The Mid-Cretaceous Frontier Formation Near the Moxa Arch, Southwestern Wyoming

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By E. A. MEREWETHER, PAUL D. BLACKMON, *and* J. C. WEBB

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A stratigraphic description, including some paleontologic and petrographic data, of lower Upper Cretaceous rocks in the Green River Basin

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THE MID-CRETACEOUS FRONTIER FORMATION NEAR THE MOXA ARCH, SOUTHWESTERN WYOMING

By E. A. MEREWETHER, PAUL D. BLACKMON, and J. C. WEBB

ABSTRACT

The Frontier Formation in the Green River Basin of Wyoming, Utah, and Colorado, consists of sandstone, siltstone, and shale, and minor conglomerate, coal, and bentonite. These strata were deposited in several marine and nonmarine environments during early Late Cretaceous time. At north-trending outcrops along the eastern edge of the overthrust belt, the Frontier is of Cenomanian, Turonian, and early Coniacian age, and commonly is about 610 m (2,000 ft) thick. The formation in that area conformably overlies the Lower Cretaceous Aspen Shale and is divided into the following members, in ascending order: Chalk Creek, Coalville, Allen Hollow, Oyster Ridge Sandstone, and Dry Hollow. In west-trending outcrops on the northern flank of the Uinta Mountains in Utah, the Frontier is middle and late Turonian, and is about 60 m (200 ft) thick. These strata disconformably overlie the Lower Cretaceous Mowry Shale. In boreholes on the Moxa arch, the upper part of the Frontier is of middle Turonian to early Coniacian age and unconformably overlies the lower part of the formation, which is early Cenomanian at the south end and probably Cenomanian to early Turonian at the north end. The Frontier on the arch thickens northward from less than 100 m (328 ft) to more than 300 m (984 ft) and conformably overlies the Mowry.

The marine and nonmarine Frontier near the Uinta Mountains, marine and nonmarine beds in the upper part of the formation on the Moxa arch, and the largely nonmarine Dry Hollow Member at the top of the Frontier in the overthrust belt are similar in age. Older strata in the formation, which are represented by the disconformable basal contact of the Frontier near the Uinta Mountains, thicken northward along the Moxa arch and westward between the arch and the overthrust belt. The large changes in thickness of the Frontier in the Green River Basin were caused mainly by differential uplift and truncation of the lower part of the formation during the early to middle Turonian and by the shoreward addition of progressively younger sandstone units at the top of the formation during the late Turonian and early Coniacian.

The sandstone in cores of the Frontier, from boreholes on the Moxa arch and the northern plunge of the Rock Springs uplift, consists of very fine grained and fine-grained litharenites and sublitharenites that were deposited in deltaic and shallow-water marine environments. These rocks consist mainly of quartz, chert, rock fragments, mixed-layer illite-smectite, mica-illite, and chlorite. Samples of the sandstone have porosities of 4.7 to 23.0 percent and permeabilities of 0.14 to 6.80 millidarcies, and seem to represent poor to fair reservoir beds for oil and gas.

The shale in cores of the Frontier Formation and the overlying basal Hilliard Shale, from the Moxa arch, Rock Springs uplift, and overthrust belt, was deposited in deltaic and offshore-marine environments. Samples of the shale are composed largely of quartz, mica-illite, mixed-layer illite-smectite, kaolin, and chlorite. They also contain from 0.27 to 4.42 percent organic carbon, in humic and sapropelic organic matter. Most of the sampled shale units are thermally mature, in terms of oil generation, and a few probably are source rocks for oil and gas.

INTRODUCTION

The Frontier Formation in the southern part of the Green River Basin (fig. 1), is composed largely of shale, siltstone, and sandstone of marine and nonmarine origin. Molluscan fossils in the marine beds indicate that the formation is of early Late Cretaceous age (Cenomanian, Turonian, and Coniacian) (fig. 2). The Frontier is about 60 m (200 ft) thick and disconformably overlies the Lower Cretaceous Mowry Shale at outcrops along the northern flank of the Uinta Mountains in Utah, and is about 610 m (2,000 ft) thick and conformably overlies the Lower Cretaceous Aspen Shale at outcrops on the east side of the overthrust belt in Wyoming (fig. 1). Sandstone units at the top of the Frontier are overlain comformably by the Upper Cretaceous Hilliard Shale in southwestern Wyoming and by the Upper Cretaceous Mancos Shale in northwestern Colorado (fig. 2).

