly intergrown. Preliminary data suggest that dolomite (which contains very little iron) occurs most commonly in the central portions of intergrowths; ankerite is peripheral to the dolomite. Al though sampling limitations precluded microprobe examination of the deeper (Neslen) sandstones, petrographic and X-ray diffraction data indicate that (a) calcite is not found in the deeper samples, (b) siderite, in minor amounts, is found only in the deeper samples, and (c) siderite appears to largely replace ankerite as the iron-bearing carbonate mineral phase.

Clay minerals, identified by X-ray diffraction of bulk rock samples, are kaolinite, illite, and small quantities of chlorite; clay mineral separations have not been done. Clays occur as detrital rock fragments (Fig.8C), replacing quartz, feldspar, and rock fragments (Figs. 9B, C), and lining and filling pores (Figs. 9D, E). Chlorite, seen only in very minor quantities in thin section and by X-ray diffraction, occurs primarily as isolated grains, which probably formed by replacement of ferromagnesian (?) minerals. It is very rarely seen replacing quartz, where it formed prior to quartz overgrowths.

Kaolinite and illite are found throughout the entire section, but account for only a few percent of the volume of the sandstones studied. Kaolinite is probably slightly more abundant than illite; it occurs as pore fillings (Figs. 9D, 10D) and is commonly intimately associated with illite (Figs. 9E, 10D). Illite is commonly seen replacing, partially to completely, rock fragments (Fig. 9C), replacing feldspar (Fig. 9B), and partially lining pores (Fig. 9E), where it may *or* may not be associated with kaolinite.

PETROGENESIS

Sedimentary nonmarine units cored at Southman Canyon gas field are generally fine grained and moderately well sorted. Examination of the sandstones with SEM, electron microprobe, and in thin section indicates that diagenetic reactions modified the entire sequence of rocks studied. Although *three* formations, spanning a vertical interval of 1,641-1,977 m, were examined, the paragenetic sequence appears to be essentially the same throughout the entire interval.

Effects of mechanical deformation, as shown by deformed micas, squeezed rock fragments, and strained or broken framework grains, are relatively minor. No evidence of pervasive fracturing was observed in thin section, although fractures were detected in one core. Grain contacts are most commonly long or concavo-convex (Taylor, 1950); only rarely are sutured contacts seen, and these are probably inherited from detrital igneous rock fragments. Grain contact relations are often somewhat obscured by what is interpreted as disintegration of polycomponent igneous rock fragments. Features normally associated with mechanical deformation, such as extensive fracturing or abundant sutured contacts, are not present; their absence suggests that burial has not been significantly greater than that now found. Although compaction reduced porosity somewhat, the reduction was more than offset by later leaching. It is possible that compaction was hindered by early carbonate cement.

The numerous diagenetic changes observed in the sandstones indicate a variety of changes in pore fluid chemistry throughout the history of the rocks. The paragenetic sequence outlined in Figure 11 summarizes the diagenetic sequence thought to apply to this sequence of rocks.

Figure 11.--NEAR HERE

Following deposition, a thin coating of chlorite formed on a few quartz grains. The sparse nature of the chlorite films suggests that iron-rich pore fluids suitable for chlorite formation were present for only a short time, in limited quantities, and were not uniformly distributed. Silica-bearing fluids were more abundant; silica overgrowths on quartz are common throughout the entire vertical sequence. Silica in solution may have come from partial dissolution of the abundant siliceous rock fragments, although the principal leaching occurred after deformation. Many of the quartz overgrowths are euhedral in part, and grew into open pores. These quartz overgrowths probably formed before appreciable compaction occurred.

Leaching, primarily of carbonate minerals and rock fragments, restored much porosity which had been lost due to chemical precipitation of minerals (carbonate?) and to compaction. Determination of the exact time when leaching first occurred is complicated by the uncertain history of early carbonate mineral formation. The secondary pores (Schmidt and others, 1977; Hayes, 1979) created by leaching are rarely larger than 75 µm; those in leached (or recrystallized) rock fragments are on the order of 1 µm (or less) across. Larger pores are due to removal of unstable detrital framework grains, e.g., feldspars, or in some cases to removal of carbonate minerals, which may themselves be secondary. Although some leaching may have occurred after kaolinite and illite formed, post-clay leaching was minor.

Much of the secondary porosity created by leaching was subsequently modified by growth of kaolinte and illite within pores. It appears that most of the dissolved mineral matter was removed in solution, and was not redeposited locally.

