Petrology, Geochemistry and Stratigraphy of Black Shale Facies of Green River Formation (Eocene), Uinta Basin, Utah

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PETROLOGY, GEOCHEMISTRY AND STRATIGRAPHY OF BLACK SHALE FACIES OF GREEN RIVER FORMATION (EOCENE), UINTA BASIN, UTAH

by M. Dane Picard[1], *William D. Thompson*[2] *and Charles Ross Williamson*[3]

ABSTRACT

The black shale facies of the Green River Formation (Eocene) probably has generated more petroleum than any other lacustrine facies. It is the most productive rock unit along the Bluebell-Altamont-Cedar Rim trend, which eventually might produce a billion barrels of oil (James Wilson, vice-president, Shell Oil Co., *in* West, 1972). Detailed sedimentologic study of the black shale facies and related beds began in 1971.

The facies contains the oldest rocks assigned to the Green River Formation in the Uinta Basin of Utah. These beds also are older than any beds assigned to the formation in Wyoming and Colorado. The upper part of the Colton Formation, a predominantly fluvial unit, is equivalent in age to the black shale facies, a predominantly lacustrine unit.

On the basis of lithology and electric log characteristics, the black shale facies is divided into five lithologic units: four lacustrine rock units designated A through D, and one fluvial unit, the Wasatch tongue of the black shale facies. Rock units B and D contain more carbonate rocks (micrite, biomicrite and sparite) than units A and C, especially in the east part of the Uinta Basin. Rock units A and C were deposited when the lake covered a smaller area and they contain more fine-grained terrigenous rocks than units B and D.

Sandstone and siltstone in the facies are arkose and lithic arkose, and contain 26 and 22 percent feldspar, respectively. Potassium feldspar is much less abundant than plagioclase and is represented mainly by microcline and lesser amounts of orthoclase. Most of the feldspar exhibits moderate to nearly complete alteration (sericitization, vacuolization and kaolinization).

The dominant carbonate rocks are micrite and dolomicrite. Algal biomicrite is next in abundance and is common in the facies. Other carbonate rocks include: silty micrite, sandy micrite, ostracodal biomicrite, sandy intramicrite, sandy sparite, algal biosparite and oosparite.

The geochemistry of five micrites and one algal biomicrite are compared with four silty micrites and four silty oil shales. All of the silty rocks contain 10 percent or more silicon, in contrast with the micrites where silicon is present in small amounts. Among other major elements, aluminum, iron, potassium (?) and titanium are all more abundant in the silty rocks than they are in the micrites. The differences probably are related to the presence of the much larger detrital fraction in the silty rocks. Larger amounts of calcium and magnesium in the micrites reflect the larger amounts of carbonate minerals in these rocks.

Among the minor elements, boron, beryllium, cobalt, copper, niobium, nickel (?), yttrium, ytterbium and zirconium are more abundant in the silty rocks than in the micrites. Apparently the large concentrations of beryllium, niobium, yttrium, ytterbium and zirconium result from their concentration in detrital minerals in the silty rocks. Strontium is more abundant in the micrites because of the large amounts of carbonate minerals in these rocks.

On the basis of the relative abundance of plagioclase feldspar and recrystallized and stretched metamorphic quartz, the major source area probably was the San Juan region of southwest Colorado. Subordinate sedimentary sources were the Uinta Mountains, Gunnison Uplift and the San Rafael Swell.

Much of the oil and gas production in the Green River Formation in the Uinta Basin is from the black shale facies or from equivalent rock units. Production from intervals within the facies occurs at: Altamont, Bluebell, Blacktail Ridge, Cedar Rim, Cottonwood Wash, Indian Ridge, Monument Butte, Pleasant Valley, Bitter Creek, Chapita Wells and Gypsum Hills. Oil in these fields mainly originated from source beds of the black shale facies. Because migration distances were

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short (less than 1 mile), exploration can be confined to areas where source beds and traps are juxtaposed.

INTRODUCTION

Scope

Although petroleum reservoir rocks have been researched considerably, few studies on the stratigraphy and petrology of fine-grained petroleum source rocks have been published and thorough studies of lacustrine source and reservoir rocks are scarce. Recent petroleum discoveries in the Uinta Basin, Utah, in the black shale facies of the Green River Formation (Eocene), have aroused substantial economic interest in the black shale facies and the fine-grained rocks it contains.

The presence of the large hydrocarbon reserves in the black shale facies prompted stratigraphic and petrologic study of the basal unit of the Green River Formation. This paper, therefore, is the first detailed study of the black shale facies, herein divided into five rock units. The principal aims of the study are: to contribute to further understanding of fine-grained sedimentary rocks; especially lacustrine fine-grained rocks; to reconstruct the environments of deposition; to contribute to source bed studies; to deduce the geologic history of Lake Uinta during deposition of the black shale facies; and to increase understanding of this important productive interval in northeast Utah.

Location and Structural Elements

The area studied (figure 1) is the Uinta Basin of northeast Utah, which is bounded by the Strawberry Reservoir on the west, the Utah-Colorado border on the east, the Uinta Mountains on the north and the Book Cliffs on the south. During the Laramide orogeny and later structural episodes the following positive structural elements were formed: the east-west trending Uinta Mountains and the north-south trending Wasatch Mountains and Douglas Creek arch. Earlier, during the Permian, the north-south trending San Rafael Swell underwent slight movement; major deformation of the swell, however, also took place during the Laramide orogeny. The Uncompahgre became a positive element during the Pennsylvanian. All of these tectonic features enclose the sharply asymmetrical Uinta Basin syncline and furnished sediment to Lake Uinta in Utah during deposition of the black shale facies.

Methods of Study

Electric well logs and lithologic logs were used to define and correlate the separate rock units in the black shale facies and to determine the changing lithology of each rock unit in wells throughout the Uinta Basin. Field studies were made to compare well log interpretations of lithology with actual outcrops. Stratigraphic cross sections (figure 2) and isopachous maps were constructed from well-log information to provide a better understanding of the stratigraphic relationships in each rock unit.

Thin sections from rock samples collected from well cores and outcrops in the south central and southeast Uinta Basin were studied petrographically. The mineral contents of two-thirds of the samples were determined by X-ray diffraction.

In addition to the reconnaissance stratigraphy, field studies were conducted in the southwest part of the Uinta Basin of the black shale facies and the Colton Formation (Paleocene?-Eocene) to determine the paleocurrent system.

HISTORY OF NOMENCLATURE

Picard (1955, p. 83) originated the term "black shale facies" for the oldest rock unit of the Green River Formation in the Uinta Basin (figure 3). As originally defined, the black shale facies underlies Bradley's (1931) delta facies and is correlative with his basal tongue of the Green River Formation and his overlying tongue of the Wasatch Formation (Paleocene?-Eocene). The designation black shale facies of the Green River Formation was used by Picard (1955, p. 84) because of the dark gray to black color of many of the fine-grained rocks in the unit. He recognized large amounts of carbonate present in the black shale facies and stressed the general extent of the black shale facies and regional correlations and relationships of the unit to closely associated rock units. At the time the rock unit was largely undescribed because of its limited surface exposure as compared with its regional subsurface extent.

Further details concerning the stratigraphy of the black shale facies were presented later in three regional cross sections (Picard, 1957); an isopachous map of the unit was included (Picard, 1957, p. 124) and the lithology, general paleontology, facies changes, correlation and paleogeography were discussed.

Abbott (1957, p. 104) retained the black shale facies nomenclature, but proposed that it be expanded to include a younger unit, the second lacustrine facies, which was originally described by Bradley (1931). This change also was made by Picard (1957) and the appropriate rock correlations are shown on his cross sections. Abbott (1957, p. 104) suggested that the terms "upper black shale facies," "Colton tongue," and "lower black shale facies" be substituted for the terms

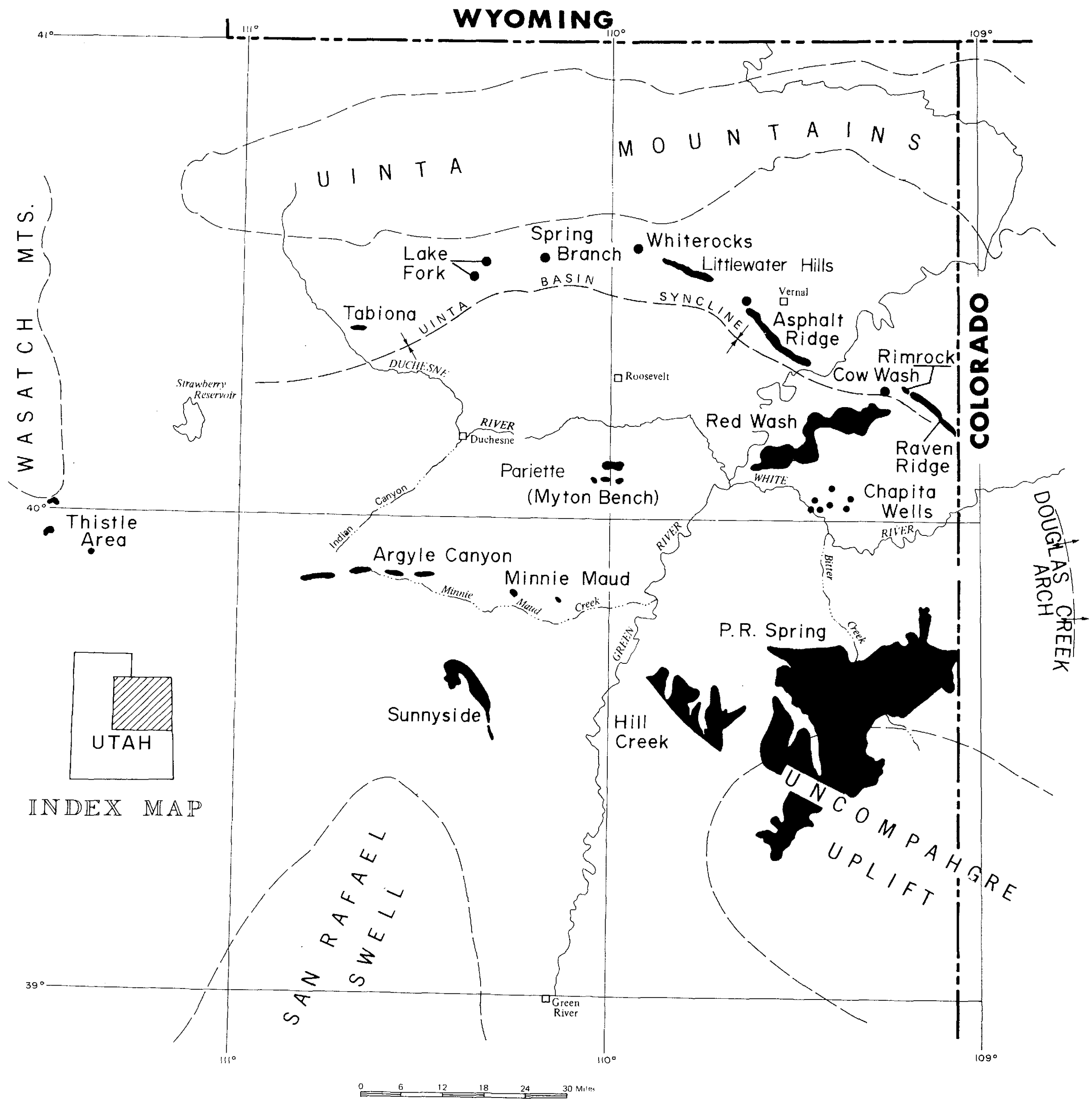


Figure 1. Index map of Uinta Basin showing positive areas, oil-impregnated sandstone deposits (black patterns), geographic localities and area of study.

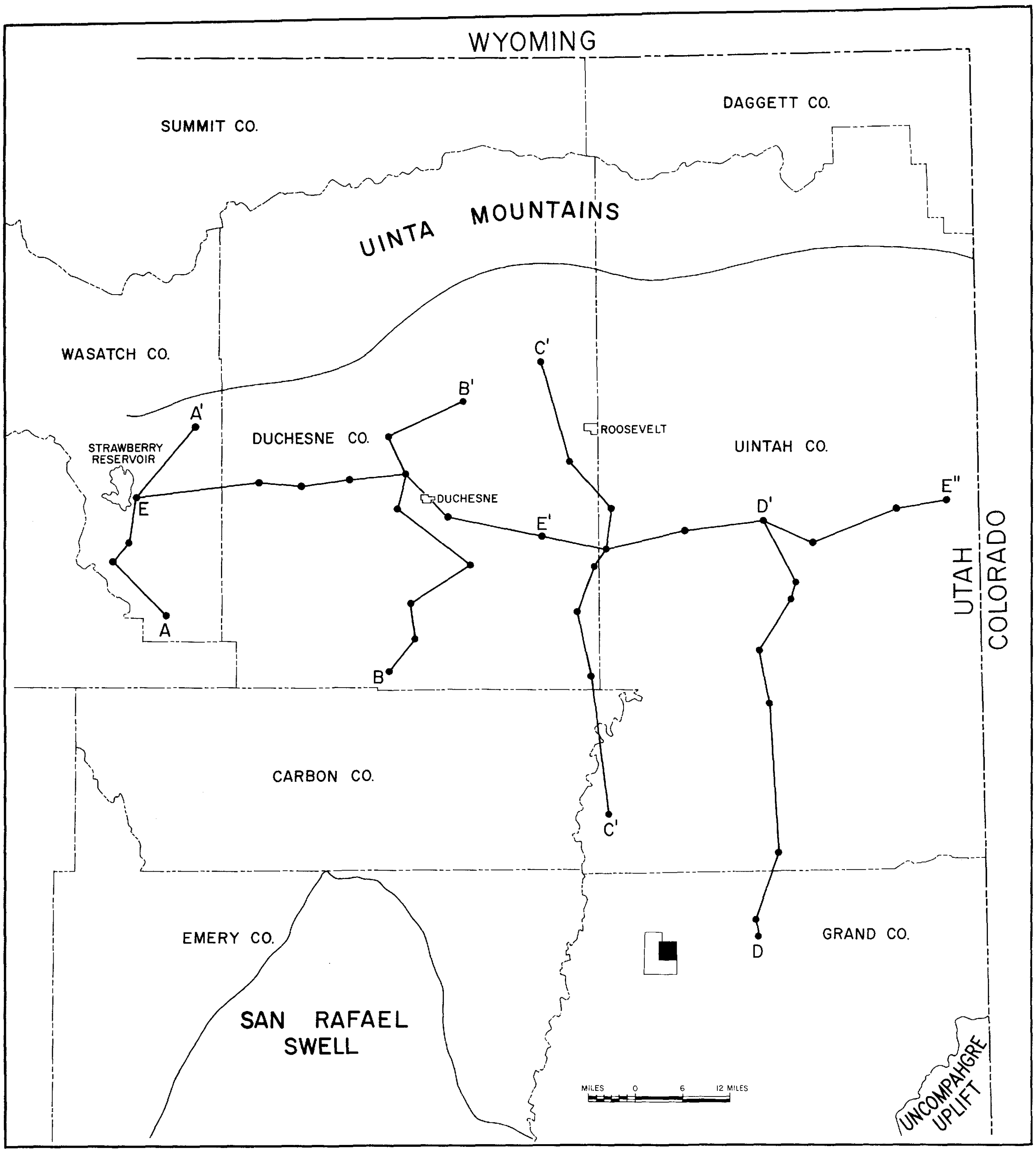


Figure 2. Index map of Uinta Basin showing location of subsurface stratigraphic cross sections.

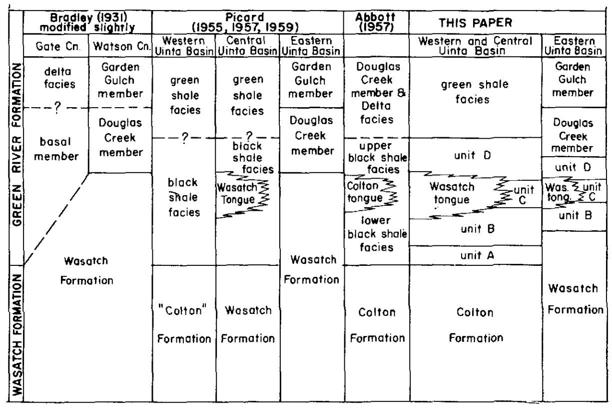


Figure 3. Stratigraphic nomenclature chart for rock units of lower part of Green River Formation in the Uinta Basin, Utah.

"second lacustrine facies," "Wasatch tongue," and "basal tongue of the Green River Formation" used by Bradley (1931).

Picard (1959) presented a correlation of the black shale facies from the central to the west part of the Uinta Basin. Previously little was known of the unit in the west because of sparse well control. Well control is still much less in the west part than in other parts of the Uinta Basin. Picard (1959, p. 148), however, suggested that the stratigraphy of the Green River Formation appeared favorable for future oil and gas production in the west Uinta Basin area. Subsequent drilling confirmed this, and, if anything, has indicated that Picard's previous suggestions were not optimistic enough concerning the economic potential of the area.

Recently Moussa (1969, p. 1740) suggested that a new nomenclature is necessary for rocks previously assigned to the black shale facies in the west Uinta Basin. On the basis of mapping north and east of Soldier Summit, Utah, he proposed adoption of the following new members (from base upward): Middle Fork tongue of the Green River Formation, Tabbyune Creek tongue of the Colton Formation and Soldier Summit Member of the Green River Formation. Apparently Moussa's members collectively are equivalent to what previously (Picard, 1957; Abbott, 1957) was designated the black shale facies, but Moussa believes (1969, p. 1470) that his three members include an additional sequence at the top. Picard (1959, p. 146) shows a thickness of 1,070 feet for the black shale facies at the Slab Canyon Unit No. 1 (sec. 26, T. 5 S., R. 10 W.), which compares with a thickness of 1,052 feet for Moussa's three members in the Soldier Summit area. Slab Canyon is only a few miles northeast of Soldier Summit.

One must conclude, on the basis of close comparison of the appropriate studies, that Picard (1955, 1957 and 1959), Abbott (1957), and Moussa (1969) all described almost exactly the same sequence of beds in the lower part of the Green River Formation. The area studied by Moussa (1969) is small–less than two townships are shown on his geologic map (p. 1738). Other workers have not adopted Moussa's nomenclature, probably for some of the reasons given here, especially the local extent of his mapping. Moussa is correct, however, in suggesting that the black shale facies can be divided into several rock units, which was done in this paper.

GENERAL STRATIGRAPHY

The black shale facies contains the oldest rocks assigned to the Green River Formation in the Uinta Basin. These beds are also older than any beds assigned to the formation in Wyoming and Colorado. The contact of the black shale facies and the Wasatch Formation (or Colton Formation) is a facies plane and is time-transgressive from the central part of the Uinta Basin toward the margins. Minor regressions and shifting back and forth of shorelines do not vitiate the general transgressive character of the contact.

The black shale facies, a predominantly lacustrine unit, is equivalent in age to the upper part of the Wasatch Formation, a predominantly fluvial unit. The exact thickness of each rock type, equivalent in time, is not known. Including part of the green shale facies overlying the black shale facies, however, there is at least 1,700 feet of transgression (as measured in rock sequence) between the Duchesne area in the central Uinta Basin and the Red Wash area on the east (Picard, 1957).

When the black shale facies originally was defined, Picard (1955) presented a reference section consisting of a lithologic log of one of the thick subsurface sequences near Duchesne, Utah. In this well (Ohio, Ute-1, sec. 26, T. 4 S., R. 3 W.), the black shale facies is 935 feet thick. Considerable drilling indicated that the maximum thickness of the black shale facies is about 1,200 feet and the unit thins to less than 200 feet near the northeast, east and south edges of the Uinta Basin.

On the basis of lithology and electric log characteristics, the black shale facies is divided into five lithologic units: four lacustrine rock units designated A through D, and one fluvial unit, the Wasatch tongue of the black shale facies. The rock units include the entire black shale facies as presently defined (Picard, 1955, 1957 and 1959; Abbott, 1957; Moussa, 1969) and they can be identified over large areas. Rock units B and D contain more carbonate rocks than units A and C, especially in the east part of the Uinta Basin. Rock

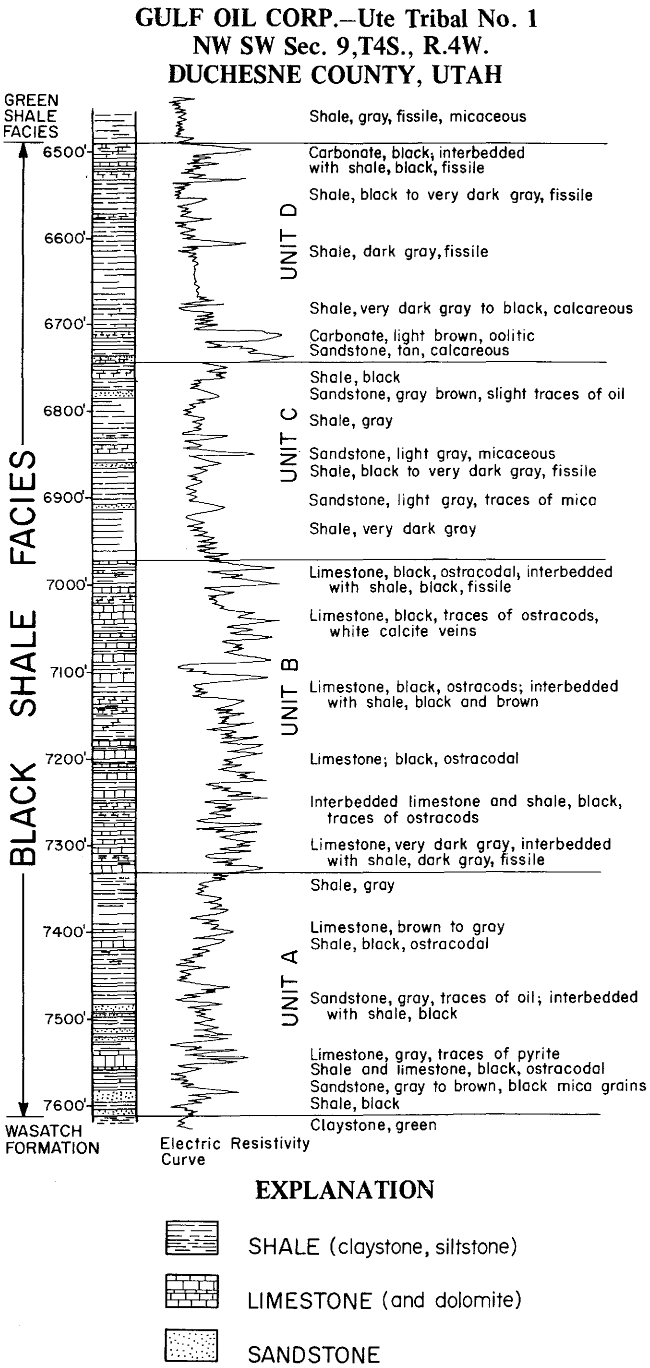


Figure 4. Typical well log section and generalized lithologic description of black shale facies. Boundaries between units A, B, C and D are given.

units A and C were deposited when the lake covered a smaller area and they contain more fine-grained terrigenous rocks than do units B and D.

Composition of the beds within the lacustrine units depends on where in the basin they were deposited. In the offshore environment (central part of the lake), mostly dark gray to black fine-grained clastics and finely crystalline, brown to dark brown, carbonate beds were deposited. Because the clastic content and particle size of rocks within the lacustrine units increase toward the edge of the depositional basin, siltstone and sandstone are more abundant in those directions. The rocks were deposited in nearshore, shallow open-water, nearshore shoal and beach-shoreface environments around the margins of Lake Uinta. Carbonate rocks in the black shale facies are coarser in texture and contain more silt- and sand-sized terrigenous grains, oolite, pisolite and shell fragments near the edges of the basin. The coarser carbonate beds were deposited in nearshore, shallow open-water, nearshore shoal and lagoonal environments.

The Wasatch tongue of the black shale facies is a fluvial unit essentially occupying the same stratigraphic interval as unit C; it also interfingers with units B and D. Lithologically, the Wasatch tongue is composed mainly of red, brown and green claystone and silty claystone (Picard, 1971) interbedded with abundant clayey siltstone, siltstone and sandstone. The Wasatch tongue also contains variegated mudstone. Principal environments represented by beds of the Wasatch tongue are fluvial-channel and fluvial-floodplain.

The depositional center of lacustrine units (the area of more continuous deposition than elsewhere) generally is oriented east-west, but a bulge near the middle of the unit suggests that Lake Uinta was somewhat egg-shaped during deposition of the black shale facies. During deposition of unit D, the area of maximum deposition shifted southward. A complete understanding of the shape of the depositional basin is not possible at this time, principally because of lack of well control on the west and northwest.

Figure 4 is a typical lithologic section from a well in the central part of the black shale facies. The contacts of the four lacustrine units (A through D) also are depicted, providing a good reference section of the lacustrine units in the black shale facies. As noted previously, a similar reference section of the black shale facies was given when the facies originally were named (Picard, 1955, p. 88-89). The four lacustrine units (A through D) can be determined easily in the original description by comparing the two lithologic logs.