Although it is clear from petrographic, X-ray diffraction, and microprobe examination that dolomite, ankerite, calcite, and minor amounts of siderite are mineral cements, the paragenetic relations of the carbonate cements in the system are not completely clear. With the possible exception of some minor amounts of microcrystalline calcite, it is thought that the carbonate minerals are of a diagenetic origin. The microcrystalline calcite may represent recrystallized detrital carbonate clasts, or it may represent an early stage of authigenic calcite. Carbonate minerals occur both as void fillings (Figs. 8A, 10A), and as replacements of detrital grains, probably of feldspar (Fig. 10C). Zoned carbonate cements (Fig. 8A) are thought to be primarily dolomite-ankerite; this belief is supported by microprobe data, which show sharp boundaries between low-iron dolomite and ankerite. Ankerite appears peripheral to dolomite and may have formed by partial conversion of dolomite (or calcite) by iron-rich solutions (Muffler and White, 1969). Partial dissolution of iron-bearing sedimentary rock fragments could provide iron in solution. Petrographic evidence clearly shows that calcite commonly replaces dolomite and (or) ankerite, and suggests that iron and magnesium in solution decreased with time.

With the exception of minor quantities of chlorite, clays are largely restricted to authigenic kaolinite and illite. Mi nor amounts of detrital clays were identified by the SEM study, but no evidence of mechanically infiltered clays was detected. No positive evidence of mixed layer clays was noted, but it is possible that clay-mineral separations would have isolated small quantities of these clays.. The early clay-forming solutions were apparently less rich in potassium than were the fluids later responsible for the fonation of illite. Kaolinite appears to be slightly earlier than illite and is restricted to growth in open pores (Figs. 9D, 10D). The platy nature of kaolinite, and its distribution, makes it especially sensitive to flowing fluids, such as might be encountered in well completion or stimulation. Illite in some cases appears to be replacing kaolinite, a feature also noted by Hancock and Taylor (1978, pl. 1 F, 2 D). The source of potassium in illite is not completely clear, although dissolution of potassium feldspar may be responsible. While potassium feldspar is never abundant, X-ray diffraction data suggest a slight increase in illite and a slight decrease in potassium feldspar in the deepest core samples (in the Neslen Formation). Illite is commonly detected repl acing, generally extensively, fine-grained sedimentary rock fragments (Fig. 9C).

DISCUSSION

We bel ieve the cored rocks were deposited in fluvial channels, but limited information precludes our determining the geometry and size of the subaerial streams. If comparison to exposures along the Book Cliffs is reasonable, individual channels in the Tuscher-Farrer interval that was cored were probably no more than a few tens of meters wide, and those of the Neslen were less.

Although the basic physical and chemical characteristics of the rocks are established by the lithologic characteristics related to their depositional history, these conditions may be subsequently modified, often dramatically, by di agenetic processes.

As would be expected in fine-grained sandstones, most of the observed pores are small, usually less than 60 µm. Many pores formed by leaching (thus forming secondary porosity) are on the order of 0.1-10 µm. The smal l er pores are very sensitive to modifications by subsequent diagenetic effects (e.g., linings, coating, or bridging by authigenic clays), and pore throats may be easily plugged by movement of clay-size fines.

Measured porosities for sandstones from the Shell Southman Canyon Unit no. 7 well range between about 3 and 13 percent. These values agree with the ranges determined by other investigators for stratigraphically similar sandstones in other parts of the Uinta Basin (U.S. Dept. of Energy , 1979, p. 27; 1980a, p. 23, 1980b, p. 21; Keighin and Sampath, 1980, Table 1). According to Beard and Weyl (1973), sediments with these characteristics have an initial porosity on the order of 35 percent and permeabilities of about 2 to 7 darcies. Although determination of modal (thin section) porosity is now commonly and easily done using thin sections impregnated with blue-dyed epoxy (Gardner, in press), the modal values rarely agree with porosities measured in the laboratory. The reasons for lack of agreement are not clear, but it is common for modal porosities to be higher than measured porosities, often significantly. It is apparent that porosity may change dramatically over short vertical distances due to the variation in grain size, the degree of cementation, and the presence of silt or clay laminae.

Several investigators (McLatchie and others, 1959; Vairogs and others, 1971; Thomas and Ward, 1972; Jones and Owens, 1979; Keighin and Sampath, 1980) showed that porosity decreases only slightly (usually less than 5 percent) as confining stress is increased to approximate that of reservoir conditions. Permeability in low-permeability sandstones is, however, drastically reduced by increases in confining pressure. The permeabilites, measured at surface conditions, for the low-permeability sandstones in the Uinta Basin are commonly in the range of 0.02 to 1 md; these values decrease by as much as 80 percent when subjected to confining pressures of 34.5 MPa (5,000 psi). It appears that pore volume is not changed significantly, but pore throats, already small because of the nature of the detritus forming the rocks and because of subsequent diagentic reactions, are reduced even further in size.

Another factor which probably reduces communication between pores is the presence of convoluted bedding. Whether due to bioturbation or to soft-sediment deformation, induced irregularities in bedding surfaces, if extensive, further complicate reservoir drainage. The common occurrence of disturbed beds is shown in Figures 3, 4, 5, and 6. Because of the limited availability of core material, we do not know the extent or continuity of these disturbed beds, but it seems reasonable that they are common in other fine-grained, channel-formed sedimentary deposits and should be considered when evaluating such rocks.

There is growing recognition that fine-grained authigenic minerals, which line pores and coat grains, thus altering pore geometry, may modify the response of resistivity logs and affect calculated water saturation and the interpretation of sonic and neutron logs (Almon, 1978). Investigations by Texas A & M (U.S. Dept. of Energy, 1980a, p. 23) show that carbonate cement also influences porosities calculated from sonic and (or) density logs. If a standard sandstone matrix density (2.65 gm cc^{-1}) is used for porosity calculations from density logs in a highly carbonate-cemented zone, porosity will be underestimated. Conversely, if a higher (e.g., 2.68 gm cc^{-1}) matrix density is used in the calculations, porosities will be overestimated in zones with little carbonate cement. The importance of knowing the mineralogic characteristics of the rocks seems obvious.

Apparent in all cores is the relation between borehole geophysical log response and lithology. In at l east three of the four cores (no logs were avail able *for* the deepest core), the highest energy crossbedding seems to correspond with low-gamma ray and good SP (Figs. 4, 6). This is to be expected, and these logs could probably be used to delineate channel sandstones. However, these same higher energy sandstones also seem to be zones of the highest amounts of carbonate cement, which is displayed as zones of high resistivity. One normally expects the highest values of resistivity to occur in the lowest energy sandstones where clay minerals and carbonate cements are more common. These relations of the core to the logs may suggest that many higher energy beds (possibly with better initial porosity and permeability) are preferentially cemented by carbonate minerals, and, therefore are not good reservoirs. It is also probable, although the evidence is sparse, that these higher energy sandstones are preferentially fractured. Figure 4 illustrates such a highly resistant carbonate-cemented sandstone that contains mineral-filled fractures. To the extent that carbonate cements are found in higher energy beds, diagenesis may be related to sedimentologic setting. If this is true, then the higher energy beds, normally considered to be preferential exploration targets, may be poor choices, at least locally. If natural open fractures are present in the carbonate-cemented (and more brittle) sandstones, these fractures may enhance permeability by allowing communication between avail able pore space.

Coal and carbonaceous claystone beds are abundant in some strati graphic units, but they are absent in thick sequences of the Mesaverde Group in the study area. However, even in the absence of coal and carbonaceous claystones, herbaceous organic matter exists in great quantities along laminae of many sandstones in core over most of the nonmarine part of the Mesaverde Group. This organic matter is particularily abundant in convoluted sandstone and siltstone beds. We suggest that the herbaceous organic matter in the sandstone and siltstone units is a principle source of the gas recovered from these rocks.

Unfortunately, cores were not taken in producing intervals of the Southman Canyon well. However, sandstones of the Neslen that bound the cored intervals are productive. We, therefore, suggest that productive sandstone reservoir rocks are similar to those sandstone cores that we examined.

ACKNOWLEDGMENTS

We wish to acknowledge support from the Nevada Operations Office of the U.S. Department of Energy, which made the research possible. Permission to sample the cores and to publish the results was generously granted by Shell Oil Company. Technical assistance was provided by D. Bieber. Discussions with our colleagues, especially W. B. Cashion, were mast helpful, but we accept full responsibility for any misinterpretations.

REFERENCES

ABBOTT, W. O., AND LISCOMB, R. L., Stratigraphy of the Book Cliffs in east-central Utah: Intermountain Assoc. of Petroleum Geologists, 7th Annual Field Conf. Guidebook, p. 120-123.

ALMON, W. R., 1978, Sandstone Diagenesis: Applications to exploration and exploitation: Am. Assoc. Petroleum Geologists Clastic Diagenesis School, Boulder Colo.