Four south-north cross sections (figures 5 to 8) and two west-east cross sections (figures 9 to 10) show the electric log correlation of rock units of the black shale facies. The long normal electric log trace was used for most of the wells except where the laterolog

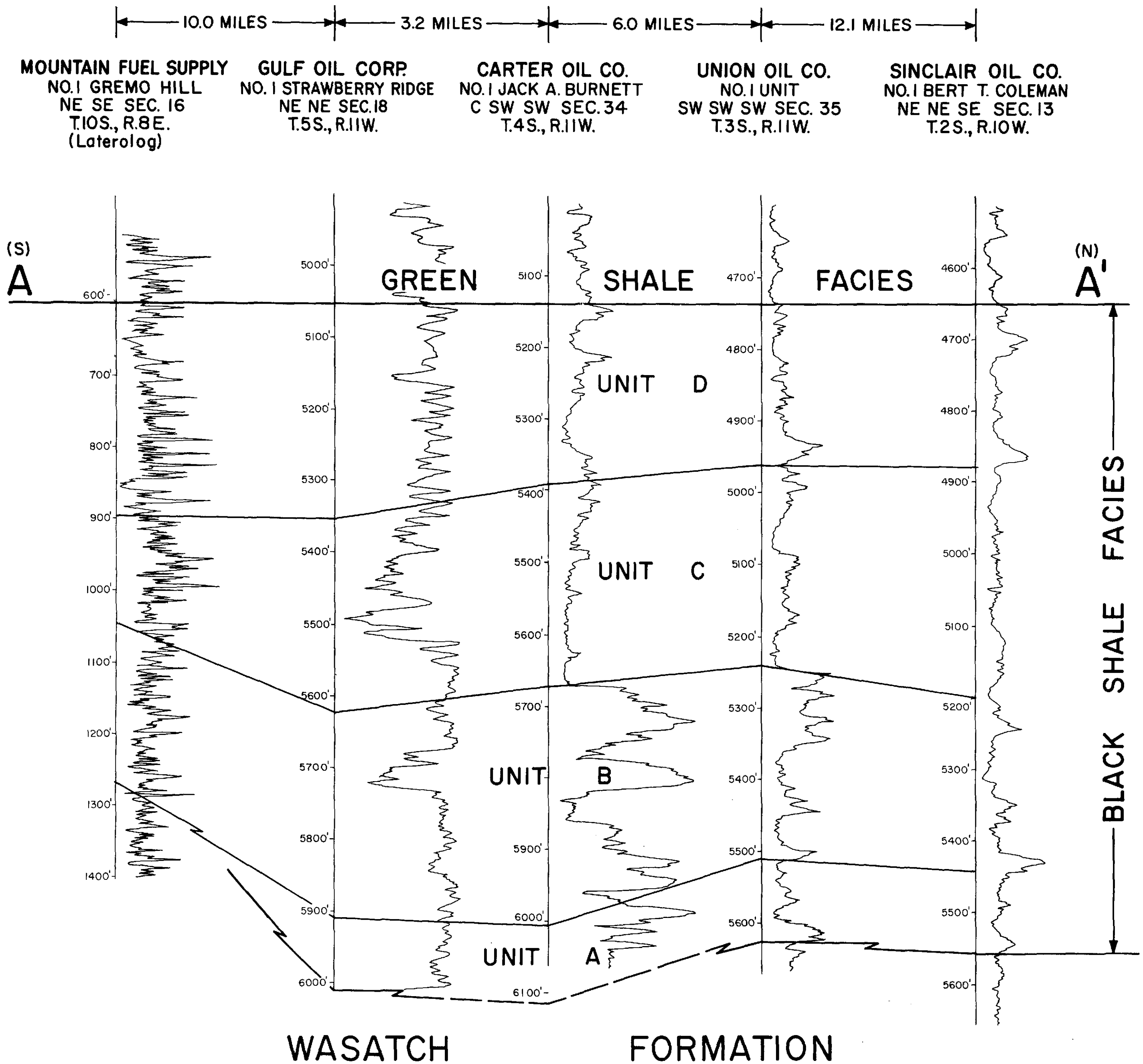


Figure 5. South-north stratigraphic cross section A-A' of black shale facies, west Uinta Basin (see figure 2 for location).

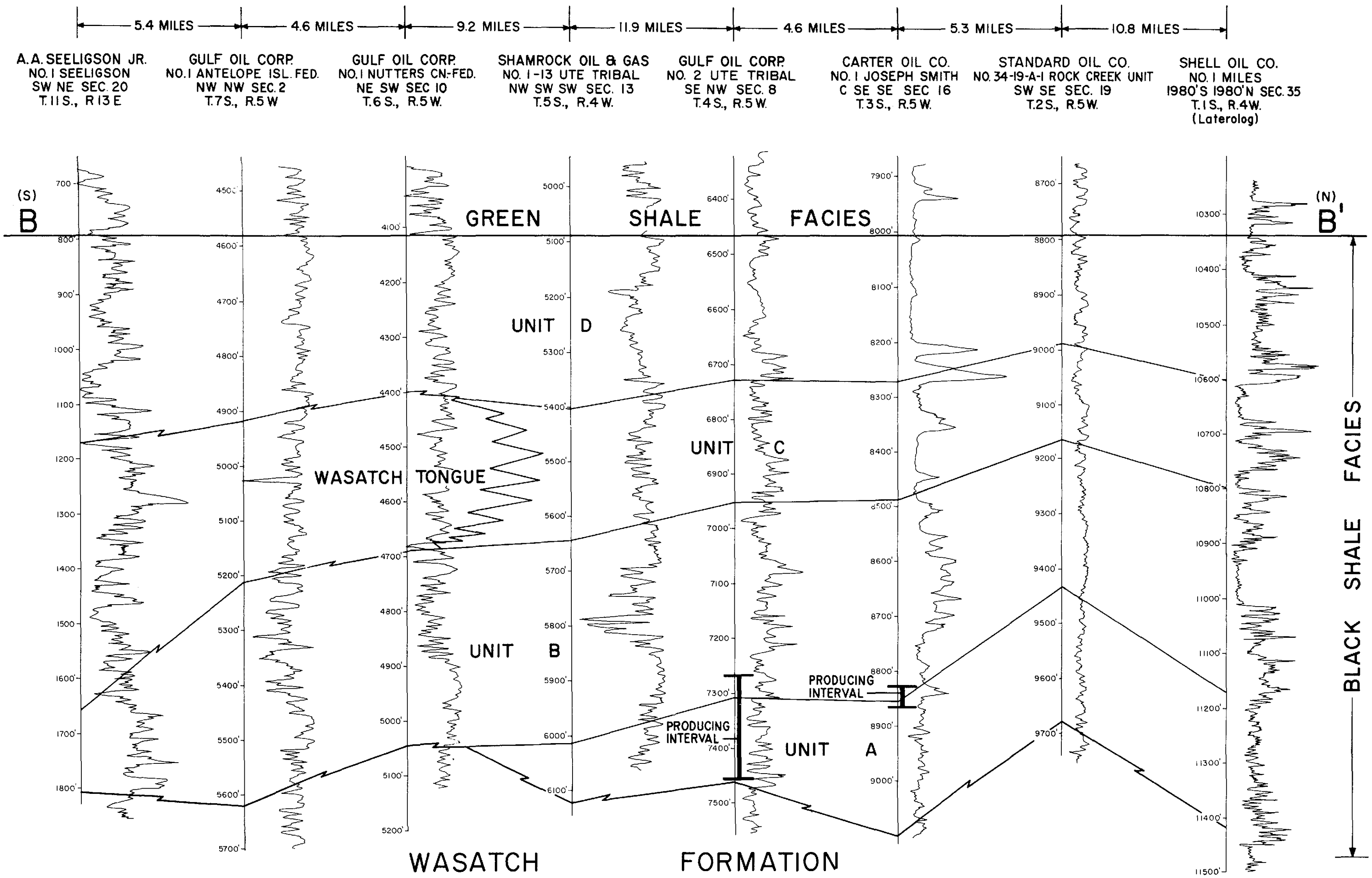


Figure 6. South-north stratigraphic cross section B-B′, central Uinta Basin (see figure 2 for location).

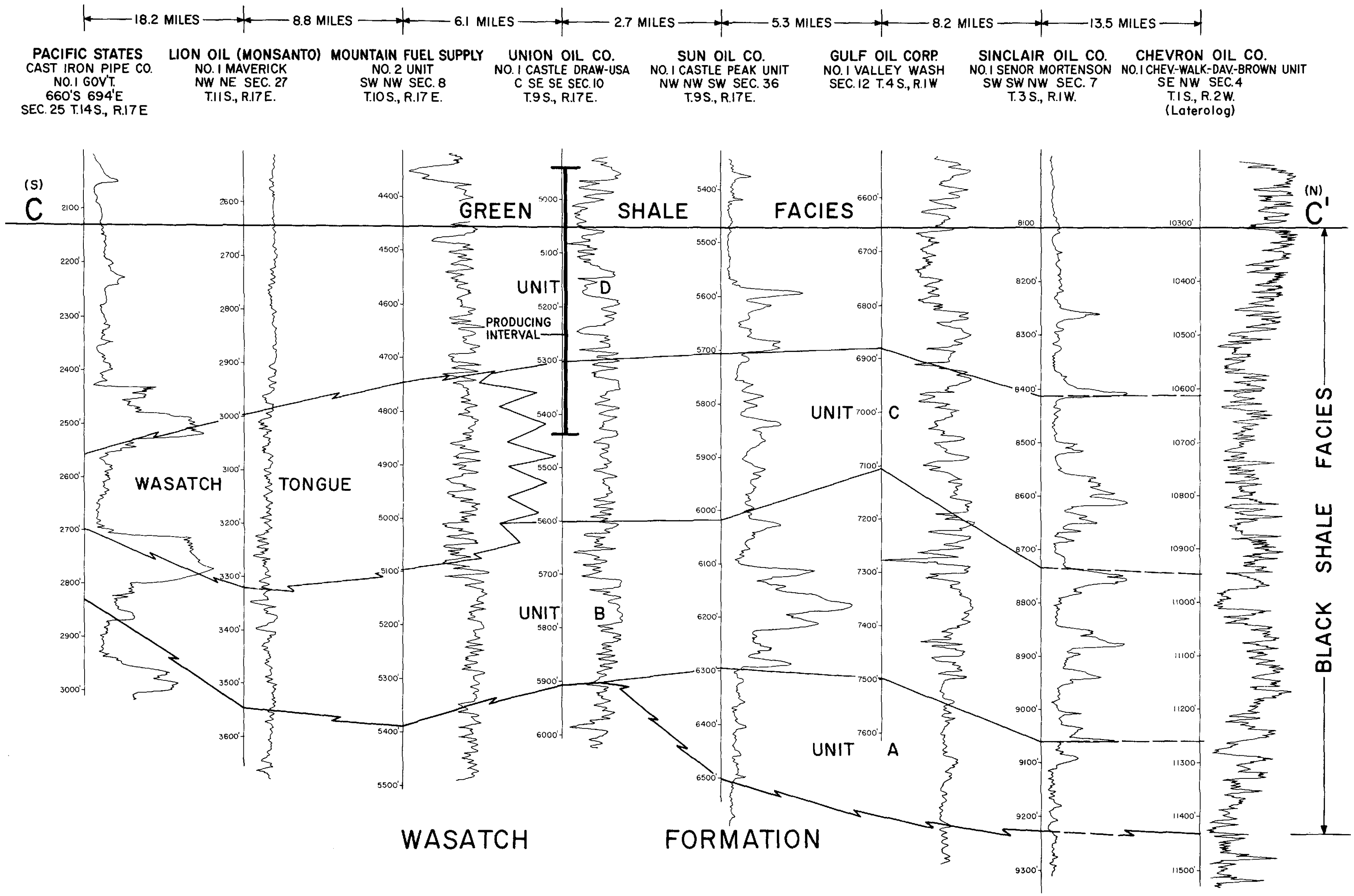


Figure 7. South-north stratigraphic cross section C-C', central Uinta Basin (see figure 2 for location).

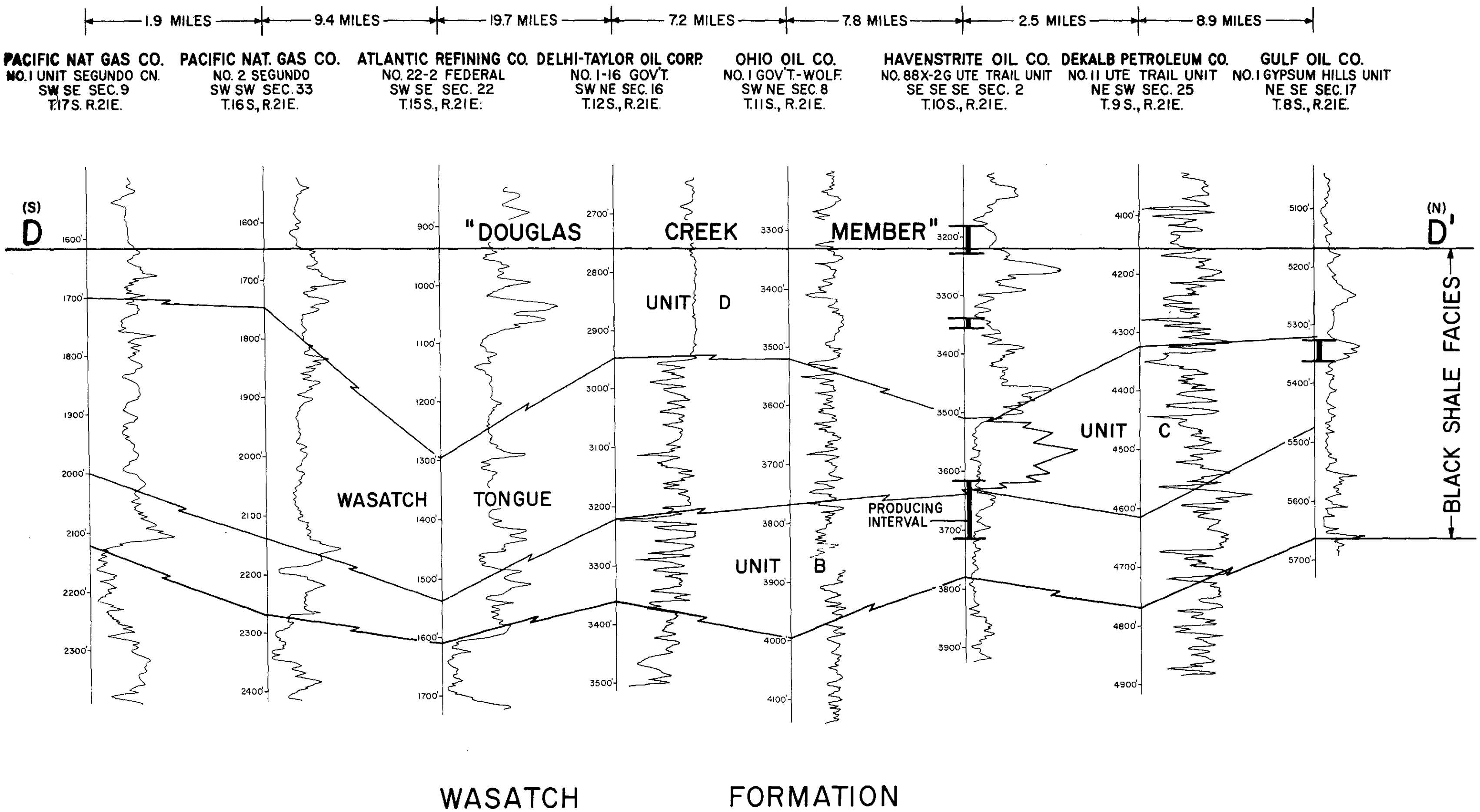


Figure 8. South-north stratigraphic cross section D-D′, east Uinta Basin (see figure 2 for location).

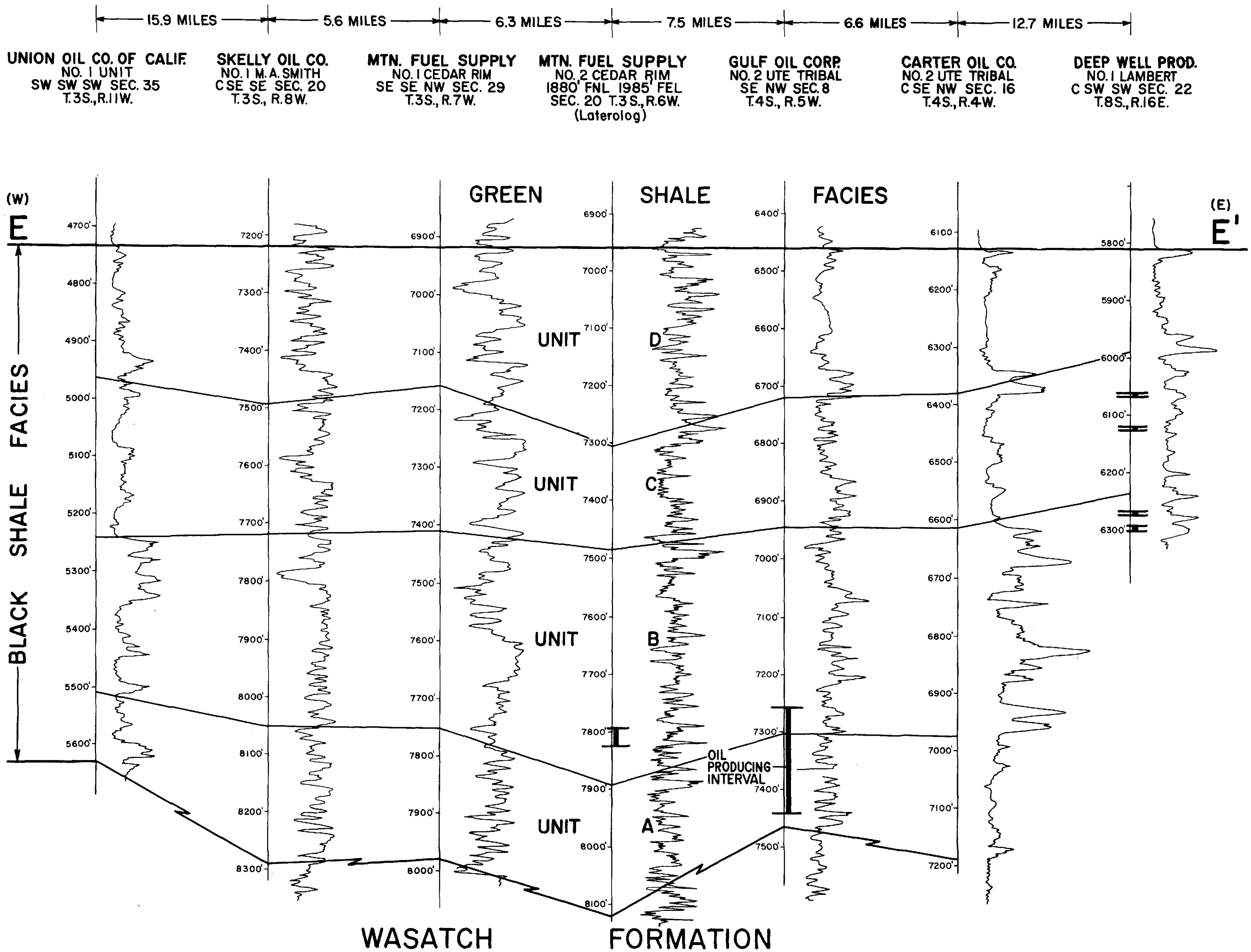


Figure 9. West-east stratigraphic cross section E-E′, west Uinta Basin (see figure 2 for location).

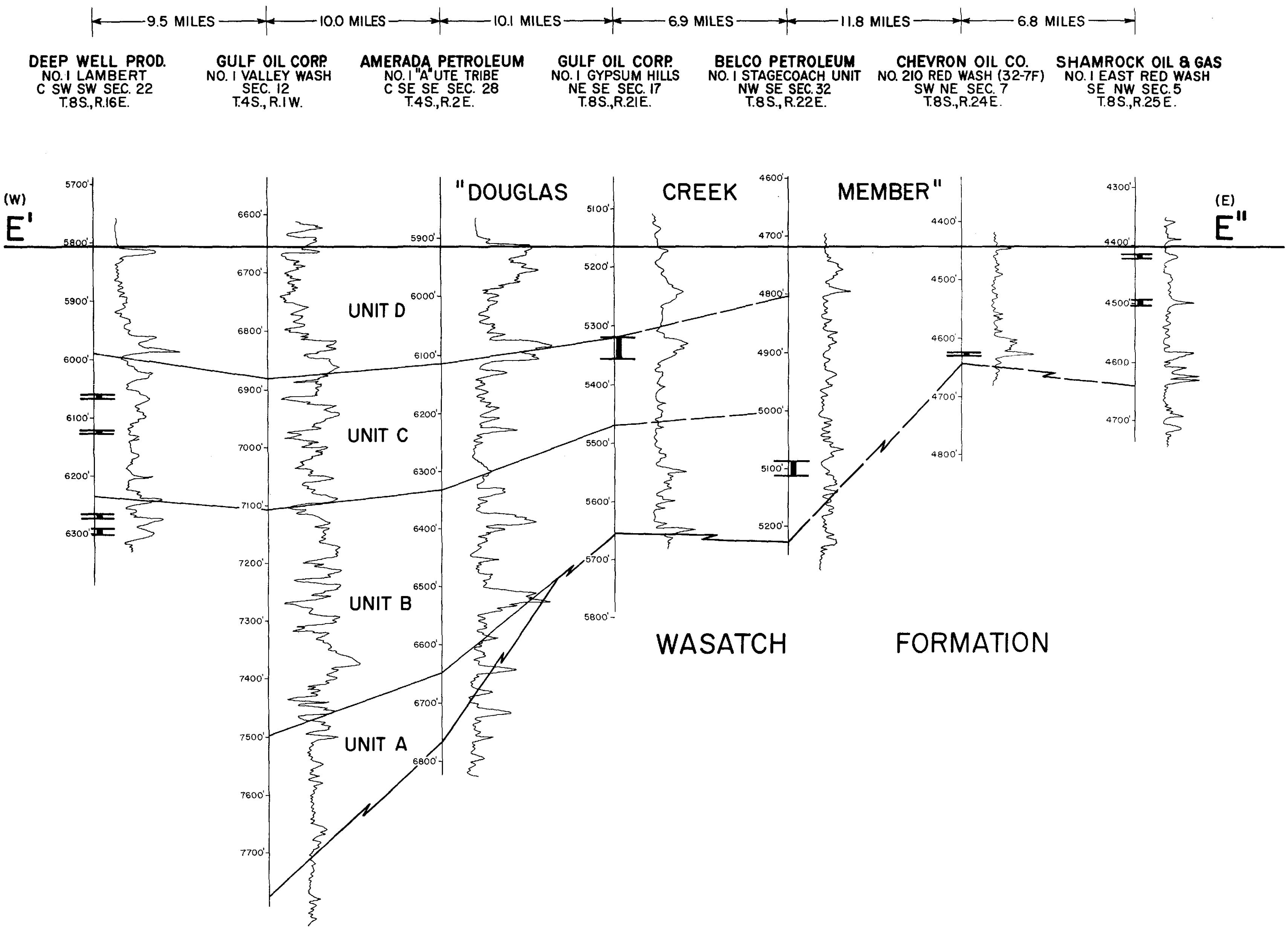


Figure 10. West-east stratigraphic cross section E′-E″, east Uinta Basin (see figure 2 for location).

trace was used as noted. Hydrocarbon-producing intervals within the black shale facies are shown. The cross sections are geographically located in figure 2.

Figure 11 is an isopachous map of the total black shale facies. The thickest part of the black shale facies extends from the central Uinta Basin near Duchesne, Utah, westward to Strawberry Reservoir. The north central part of the basin also apparently contains thick sections, but lack of adequate well control makes the details of the shape and thickness in this area speculative. The black shale facies thins rapidly north and south, but more slowly to the east (figure 11). The thinning toward the Utah-Colorado border was caused by the Douglas Creek arch, which may have existed only as islands during deposition of the black shale facies.

UNIT A

Distribution and Thickness

An isopachous map of unit A (figure 12) shows its thickness ranging from less than 100 to more than 300 feet; four areas have thicknesses greater than 200 feet. The areas of greatest thickness represent parts of the basin where deposition was more continuous than elsewhere and reflect the areas where deposition commenced in Lake Uinta. Three of the thick areas define an east-west oriented band (figure 12), which is the depositional axis in the initial basin during deposition of the black shale facies. There may have been four or more separate lakes to begin with, but the initial lakes soon coalesced to form Lake Uinta.

The thickest portion of the depositional basin is located on the west, southwest of Strawberry Reservoir (figure 12). Deposition likely commenced in the black shale facies in this west area and transgressed eastward as the initial lakes coalesced. Unit A probably is much more extensive in the west than shown in figure 12; additional drilling is needed to define the west part of the Green River Formation in the Uinta Basin.