BEARD, D. C., AND WEYL, P. K., 1973, Influence of texture on porosity and permeability of unconsolidated sand: Am. Assoc. Petroleum Geologists Bull., v. 54, no. 2, p. 346-349.

CAMPBELL, J. A., AND BACON, R. S., 1976, Pentration chart of Utah oil and gas fields: Utah State Geol. and Mineral Survey Oil and Gas Field Studies No. 14, Penetration Chart, pl. 1.

CASHION, W. B., 1973, Geologic and structure map of the Grand Junction quadrangle, *Colorado* and Utah: U.S. Geol. Survey- Misc. Geol. Inv. Map I-736.

FISHER, D. J., 1936, The Book Cliffs coal field in Emery and Grand Counties, Utah: U.S. Geol. Survey Bull. 852, 104 p.

FISHER, D. J., ERDMANN, C. E., and REESIDE, J. B., JR., 1960, Cretaceous and Tertiary formations of the Book Cliffs, Carbon, Emery, and Grand Counties, Utah, and Garfield and Mesa Counties, Colorado: U.S. Geol. Survey Prof. Paper 332, 80 p.

FOLK, R. L., 1974, Petrology of sedimentary rocks: Austin, Texas, Hemphill Pub. Co., 182 p.

FOUCH, T. D., AND CASHION, W. B., 1979, Distribution of rock types, lithologic groups, and depositional environments for some lower Tertiary and Upper and Lower Cretaceous, and Upper and Middle Jurassic rocks in the subsurface between Altamont oil field and San Arroya gas field, northcentral to southeastern Uinta Basin, Utah: U.S. Geol. Survey Open-File Report 79-365, 2 sheets.

GARDNER, K. L., in press, Impregnation technique using colored epoxy to define porosity in petrographic thin sections: Canadian Jour. Earth Sci.

HANCOCK, N. J., AND TAYLOR, A. M., 1978, Clay mineral diagenesis and oil migration in the Middle Jurassic Brent Sand Formation: Geol. Soc. London Jour., v. 135, pt. 1, p. 69-72.

HAYES, J. B., 1979, Sandstone diagenesis - The hole truth: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. No. 26, p. 127-139.

JOHNSON, R. C., 1979a, Cross section A-A' of Upper Cretaceous and lower Tertiary rocks, northern Piceance Creek Basin, Colorado: U.S. Geol. Survey Misc. Field Inv. Map MF-1129-A, 2 sheets.

______1979b, Cross section B-B' of Upper Cretaceous and lower Tertiary rocks, northern Piceance Creek Basin, Colorado: U.S. Geol. Survey Misc. Field Inv. Map MF-1129-B, 2 sheets.

JOHNSON, R. C., 1979c, Cross secton C-C' of Upper Cretaceous and lower Tertiary rocks, northern Piceance Creek Basin, Colorado: U.S. Geol. Survey Misc. Field Inv. Map MF-1129-C, 2 sheets.

JOHNSON, R. C., GRANICA, M. P., AND DESSENBERGER, N. C., 1979a, Cross section A-A' of Upper Cretaceous and lower Tertiary rocks, southern Piceance Creek Basin, Colorado: U.S. Geol. Survey Misc. Field Inv. Map MF-1130-A, 2 sheets.

1979b, Cross section B-B' of Upper Cretaceous and lower Tertiary rocks, southern Piceance Creek Basin, Colorado: U.S. Geol. Survey Misc. Field Inv. Map MF-1130-B, 2 sheets.

1979c, Cross section C-C' of Upper Cretaceous and lower Tertiary rocks, southern Piceance Creek Basin, Colorado: U.S. Geol. Survey Misc. Field Inv. Map MF-1130-C, 2 sheets.

JOHNSON, R. C., MAY, FRED, HANSLEY, P. L., PITMAN, J. K., AND FOUCH, T. D., 1980, Petrography, X-ray mineralogy, and palynology of a measured section of the Upper Cretaceous Mesaverde Group in Hunter Canyon, western Colorado: U.S. Geol. Survey Oil and Gas Inv. Chart OC-91.

JONES, F. O., AND OWENS, W. W., 1979, A laboratory study of low-permeability gas sands: Soc. Petroleum Engineers Paper SPE 7551, Proc., 1979 SPE Symposium on Low-Permeability Gas Reservoirs, May 20-22, Denver, Colo., p. 325-334.

KEIGHIN, C. W., 1979, Influence of diagenetic reactions on reservoir properties of the Neslen, Farrer, and Tuscher Formations, Uinta Basin, Utah: Soc. Petroleum Engineers Paper SPE 7919, Proc., 1979 SPE Symposium on Low-Permeability Gas Reservoirs, May 20-22, Denver, Colo., p. 77-84.

KEIGHIN, C. W., AND FOUCH, T. D., 1979, Influence of diagenetic reactions on nonmarine Upper Cretaceous rocks of the Southman Canyon gas field, Uinta Basin, Utah (abs.): Am. Assoc. Petroleum Geologists Bull., v. 54, no. 5, p. 832-833.

KEIGHIN, C. W., AND SAMPATH, K., 1980, Evaluation of pore geometry of some low-permeability sandstones, Uinta Basin, Utah: SPE paper 9251, Soc. of Petroleum Engineers 55th Annual Technical Conf. and Exhibition, Dallas, Texas. September 21-24, 1980.

McLATCHIE, A. S., HEMSTOCK, R. A., AND YOUNG, J. W., 1958, The effective compressibility of reservoir rock and its effect on permeability: Jour. Petroleum Technology, (June 1958), p. 49-51.

MUFFLER, L. J. P., AND WHITE, D. E., 1969, Active metamorphism of Upper Cenozoic sediments in the Salton Sea geothermal field and the Salton Sea trough, southeastern California: Geol. Sac, America Bull., v. 80, no. 2, p. 157-182.

PETERSON, F., AND RYDER, R. T., 1975, Cretaceous rocks in the Henry Mountains Region, Utah, and their relation to neighboring regions, in Fassett, J. E., ed., Canyonlands Country: Four Corners Geol. Soc. Guidebook, 8th Annual Field Conf., 1975, p. 167-189.

SCHMIDT, V., McDONALD, D. A., AND PLATTE, R. L., 1977, Pore geometry and reservoir aspects of secondary porosity in sandstones: Canadian Petroleum Geol. Bull., v. 25, no. 2, p. 271-290.

TAYLOR, J. M., 1950, Pore-space reduction in sandstones: Am. Assoc. Petroleum Geologists Bull., v. 34, no. 4, p. 701-716.

THOMAS, R. D., AND WARD, O. C., 1972, Effect of overburden pressure and water saturation on gas permeabilities of tight sandstone cores: Jour. Petroleum Technology (February 1972), p. 120-124.

U.S. DEPARTMENT OF ENERGY, 1979, Western Gas Sands Project Status Report, 1 July-31 July, 1979, p. 27: available as Report DOE/BC/01569-12, available from U.S. Department of Commerce, Natl. Technical Information Service, Springfield, Va., 22161.

______1980a, Western Gas Sands Project Status Report, 1 Feb.-29 Feb., 1980, p. 23: available as Report DOE/BC/10003-6, available from U.S. Department of Commerce, Natl. Technical Information Service, Springfield, Va., 22161.

______1980b, Western Gas Sands Project Status Report, 1 March-31 March, 1980, p. 21: available as Report DOE/BC/10003-7, available from US. Department of Commerce, Natl. Technical Information Service, Springfield, Va., 22161.

VAIROGS, J., HEARN, C. L., DAREING, D. W., AND RHODES, V. W., 1971, Effect of rock stress on gas production from low-permeability rocks: Jour. Petroleum Technology (Sept. 1971), p. 1161-1167.

YOUNG, R. G., 1966, Stratigraphy of coal-bearing rocks of Book Cliffs, Utah-Colorado, in central Utah coals: A guidebook prepared for the Geological Society of America and associated societies: Utah Geol. and Mineralog. Survey Bull. 80, p. 7-21.

Figure 1.--Index map of northeastern Utah showing exposure of some Upper Cretaceous and Tertiary rocks, oil, and/or gas fields; approximate line of section (A--A') illustrated in Figure 2; and site of core samples.

Figure 2.--Diagrammatic cross-section A--A' of Upper Cretaceous and lower Tertiary rocks from the Wasatch Plateau to the Utah-Colorado boundary; Figure 1 shows the approximate line of section. The major rock groups and stratigraphic nomenclature commonly applied to these rocks are shown in the cross-section.

Figure 3A.--Symbols used in graphic sections.

Figure 3B.--Graphical representation of rock types, general bedforms, and summary of petrographic examination in units cored between 1,960 and 1,977 m in the Shell Southman Canyon Unit no. 7. Figure 1 shows the location of this well. Geophysical logs are not available for the interval.