Lithology

The lithology of unit A reflects varying lacustrine environments of deposition. Along the central axis of the basin offshore lacustrine rocks were deposited. The most abundant rocks are black, dark gray and grayish green, thinly laminated, carbonaceous claystone, silty claystone, clayey and silty mudstone, and clayey siltstone. Ostracods are common. Most of the features in the rocks are the result of deposition below wave base where organic-rich oozes accumulated slowly. Water depths are interpreted to be less than 100 feet in Lake Uinta during deposition of unit A.

Gray or medium brown to brown, crystalline, fine-grained, clayey, ostrocodal limestone is common in unit A as are thin beds of oolite and dolomite.

Terrigenous material in the rocks of unit A increases towards the margins of the basin. The dark gray to black claystone and mudstone is replaced by siltstone and sandstone deposited in nearshore, shallow open-water and beach-shoreface environments. In shallow water deposits, the carbonate beds contain silt- and sand-sized terrigenous grains and broken fossil fragments. Fluvial and lacustrine rocks interfinger at the basin margins in unit A.

Contacts

The basal contact of unit A and the underlying fluvial Wasatch Formation (or Colton Formation) is transgressive, as discussed previously. Picard (1955, p. 84) placed the contact between the black shale facies and the Wasatch Formation at the top of the uppermost red shale of the Wasatch Formation. In a later paper, Picard (1957) attempted to place the base of the black shale facies at a consistent electric log marker. The base of unit A as used here (figures 5 to 7) is the same as that used by Picard (1955, 1957 and 1959) and Abbott (1957), and, in general, by most other workers in the Uinta Basin. There may, however, be some variation in placement of the base of the black shale facies because the lower part of unit A is gradational with the upper part of the Wasatch Formation.

The contact of unit A with the overlying unit B is discussed in the next section.

UNIT B

Distribution and Thickness

Unit B ranges in thickness from less than 100 to more than 400 feet with three specific areas thicker than 300 feet (figure 13). The largest thick area is on the west (figure 13) and nearly coincides with the thick band in unit A (figure 12). This correlation indicates that the axis of greatest deposition remained nearly constant during deposition of lacustrine units A and B.

During deposition of the upper part of unit B, however, Lake Uinta transgressed eastward and lacustrine deposition commenced in Lake Uinta in northwest Colorado near the Douglas Creek arch and the Colorado-Utah border. Some of the beds deposited during this event have been removed by erosion; other beds are exposed in northwest Colorado.

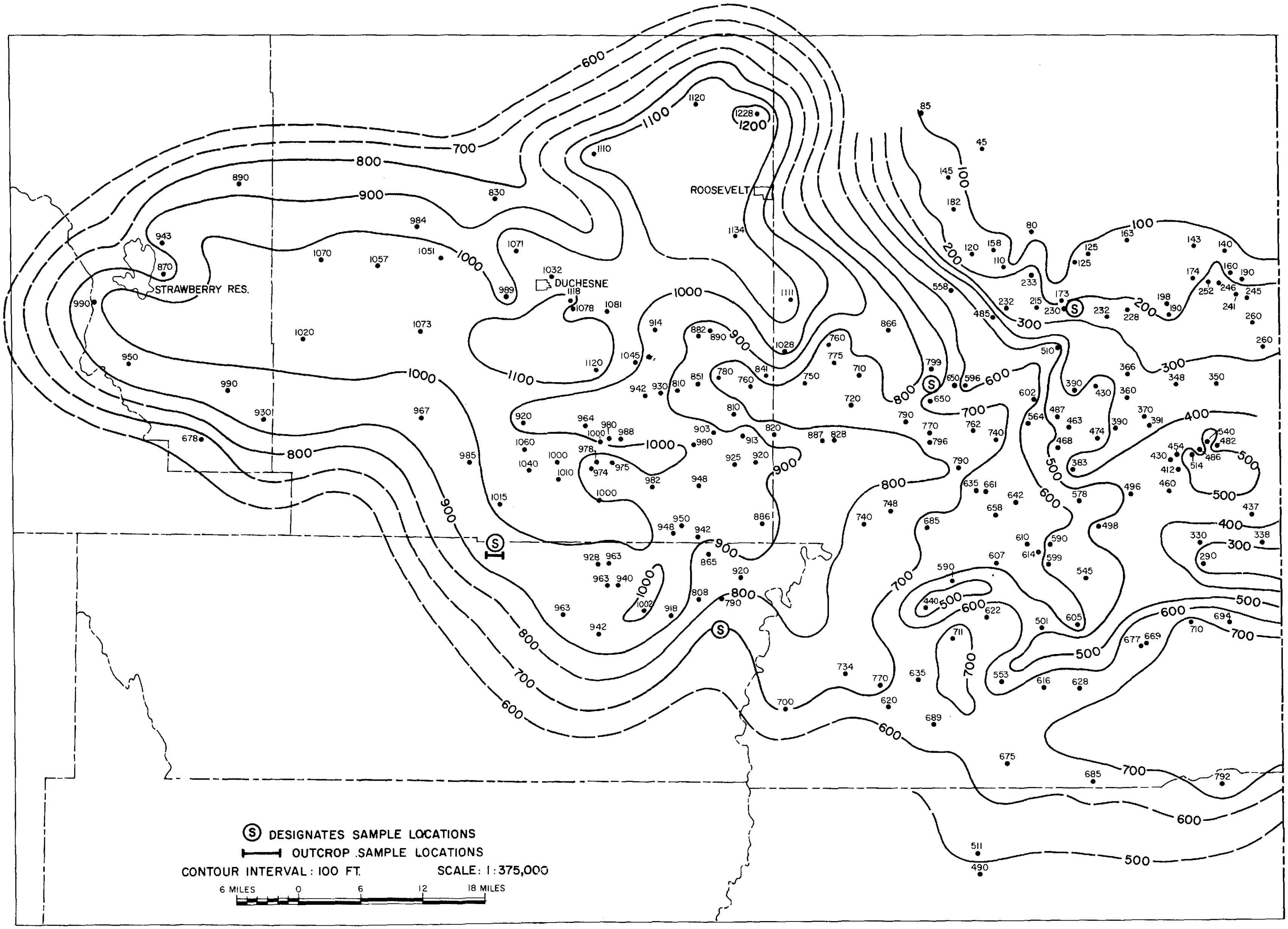


Figure 11. Isopachous map of black shale facies.

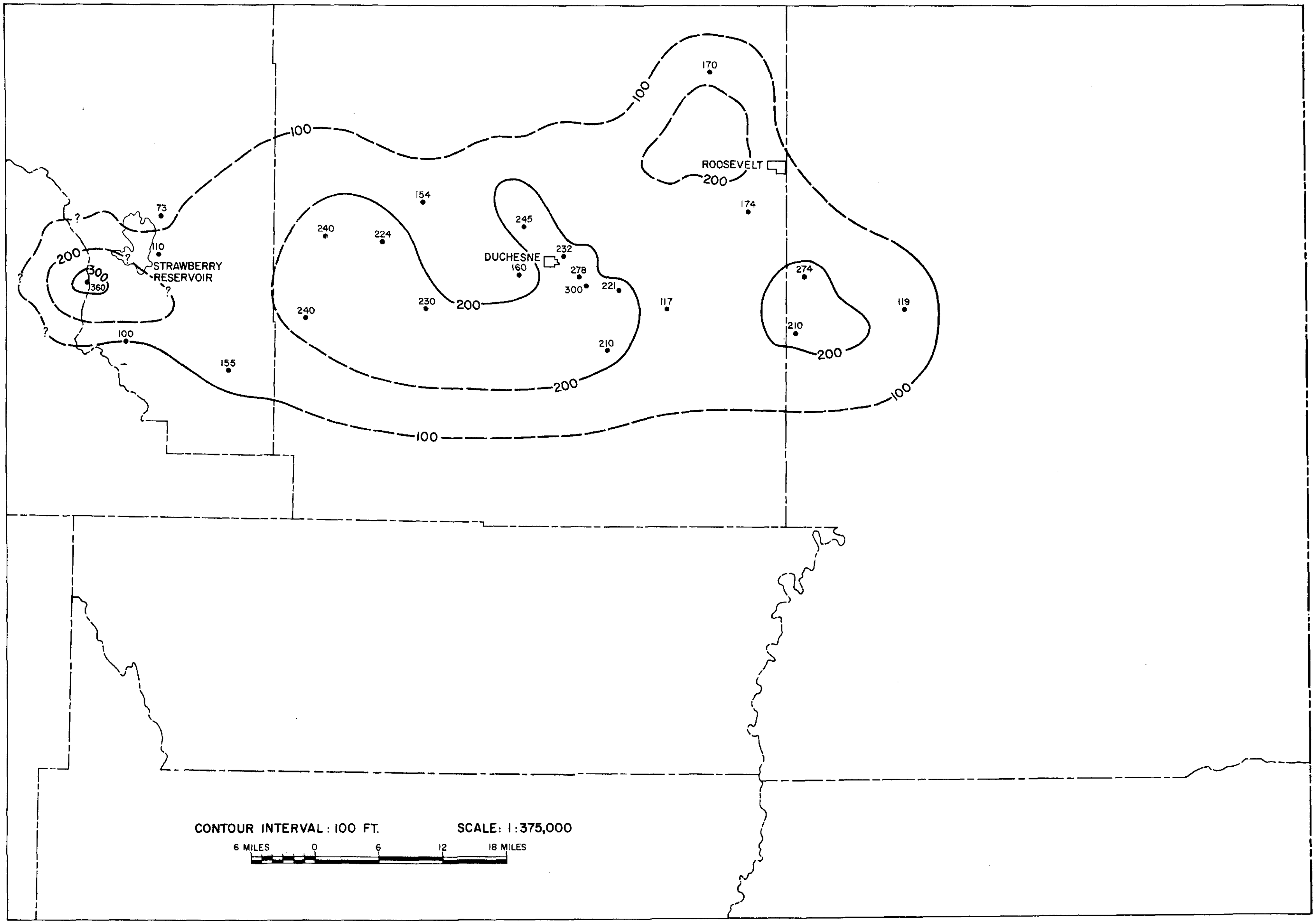


Figure 12. Isopachous map of unit A of black shale facies.

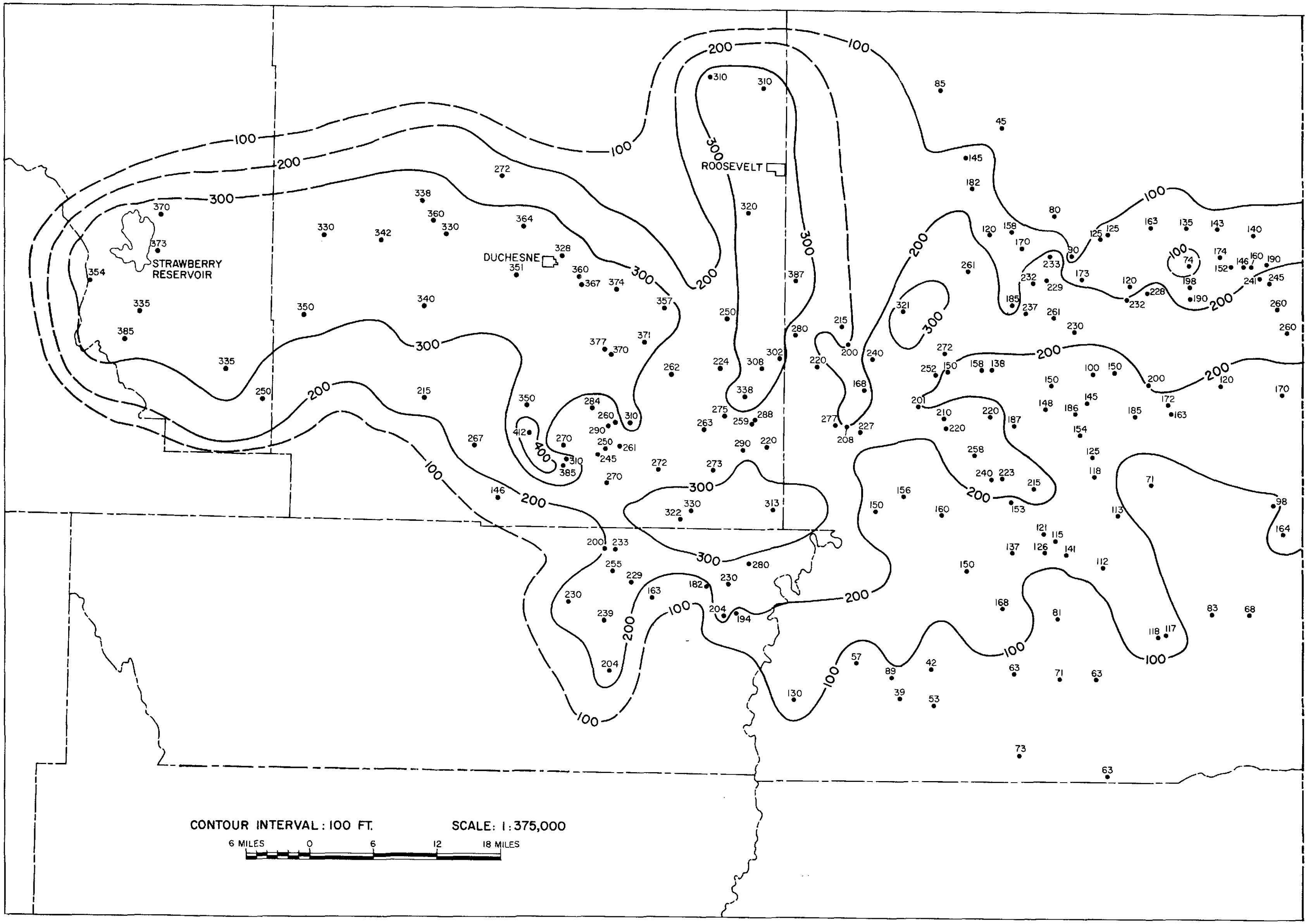


Figure 13. Isopachous map of unit B of black shale facies.

The shape of the basin changed during deposition of unit B and first assumes the general egg-shaped form mentioned for the isopachous map of the total black shale facies. The basin west of Roosevelt, Utah, which was present during deposition of unit A (figure 12), expanded during deposition of unit B and isopachous contours reflect this growth as they bulge to the north and south near the middle of unit B (figure 13).

The expansion of Lake Uinta during unit B time is striking. The lake transgressed across its entire previous margins, especially expanding to the east and southeast (figure 13). The extent of Lake Uinta was about twice as large during unit B time as it was during unit A time, reflecting the remarkable transgression of the lake to almost the maximum extent it attained during deposition of the black shale facies.

Lithology

In the offshore environment of unit B in the deeper parts of the basin, carbonate rocks are slightly more abundant than fine-grained clastic rocks. Brown, dark brown, brown black, crystalline, very fine to fine-grained, clayey and carbonaceous carbonate beds are the most abundant rocks. Many of the carbonate beds contain ostracods. Coquinal and coquinoid units containing algae and ostracods are common. The carbonate beds frequently show traces of hydrocarbons.

Fine-grained clastic rocks (claystone, silty claystone and mudstone) in unit B are mostly black, dark gray to dark brownish gray, tan, thinly laminated, pyritic and ostracodal. Rare calcite veins are present.

Oil shale is present in rare amounts in unit B. These rocks, which are not shale and do not contain oil, are calcareous or dolomitic, well indurated, silty claystones. In many instances they contain sufficient fine-grained carbonate to be called micrite-microspar or silty micrite. Variable amounts of organic matter in the form of kerogen occur in the oil shale. Rocks rich in kerogen tend to be papery and dark in color (olive black, 542/1: Goddard color chart, 1948); those that are poor in kerogen are massive and light colored. The oil shale was deposited in an offshore environment below wave base where organic-rich oozes accumulated slowly.

Minor amounts of light gray, very fine-grained, calcareous sandstone, and medium gray, calcareous, clayey siltstone and siltstone are present in unit B.

Carbonate beds are still abundant in unit B near the margins of the basin even though clastic beds become increasingly abundant at the basin margins. Ostracodal and algal, coquinal and coquinoidal beds are characteristic of unit B at many localities. From the thickest sections of the unit eastward to the Utah-Colorado border, the carbonate beds become increasingly clayey, silty and sandy, and coarser in texture. The carbonate beds also contain oolite, pisolite and fossil fragments (algae, ostracods, pelecypods and gastropods).

Shallow water deposition in unit B is indicated by the presence of lignite beds in the east part of the Uinta Basin. Abbott (1957, p. 104) also noted lignite in the same unit near Soldier Summit and Sunnyside, Utah.

Light gray, light brown, calcareous, "salt-and-pepper" sandstone, clayey siltstone and siltstone become more abundant near the margins of the basin. On the southeast, near the outermost margin of the basin, mottled brown-red and green sandstone and fine-grained clastic rocks of fluvial origin interfinger with the lacustrine carbonate.

Contacts

Where both units A and B are present in the same section, the contact between the two is placed at the base of the lowermost thick carbonate sequence. In general, this position is easily recognized on electric well logs (figures 5 to 7 and 9 to 10). At localities where unit B is directly underlain by fluvial beds of the Wasatch Formation (or Colton Formation in the west Uinta Basin), the contact is placed at the top of the uppermost fluvial bed. Figure 8 illustrates placement of the contact on the east side of the Uinta Basin.

UNIT C

Distribution and Thickness

Unit C and the Wasatch tongue of the black shale facies are shown on the same isopachous map because both units occupy about the same stratigraphic position (figure 14). The dashed thick line represents the lateral contact between unit C and the Wasatch tongue. It separates dominantly lacustrine rocks (unit C) from fluvial rocks (Wasatch tongue) and represents the approximate position of the average shoreline during the time of deposition of unit C and the Wasatch tongue. Considerable effort was expended to determine the position of the average shoreline, and the lithologic relationships in more than 50 wells were examined carefully. Because of numerous minor lake level fluctuations and intertonguing of the two facies, however, the location of the average shoreline must be regarded as an interpretation.

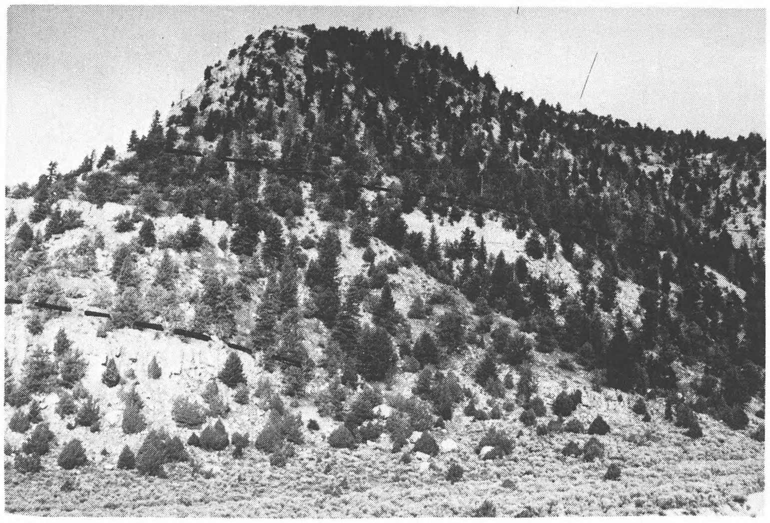


Figure 14. Unit B, Wasatch tongue, and unit D at SE¼ sec. 12 T. 12 S., R. 12 E.

Present well control indicates that unit C ranges from about 150 to more than 300 feet thick. On the northwest, well control is slight and the distribution and thickness of the unit is not known.

On the west and north (vicinity of Roosevelt, Utah), thick sequences of lacustrine rocks are present in about the same areas in units B and C (figures 13 and 15). This relationship indicates that during the time units B and C were deposited, Lake Uinta occupied essentially the same basin in this part of the Uinta Basin. However, unit C is thin or absent in the east part of the Uinta Basin (figure 15), indicating that unit C represents a much lower lake level than was present during deposition of unit B.

The distribution of the Wasatch tongue also indicates that Lake Uinta was much reduced during the time of deposition of unit C. Lake waters in the south margin of the basin regressed markedly to the north and the fluvial beds of the Wasatch tongue were deposited over more than one-half of the previous lake basin (see figure 13, isopachous map of lacustrine unit B). Apparently, Lake Uinta was not much larger during deposition of unit C than it was during deposition of unit A. The thickness distribution of the Wasatch tongue is indicative of deltaic deposition on the southwest with an apparent major source area on the southwest. The Wasatch tongue on the southwest ranges in thickness from about 300 feet to 485 feet. On the southeast, it is from about 100 to 400 feet thick and occupies almost the entire east third of the basin.

Lithology

Unit C is characterized by fine-grained clastics, sandstone and carbonate of lacustrine origin. In the offshore environments of the central parts of the lake basin, unit C consists mainly of dark colored, fine-grained clastics (claystone, silty claystone, clayey and silty mudstone). The most abundant rocks are medium to dark brown, gray to black, grayish green, slightly fissile, calcareous, micaceous and pyritic fine-grained clastics.

Clayey siltstone, siltstone and sandstone increase in abundance toward the basin margins. The rocks are light gray or light brown, calcareous, micaceous and composed dominantly of very fine sand to silt-sized grains.

Carbonate rocks are less abundant in unit C than the fine-grained clastics, siltstone or sandstone. There are some carbonate beds, however, which are characteristically light brown to brown, crystalline, very fine to fine-grained and commonly ostracodal.

Unit C interfingers laterally with the fluvial Wasatch tongue of the black shale facies. Along this contact, black, soft, brittle lignite is common. The lignite indicates shallow-water, nearshore deposition, probably in lagoons and bays.

Contacts

The lower contact of unit C is placed at the top of the youngest prominent bed of unit B that gives a distinctly resistive peak on electric well logs. Where both units B and C are present in the same section, the contact between them is not difficult to determine, even though there is some gradation in lithologies near the boundary. The distinguishing feature is the much larger amount of carbonate in unit B compared with unit C.

The contact between units B and C is a facies contact, separating two distinct lithogenetic units that vary in age from place to place. For the area shown in the cross sections, however, it is believed the variation in age is not large and that unit C was deposited in nearly the same time interval throughout the lake basin. The regression of Lake Uinta from the east and south parts of the Uinta Basin to the much smaller lake of unit C time probably was a relatively rapid event because nearly equal thicknesses of lacustrine sediment were deposited throughout the lake basin on the west and north (figure 15). Further support for this interpretation is the presence of regionally correlatable rock units within unit C on the west and north.

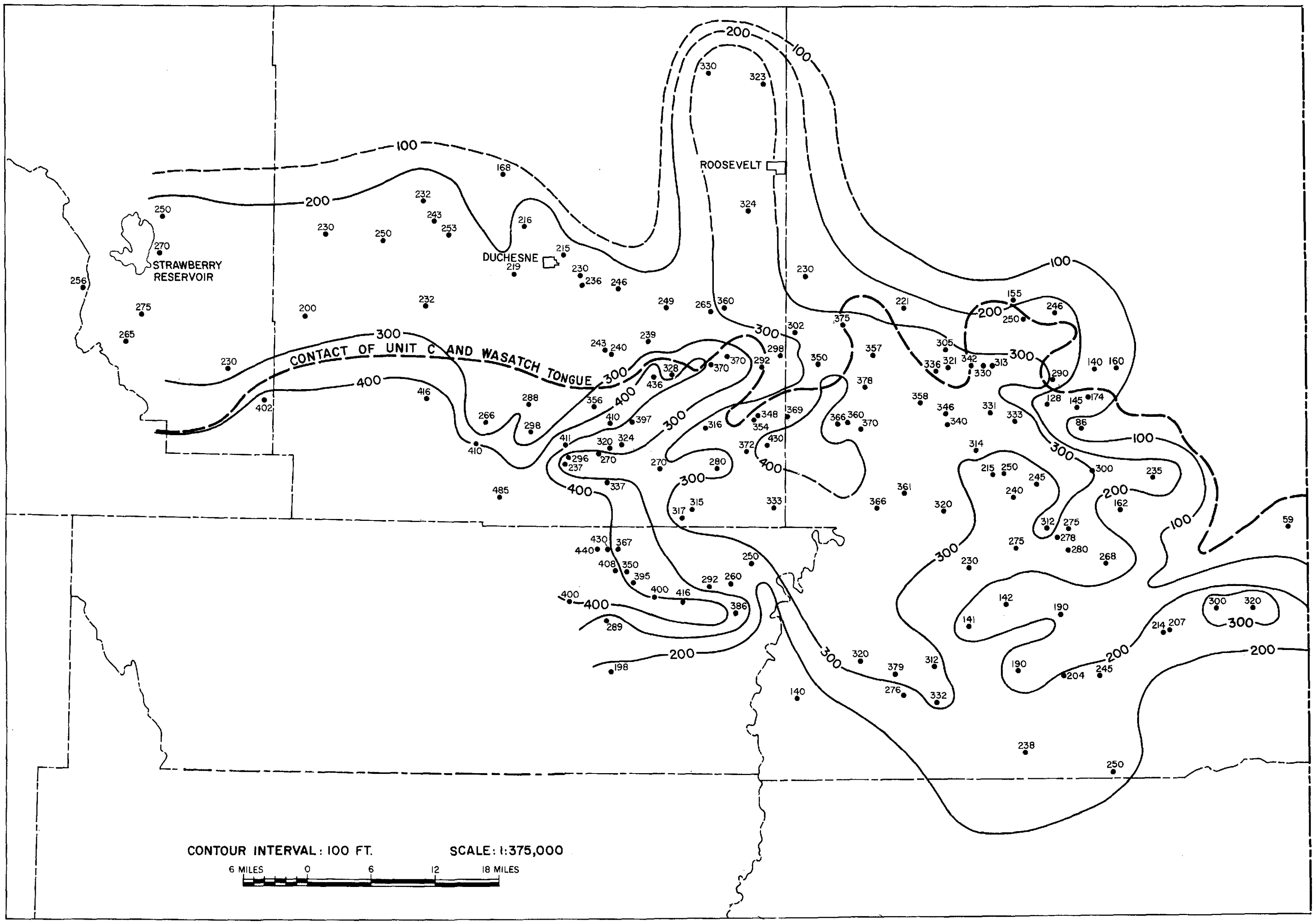


Figure 15. Isopachous map of unit C of black shale facies.

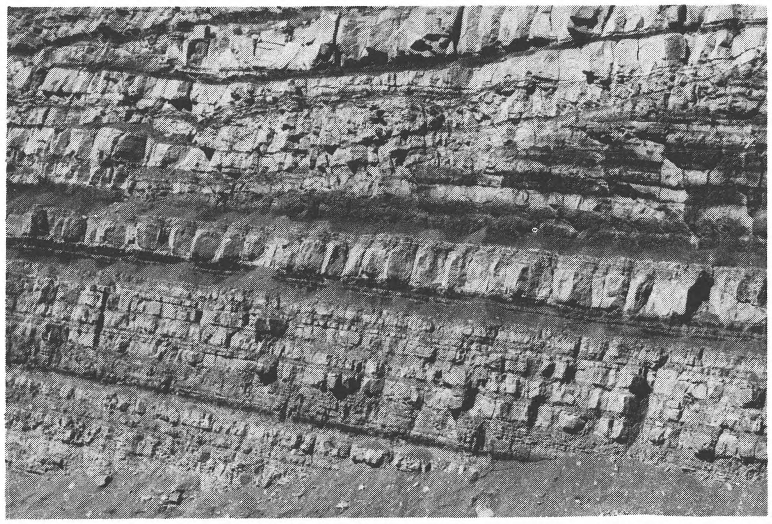


Figure 16. Photograph of part of Wasatch tongue of black shale facies, Indian Canyon area.

The upper contact of unit C is placed at the base of the lowermost thick carbonate bed of unit D.

WASATCH TONGUE OF BLACK SHALE FACIES

Distribution and Thickness

The distribution and thickness of the Wasatch tongue was discussed in the previous section. Generally, the Wasatch tongue is thicker than the lacustrine unit C.

Lithology

The Wasatch tongue is a fluvial unit deposited in fluvial-channel and fluvial-floodplain environments (figure 16). Streams were meandering and braided and apparently flowed dominantly to the north and northeast from highlands on the south and southwest.

Sandstone, siltstone and claystone are present in the Wasatch tongue in about equal abundance. Light gray, light brown, micaceous sandstone and light to dark gray, brown and greenish gray siltstone interfinger with variegated claystone.

Contacts

The lower contact of the Wasatch tongue with the underlying unit B is regressive and is placed at the base of the oldest fluvial bed in the sequence. The upper contact is transgressive and placed at the top of the youngest fluvial bed in the fluvial sequence. Fluvial beds in the Wasatch tongue interfinger with units B, D and C at the contacts, but the Wasatch tongue is essentially equivalent to unit C (figures 13 and 15).

UNIT D

Distribution and Thickness

Unit D is the thickest lacustrine unit of the black shale facies, ranging from less than 100 to almost 500 feet thick (figures 17 and 18). In the west part of the basin (Duchesne-Strawberry Reservoir area), the isopachous pattern is similar for unit D to that for the older lacustrine units (A, B and C). The depositional basin was elongate and oriented west-east.

In the east part of the basin, the isopachous pattern is different for unit D than for unit C. During deposition of unit D, Lake Uinta transgressed extensively to the south and southeast and lacustrine beds of unit D overlie fluvial beds of the Wasatch tongue. Unit D is especially thick in the south part of the Uinta Basin, west of the Green River (figure 17). Apparently, Lake Uinta also transgressed farther to the southeast during deposition of unit D than it did at any other time during deposition of the black shale facies.

The more than 400-foot thick part of unit D in the south central part of the Uinta Basin (figure 17) is in approximately the same location as one of the thicker parts of unit B and also the thickest part of the Wasatch tongue. This south central part of the basin was a major depositional center for sediment derived from source areas on the southwest.

On the north, the 100-foot contour is in almost the same geographic position for both units C and D, which suggests that the north margin of Lake Uinta was essentially stable for a long period of time.

Lithology

Fine-grained rocks (claystone, silty claystone and clayey and silty mudstone) are the most abundant rocks in the central basin sequences of unit D. Characteristically they are black (also gray, dark grayish brown and greenish gray), carbonaceous, calcareous, pyritic and fissile. Very fine to fine-grained, tan, gray-brown, brown to brownish black, crystalline, carbonaceous, clayey, micaceous and thinly laminated carbonate is also common, but is much less abundant than the fine-grained clastic rocks. Minor amounts of oil shale were deposited with the fine-grained clastics and carbonates in these offshore environments of deposition.

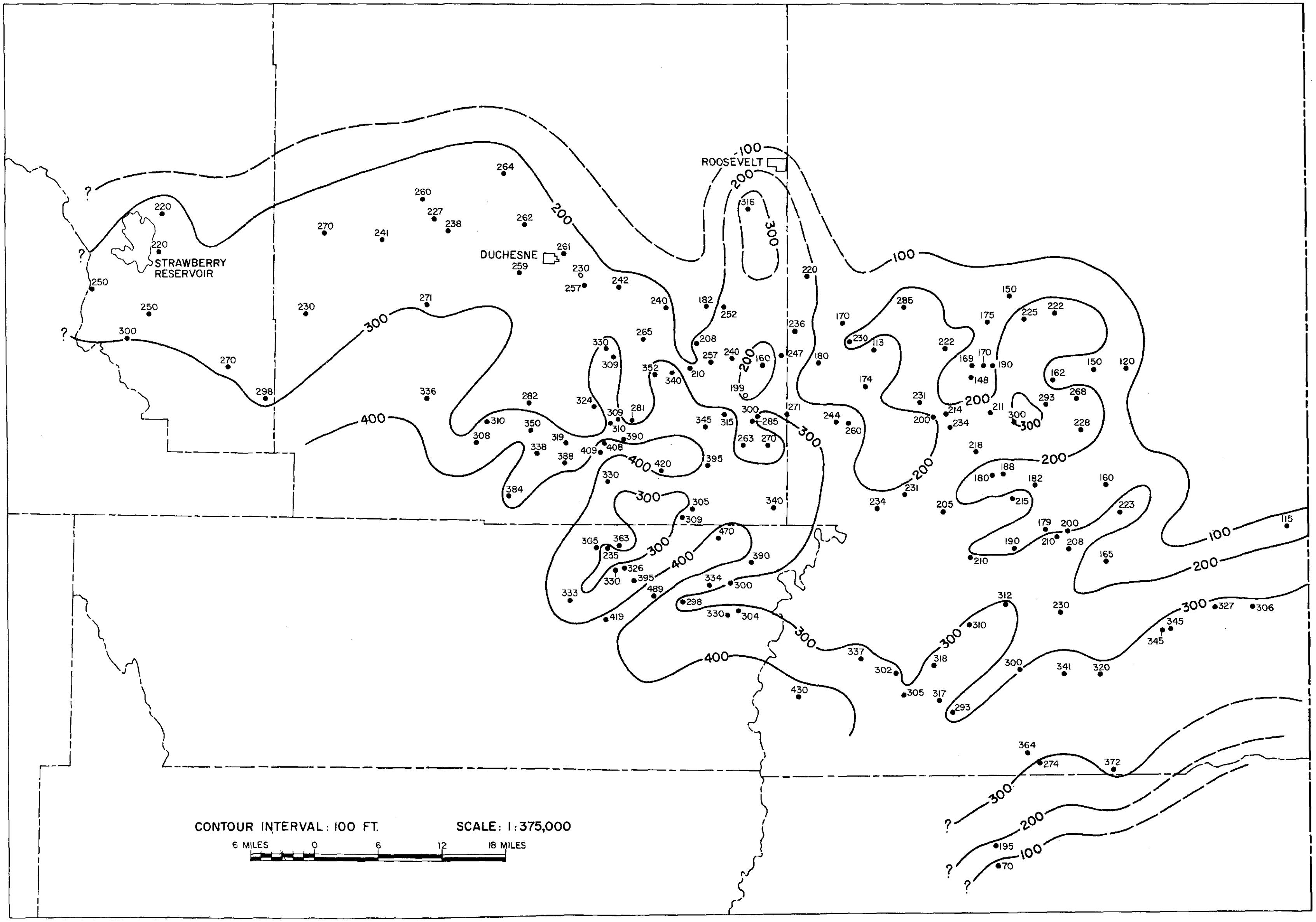


Figure 17. Isopachous map of unit D of black shale facies.

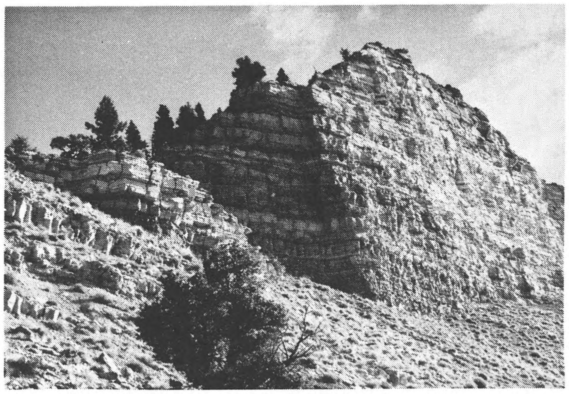


Figure 18. Lacustrine beds of unit D at NE¼ sec. 17, T. 12 S., R. 13 E.

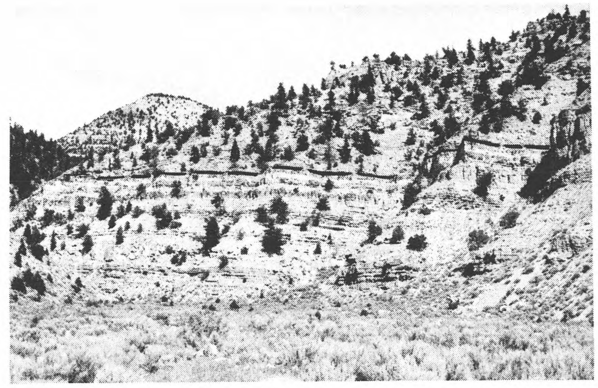


Figure 19. Unit D and green shale facies of Green River Formation, Minnie Maude Creek. Dashed line shows position of contact between the two rock units.

Toward the margins of the basin, the clastic content of unit D increases. Siltstone and sandstone are much more abundant near the margins than they are in the central basin sequences. Carbonate beds are persistent from the central basin sequences, but become much coarser grained at the margins. Ostracodal coquina, oolite and pisolite, deposited in nearshore environments, are common in the southeast part of the basin.

Contacts

Where unit C is present, the lower contact of unit D is the base of a prominent thick carbonate sequence. Where the Wasatch tongue underlies unit D, the lower contact is the top of the youngest fluvial bed.

The upper contact of unit D (figure 19) is placed at the top of an electrically resistive carbonate sequence below the grayish green fine-grained clastics of the green shale facies. This upper contact, however, is extremely difficult to trace eastward.

GENERAL PETROLOGY

Methods of Study

Sixty-one thin sections of rocks from the black shale facies were examined to determine composition (appendix). A total of 200 points was counted in each of ten sandstone thin sections and six siltstone thin sections, and a total of 100 points was counted in each of forty-four carbonate thin sections. For ease in comparing mineral contents, the means, standard deviations (Folk, 1968, p. 55) and ranges ($\pm 1\sigma$) for each major group were calculated. Results of the modal analyses are reproducible to ± 10 percent of the major constituents (quartz, authigenic carbonate, feldspar, matrix and allochems). Where possible, the thin sections were cut perpendicular to bedding.

Thin sections were made from rock samples taken from well cores and from surface outcrops. Rock samples 1 to 35, 41, and 42 are from Sun Oil Co.'s well, South Ouray No. 2 (sec. 20, T. 9 S., R. 20 E.), Uintah County, Utah. Rock samples 36 to 38 are from El Paso Natural Gas Co.'s well, Peters Point No. 4 (sec. 24, T. 13 S., R. 16 E.), Carbon County, Utah. Rock samples 39 and 40 are from cores taken from Standard Oil of California Co.'s well, White River No. 2 (sec. 10, T. 8 S., R. 22 E.), Uintah County, Utah. All cores used in this study were borrowed from the Utah Geological and Mineralogical Survey Sample Library, University of Utah. Rock samples 43 to 61 are from surface outcrops of the black shale facies, approximately one-half mile east of the junction of Utah State Highway 53 and Minnie Maude Creek (secs. 17 and 18, T. 12 S., R. 13 E.).

X-ray analyses of samples 1 to 42, made to determine gross mineral content, helped ascertain the presence and relative abundance of minerals not easily recognizable with the petrographic microscope, such as untwinned plagioclase feldspar, microcrystalline dolomite and clay (illite and chlorite).

Rock Nomenclature

The terminology for the rocks described follows:

Sandstone contains more than 50 percent material less than 2 mm and greater than 1/16 mm in diameter. *Siltstone* consists of more than 50 percent material between 1/256 mm and 1/16 mm. *Claystone* is a clastic rock consisting of more than 50 percent material finer than 1/256 mm. Silty and sandy are useful modifiers when the clay-sized material is less than

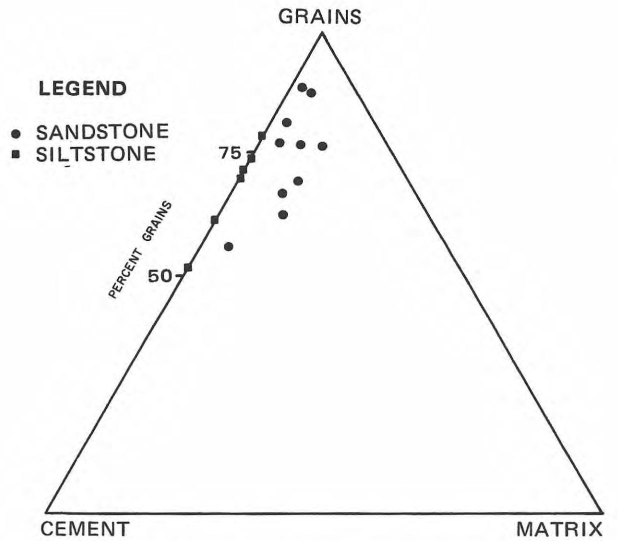


Figure 20. Three-component plot of grains, matrix and cement of siltstone and sandstone.

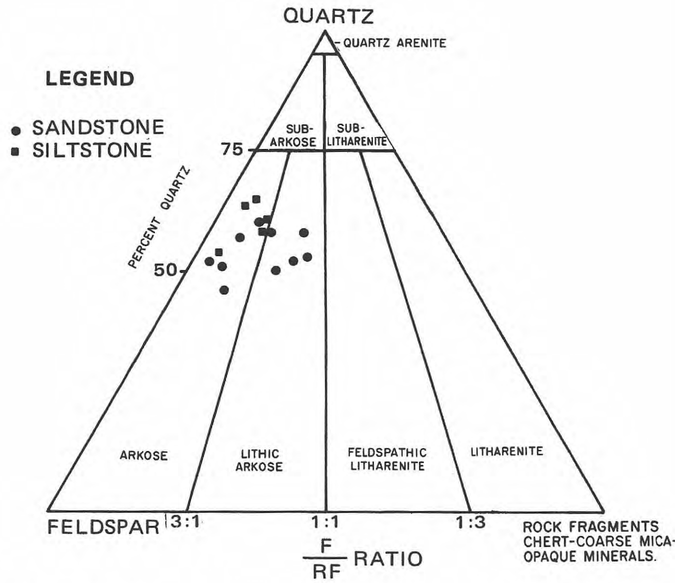


Figure 21. Three-component plot of quartz, feldspar (plus feldspar-rich igneous rock fragments) and rock fragments (including chert, opaques and coarse mica) of siltstone and sandstone of black shale facies.

75 percent, but more than 50 percent. *Mudstone* is composed of a mixture of clay-, silt- and sand-sized particles, none of which equals 50 percent of the rock. *Carbonate rock* contains at least 50 percent calcite and (or) dolomite. Terrigenous rocks are further classified as arkose and lithic arkose (Folk, 1968, p. 124). Carbonate rocks are classified according to the scheme proposed by Folk (1968, p. 135). Clay particles are difficult to distinguish from microcrystalline carbonate in the fine-grained rocks and the two are combined.

In the sixty-one thin sections studied, the rock types are: micrite, 26 percent; sandstone, 16 percent; algal biomicrite, 11 percent; and siltstone, silty micrite, algal biosparite, sandy micrite, sandy sparite, oosparite, ostracodal biomicrite, sandy intramicrite and claystone, 47 percent.

SANDSTONE AND SILTSTONE

General

The modal analyses, mean composition, standard deviation and range ($\pm 1\sigma$) of the sandstone and siltstone are given in tables 1 and 2. A three-component plot of grains, matrix and cement is given in figure 20. The principal framework constituents are (in order of abundance): quartz, feldspar, chert and coarse mica (detrital mica larger than 1/16 mm in diameter). Percentage compositions of the framework constituents, after recalculation to 100 percent, are plotted in figure 21. The quartz pole includes all types of quartz including metamorphic quartz. The feldspar pole

Table 1. Modal analyses of sandstone, black shale facies, Green River Formation, southeast Uinta Basin, Utah (200 points counted per thin section).

Constituent	Sample No.												Range
(percent)	4	8	10	11	18	20	24	25	36	37	Mean	σ	$\pm 1\ \sigma$
Quartz	30	46	40	41	39	38	40	41	40	47	40.1	4.5	35.6-44.6
Chert	9	5	10	12	3	3	11	7	5	4	6.9	3.8	3.1-10.7
K-feldspar	1	1	2	2	2	2	1	2	2	2	1.7	0.7	1.0- 2.4
Plagioclase	14	29	23	20	31	18	17	20	36	38	24.6	8.5	16.1-33.1
Coarse mica	2		1	1	1	1	1	1	3		1.1	1.5	0.0- 2.6
Opaque minerals						1							
Rock fragments													
Authigenic carbonate													
Micrite-microspar				2	1	1	9	14		2	2.9	4.3	0.0- 7.2
Sparry carbonate	39	15	20	13	11	25	11	11	9	7	16.1	9.7	6.4-25.8
Allochems													
Oolites								2	1				
Fossils													
Intraclasts		1		2									
Matrix	5	3	4	7	12	11	10	2	4		5.8	3.8	2.0- 9.6
Quartz-feldspar ratio	2.0	1.5	1.6	1.9	1.2	1.9	2.2	1.9	1.1	1.1	1.7		

Table 2. Modal analyses of siltstone, black shale facies, Green River Formation, Minnie Maude Creek area, south Uinta Basin, Utah (200 points counted per thin section).

Constituent (percent)	Sample No. 45	46	47	51	53	57	Mean	σ	Range ± 1 σ
Quartz	40	37	44	34	44	38	39.5	3.9	35.6-43.4
Chert	5	1	2	1	2	1	2.0	0.1	1.9-2.1
K-feldspar	2		1						
Plagioclase	24	18	21	15	24	30	22.0	5.2	16.8-27.2
Coarse mica		1	2	1	3	1	1.3	1.0	0.3-2.3
Opaque minerals	3	4			1	1	1.5	1.7	0.0-3.2
Rock fragments			1						
Authigenic carbonate									
Micrite-microspar	9	23	20	35	9	22	19.6	10.0	9.6-29.6
Sparry carbonate	17	16	9	14	12	7	12.5	3.4	9.1-15.9
Allochems									
Oolites					5				
Fossils									
Intraclasts									
Quartz-feldspar ratio	1.5	2.0	2.0	2.3	1.8	1.6	1.9	0.4	1.5- 2.3

includes all feldspar and feldspar-rich igneous rock fragments, and the rock fragment pole includes chert, coarse mica and opaque minerals. The rock names are those proposed by Folk (1968, p. 123-124). One-half of the sandstone and all of the siltstone are arkose. The other half of the sandstone is lithic arkose.

Figure 20 is a three-component plot of grains, matrix and cement. It summarizes the distribution of the end members in the sandstone and siltstone samples. The sandstone contains an average of about 7 percent matrix, ranging from 5 to 18 percent. The most abundant matrix constituents are quartz, feldspar and clay minerals. X-ray study shows that chlorite and illite are the most abundant clay minerals and illite is the more abundant of the two. In figure 20, the siltstone samples all fall along the zero matrix line. Clay-sized particles, which constitute matrix material in siltstone, are difficult to distinguish from microcrystalline carbonate in these thin sections. A comparison of table 2 with table 1 shows that the mean of micrite-microspar for siltstone (19.5 percent) is much greater than the mean for sandstone (1.8 percent). The lack of matrix and the increased percentage of micrite in the siltstone is the result of combining clay-sized particles and micrite.

Quartz Types

The dominant quartz in the sandstone and siltstone, comprising approximately 75 percent of the quartz fraction, has straight to slightly undulose extinction and only a few vacuoles and microlites. Folk (1968, p. 70-77) terms this common quartz, which is derived from granite and gneiss source rocks and, to lesser extent, from recrystallized metamorphic rocks. Rutile needles and tourmaline crystals are present as inclusions in the common quartz, but are rare.

The second most abundant quartz type is recrystallized metamorphic quartz, which averages about 18 percent of the total quartz in the sandstone and siltstone. It ranges from 8 percent to more than 20 percent of the quartz fraction; one sample contained about 40 percent recrystallized quartz. Recrystallized metamorphic quartz is characterized by composite grains, each of which is a mosaic of two or more equant, interlocking grains separated by straight boundaries. Separate grains have straight to slightly undulose extinction. Recrystallized metamorphic quartz is derived from highly metamorphosed rocks such as metaquartzite and gneiss (Folk, 1968, p. 73).

Stretched metamorphic quartz represents less than 7 percent of the quartz fraction and is characterized by moderate to strongly undulose extinction of composite grains and smooth or crenulated borders between sub-individuals. Vein and volcanic quartz were noted in several thin sections, but constitute only minor amounts (less than 1 percent) of the total quartz fraction. The vein quartz is characterized by abundant vacuoles and slightly undulose to semi-composite extinction. Volcanic quartz can be recognized by its idiomorphic hexagonal-bipyramidal shape, straight sides and rounded corners, and by its straight extinction and common embayments.

Feldspar

Feldspar is the second most abundant framework constituent in the sandstone and siltstone, averaging about 22 percent of the siltstone and about 26 percent of the sandstone. Plagioclase is the dominant feldspar (tables 1 and 2) and is mostly untwinned. Albite twinning is shown by some grains. Potassium feldspar is much less abundant than plagioclase and is represented mainly by microcline and lesser amounts of orthoclase.

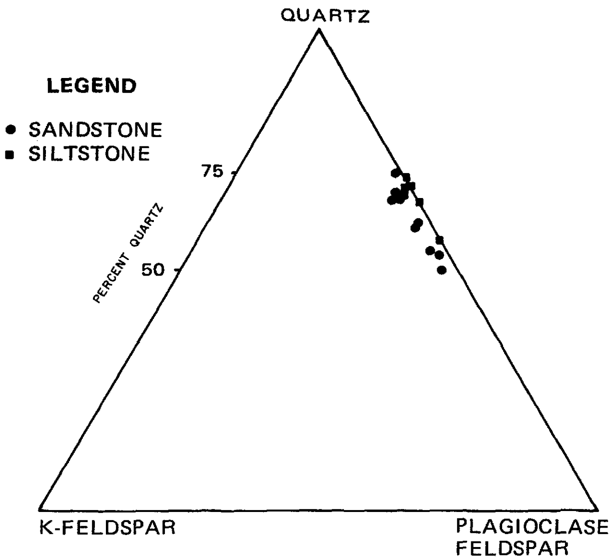


Figure 22. Three-component plot of quartz, K-feldspar and plagioclase of siltstone and sandstone.

Alteration of the feldspar is variable; most of the feldspar fraction exhibits moderate to nearly complete alteration (so complete that the grain is barely recognizable). Less than 8 percent of the feldspar is fresh and unaltered. Three types of alteration are present: sericitization (or illitization), vacuolization and kaolinization. Of these, sericitization and vacuolization are the most abundant. Vacuolization imparts a cloudy, brownish appearance to the grain. Sericitization forms tiny flakes that have a yellowish birefringence, ranging from a few crystals of sericite developed in cleavage planes to complete alteration of feldspar giving an aggregate of randomly oriented sericite crystals. Kaolinite forms tiny flakes throughout feldspar grains giving them a gray birefringence. Because of the complete alteration of some grains, much of the feldspar may be from humid source areas.