Figure 4.--Graphical representation of rock types, general bedforms, and summary of petrographic examination in units cored between 1,880 and 1,890 m in Shell Southman Canyon Unit no. 7. Figure 1 shows the location of this well. Symbols used to illustrate lithology are defined in Figure 3. Solid line to left of rock column is gamma-ray log; dashed line to left of rock column is spontaneous potential log. Solid line to right of bedforms column is electrical resistivity log.

Figure 5.--Graphical representation of rock types, general bedforms, and summary of petrographic examination *in* units cored between 1,793 and 1,808 m in Shell Southman Canyon Unit no. 7. Figure 1 shows the location of this well. Symbols used to illustrate lithology are defined in Figure 3. Log representations are as in Figure 4.

Figure 6.--Graphical representation of rock types, general bedforms, and summary of petrographic examination in units cored between 1,641 and 1,655 m in Shell Southman Canyon Unit no. 7. Figure 1 shows the location of this well. Symbols used to illustrate lithology are defined in Figure 3. Log representations are as in Figures 4 and 5.

UGR File #505
USGS
Abstract

Table 1.--Summary of modal measurements of sandstone samples, Shell Southman Canyon Unit, no. 7 (NW1/4NW1/4, sec. 24, T. 10 S., R. 23 E.).

Figure 7.--Mineral composition of framework grains and sandstone classification (Folk, 1974, p. 129) of the sandstones in the Southman Canyon Unit, no. 7 well. The samples between 1,625.5 and 1,808.4 m are assigned to the Tuscher and Farrer Formations, undifferentiated; those samples between 1,880.6 and 1,976.9 m are assigned to the Neslen Formation.

Figure 8.--Effects of mechanical deformation are generally rather minor. A, Photomicrograph illustrating pore-filling intergranular carbonate, (C) (two generations(?)) abutting strained detrital quartz, (Q) grain with a silica overgrowth (O). Crossed polars, depth 1,776.4 m. B, Photomicrograph of lightly deformed volcanic rock fragment (Rv) quartz (Q), compacted chert (Rc) fragment, and intergranular secondary carbonate (C); pore partially filled with authigenic clays. Plain light, depth 1,644.5 m. C, Scanning electron micrograph of detrital clay (→) clast (?) squeezed between detrital quartz (Q) grain, and partially altered matrix (M). Depth 1,795.1 m.

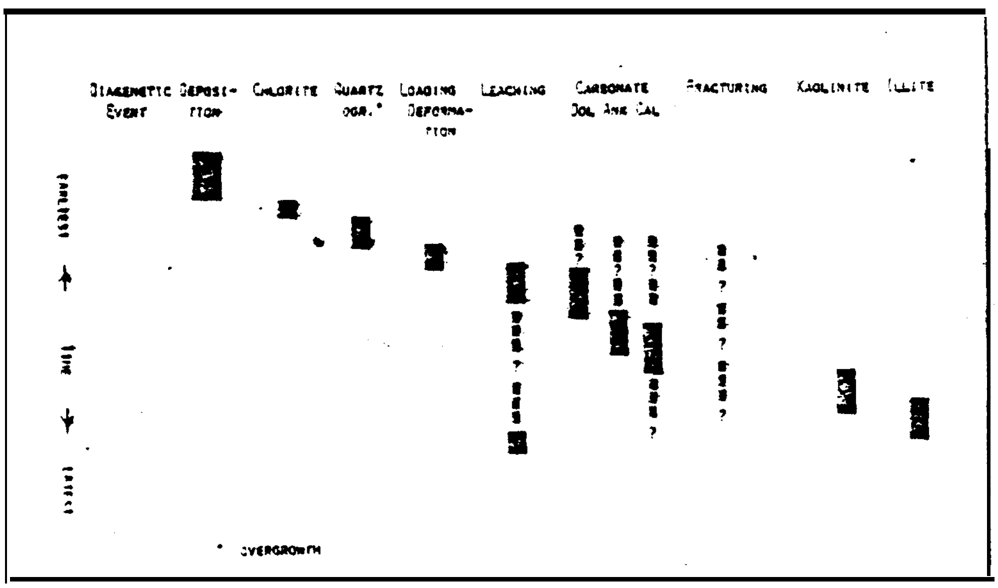
Figure 9.--Diagenetic modifications have reduced primary porosity, but have created secondary porosity through leaching. A, Photomicrograph of detrital quartz with silica overgrowths almost completely filling pore space. Silica overgrowths are usually not this extensive. Plain light, depth 1,653.8 m. B, Scanning electron micrograph of extensively leached feldspar, and authigenic pore-lining illite. Depth 1,801.5 m. C, Scanning electron micrograph of authigenic quartz (Q) and intergranular matrix (possibly a chart grain now largely altered to illite). Depth 1,880.1 m. D, Scanning electron micrograph of abundant authigenic clay--primarily platy kaolinite (K)--lining pores. Depth 1,644.5 m. E, Scanning electron micrograph illustrating relationships between authigenic illite (I), kaolinite (K), and quartz (Q). Authigenic minerals forms pore linings with a very high surface area. Depth 1,801.5 m.

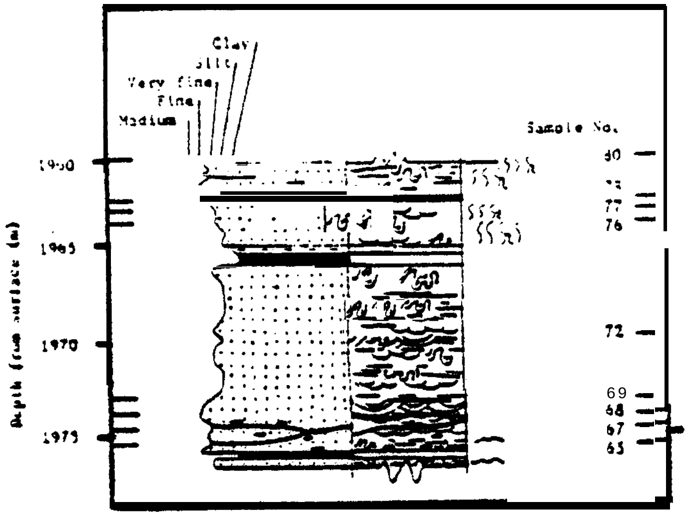
Figure 10.--Carbonates occur in intergranular pore space and as replacements. A, Photomicrograph of authigenic, pore-filling carbonate (energy dispersive spectroscopy suggests the carbonate is ankerite). Depth 1,882.5 m. B, Photomicrograph of detrital chart (Rc) grain containing rhombs of authigenic carbonate (→). Plain light, depth 1,974 m. C, Photomicrograph of sparry, void-filling carbonate (C) and carbonate (Cr) which appears to have completely replaced a feldspar (?) grain. Clay-bearing carbonate (→) is intergranular between detrital quartz grains. Plain light, depth 1,643 m. D, Photomicrograph illustrating authigenic pore-filling kaolinite (K), authigenic illite (I) replacing (?) matrix *or* quartz, detrital quartz (Q), and authigenic carbonate (C) replacing a chert (Rc) grain, and minor pore space (P). Plain light, depth 1,974 m.

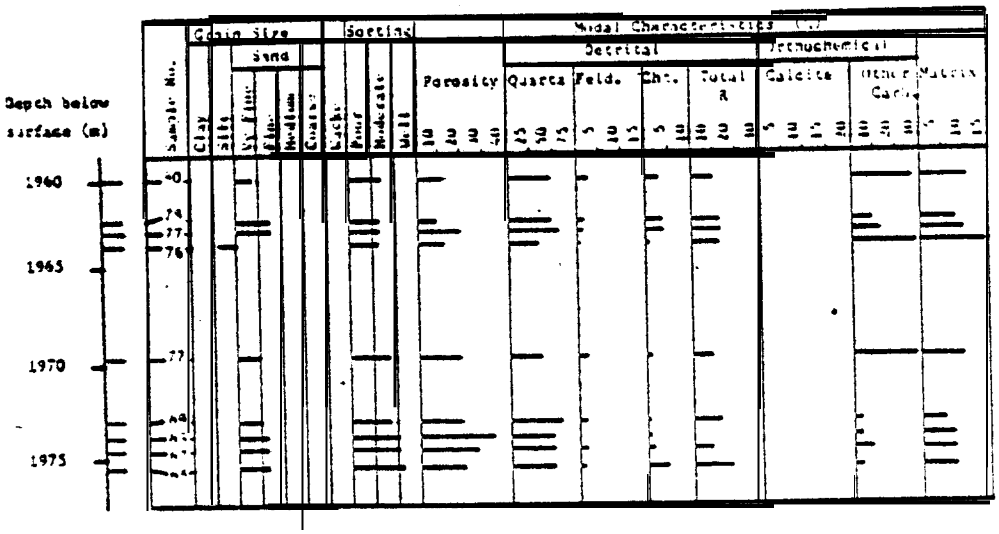
USGS
Abstract

Figure 11.--Suggested paragenetic sequence for sandstones at Southman Canyon.