Figure 22 summarizes the relationships between percentages of quartz, potassium feldspar and plagioclase feldspar. Potassium feldspar (?) is considerably less abundant than plagioclase feldspar in both the sandstone and siltstone (tables 1 and 2). The lack of potassium feldspar probably results from the lack of potassium feldspar in the source rocks. The possibility that only a partial staining of the K-feldspar grains occurred and that much of the untwinned plagioclase might actually be K-feldspar is rejected. Although this possibility might account for a small part of the great difference in relative abundance of the two feldspars, X-ray diffraction analysis of the sandstone samples also indicates that K-feldspar is considerably less abundant than plagioclase. In most of the sandstone samples analyzed by X-ray diffraction techniques, K-feldspar was subordinate or entirely absent. The siltstone samples also contain only minor amounts of K-feldspar (table 2). Siltstone samples were not analyzed by X-ray diffraction.

Authigenic Carbonate, Chert and Mica

Authigenic carbonate contained in the sandstone and siltstone occurs as sparry carbonate and micrite-microspar consists of subtranslucent carbonate grains ranging from 1 to 8 microns in diameter. Sparry carbonate generally forms crystals 10 microns or more in diameter and can be distinguished from microcrystalline carbonate by its clarity and its coarser crystal size. In the sandstone, sparry carbonate content ranges from 7.0 to 39.5 percent, averaging about 16 percent (table 1). The micrite-microspar content in the sandstone ranges from 0.5 to 12.5 percent, averaging about 2 percent. The amount of sparry carbonate in the siltstone ranges from 9 to 16 percent (table 2), averaging about 12 percent; micrite-microspar ranges from 8 to 35 percent, averaging about 20 percent.

Dolomite rhombohedra were noted in almost every sandstone or siltstone thin section. Additional information derived from X-ray diffraction study indicates that calcite and dolomite are present in all of the sandstone. Dolomite is more abundant than calcite in one-half of the thin sections; calcite is more abundant than dolomite in the other half.

Chert grains average about 6.8 percent of the sandstone and range from 2.5 to 13.0 percent (table 1). They average about 1.8 percent of the siltstone and range from 0.5 to 4.0 percent (table 2). The chert is dominantly composed of microcrystalline quartz grains and exhibits interference colors of light to dark gray.

Coarse mica in the sandstone and siltstone is almost all muscovite and biotite in about equal amounts. Most of the mica is larger than the principal framework constituents (quartz and feldspar). In the modal analyses, mica smaller than 1/16 mm is included with the matrix or with the micrite-microspar (siltstone).

Sedimentary Structures

A detailed study of the bedding types and sedimentary structures was not made. Photographs of characteristic structures in the black shale facies in the southwest margin of the basin (Indian Canyon, Minnie Maude Creek and Gate Canyon), however, are included (figures 23 to 29).

SILTY AND SANDY MICRITE

Silty micrite (figures 30 to 32) is much more abundant than sandy micrite in the black shale facies

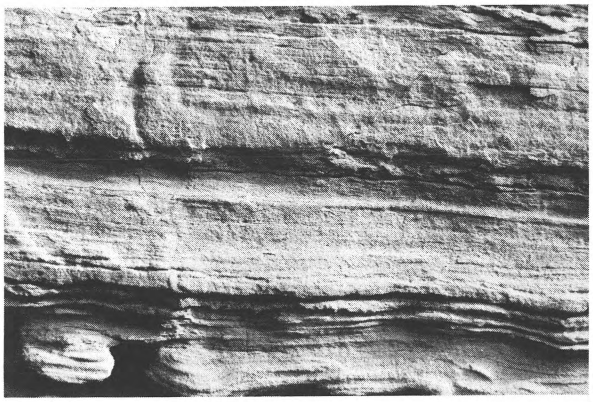


Figure 23. Horizontal and wavy stratification in sandstone of unit D, Minnie Maude Creek, south Uinta Basin.

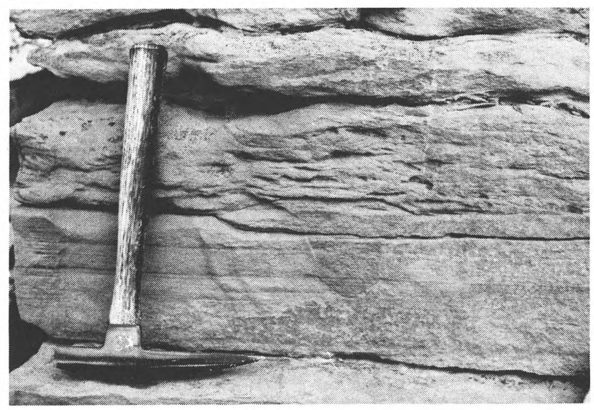


Figure 24. Horizontal stratification, micro cross-stratification and ripple stratification in sandstone of Wasatch tongue, Minnie Maude Creek. From hammer head upward the sequence is: horizontal discontinuous stratification (upper-flow regime), scour fill (middle), micro cross-stratification (lower-flow regime) and ripple stratification (lower-flow regime). This is most of a fluvial channel fill sequence. Decreasing current velocity is indicated by the vertical trend in sedimentary structures. Hammer is about 12 inches long.

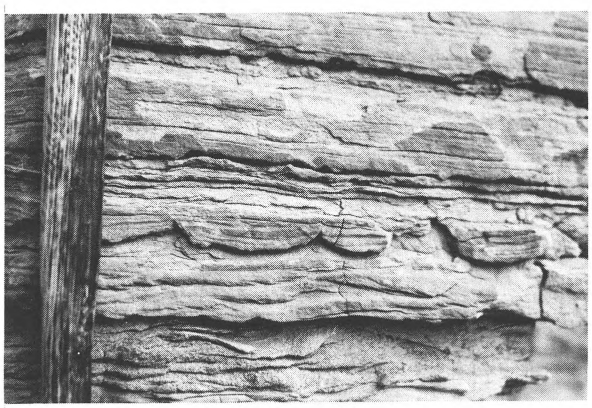


Figure 25. Horizontal stratification, micro cross-stratification and ripple stratification in unit D, Minnie Maude Creek. Note thin bed of interbedded oolite at bottom of photograph. Length of hammer handle is about 9 inches long.

Figure 26. Small-scale trough, cross-stratification in sandstone of Wasatch tongue.

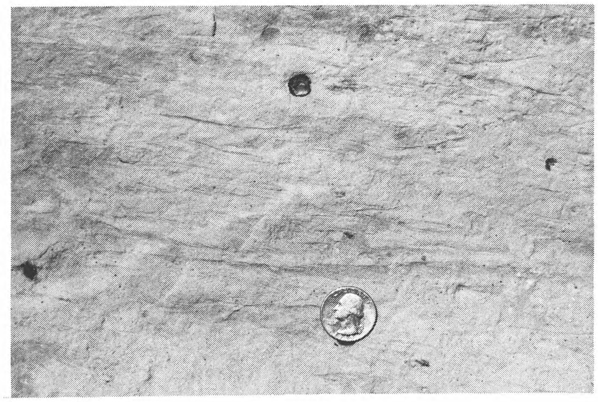


Figure 27. Close-up of micro cross-stratification in unit B, Indian Canyon area. Quarter for scale.

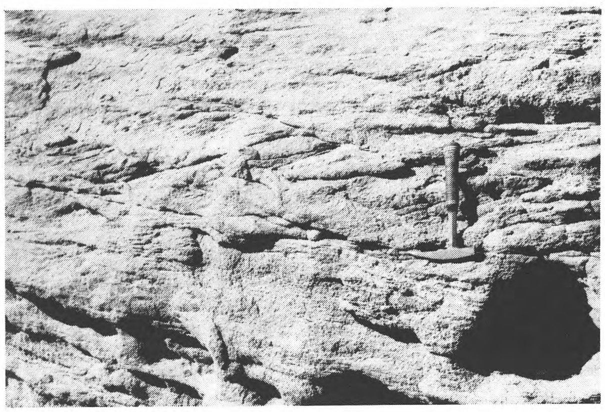


Figure 28. Medium-scale trough cross-stratification in Wasatch tongue, Minnie Maude Creek. Hammer for scale.

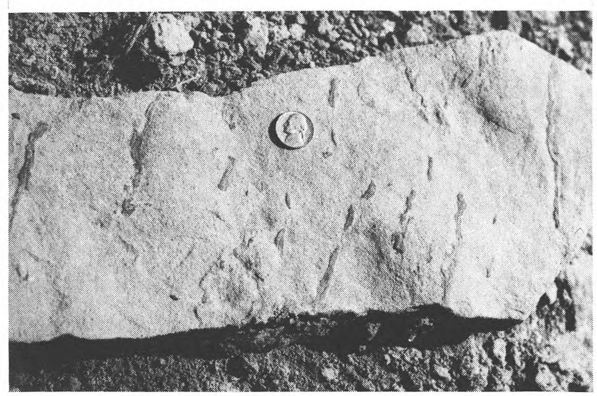


Figure 29. Linear-shrinkage cracks in unit D, Minnie Maude Creek. Note well developed orientation of cracks. Nickel for scale.

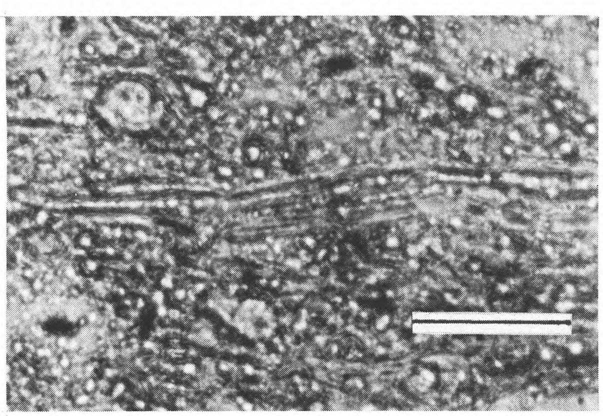


Figure 30. Photomicrograph of silty micrite (limestone) from unit D. Rock contains about 10 percent detrital grains and 90 percent micrite-microspar-clay. Rock is olive-black. Note algal "plates." Scale is 0.3 mm.

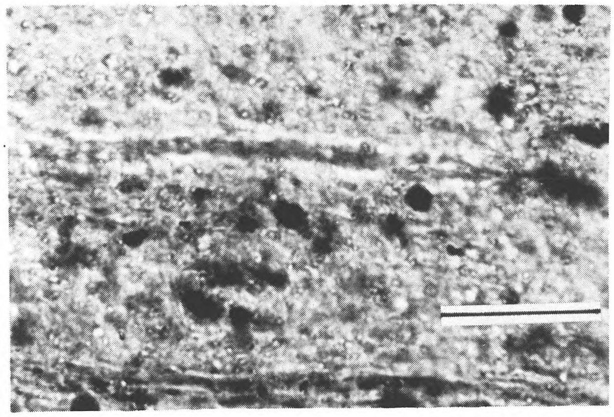


Figure 31. Photomicrograph of silty micrite from unit D. Dark, opaque minerals are pyrite. Rock is olive black. Scale is 0.3 mm.

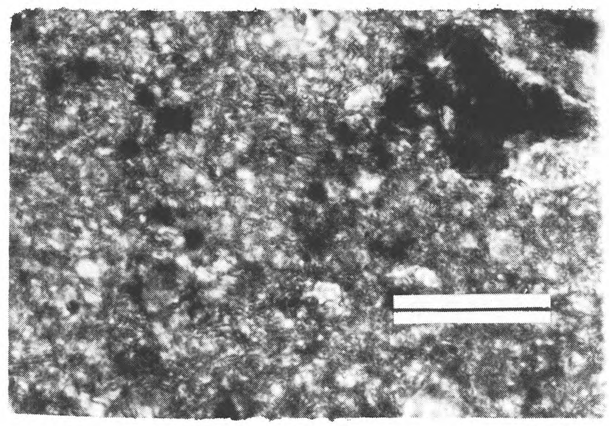


Figure 32. Photomicrograph of silty micrite from Wasatch tongue. Contains about 20 percent detrital grains, 10 percent sparry carbonate and 70 percent micrite-microspar-clay. Opaque minerals are dominantly pyrite. Calcite is more abundant than dolomite. Color is brown-black. Rock contains sufficient kerogen to be called low-grade oil shale. Scale is 0.3 mm.

(table 3); it has a mud-supported texture and a sub-angular, poorly sorted terrigenous fraction. The main constituents are micrite-microspar-clay, silt- or sand-sized clastic grains (quartz and feldspar), opaque minerals and sparry carbonate.

Allochems occur in trace amounts. Microcrystalline carbonate aggregates (pellets) and charophyte fragments were noted. Neomorphic sparry calcite is present in irregular patches transitional with micrite. The neomorphic spar composes up to 13 percent of some thin sections.

Modal analyses of the silty and sandy micrite and a sandy intramicrite are given in table 3. Both calcite and dolomite are present in most of these samples. In about one-half of the samples calcite is dominant; in the other half, dolomite is more abundant than calcite.

The silty and sandy micrite is similar in origin to micrite, but contains more than 10 percent silt- or sand-sized particles. Figures 33 and 34 show the close relationship between micrite and silty and sandy micrite.

Silty and sandy micrite was deposited on mud-flats, in lacustrine lagoons associated with a large deltaic complex prograding from the south, and offshore

Table 3. Modal analyses of silty and sandy micrite, black shale facies, Green River Formation, Minnie Maude Creek area and southeast Uinta Basin, Utah (100 points counted per thin section).

Constituent (percent)	Silty Micrite												Sandy Micrite		Sandy Intramacrite
	Sample No.									Mean	σ	Range	Sample No.		Sample No.
	5	7	9	13	14	16	21	26	54			± 1 σ	17	35	38
Allochems															
Fossils								2							
Oolites															
Intraclasts													1		46
Sparry carbonate	2	13	2		2		13	3	7	4.4	5.3	0.0- 9.7		10	3
Micrite-microspar-clay	73	68	86	54	64	90	39	78	44	66.2	17.8	48.4-84.0	48	52	25
Quartz	17	14	7	31	21	9	32	14	28	18.8	9.5	9.3-28.3	21	19	10
Chert				1									3		3
K-feldspar				2	2				2				3	2	
Plagioclase	4	2	3	8	8	1	11	1	11	5.4	4.0	1.4–9.4	12	9	7
Rock fragments													2		1
Coarse mica		1		2	1		3		2	1.0	1.5	0.0- 2.5	1	2	2
Matrix													8	6	
Opaque minerals	4	2	2	2	2		2	2	6	3.1	3.0	0.1- 6.1	1		3
Carbonate (X-ray analysis)															
Dolomite	D	D	D	D	D	D	D	D					D	D	D
Calcite	C	C	C	C	C	C	C	C					C	C	C
Relative abundance	D>C	C>D		C>D	C>D		D>C	C>D					D>C	C>D	D>C

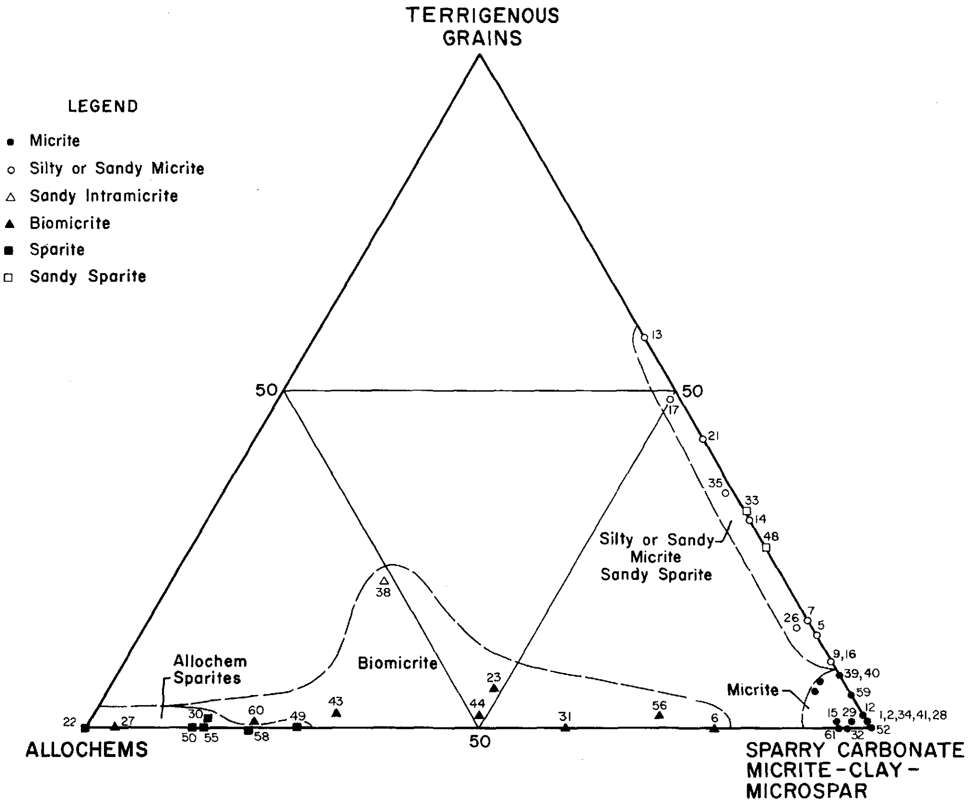


Figure 33. Three-component plot of terrigenous grains, allochems and sparry carbonate and micrite-microspar-clay in carbonate rocks of black shale facies.

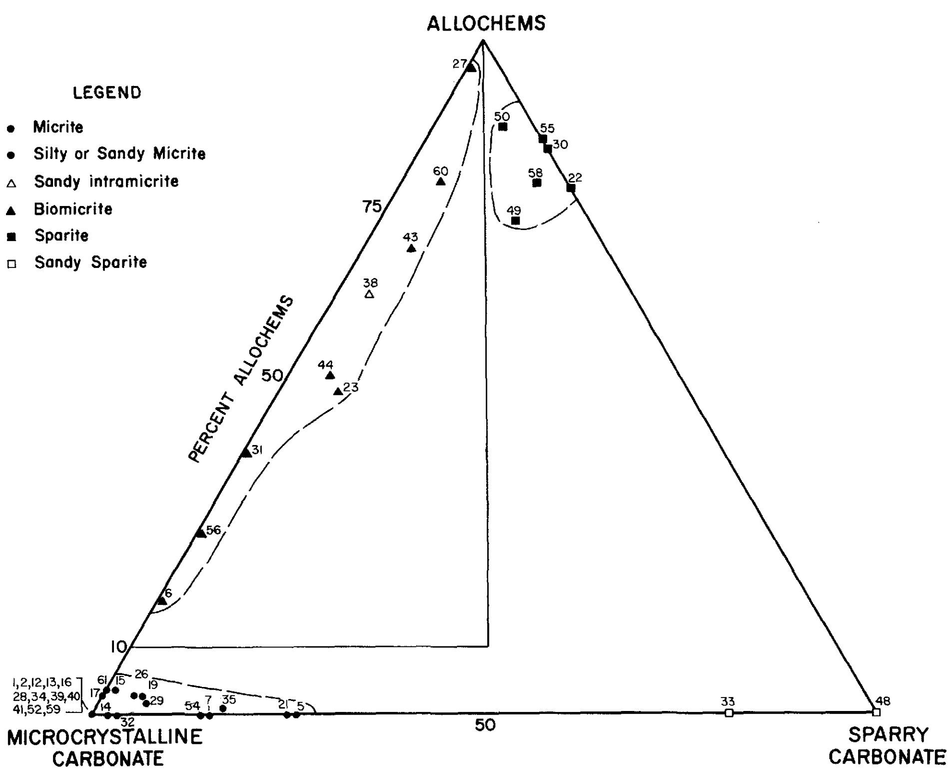


Figure 34. Three-component plot of microcrystalline carbonate (including clay-sized particles), allochemical grains (intraclasts, oolites and fossils), and sparry carbonate in carbonate rocks of black shale facies.

Figure 35. Plant fragments in unit B, Indian Canyon area. Quarter for scale.

in much deeper water. The environments are typified by calm water deposition of micrite.

Broad expanses of carbonate-clay mudflats bordered Lake Uinta, particularly on the gently sloping south margin of the basin. Clay and micrite deposited on mudflats and in shallow nearshore lagoons were periodically subjected to subaerial exposure. Dessication cracks, salt molds, vascular plant remains (figure 35) and the paucity of lacustrine organisms suggest that micrite and sandy, silty or clayey micrite were at times subaerially exposed during deposition. Some micrite (also silty and sandy micrite) also contains poorly sorted aggregates of micrite that was eroded from surrounding mudflats.

The micritic offshore facies was deposited below wave-base under strongly reducing conditions probably enhanced by chemical and (or) thermal stratification of the lake. The opaque minerals noted in the silty and sandy micrite are mostly pyrite and marcasite, which is indicative of the reducing conditions. Thin beds of ooliths and microcrystalline carbonate aggregates washed into the offshore environment from adjacent shallow water shoals also are found in deposits of the deep central part of the lake.

Despite the similarites between the deposits of the offshore deep water and nearshore, protected shallow-water environments, their sedimentary products can be differentiated on the basis of associated lithologies. Fluvial sandstone, siltstone and claystone and nearshore-shoreline lacustrine sandstone and sandy carbonate rocks are interbedded with lagoonal carbonate. A silty or sandy micrite bounded by trough cross-stratified well sorted sandstone or dissected by fluvial channels is not likely to be an offshore, deep water deposit. Although the depositional centers of the black shale facies gradually shifted many times, it is unlikely that the shifts frequently transposed deep water offshore facies onto nearshore or shoreline facies.

The sandy intramicrite shown in table 3 is composed almost entirely of micrite intraclasts and sandy micrite cement. The intraclasts are pieces of weakly consolidated carbonate sediment that were torn up and redeposited by currents, indicating an increase in current velocity. The increased velocity most likely is the result of storms lowering the wave-base by partial emergence, or the possible tectonic instability of the basin of deposition (Folk, 1968, p. 153). Intramicrite is a relatively rare rock because currents strong enough

Table 4. Modal analyses of biomicrite, black shale facies, Green River Formation, Minnie Maude Creek area and southeast Uinta Basin, Utah (100 points counted per thin section).

Constituent (percent)	Algal Biomicrite										Ostracod Biomicrite Sample No.
	Sample No.									Range	
	6	23	31	43	44	56	60	Mean	σ	$\pm 1\ \sigma$	27
Allochems											
Fossils	17	43	35	64	46	26	78	44.1	26.5	17.6-70.6	96
Oolites											
Intraclasts											
Sparry carbonate		6		5	5	3	5	3.4	2.5	0.9- 5.9	
Micrite-microspar-clay	80	41	54	25	41	68	16	46.4	22.7	23.7-69.1	4
Quartz		3		2	2	3	1	1.6	1.3	0.3- 2.9	
Chert											
K-feldspar											
Plagioclase		2		1							
Rock fragments		1									
Coarse mica											
Matrix											
Opaque minerals	3	4	11	3	6			3.9	3.8	0.1- 7.7	
Carbonate (X-ray analysis)											
Dolomite		D									D
Calcite	C	C	C								C
Relative abundance		C>D									D>C

to transport large carbonate rock fragments are also capable of washing away micro crystalline ooze. Deposition of the intramicrite took place in an environment of stronger currents than those present during deposition of the silty or sandy micrite.

BIOMICRITE

Modal analyses of the biomicrite are given in table 4. These carbonates are almost entirely composed of fossils (algae and ostracods) and micrite-microspar-clay. Sparry carbonate, quartz and opaque minerals (pyrite and marcasite) are minor constituents. The biomicrites occupy an area between the microcrystalline carbonate-clay pole and the allochem pole (figure 33). Folk (1968, p. 155-158) suggested the currents in the microcrystalline-allochemical rock-producing environment are weak and short lived, stronger than those currents in the microcrystalline environment, but still not strong enough or persistent enough to winnow the microcrystalline ooze. Sparry carbonate is subordinate (table 4) because little pore space was available.

More than one-half of the biomicrite has a grain-supported texture (figure 36). Algal fragments and ostracods are the most abundant fossils; gastropod biomicrite is abundant only at the base of the black shale facies. Terrigenous material does not exceed 5 percent in any of the biomicrite samples. Vascular plant fossils are present in biomicrite at Indian Canyon (figure 35).

On the basis of the modal analyses (table 4), the average biomicrite contains: micrite-microspar-clay and fossils, 90 percent; opaque minerals (pyrite and marcasite), 4 percent; sparry carbonate, 3 to 4 percent; and quartz, 1 to 2 percent. In the thin sections algal fragments are much more abundant than ostracod fragments.

Algal and ostracodal biomicrite in the black shale facies generally is olive black (5Y 2/1) or dusky yellowish brown (10YR 2/2). Gastropod biomicrite is medium gray (N5) or slightly darker.