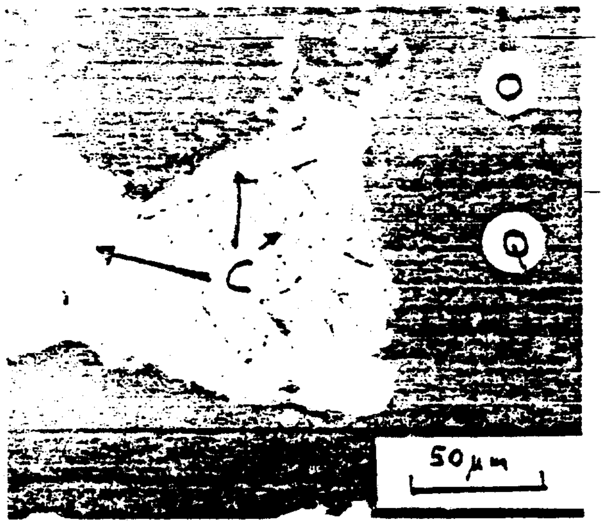
UGR File #505
USGS
Abstract

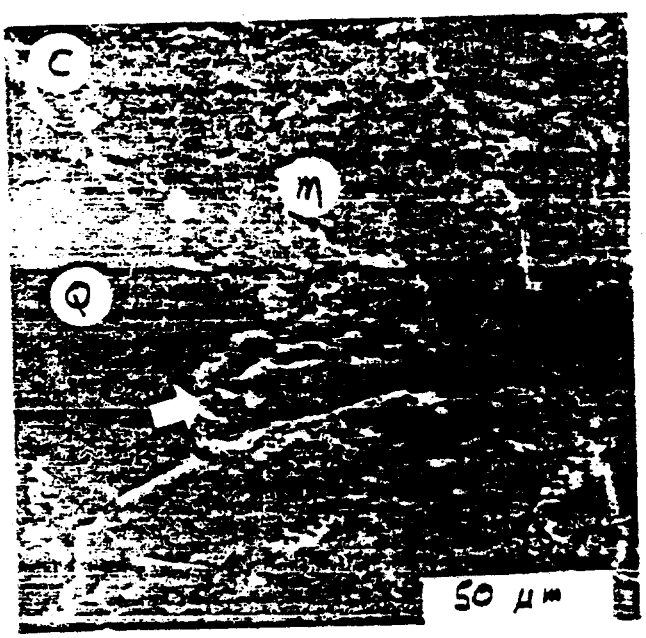



Clay
Silt
Very fine
Fine
Medium
Sample No.
Depth (from surface (m))
1960
1965
1970
1975
77
76
72
69
68
67
65

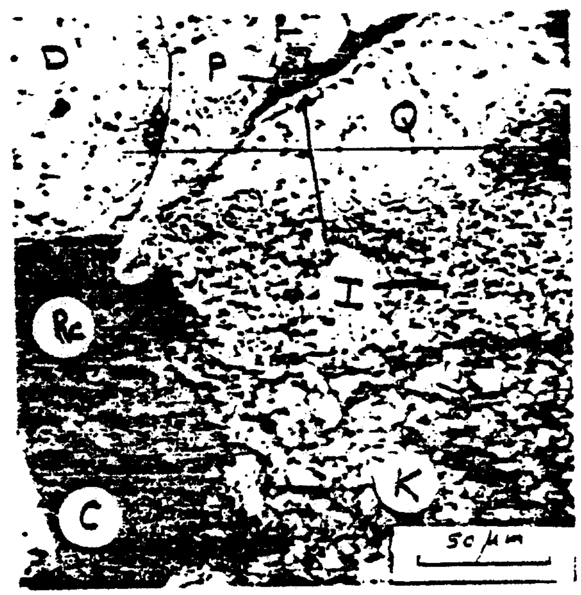

Depth below surface (m)
Sample No.
Grain Size
Sand
Clay
Silt
Vy Fine
Fine
Medium
Coarse
Sorting
Poor
Moderate
Well
Porosity
Modal Characteristics
Detrital
Quartz
Feld.
Cht.
Total R
Calcite
Matrix
1960
1965
1970
1975

US?. File #505
USGS
Abstract





UGR File #503
USGS
Abstract



UGR File #505
USGS
Abstract