Biomicrite is especially common in the black shale facies at Indian Canyon where it is interbedded with evenly laminated claystone, micrite and biosparite (figure 37). The biomicrite is thinly laminated and fissile. Gastropod biomicrite apparently is restricted to the basal part of the black shale facies and the Douglas Creek Member.

Most of the ostracod, gastropod and pelecypod biomicrite in the black shale facies probably accumulated in nearshore, shallow, protected waters. Shells are intact and filled with micrite.

Gastropods and pelecypods associate with one another (figures 38 and 39) whereas ostracods tend to occur separately from the molluscs. Ostracods are much more abundant than gastropods and pelecypods. Gastropods and pelecypods probably could not survive as severe physical and chemical conditions as the ostracods. The restricted occurrence of gastropod and pelecypod biomicrite at the base of the Green River Formation in the Uinta Basin is attributed to the limited salinity tolerances of the molluscs. Apparently freshwater conditions prevailed in the early stages of Lake Uinta and freshwater gastropods and pelecypods were abundant. At least one gastropod (*Helix*) found in biomicrite was a land snail washed into the lake from surrounding land areas or drowned by an expanding lake (LaRocque, 1956, p. 143). All other identified gastropods are freshwater molluscs (LaRocque, 1956, p. 143) that probably inhabited lacustrine lagoons or isolated ponds and lakes. LaRocque (1960, p. 63) noted that *Viviparus* (a common gastropod in biomicrite) preferred shallow water and a muddy substrate and was abundant only where food in the form of minute lower plants and decaying animal matter was in ample supply.

The algal biomicrite (figure 36) was deposited in nearshore shoal, nearshore, shallow, open-water and lagoon environments at sites where the micrite was not winnowed because of low-water turbulence. Apparently most of the algal carbonate had little relief above the lake bottom, but some of it must have had as much as 1.3 meters of relief (Williamson, 1972, p. 56). Poorly washed biomicrite formed landward of algal shoals and barriers and in nearshore and lagoonal areas where currents were weak and intermittent.

SPARITE

Silty and Sandy Sparite

Silty and sandy sparite is a relatively common carbonate rock type in the Green River Formation. To distinguish silty and sandy sparite from calcareous siltstone and sandstone in the field is difficult, however, because the sparite is transitional with the terrigenous rocks (Picard and High, 1972).

In outcrops along the south margin of the basin, silty and sandy sparite is yellowish gray (5Y 7/2) to very light gray (N8). The most abundant bedding is horizontal lamination; small- and medium-scale trough cross-stratification also is common. Sandy sparite units generally are between 0.5 and 2.5 meters thick, but units as thick as 10.0 meters are present. Sandstone, siltstone and oolitic carbonate rocks generally occur immediately above and below sparite and are gradational with the sparite. Terrigenous grains in silty and

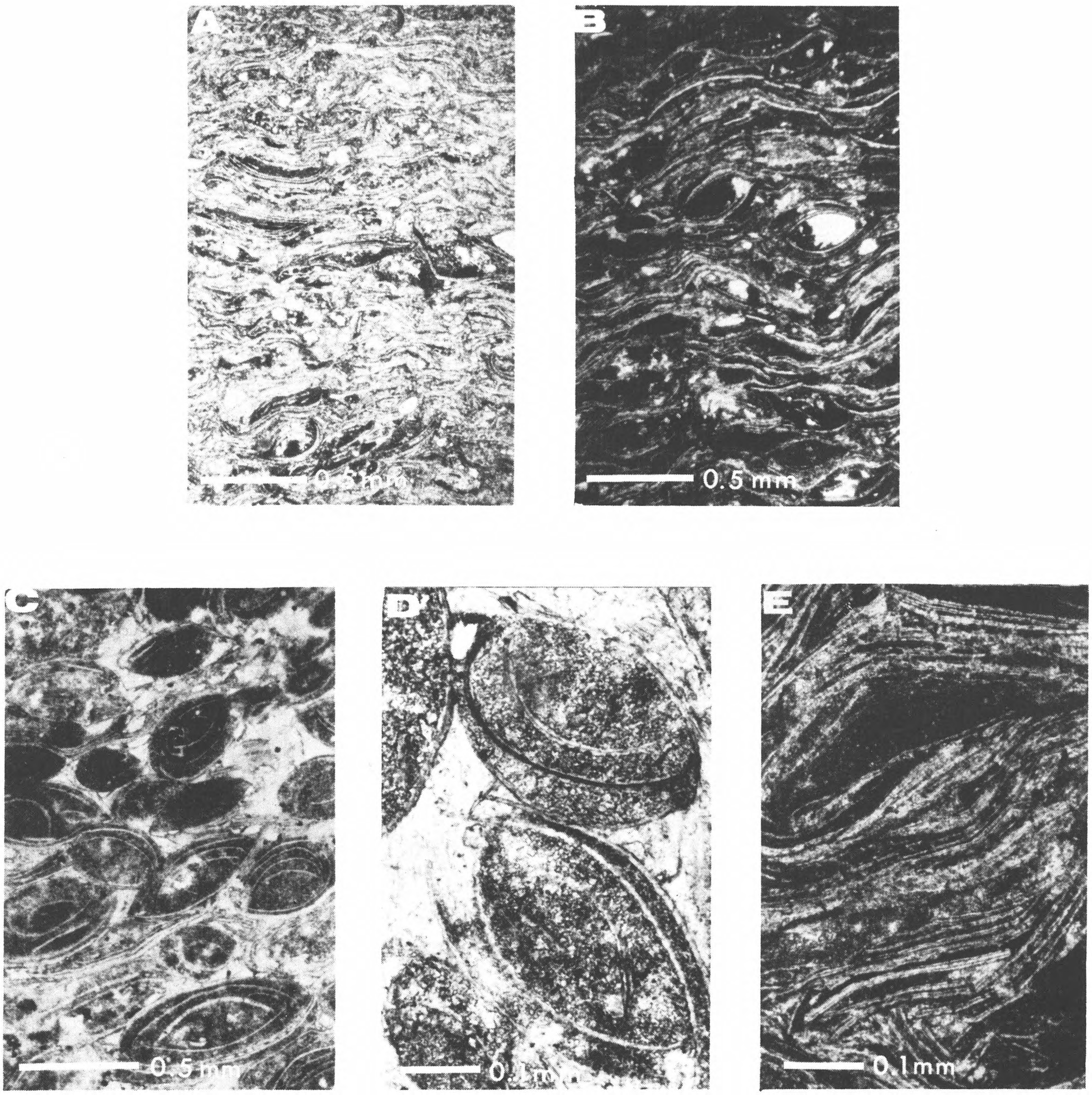


Figure 36. Photomicrographs of biomicrite and biosparite. **A.** Grain-supported algal biosparite with fragmental algal "plates." Plane light. **B.** Grain-supported algal biomicrite and ostracods. Some of the algal plates are nearly in growth position and apparently supplied a substrate for the ostracods. Plane light. **C.** Grain-supported ostracod biosparite. A few algal fragments are present, but most fossils are articulated mud-filled ostracods containing several molt stage carapaces. Plane light. **D.** High magnification of ostracod biosparite. Staining indicates that ostracod shells and spar are calcite and mud fillings are dolomicrite. Plane light. **E.** High magnification of algal biomicrite. Note the fragmented nature of the plates and their faintly preserved internal structure. Plane light.

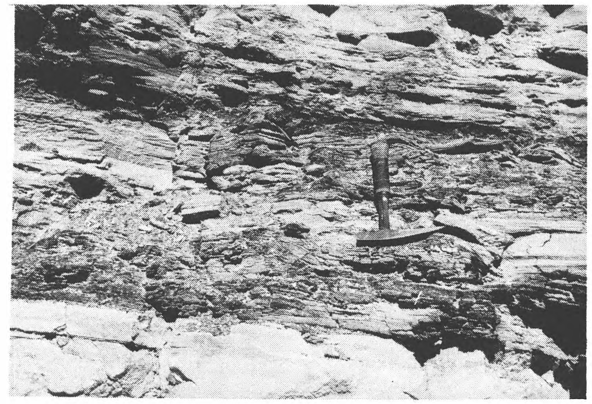


Figure 37. Interbedded micrite, biomicrite, biosparite, calcareous claystone and calcareous, silty claystone at Indian Canyon. Hammer for scale.

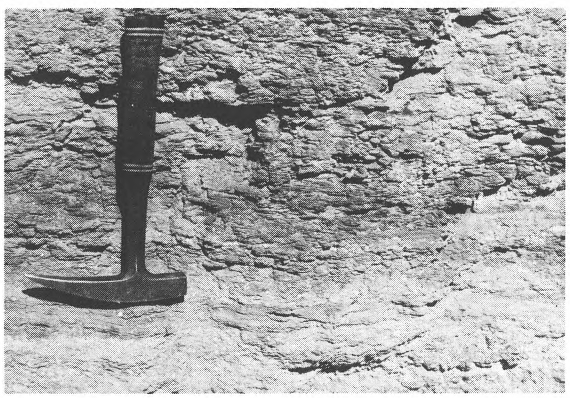


Figure 38. Gastropods and pelecypods in olive black, fine-grained, clastic rocks of unit B, Indian Canyon area. Hammer for scale.

Figure 39. Close-up of figure 38. Note abundant layers of gastropods and pelecypods. Quarter for scale.

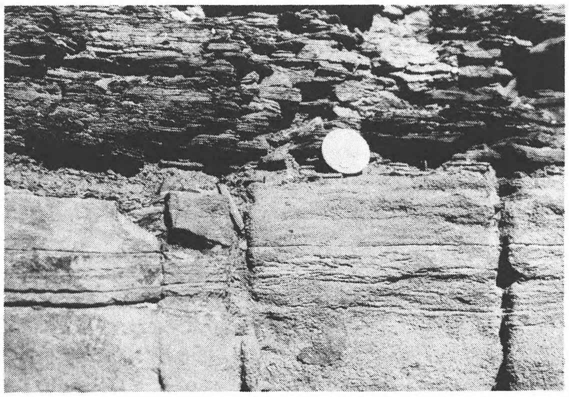


Figure 40. Contact of oosparite and olive black, fine-grained, clastic unit in unit B, Indian Canyon area. Oosparite is dominantly horizontally stratified. Note fissility of fine-grained clastic beds. Quarter for scale.

sandy sparites range from .05 to .5 millimeters in diameter and are subangular and well sorted.

Modal analyses of two sandy sparites indicate that they are composed of about 35 percent terrigenous grains and 57 percent sparry carbonate (table 5). In many sparites the sparry carbonate completely surrounds and isolates the terrigenous grains. This "floating" cement-supported texture probably formed by interparticle expansion during cementation and partial replacement of quartz and feldspar grains by sparry carbonate. Similar replacement textures were described by Walker (1957 and 1960), Jacka (1970) and Dapples (1971). The anomalous angularity of the grains in the well sorted sandstone is attributed to grain boundary irregularities because of the impingement of carbonate cement. In many grains, the original grain outline is faintly preserved in the replacing carbonate cement.

Oosparite

Two oosparites were examined in detail (table 5). They are composed of about 77 percent oolite (with some intermixed fossils) and about 18 percent sparry carbonate. Thus, these oosparites are low in terrigenous content and have high proportions of allochems relative to spar cement. Only trace amounts of micrite-microspar-clay occur in either rock.

Oosparite units range from a few centimeters to about 5 meters thick, but generally are .5 to 1.0 meters thick and form resistant ledges that can be traced laterally for two kilometers or more (figure 40). Stratification is indistinct in oosparite containing pisoliths. Rocks with ooliths commonly are cross-stratified (figures 41 and 42). Massive, "structureless" oosparite frequently exhibits intercalations of uneven horizontal laminations developed by algal mats. Oosparite is dark yellowish orange (10YR 6/6) to very pale orange (10YR 9/2). Generally it is interbedded with well sorted sandstone, siltstone and sandy sparite, and commonly grades upward into algal biolithite. Some oosparite is extensively burrowed (figure 43).

Considerable recrystallization has occurred in some of the oosparite. The internal concentric structure of the ooliths has been destroyed and the structure is present only as ghostly remnants. X-ray diffraction analysis indicates that the dominant carbonate in the oosparite is dolomite (table 5). Extensive dolomitization is responsible for the destruction of the structure of the ooliths.

Biosparite

Biosparite has a grain-supported texture (figure 36). Algal fragments are the most abundant fossils, but ostracods and ooliths are common in some biosparite in the black shale facies. Gastropod biosparite is present in small amounts in the base of the formation.

The most common biosparite is pale orange (10YR 7/6) to grayish orange (10YR 7/4) algal and ostracod biosparite. Algal biosparite is more abundant in the black shale facies than ostracod biosparite. Biosparite units generally are from .5 to 2 meters thick and are conformable with adjacent beds. At Indian Canyon, biosparite is interbedded with carbonaceous claystone, micrite and biomicrite. Vascular plant fossils are present in the biosparite at Indian Canyon.

Table 5. Modal analyses of sparite, black shale facies, Green River Formation, Minnie Maude Creek area and southeast Uinta Basin, Utah (100 points counted per thin section).

Constituent (percent)	Algal Biosparite							Oosparite Sample No.		Sandy Sparite Sample No.	
	Sample No.						Range				
	49	50	55	58	Mean	σ	$\pm 1\,\sigma$	22	30	33	48
Allochems											
Fossils	73	86	85	79	80.8	6.0	74.8-86.8	3	6		
Oolites								76	78		
Intraclasts											
Sparry carbonate	17	10	15	17	14.8	3.3	11.5-18.1	21	15	50	64
Micrite-microspar-clay	10	4		4	4.5	4.1	0.4- 8.6			11	
Quartz									1	15	20
Chert										2	
K-feldspar											
Plagioclase										12	7
Rock fragments										2	
Coarse mica										2	
Matrix										1	
Opaque minerals										5	9
Carbonate (X-ray analysis)											
Dolomite								D	D	C	
Calcite								C	C	D	
Relative abundance								D>C	D>C	C>D	

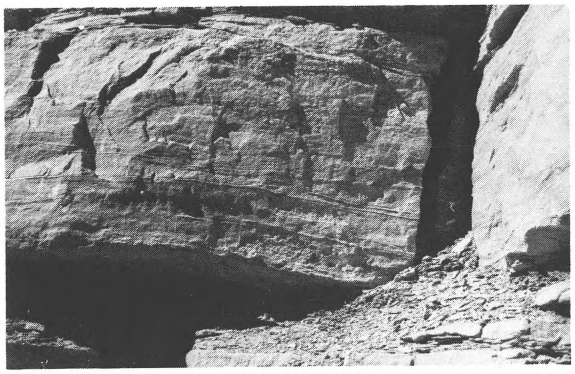


Figure 41. Micro cross-stratified oosparite in unit B, Indian Canyon area. Algal plates are abundant in the oosparite and partly contribute to development of bedding. Thickness of oosparite unit is about 0.5 meters.

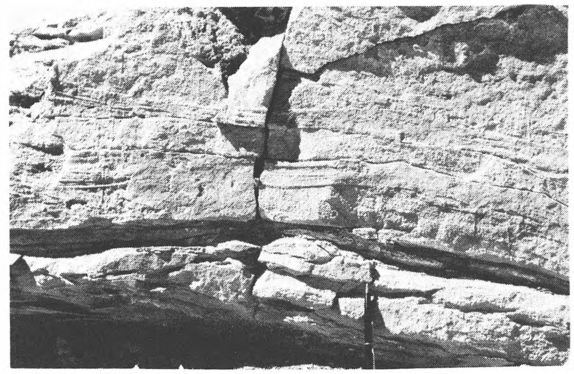


Figure 42. Micro cross-stratified and wavy stratified oosparite in unit B, Indian Canyon area. Pisoliths and algal plates are common. Pencil for scale.

Algal and ostracod biosparites are cleanly washed, grain-supported rocks whose allochems show evidence of transportation and abrasion. Algal fragments are broken to sand- or silt-sized particles and ostracod carapaces generally are disarticulated. The rocks contain little micrite-microspar-clay (0 to 10 percent; table 5) and few allochems other than fossils. Nearly all the biosparites contain algal and ostracod fragments, but algal fragments are more abundant in the black shale facies.

Environments of Deposition

Broad shoals developed during regressions of the lake and carbonate deposition was dominant as the lake remained level or slightly transgressed (Picard and High, 1968a, p. 382). Carbonate shoal deposits are characterized by cross-stratified oosparite and sandy oosparite, which generally is capped by algal biolithite. Commonly, dolomitization has destroyed the internal structure of the ooliths. Terrigenous sand and silt grains are not nearly as abundant in shoal deposits as in nearshore and shoreline deposits. Horizontal stratification, small- and medium-scale cross-stratification, oolite and algal mats are abundant in beds deposited in the nearshore shoal environments. Accretionary linear asymmetrical ripple marks and pisolite are common characteristics. Lacustrine shoal deposits contain a suite of sedimentary structures similar to those of recent oolith shoals in the Bahamas (Imbrie and Buchanan, 1965) where the stratification is mainly formed by bottom traction in shallow water (less than 3 meters).

Figure 43. Burrowed oosparite in unit B, Indian Canyon area. Nickel for scale.

Algal and ostracod biosparite are suggestive of slightly deeper, well oxygenated nearshore environments that were strongly affected by wave action. The terrigenous supply to these areas varied depending on the proximity of inflowing streams. The algal biosparite noted here (table 5) contains essentially no terrigenous material. In these environments, allochems were fragmented, abraded and tightly packed. The rocks indicate excellent sorting. Horizontal stratification, wavy stratification, small-scale trough cross-stratification and siltstone beds characterize the facies. Some ostracod carapaces remain articulated and near their original growth position.

Sandstone and sandy sparite deposited in beach-shoreface environments are interbedded with nearshore biosparite and siltstone. Locally, shoals developed enough relief to significantly influence deposition in backshoal areas. Bradley (1929a) found most algal carbonates had little relief above the lake bottom, but a few of them must have had as much as 1.5 meters of relief. Poorly washed micrite, oomicrite and biomicrite locally formed landward of the barriers.

Algal and ostracod biosparite is especially common in the black shale facies at Indian Canyon and elsewhere along the south margin of the basin where the nearshore and shoreline facies intertongue.

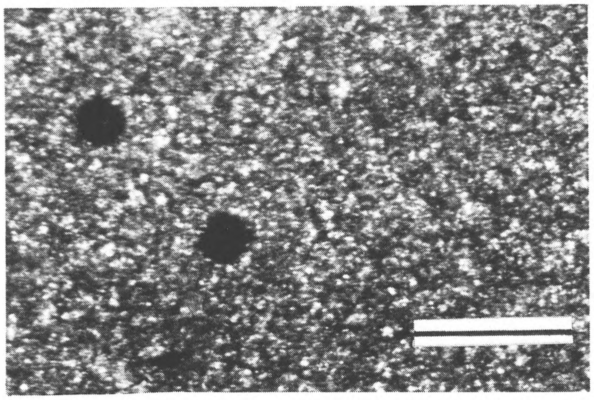


Figure 44. Photomicrograph of dolomicrite from unit D. Rock contains only about 2 percent detrital grains. Opaque minerals are pyrite. Rock color is olive black. Scale is 0.3 mm.

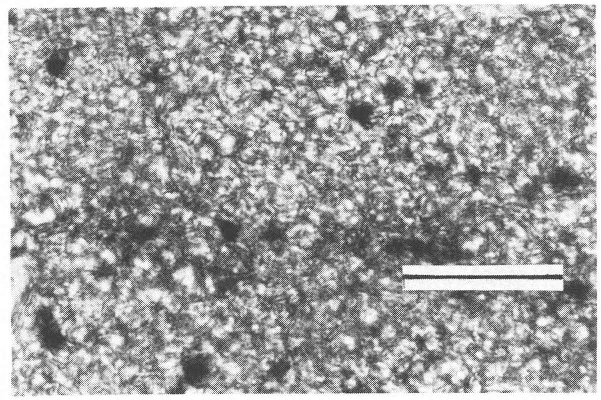


Figure 45. Photomicrograph of micrite (calcite is greater than dolomite) from unit B (table 8, sample 2). Rock contains about 3 percent sparry carbonate and more than 90 percent micrite-microspar-clay. Common opaque minerals (2 to 3 percent) are pyrite. Rock color is olive black. Scale is 0.3 mm.

MICRITE

Petrography

Micrite is the most abundant carbonate rock in the black shale facies (figures 44 and 45); it ranges in color from olive black (5Y 2/1) to white (N9) with most micrite, light gray (N8) or pinkish to yellowish gray (5YR 8/1 to 5Y 8/1). Light colored micrite is conspicuous in outcrop and breaks with a distinctive subconchoidal fracture. Thicknesses of micrite units reach a maximum of 8 meters, but seldom exceed 2 meters. Very thin horizontal stratification is abundant and characteristic of the micrite. Small-scale low-angle planar cross-stratification is common. Chert nodules and lenses, synerisis cracks and dessication cracks are locally common.

Micrite is associated with many different rocks, greenish gray calcareous carbonaceous claystone and mudstone, and biomicrite and oomicrite being the most common interbedded lithologies.

The main constituents of micrite are microcrystalline carbonate, microspar and clay, which averages about 92 percent in the modal analyses (table 6).

Table 6. Modal analyses of micrite, black shale facies, Green River Formation, Minnie Maude Creek area and southeast Uinta Basin, Utah (100 points counted per thin section).

Constituents (percent)	Sample No.															Mean	σ	Range ± 1 σ
	1	2	12	15	19	28	29	32	34	39	40	41	52	59	61			
Allochems																		
Fossils				4	3		2	3							4			
Oolites																		
Intraclasts																		
Sparry carbonate				1	4		5					1	2					
Micrite-microspar-clay	93	98	90	90	82	98	88	94	97	85	86	98	98	95	92	91.8	6.0	85.8-97.8
Quartz	3	1	2	1	5	1	1		1	7	7	1		5		2.3	2.5	0.0- 4.8
Chert																		
K-feldspar																		
Plagioclase					2					1	1							
Rock fragments																		
Coarse mica			1		3						1							
Matrix																		
Opaque minerals	4	1	7	4	1	1	4	3	2	7	5				4	3.3	3.5	0.0- 6.8
Carbonate (X-ray analysis)																		
Dolomite	D	D	D		D	D		D		D	D	D						
Calcite	C	C	C	C	C	C	C	C	C	C	C	C						
Relative abundance	D>C	D>C	C>D	C>D	D>C	D>C		C>D		D>C	D>C	C>D						

Micrite-microspar-clay forms grains up to 8 mm in diameter and is generally subtranslucent in thin section. The micrite contains less than 4 percent silt-sized terrigenous grains mostly consisting of quartz and trace amounts of plagioclase.

Of the fifteen samples of micritic carbonate Williamson (1972, p. 44) treated for insoluble residues, only three samples had clay content greater than 15 percent; the maximum was 28 percent. In an earlier study, Leamer (1966) treated twenty samples of micritic carbonate from the Green River Formation and also found relatively small amounts of clay (25 percent maximum). Some of the micrite in the black shale facies should be termed clayey micrite.

Much of the micrite displays clotted (grumous) microscopic texture. Diffusely bordered, light brown, microcrystalline carbonate clots, generally between 30 and 100 mm in diameter, are separated by clearer, slightly coarser micrite or by vaguely defined pores. Similar grumous textures are common in fine-grained marine carbonate. Cayeux (1970, p. 289) attributed such textures to partial incipient recrystallization of surrounding calcium carbonate. The reason for selective recrystallization is not clear. Carozzi (1960, p. 210) suggested that partial recrystallization may be caused by an original admixture of aragonite in the calcareous mud. A second hypothesis for the clotted texture considered the clots to be primary algal deposits (Hadding, 1958; cited by Carozzi, 1960, p. 210). The clotted texture of primary algal deposits is well illustrated by aggregates and algal crusts from the Green River Formation, but algae are not responsible for the clotting that is prevalent in the micrite. The texture is secondary in origin, caused by partial pervasive neomorphism and accentuated by selective dolomitization.

Opaque minerals, which were identified as dominantly pyrite and marcasite, average about 3 percent reaching a maximum of 11 percent (table 6). Minor amounts of hematite-stained carbonate also occur. Several thin sections contain pyrite in distinct lenses and pockets that are elongate parallel with bedding planes. Krauskopf (1967, p. 275) notes that metal sulfides (of which pyrite and marcasite are the most common) can be expected to form as sedimentary minerals only in very reducing environments (generally environments with abundant organic material). Micrite containing bedded pyrite and organic material is deposited in an oxygen deficient, strongly reducing environment. The hematite staining noted on some carbonate is from a later post-depositional event when oxidation of iron-rich minerals occurred.

Another indicator of a strongly reducing environment is the undisturbed laminar bedding in many of the micrite thin sections. Normal benthos or bottom-dwelling organisms do not live in oxygen deficient environments and thus were not present to disturb the delicate laminations.

Environments of Deposition

The low terrigenous micrites summarized here are believed to have been deposited in deep water, offshore environments. Such micrite can be confused with microcrystalline carbonate deposited in lagoonal and mudflat settings. All the environments are characterized by calm-water deposition of micrite. The rock sequences also are likely to contain dark, organic-rich rocks (oil shale) that are thinly laminated or varved and that contain dolomicrite, pyrite and clay minerals. Of the micrite studied by X-ray diffraction one-half contains more dolomite than calcite (table 6). Apparently, all the micrite, whether deposited in lagoonal, mudflat or offshore settings, contains large amounts of opaque minerals (about 3 percent).

The depth of water of the offshore, deep water environments is of particular concern in studies of the Green River Formation. Picard (1959, p. 141) indicated that Lake Uinta was no deeper than about 200 feet during its history and, for most of its duration, was much shallower. A relative water depth chart prepared by him (1959, p. 143) indicates the fluctuations in the lake level for the various rock units in the west part of the Uinta Basin.

Bradley (1929, p. 103) suggested that a depth of only 75 to 100 feet was sufficient to preserve the fine laminations characteristic of much of the formation. Later he (1931, p. 28) noted that the lakes frequently were shallow at stages of low rainfall. Milton and Eugster (1959, p. 120) reported that Bradley believed much of Lake Uinta had a depth of several hundred feet and that during deposition of the oil shale, Lake Uinta may have been greater than 1,000 feet deep. In contrast, Baer (1969, p. 25) suggested that low-grade oil shale accumulated in deltaic settings in the west Uinta Basin. Four lakes producing a type of organic ooze–perhaps a modern analogue of the precursors of rich oil shale–are shallow and do not exceed about 30 feet in water depth (Bradley, 1966, p. 1334). Several geologists proposed that oil shale forms in shallow water lagoonal environments as well as deeper water offshore lacustrine environments (Twenhofel, 1926, p. 302; Greensmith, 1962, p. 362; Cashion, 1967, p. 16). The water depth for the offshore environment of micrite deposition in the black shale facies probably was greater than 20 feet (approximate wave base for a large lake), but less than 100 feet.

Synerisis cracks and incomplete shrinkage cracks are characteristic offshore deep water (20 to 100 feet) features that might be mistaken as evidence of subaerial exposure during deposition (Picard, 1966). Thin beds of ooliths and microcrystalline carbonate aggregates, washed into the offshore environment from adjacent shallow water shoals, also occur in deposits from the deep central part of the lake. Evidence for the relatively shallow maximum depth of the offshore environment includes stromatolites and, locally, rapid facies changes to shallow water deposits.

In a previous section on silty and sandy micrite, the means for distinguishing micrite deposits of the offshore deep water environment and the nearshore protected shallow water environment were discussed.

GEOCHEMISTRY

General

The distribution of chemical elements in fourteen samples of "black" fine-grained rocks from the black shale facies was examined to determine which elements accompany the major rock-forming constituents (detrital minerals and carbonate minerals). Initially this study was designed to obtain information that could be compared with other geochemical studies of black shale in the Green River Formation (Vine and Tourtelot, 1969). The sample localities are given in the appendix and general petrographic descriptions of the samples summarized in tables 7 and 8.

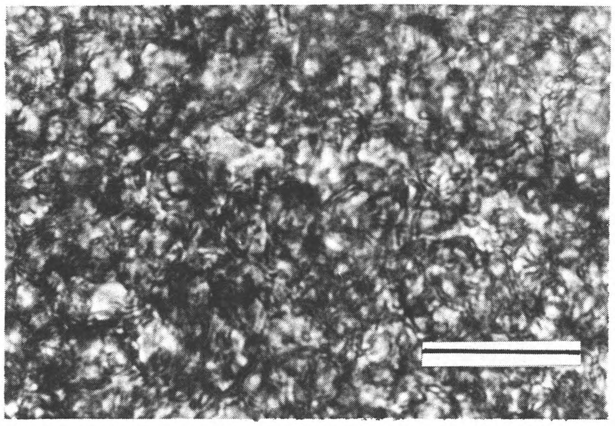
The term black shale as used by Vine and Tourtelot (1969, p. A4) includes a variety of dark colored fine-grained sedimentary rocks deposited in marine or saline lake environments and composed of a mixture of detrital minerals, chemically or biologically precipitated minerals and organic matter. According to these authors, the fine-grained texture of the rocks makes definition of precise boundaries between the various types impractical, especially for field classification. As will be shown, a wide variety of rocks are included under the general term black shale.

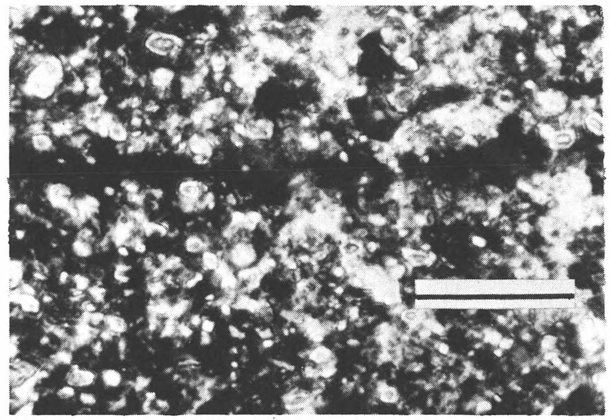
Detailed petrographic examination at high magnifications (400 X) of the black shale samples from the black shale facies indicates that they contain large amounts of carbonate (both calcite and dolomite). Accordingly, they are divided into four rock types: micrite (figure 46), algal biomicrite (figure 36), silty micrite (figures 30 to 32), and silty, low-grade, oil shale (figures 47 and 48). All of the silty rocks (table 7) contain at least 10 percent detrital grains (quartz and feldspar). The micrite contains only about 1 percent detrital grains (table 8) on the basis of modal

Table 7. Summary of petrographic properties of silty micrite and silty, low-grade, oil-shale samples.

Petrographic properties	Silty Micrite Sample No.				Silty Oil Shale Sample No.			
	5	9	16	42	3	7	26	41
Detrital grains (percent)	21	10	10			17	15	
Opaque minerals (percent)	4	2				2	2	
Allochems (percent)							2	
Sparry carbonate (percent)	2	2				13	3	
Micrite-microspar-clay (percent)	73	86	90			68	78	
Carbonate (X-ray)								
Calcite	C	C	C	C		C	C	C
Dolomite	D	D		D		D	D	D
	D>C			C>D		C>D	C>D	C>D
Feldspar (X-ray)	P	P	P	P	P	P	P	P
Plagioclase	K	K		K		K	K	K
K-spar	P>K	P>K	P>K	P>K	P>K	P>K	P>K	P>K
Pyrite (X-ray)					X	X	X	X
Rock color	olive black	dark gray	olive black	olive gray	olive black	black	brown black	black
Rock unit	C	B	D	Douglas Cr. Mbr.	D	B	Twt	B

C=calcite; D=dolomite; P=plagioclase feldspar; K=potassium feldspar; and X=present.





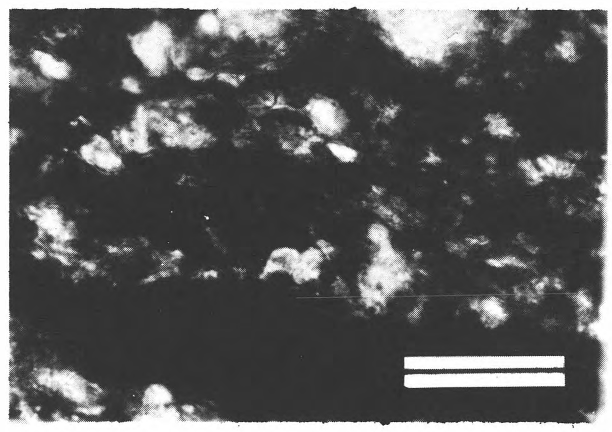


Figure 46. (Top left). Photomicrograph of dolomicrite from unit D (table 8, sample 2). On the basis of modal analysis, the rock contains about 2 percent detrital grains. Color is olive black. Scale is 0.3 mm.

Figure 47. (Top right). Photomicrograph of silty, low-grade oil shale from unit D (table 7, sample 3). Rock color is olive black. Scale is 0.3 mm.

Figure 48. (Immediate right). Photomicrograph of silty oil shale from unit B (table 7, sample 7). Rock color is black. Scale is 0.3 mm.

Table 8. Summary of petrographic properties of micrite samples and algal biomicrite.

Petrographic properties	Micrite (Sample No.)					Algal biomicrite
	2	29	32	34	28	31
Detrital grains (percent)	1	1		1	1	
Opaque minerals (percent)	1	4	3	2	1	11
		2	3			35
Sparry carbonate (percent)		5				
Micrite-microspar-clay (percent)	98	88	94	97	98	54
Carbonate (X-ray)						
Calcite	C	C	C	C	C	C
Dolomite	D		D		D	
	D>C		C>D		D>C	
Feldspar (X-ray)						
Plagioclase	P	P	P(?)		P	
K-spar	K					
	P>K	P>K			P>K	
Pyrite (X-ray)		X	X			X
Rock color	olive black	brown black	olive black	olive black	olive black	olive black
Rock unit	D	B	B	B	B	B

C=calcite; D=dolomite; P=plagioclase feldspar; K=potassium feldspar; and X=present.

analyses. Because rocks containing solid organic matter (kerogen) yield oil and gas on destructive distillation, they are designated silty oil shale. These oil shales, however, are low grade (low oil yield in gallons per ton) and are characterized by at least 10 percent silt-sized detrital grains. All the samples contain some organic matter, but much less than is typical of moderate to good oil shale in the Uinta or Piceance Creek basins.

Although quartz is much more abundant than feldspar, all of the silty rocks contain detrital feldspar grains. More than one-half of the micrite also contains detrital feldspar, but generally in amounts too small (less than 1 percent) to be noted in routine modal analysis. In all thin sections where feldspar was found optically or by X-ray methods, plagioclase feldspar is more abundant than potassium feldspar (tables 7 and 8).

Calcite is more abundant than dolomite. Allochems and sparry carbonate are present in small amounts only, except for two samples—one containing 13 percent sparry carbonate (table 7), the other 35 percent allochems (mostly algal remains; table 8). The opaque minerals noted (tables 7 and 8) are pyrite and marcasite.

Eight of the samples are from the B unit, three are from the D unit. One sample each is from the Douglas Creek Member, the Wasatch tongue and the C unit. All the rocks were deposited in lacustrine environments.

Bedding is well developed in all of the samples and is characterized by very thin horizontal laminations. There is good parallelism between laminae, even though some of the bedding is slightly wavy. Two hundred and fifty lamina were noted in a vertical interval of 1.0 centimeter of one silty, low-grade, oil shale sample, which indicates the thinness of the bedding. Commonly, couplets in which alternating laminae are gray and brown are well developed. The brown layer contains larger amounts of organic material than the lighter layer and these probably are varves. The lighter colored layers contain more carbonate (micrite) than the darker colored layers.

Analytical Method

The analyses reported here were made primarily by the routine six-step emission spectrographic method, which is similar to the three-step method described by Myers, Havens and Dunton (1961). Results for the six-step method are identified with geometric intervals whose boundaries are 1.2, 0.83, 0.56, 0.38, 0.26, 0.18, 0.12, 0.083, etc. and are arbitrarily reported as the geometric midpoints of these intervals, using the numbers 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, 0.07, etc. (Vine and Tourtelot, 1969). The precision of a reported value is approximately plus or minus one interval at 68-percent confidence or two intervals at 95-percent confidence.

Through the courtesy of J. D. Vine, B. W. Lanthorn, analyst, U. S. Geological Survey performed the analyses.

Comparison of Micrites and Silty Rocks

Chemical analyses of five micrites and one algal biomicrite are given in table 9. Comparable information for four silty micrites and four silty, low-grade oil shales are given in table 10. A comparison of the silty rocks and the micrites reveals significant differences in their geochemistry.

All of the silty rocks contain 10 percent or more silicon, in contrast with the micrites which generally contain silicon in smaller amounts (tables 9 and 10). Among the other major elements, aluminum, iron, potassium (?) and titanium are all more abundant in the silty rocks than they are in the micrites. The differences are believed primarily related to the presence of the much larger detrital fraction in the silty rocks compared with the micrites and the algal biomicrite. Larger amounts of calcium and magnesium in the micrites reflect the larger amounts of carbonate minerals in the rocks.

Among the minor elements, boron, beryllium, cobalt, copper, niobium, nickel (?), yttrium, ytterbium and zirconium are more abundant in the silty micrite and silty oil shale than they are in the micrite (tables 9 and 10). Apparently the larger concentrations of beryllium, niobium, yttrium, ytterbium and zirconium result from their concentration in detrital minerals in the silty micrite and silty oil shale. Yttrium is present in nature with the fourteen lanthanons (Pauling, 1964, p. 608), cerium (atomic number 58) to lutetium (atomic number 71). All of these elements except for promethium (made artificially) are present in nature in small amounts, the principle source being monazite, an accessory mineral in granites, gneisses, aplites and pegmatites. The larger amounts of zirconium undoubtedly are related to larger amounts of zircon in the silty rocks. Niobium and tantalum generally occur together in the minerals columbite and tantalite, which are common in pegmatite veins. The beryllium probably is present in beryl, a common mineral in granitic rocks, either in druses or in pegmatite veins.

The meaning of the probable concentrations of boron, cobalt, copper and nickel in the silty rocks is not evident. None of these elements are common in

Table 9. Abundance of major and minor elements in micrite and algal biomicrite of the black shale facies.

	Micrite					Algal Biomicrite			
	Sample No.					Sample No.		Standard	Range
Element	2	29	32	34	28	31	Mean	deviation	(± 1SD)
(percent)									
Silicon	7	>10	>10	3	5	1	<10		
Aluminum	3	3	3	2	2	1	2.3	0.8	1.5 - 3.1
Iron	3	1.5	1.5	0.7	1.5	1	1.5	0.8	0.7 - 2.3
Magnesium	2	1.5	1	0.7	2	2	1.5	0.6	0.9 - 2.1
Calcium	7	3	7	>10	7	>10			
Sodium	2	1.5	1.5	0.7	1	0.7	1.2	0.5	0.7 - 1.7
Potassium	2	2	3	1.5	1.5	<1.5	1.8		
Titanium	0.1	0.1	0.15	0.1	0.1	0.05	0.10	0 03	0.07 - 0.13
(ppm)									
Manganese	300	150	150	1,500	300	300	450		
Boron	30	70	30	N	20	N	25		
Barium	500	300	500	300	300	300	366	103.3	262.7 -469.3
Beryllium	L	1	N	N	N	N	N		
Cobalt	5	15	7	15	7	10	9.8	4.3	5.5 - 14.1
Chromium	70	50	70	50	50	50	57	10.3	46.7 - 67.3
Copper	30	30	30	30	30	30	30		
Gallium	15	20	20	10	15	10	15	4.5	10.5 - 19.5
Lanthanum	50	50	50	<70	50	30	50		
Molybdenum	20	L	5	10	7	7	8.1		
Niobium	10	10	L	N	N	<10	<10		
Nickel	15	30	20	10	15	10	17	7.6	9.4 - 24.6
Lead	20	15	15	30	15	20	19	5.8	13.2 - 24.8
Scandium	15	7	7	N	7	N	6		
Strontium	500	300	1.000	300	700	1,000	633	320.4	312.6 -953.4
Vanadium	50	100	100	30	70	20	62	34.3	27.7 - 96.3
Yttrium	20	10	15	15	15	N	12		
Ytterbium	1	1	1.5	L	1.5	1	1		
Zirconium	30	30	30	10	30	20	25	8.4	16.6 - 33.4

N=Not detected, at limit of detection or at value shown.
L=Detected, but below limit of determination or below value shown.

detrital minerals. Besides, that the nickel is significantly more abundant in the silty rocks is not certain because the differences in the two groupings of rocks (tables 9 and 10) and the number or samples in each group are small. Cobalt and nickel, however, are associated in the same minerals. Therefore, it is suggested that all of these elements (boron, cobalt, copper and nickel) are more abundant in the silty rocks. Their greater abundance may be related to the genesis of low-grade oil shale and not to the mineralogy of the detrital fraction. Boron, copper and nickel are more abundant in the silty oil shale than in the silty micrite; cobalt is more abundant in the silty micrite. Copper, nickel and cobalt commonly occur with organic matter and are locally enriched in some black, fine-grained rocks (Vine and Tourtelot, 1969, p. A34).

Strontium is more abundant in the micrites (table 9) than in the silty rocks (table 10) because of the larger amounts of carbonate minerals in these rocks.

Comparison With Oil Shale

Vine and Tourtelot (1969, p. A8) analyzed twenty-nine samples of oil shale from the Green River Formation in the Piceance Creek Basin, Garfield County, Colorado–twenty-six large block samples collected from a quarry near Debeque, Colorado, and three outcrop samples collected from Cascade Canyon, about 14 miles north of Debeque. The quarry samples were collected from a stratigraphic interval of about 18 feet that includes the Mahogany marker bed about 3 feet below the top (Vine and Tourtelot, 1969). The Cascade Canyon samples were collected from approximately the same stratigraphic interval.

The silty rocks studied here more closely resemble the Green River oil shale than do the micrites (table 11). Of the major elements, silicon, aluminum, iron, potassium and titanium do not differ significantly in the silty rocks and in the Green River oil shale. Both magnesium and sodium are much more abundant in the Green River oil shale than in the silty micrite, silty oil shale and micrite.

Among the minor elements, manganese, boron, copper, nickel and lead are present in similar amounts in both the Green River oil shale and the silty rocks (table 11). Unfortunately Vine and Tourtelot (1969) do not present comparable information for beryllium, niobium, yttrium and ytterbium.

The silty rocks studied here do not contain as much calcium, magnesium and strontium as the average oil shale of Vine and Tourtelot (1969). Their oil shale, therefore, contains more carbonate than does the silty micrite and silty oil shale. The silty rocks of the black shale facies contain larger amounts of silt- and clay-

Table 10. Abundance of major and minor elements in silty micrite and silty low-grade oil shale of the black shale facies.

Element	Silty micrite				Silty oil shale				Mean	Standard deviation	Range (± S D)
	5	9	16	42	3	7	26	41			
(percent)											
Silicon	>10	>10	>10	>10	>10	>10	10	10	>10		
Aluminum	2	7	2	7	5	3	5	3	4.3	2.3	2.0 - 6.6
Iron	2	3	2	5	2	3	0.7	3	2.6	1.3	1.3 - 3.9
Magnesium	1	1.5	1.5	1.5	0.7	0.5	0.7	0.7	1.0	0.4	0.6 - 1.4
Calcium	5	5	7	3	2	5	>10	7			
Sodium	1.5	1	2	3	1	2	1	0.7	1.5	0.8	0.7 - 2.3
Potassium	3	3	3	3	3	3	1.5	3	2.8	0.5	2.3 - 3.3
Titanium	0.15	0.20	0.20	0.50	0.30	0.15	0.30	0.15	0.24	0.1	0.14- 0.34
(ppm)											
Manganese	700	200	200	300	200	300	500	300	337		
Boron	20	30	70	50	100	20	50	30	46	27.7	18.3 - 73.7
Barium	200	200	500	500	700	200	300	200	350	192.7	157.3 -542.7
Beryllium	1	2	1	1.5	2	1	<2	1.5	1.4		
Cobalt	5	70	300	30	15	7	10	15	56.5	100.6	0.0 -157.1
Chromium	30	50	50	70	70	100	70	70	64	20.6	43.4 - 84.6
Copper	30	50	30	50	70	100	30	70	54	27.5	26.5 - 81.5
Gallium	15	30	30	20	20	15	15	20	21	6.2	14.8 - 27.2
Lanthanum	30	50	50	100	70	50	<70	70	59		
Molybdenum	7	5	3	7	3	3	15	10	6.6	4.2	2.4 - 10.8
Niobium	10	20	100	15	10	10	10	10	23	31.3	0.0 - 54.3
Nickel	15	30	20	30	50	30	20	30	28	10.7	17.3 - 38.7
Lead	30	15	20	20	30	20	20	30	23	5.9	17.1 - 28.9
Scandium	7	15	10	15	15	7	10	10	11	3.4	7.6 - 14.4
Strontium	200	200	700	300	200	200	500	150	306	193.5	112.5 -499.5
Vanadium	30	70	70	50	30	70	70	70	57	18.3	38.7 - 75.3
Yttrium	20	20	20	30	20	20	20	50	25	10.7	14.3 - 35.7
Ytterbium	2	2	2	3	2	1.5	1	3	2.1	0.7	1.4 - 2.8
Zirconium	100	70	150	150	70	100	100	50	99	36.4	62.6 -135.4

sized detrital grains (quartz and feldspar) than the oil shale studied by Vine and Tourtelot (1969).

The geochemical comparisons discussed clearly indicate the need for detailed petrographic studies in conjunction with future geochemical studies of fine-grained sedimentary rocks. The Green River oil shale studied by Vine and Tourtelot (1969) is not "black shale," black claystone or siltstone. Vine and Tourtelot (1969, p. A8) indicate that the organic matter is kerogen and the mineral material is a fine-grained mixture of authigenic and detrital minerals, including quartz, dolomite, calcite, analcime, mica and plagioclase, and minor amounts of pyrrhotite or pyrite.

Comparison with Average Shale and Average Carbonate

The fine-grained rocks of the black shale facies also are compared with the average shale and carbonate of Turekian and Wedepohl (1961). Their average sedimentary rocks (shale, sandstone and carbonate) are compiled mainly from miogeosynclinal sequences and include rocks where reasonably thorough chemical degradation of the original source rock is supposed to have occurred.

In terms of the major elements, the silty rocks and the micrites are much more closely related to the average shale than they are to the average carbonate. The black shale facies samples have considerably more silicon, aluminum, iron, sodium, potassium and titanium than the average carbonate of Turekian and Wedepohl (1961). Further, both calcium and magnesium are much more abundant in the average carbonate than they are in the black shale facies samples (table 11).

The abundances of minor elements in the black shale silty rocks and micrites are more like those of the average shale than of the average carbonate. In general, the average carbonate contains much less of the minor elements than the samples studied here, except for manganese, boron, nickel, lead, strontium, yttrium and zirconium. Of these elements, boron, nickel, lead, strontium and zirconium occur in similar amounts in the average carbonate and average micrite of the black shale facies (table 11). Minor elements with similar abundances in silty rocks of the black shale facies and the average shale include: boron, barium, beryllium, chromium, copper, gallium, lanthanum, niobium, lead, scandium, strontium, vanadium, yttrium, ytterbium and zirconium.

Table 11. Average abundance (in percent) of major and minor elements in Green River oil shale, average shale, and average carbonate compared with fine-grained rocks of black shale facies.

Element	Average Green River oil shale (29 spls.) (Vine and Tourtelot, 1969)	Average silty micrite and silty oil shale (8 spls; this study)	Average micrite (6 spls; this study)	Average shale (Turekian and Wedepohl, 1961)	Average carbonate (Turekian and Wedepohl, 1961)
(percent)					
Silicon	>10	>10	>10	7.3	2.4
Aluminium	5.0	4.3	2.3	8.0	0.42
Iron	1.94	2.6	1.5	4.72	0.38
Magnesium	3.2	1.0	1.5	1.5	4.7
Calcium	>10	>5.5	>7.3	2.21	30.2
Sodium	2.8	1.5	1.2	0.96	.04
Potassium	2.8	2.8	1.8	2.66	0.27
Titanium	0.16	0.24	0.10	0.46	.04
(percent)					
Manganese	.0340	.0337	.0450	.0850	.11
Boron	.0072	.0046	.0025	.0100	.0020
Barium	.083	.0350	.0366	.0580	.0010
Beryllium		.00014	N	.0003	
Cobalt	.00097	.0056	.00098	.0019	.00001
Chromium	.0026	.0064	.0057	.0090	.0011
Copper	.0058	.0054	.0030	.0045	.0004
Gallium	.0014	.0021	.0015	.0019	.0004
Lanthanum		.0059	.0050	.0092	
Molybdenum	.0015	.00066	.00081	.00026	.00004
Niobium		.0023	>.0010	.0011	.00003
Nickel	.0040	.0028	.0017	.0068	.0020
Lead	.0027	.0023	.0019	.0020	.0009
Scandium	.00073	.0011	.0006	.0013	.0001
Strontium	.20	.0306	.0633	.0300	.0610
Vanadium	.014	.0057	.0062	.0130	.0020
Yttrium		.0025	.0012	.0026	.0030
Ytterbium		.00021	.0001	.00026	.00005
Zirconium	.0039	.0099	.0025	.0160	.0019

PALEOCURRENTS

General

Paleocurrents are useful to interpret environments of deposition, to reconstruct average shorelines in shallow marine (Picard and High, 1968b) and lacustrine settings (Picard, 1967), and to delineate the paleoslope of fluvial settings. Paleocurrent information also can be applied to reconstruct the orientation of linear sandstone bodies. Although paleocurrent patterns are not diagnostic of depositional environments, they rank with bedding types and sedimentary structures in usefulness and reliability as environmental indicators.

Paleocurrent directions were measured, therefore, in several fluvial sandstone bodies in the upper part of the Wasatch Formation and in the Wasatch tongue of the black shale facies. A total of 32 paleocurrent measurements was made at Indian Canyon and Gate Canyon in the south part of the Uinta Basin.

Field Procedure

Paleocurrent directions were measured from thirty sets of micro cross-stratification, from five sets of medium-scale, trough cross-stratification, and from one bed containing asymmetric, linear ripple marks. Cross strata were measured in the direction of maximum foreset inclination; the ripple marks normal to the ripple crests in the direction of inclination of foreset laminae. The internal structure of the ripple marks was examined.

In the south part of the Uinta Basin, micro cross-stratification is the most reliable paleocurrent indicator in the black shale facies. Ripple marks are rare in both the black shale facies and the upper part of the Wasatch Formation. Medium- and large-scale trough cross-stratification is rare in the black shale facies.

Analysis of Measurements

Paleocurrent directions measured in the field are interpreted without correction for tectonic tilt, because resultant changes in paleocurrent orientation are less than the errors of field measurement. The maximum regional dip at the two localities is less than 3°

For each locality, paleocurrent directions from individual sandstone units are plotted on figures 49 and 50. Individual groups of measurements for each

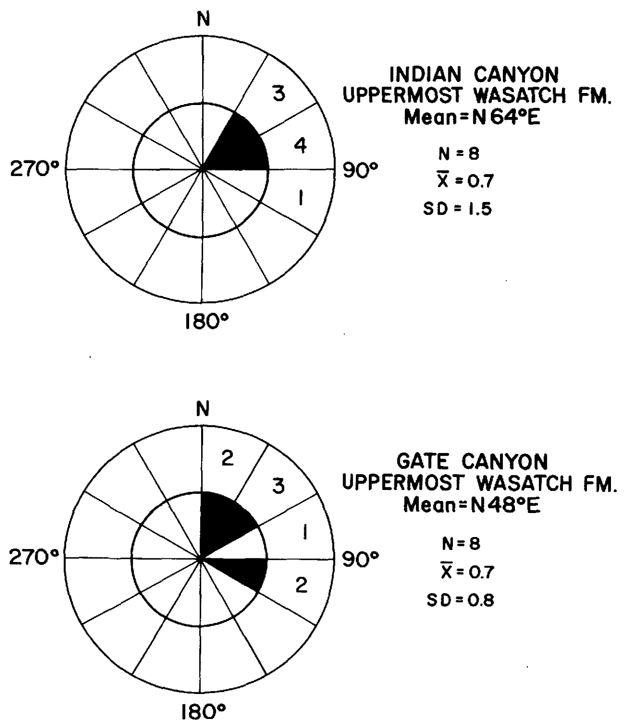


Figure 49. Fluvial paleocurrent pattern in uppermost part of Wasatch Formation (Colton Formation), Indian Canyon and Gate Canyon areas.

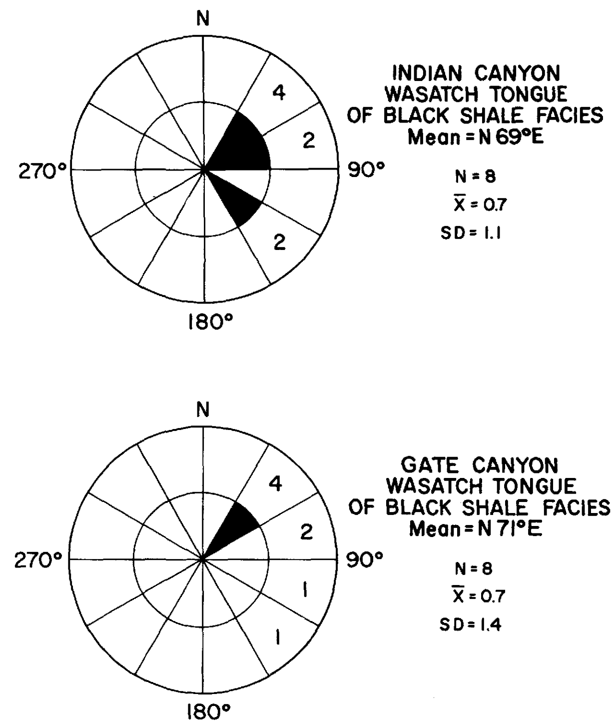


Figure 50. Fluvial paleocurrent pattern in Wasatch tongue of black shale facies, Indian Canyon and Gate Canyon areas.

stratigraphic unit are analyzed by a method suggested by Tanner (1959). The compass is divided into twelve 30° segments and the number of paleocurrent observations present within each segment is noted. The mean number of measurements for each segment and the standard deviation are calculated. Those segments that contain observed measurements in excess of one standard deviation above the mean are considered significant paleocurrent intervals. The significant intervals are shown in black on figures 49 and 50; the mean paleocurrent direction also is given for each stratigraphic interval at each locality.

Results and Interpretation

The paleocurrent directions are remarkably consistent for both localities and for the two stratigraphic intervals. Since all the measurements are from fluvial sandstone bodies, the results reflect the direction of stream flow in this part of the Uinta Basin during deposition of the upper part of the Wasatch Formation and the Wasatch tongue of the black shale facies. Streams, therefore, were flowing to the northeast (about N. 65° E.), presumably from highlands on the southwest. Although the number of measurements is small, the results indicate that source areas were on the south and southwest for sediment in this part of the Uinta Basin.

PROVENANCE

Petrographic examination of the sandstone and siltstone yielded information about the topography and composition of the rocks in the source areas. On the basis of the relative abundance of plagioclase feldspar and recrystallized and stretched metamorphic quartz, the major source area was most likely the San Juan region of southwest Colorado. Subordinate sedimentary sources were the Uinta Mountains, Gunnison Uplift and the San Rafael Swell.

The composition of the terrigenous rocks in the black shale facies is suggestive of tectonic activity in the source areas. Most of the sandstone and siltstone samples are arkose or lithic arkose. Feldspar is decomposed easily by weathering and if it persists in large amounts, special conditions are thought necessary. Folk (1968, p. 127) suggested two possibilities: (1) a climatic arkose, which owes its high feldspar content to a cool and (or) dry climate, or (2) a tectonic arkose in which the source area was uplifted and eroded so rapidly that weathering was not completed. A diagnostic feature of tectonic arkose is that it contains a mixture of fresh and strongly weathered feldspars of the same species. This results when fresh feldspar on rugged relief is eroded from bedrock in the bottoms of vigorous down-cutting stream channels, and the strongly weathered feldspar comes from soil mantle.

The sandstone and siltstone in the black shale facies contains an average of about 22 to 25 percent plagioclase. Approximately one-tenth of the feldspar is fresh and the rest is moderately to strongly weathered, suggesting a tectonic arkose origin.

The stabilities of feldspar species to different climatic and transportation regimes, however, are poorly understood (Blatt, 1967, p. 1035 and Todd, 1968). The rate at which feldspar is reduced in size by transport apparently depends primarily on its weathering state (Phillips, 1881, p. 22-23; Martens, 1931), the duration and intensity of stream, surf or wind action, and the presence of structural weaknesses within grains, such as perthitic intergrowths or twin composition planes (Blatt, 1967, p. 1035). Phase boundaries between perthite lamellae act as surfaces along which decomposition readily takes place and as surfaces of relatively easy fracture. For example, a greater number of fine orthoclase microperthite fragments would be generated by breakage during transport than would be produced by similar transport of orthoclase (Todd, 1968, p. 840). Pittman (1969, p. 1432) found that in an area of high relief, plagioclase breaks readily during stream transport along composition and twin planes. C-twins tend to be destroyed relative to A-twins during stream transport. As a consequence, Carlsbad-twinned feldspar is rare in most feldspathic sandstone. Further, untwinned plagioclase increases relative to twinned plagioclase in a downstream direction (Pittman, 1969, p. 1437).

Folk (1968, p. 130) contends that plagioclase arkose is the product either of volcanic activity or the erosion of basic plutonic rocks. Volcanic activity is rejected as a significant source in the black shale facies because of the entire quartz fraction (more than 1,300 grains) examined, less than four grains appear to be volcanic quartz and they are questionable. The composition of the siltstone and sandstone samples suggests a varied source terrane. Much of the quartz is common quartz and may be indicative of granite-gneiss terrane. Evidence for this is the angular nature of most of the quartz grains. Some of the common quartz is rounded and may derive from recycled sedimentary sources. The recrystallized and stretched metamorphic quartz in the sandstone and siltstone suggests significant contributions from metamorphosed terranes composed of former quartz-bearing rocks (granite, schist or vein quartz) and metaquartzite or gneissic rocks.

Eardley (1962, p. 424) suggested that the Uinta Basin formed as a result of downwarping that was active in Late Cretaceous, Paleocene and Eocene time. To explain the deposition of tectonic arkose without major uplift requires that downwarping be a dominant process. Subsidence could drop the base level sufficiently for streams to cut into feldspar-containing bedrock as they establish new gradients. All of the surrounding positive structural elements were potential sedimentary source areas. The San Rafael Swell on the southwest and the Uinta Mountains on the north may have been undergoing gentle uplift (Eardley, 1962, p. 423 and 1968, p. 92) and, undoubtedly, contributed sediments (carbonate as well as common quartz) to Lake Uinta. Neither the San Rafael Swell or the Uinta Mountains, however, were capable of producing the abundant feldspar or metamorphic quartz types found in the black shale facies.

The dominant positive area southeast of Lake Uinta during the early Tertiary was the Gunnison Uplift of west central Colorado (Hansen, 1965, p. 21). In the Gunnison Uplift, Precambrian crystalline rock was not exposed during the early Tertiary, but was covered by a thick mantle of Mesozoic sandstone and fine-grained sedimentary rock. Exposure of the Precambrian basement did not take place until late Pliocene time (Hansen, 1965, p. 19). Thus any feldspar shed from the Gunnison Uplift was eroded from the Mesozoic sedimentary cover.

A more probable source for the abundant feldspar in the black shale facies was the San Juan Mountains area of southwest Colorado. Here a thick sequence of Oligocene and Miocene volcanics rests on an extensive early Tertiary erosional surface cut into the Precambrian basement. In late Cretaceous and early Tertiary time the San Juan area was the site of domal uplift, monoclinal folding, faulting and subsequent erosion. Apparently significant extrusive and intrusive activity occurred characterized by granodioritic stocks, laccoliths, dikes and sills (Steven, 1968, p. 719-720). All of the early Tertiary volcanics were eroded before the main eruption of Oligocene and Miocene volcanics. The only evidence of the early Tertiary volcanic activity is found in the sparse outcrops of Paleocene through early Eocene sedimentary rock in the area. A Paleocene or early Eocene till (?) (Ridgeway till) along the north margin of the San Juan region contains clasts derived from Precambrian metamorphics, Paleozoic and Mesozoic formations, and volcanic tuff and granodiorite.

The Wasatch Formation also contains evidence of highlands in the San Juan region during the early Tertiary. Only thin patches of Wasatch are found in the immediate San Juan Mountain area, but on the south and north in the San Juan Basin of New Mexico and Piceance Creek Basin of Colorado, the Wasatch is greater than 1,000 feet thick (Larsen and Cross, 1956, p. 58; Donnell, 1961, p. 846). The Wasatch in the San Juan Mountain region is mostly interbedded variegated claystone and siltstone and coarse conglomeratic sandstone and arkose that contains abundant pink feldspar (Larsen and Cross, 1956, p. 58).

Considerable evidence, therefore, suggests that during Paleocene and Eocene time a vast uplifted erosional surface existed in the San Juan Mountain area of southwest Colorado. The erosional surface exposed Precambrian crystalline rock, Paleozoic and Mesozoic sedimentary rock and early Cenozoic granodioritic intrusives. The Precambrian rocks consist of a complex assemblage of highly metamorphosed schists and gneisses, moderately metamorphosed volcanics and numerous granitic stocks, sills and dikes. The composition of the rocks is described in detail by Larsen and Cross (1956). The Paleozoic and Mesozoic sedimentary rocks are mostly carbonate, sandstone, siltstone, claystone and quartzite, with less abundant arkose and redbeds. Thus, detritus shed from the San Juan Mountain area during black shale facies time was rich in common and metamorphic quartz, plagioclase and potassium feldspar.

HYDROCARBONS IN CONTINENTAL ROCKS

The general belief that oil and gas in substantial quantities originate only in marine environments has been slow to expire. Recent work indicates that continental rocks contain adequate petroleum source beds and some evidence exists that nonmarine petroleum differs from marine petroleum. Hunt, Stewart and Dickey (1954) demonstrated a correlation between certain solid hydrocarbons of the Uinta Basin and extracts from Tertiary beds believed to be their source. The type of hydrocarbon changed as the environment of deposition changed and, with increasing salinities of Lake Uinta, ozocerite, albertite, gilsonite and wurtzilite formed successively (Hunt, Stewart and Dickey, 1954, p. 1692).

Smith (1954, p. 377) found that in recent sediments, liquid hydrocarbons originate in a wide variety of salty, brackish and freshwater deposits. Similarly, Swain and Prokopovich (1954), Swain (1956, p. 600), and Judson and Murray (1956, p. 748-749) noted the presence of hydrocarbons in bottom deposits of lakes in Minnesota and Wisconsin.

Other workers, for less quantitative reasons, proposed an indigenous origin for various continental Tertiary hydrocarbon accumulations of the Rocky Mountain region. Felts (1954, p. 1668) suggested that the oil in the Green River Formation of the Uinta Basin had an indigenous origin; Nightingale (1930 and 1935) believed an in-place hypothesis of origin necessary to explain the nonmarine Tertiary accumulations at Hiawatha and Powder Wash in northwest Colorado and Wyoming; and Picard (1956, p. 2960; 1959, p. 147; 1962) suggested that oil and gas in Tertiary fields of Utah and Colorado are indigenous to the continental formations and that lacustrine facies were largely responsible for their formation.

Swain, Blumentals and Prokopovich (1958, p. 184), on the basis of a study of bitumens of Precambrian sedimentary formations in Minnesota, concluded that the high content of saturated hydrocarbons and low asphaltenes and tars in the Thompson Slate and Rove Formation graywacke is suggestive of deposition in oligotrophic lakes. In contrast, bitumens in the argillite of the Rove Formation and the Cuyuna ("Biwabik") Formation resemble those of modern Gulf of Mexico sediment, suggesting a marine environment.

Picard (1960) compared the general characteristics, weight distributions of boiling fractions, correlation indices of boiling fractions, and the organic compounds in the residuum of oils from nonmarine fields in the Uinta Basin of Utah and from the Eagle Springs field in Nevada and demonstrated that the Eagle Springs crude is similar to Tertiary oils of the Uinta Basin. He postulated that the environments responsible for formation of each oil were alike. The Sheep Pass Formation (Eocene), which contains most of the oil at Eagle Springs, is largely a lacustrine deposit and closely resembles some of the lacustrine rocks in the Green River Formation. Similarly, Bass (1964, p. 204) compared the curves of correlation indices of crude oils of different reservoirs in the Green River Formation in the Uinta Basin and concluded that the composition of the oil was controlled primarily by the depositional environments of the reservoir and source rocks.

The recent study of Degens, Chilingar and Pierce (1963) also indicates that petroleum originates in lacustrine environments. They conclude (p. 14) that petrographic, paleontologic and geochemical information from petroliferous nodules in freshwater lacustrine deposits of Miocene age from California supports a biogenic origin for the petroleum, which was collected by means of interstitial waters from the surrounding freshwater lake beds during early diagenesis.

Substantial evidence now exists which indicates that both lacustrine and fluvial rocks contain source beds of oil and gas. Original deposition was in saline lakes or in fresh to brackish water. Migration distances from source to reservoir were generally small. Figure 51 shows the cumulative oil production of fields in parts of the Rocky Mountains and Nevada whose oil formed mainly in lacustrine source rocks. Table 12 is a summary of oil-impregnated sandstone deposits in the Uinta Basin. The hydrocarbon potential of lacustrine and fluvial rocks is large, as indicated by production in the Red Wash and Altamont areas. Even the productive

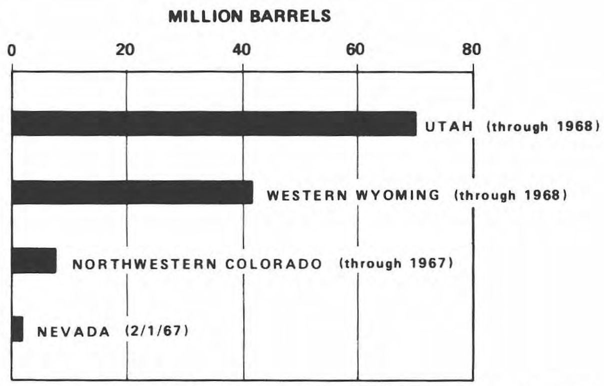


Figure 51. Cumulative Tertiary oil production from lacustrine rocks in Utah, west Wyoming, northwest Colorado and Nevada.

rock units have not been studied in the detail necessary to realize their ultimate oil and gas potential.

OIL PRODUCTION FROM BLACK SHALE FACIES

Much of the oil and gas production in the Green River Formation in the Uinta Basin is from the black shale facies or from rock units equivalent to it. Intervals within the black shale facies show production in the following Uinta Basin fields: Altamont, Bluebell, Blacktail Ridge, Cedar Rim, Cottonwood Wash, Indian Ridge, Monument Butte, Pleasant Valley, Bitter Creek, Chapita Wells and Gypsum Hills. All of the lacustrine rock units (A, B, C and D) of the black shale facies contain productive intervals. Of the wells used to construct the stratigraphic cross sections, each rock unit contains the following number of productive intervals: unit A, three; unit B, eight; unit C, eight; and unit D, four. Unit A probably contains the least number of productive intervals because it is the thinnest and least extensive areally of the lacustrine units.

It is likely that all of the oil now produced from the black shale facies originated in lacustrine source beds of the unit. Principal characteristics of the presumed source beds are: (1) fine grain size; (2) moderate to abundant visible organic material; (3) dark color (dark gray, brown-black, black, olive gray, olive black, and (4) microlaminations. Lithologically, the source beds are claystone, silty claystone, mudstone and silty and clayey micrite. Some of the rocks could be described as "oil shale," but most of what is termed oil shale in the Green River Formation of the Uinta Basin probably did not yield its oil to present productive intervals. Fossils are not common in the source rocks, but ostracods, pelecypods and gastropods are present in small amounts in some source rocks. Algae also are common in some presumed source beds. The

Table 12. Summary of oil-impregnated sandstone deposits in Uinta Basin, Utah (Covington, 1964; Garvin, 1969; Byrd, 1970; and Ritzma, 1969; and Ritzma, 1973, personal communication). Essentially all of the oil originated in the Green River Formation. Much of it is present in nearshore lacustrine sandstone.

Deposit	Formation in which oil impregnation occurs	Gross bbls. oil in place (million, unless otherwise indicated)
P. R. Spring	Green River Fm. (Eocene)	3.7- 4.0 billion
Sunnyside	Wasatch-Green River Fms.	3.5- 4.0 billion
Asphalt Ridge	Mesaverde-Duchesne River Fms.	1.0- 1.2 billion
Whiterocks	Nugget Ss. (Jurassic?)	65.0-125.0
Raven Ridge	Green River Fm. (Eocene)	100.0-125.0
Chapita Wells	Uinta Fm. (Eocene)	7.5- 8.0
Tabiona	Currant Creek (Cret.-Eocene)-Uinta Fms.	4.5- 5.0
Lake Fork	Duchesne River Fm. (Eocene?)	7.5- 8.0
Pariette (Myton Bench)	Uinta Fm. (Eocene)	10.0- 15.0
Argyle Canyon-Minnie Maud	Green River Fm. (Eocene)	125.0-150.0
Spring Branch	Duchesne River Fm. (Eocene?)	1.5- 2.0
Asphalt Ridge, NW	Mesaverde Fm. (Cretaceous)	12.0- 15.0
Spring Hollow	Uinta Formation (Eocene)	minor
Upper Kane Hollow	Green River Fm. (Eocene)	minor
Cow Wash	Green River Fm. (Eocene)	1.0- 1.2
Rimrock	Wasatch-Green River Fms.	30.0- 35.0
Thistle Area	Green River Fm. (Eocene)	2.2- 2.5
Hill Creek	Green River Fm. (Eocene)	1.0- 1.2 billion
Littlewater Hills	Duchesne River Fm. (Eocene?)	10.0- 11.0

source beds were deposited in offshore environments and are characterized by parallel stratification, synerisis cracks, varves and other thin laminations. The offshore environment was reducing, tectonically stable and had the greatest water depths; there were essentially no bottom currents. Pyrite and marcasite are characteristic accessory minerals of fine-grained rocks produced in the setting.

The writers believe that oil in the black shale facies was formed essentially in place and that migration distances were short (less than 1 mile). Exploration can thus be confined to areas where source beds and traps are juxtaposed.

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APPENDIX

Summary of thin-section samples.

Sample No.	Rock name	Color (Goddard, 1948)	Rock unit
1	Micrite	Olive black (5Y 2/1)	D
2	Micrite	Olive black (5Y 2/1)	D
3	Claystone? (silty oil shale)	Olive black (5Y 2/1)	D
4	Lithic arkose sandstone	Light gray (N7) with black specks	C
5	Silty micrite	Olive black (5Y 2/1)	C
6	Algal biomicrite	Brownish black (5YR 2/1)	B
7	Silty oil shale	Black (N1)	B
8	Arkose sandstone	Light gray (N7) with black specks	B
9	Silty micrite	Dark gray (N3)	B
10	Lithic arkose	Light gray (N7)	B
11	Lithic arkose sandstone	Light gray (N7)	A?
12	Micrite	Brownish gray (5YR 4/1)	A?
13	Silty micrite	Dark greenish gray (5GY 4/1)	D
14	Silty micrite	Olive gray (5Y 4/1)	D
15	Micrite	Brownish black (5YR 2/1)	D
16	Silty micrite	Olive black (5Y 2/1)	D
17	Sandy micrite	Dark greenish gray	Twt
18	Arkose sandstone	Light gray (N7)	Twt
19	Micrite	Olive gray (5Y 3/1)	Twt
20	Arkose sandstone	Medium light gray (N6)	Twt
21	Silty micrite	Olive black (5Y 2/1)	Twt
22	Oosparite	Dark yellowish brown (10YR 4/2)	Twt
23	Algal biomicrite	Dusky yellowish brown (10YR 2/2)	Twt
24	Lithic arkose sandstone	Light olive gray (5Y 6/1)	Twt
25	Lithic arkose sandstone	Olive gray (5Y 4/1)	Twt
26	Silty oil shale	Browish black (5YR 2/1)	Twt
27	Ostracod biomicrite	Olive gray (5Y 4/1)	B
28	Micrite	Olive black (5Y 2/1)	B
29	Micrite	Brownish black (5YR 2/1)	B
30	Oosparite	Olive gray (5Y 4/1)	B
31	Algal biomicrite	Olive black (5Y 2/1)	B
32	Micrite	Olive black (5Y 2/1)	B
33	Sandy sparite	Medium gray (N5)	B
34	Micrite	Olive black (5Y 2/1)	B
35	Sandy micrite	Olive gray (5Y 4/1)	B
36	Arkose sandstone	Dark yellowish brown (10YR 4/2)	B?
37	Arkose sandstone	Dark yellowish brown (10YR 4/2)	B?
38	Sandy intramicrite	Olive gray (5Y 4/1)	B
39	Micrite	Olive gray (5Y 4/1)	Douglas Creek Member?
40	Micrite	Olive gray (5Y 4/1)	Douglas Creek Member?
41	Silty oil shale	Black (N1)	B

Appendix (*continued*)

Sample No.	Rock name	Color (Goddard, 1948)	Rock unit
42	Silty micrite	Olive gray (5Y 4/1)	Douglas Creek Member?
43	Algal biomicrite	Moderate yellowish brown (10YR 5/4)	B
44	Algal biomicrite	Moderate yellowish brown (10YR 5/4)	B or Twt?
45	Arkose siltstone	Grayish orange (10YR 7/4)	Twt
46	Arkose siltstone	Dark yellowish orange (10YR 6/6)	Twt
47	Arkose sandy siltstone	Yellowish gray (5Y 7/2)	Twt
48	Sandy sparite	Pale yellowish brown (10YR 6/2)	D
49	Algal biosparite	Grayish orange (10YR 7/4)	D
50	Algal biosparite	Grayish orange (10YR 7/4)	D
51	Arkose sandy siltstone	Dark yellowish orange (10YR 6/6)	D
52	Micrite	Moderate yellowish brown (10YR 5/4)	D
53	Arkose sandy siltstone	Dark yellowish orange (10YR 6/6)	D
54	Silty micrite	Dusky yellow (5Y 6/4)	D
55	Algal biosparite	Grayish orange (10YR 7/4)	D
56	Algal biomicrite	Pale yellowish brown (10YR 6/2)	D
57	Arkose siltstone	Moderate yellowish brown (10YR 5/4)	D
58	Algal biosparite	Dark yellowish brown (10YR 4/2)	D
59	Micrite	Dusky yellowish brown (10YR 2/2)	D
60	Algal biomicrite	Dark yellowish orange (10YR 6/6)	D
61	Micrite	Pale yellowish brown (10YR 6/2)	D