The main purposes of this study of the Frontier Formation are to synthesize relevant published and unpublished stratigraphic data, to provide new paleontologic and petrographic information, and to present interpretations concerning the areal extent and depositional origin of some strata within the formation. Outcrops were examined and fossils were collected for this investigation by W. A. Cobban and E. A. Merewether in 1974 and by E. A. Merewether in 1979. The Frontier in the subsurface was studied in 1980 by using borehole logs and cores. Molluscan fossils from the outcrops and cores were compared with W. A. Cobban's (written commun., 1981) sequence of Late Cretaceous index-fossils to establish the relative ages of beds in the formation. Samples of sandstone from cores were disaggregated and sieved to determine grain size and were analyzed by X-ray diffraction to establish mineral composition. Thin sections of samples from cores were examined to describe the mineralogy, texture, and porosity of some sandstone units. The elemental composition of sandstone samples from cores was determined by atomic absorption spectrophotometry (Shapiro, 1975), and semiquantitative, emission spectroscopy. Samples of shale from cores were analyzed by X-ray diffraction to establish their mineral composition and by chemical and pyrolytic procedures (Claypool and Reed, 1976; Espitalie' and others, 1977) to establish their organic composition. The hydrocarbon potential and thermal maturity of the sampled shale were determined from the pyrolysis and reflectance of constituent organic material.

ACKNOWLEDGMENTS

The U.S. Department of Energy, Western Gas Sands Project, provided most of the funds used for this investigation. Some cores and borehole records described in this study were contributed to the U.S. Geological Survey by C & K Petroleum, Inc.[1] Unpublished descriptions of outcrops on the north flank of the Uinta Mountains were supplied by C. M. Molenaar. W. A. Cobban and N. F. Sohl identified the fossil mollusks cited in the following pages. The fossils were prepared for study by R. E. Burkholder. R. M. Pollastro and J. W. Bader established the mineral composition of samples of shale. Vitrinite reflectance values for the shale samples were supplied by M. J. Pawlewicz. G. E. Claypool and T. A. Daws determined the organic composition of samples of shale and sandstone. The porosity and permeability of several sandstone samples were measured by J. W. Bader. L. R. Mahrt prepared samples of selected mineral grains, which were identified by D. L. Gautier. K. L. Gardner prepared thin sections of sandstone and sand grains. Samples of sandstone were examined and photographed with a scanning electron microscope (SEM) by C. W. Keighin. Rapid rock analyses (Shapiro, 1975) of sandstone samples were provided by F. W. Brown and J. G. Reid. Semiquantitative spectrographic analyses of sandstone were provided by Leung Mei, W. B. Crandell, and D. W. Golightly. Correlation coefficients for analytical data were determined by J. J. Connor. The generous assistance of the U.S. Department of Energy, C & K Petroleum, Inc., and the above-named employees of the U.S. Geological Survey is gratefully acknowledged.

PREVIOUS WORK

The Frontier Formation and the overlying Hilliard Shale were named and described by Knight (1902) from outcrops in the vicinity of Kemmerer, Wyo., near the western edge of the Green River Basin (fig. 1). Veatch (1907) reported that the Frontier on the west side of the Green River Basin is of Colorado age (mid-Cretaceous) and named a group of sandstone beds in the upper part of the formation the Oyster Ridge Sandstone Member. Veatch (1907) also named the Aspen Shale which underlies the Frontier in westernmost Wyoming. The Frontier at Cumberland Gap, south of Kemmerer (fig. 1), and at other localities near the Green River Basin was described and assigned to the Cenomanian, Turonian, and Coniacian Stages by Cobban and Reeside (1952). Reeside (1955) also described the Frontier, the associated fossils, and a hiatus at the base of the formation at outcrops along Vermillion Creek near the Uinta Mountains in northwestern Colorado (fig. 1). The outcropping Frontier at Vermillion Creek, Colo., Cumberland Gap, Wyo., and Coalville, Utah, was later investigated by Hale (1960, 1962). He recognized Reeside's (1955) unconformity at the Frontier-Mowry contact near the Uinta Mountains in the southern part of the Green River Basin, and proposed an unconformity at the top of the Oyster Ridge Sandstone Member of the Frontier at Cumberland Gap near the western edge of the basin. Hale (1962) also indicated that the formation at Vermillion Creek is represented at Cumberland Gap by a hiatus above the Oyster Ridge Sandstone Member. The unconformity at the base of the Frontier near the Uinta Mountains also was described by Weimer (1962), who suggested that the associated hiatus had been caused by an uplift in the Uinta Mountains area during the early Late Cretaceous. Hansen (1965) mapped and described outcrops of the Frontier on the northern flank of the Uinta Mountains near Flaming Gorge Reservoir. In southwestern Wyoming near the Moxa arch (fig. 1), DeChadenedes (1975) described and interpreted the Frontier Formation at outcrops and in the subsurface. In his regional study, the Oyster Ridge Sandstone Member was called the "first Frontier sandstone", an underlying unit of marine shale was recognized, a marine sandstone underlying the shale was called the "second Frontier sandstone", and a sandstone in the lower part of the formation was called "third Frontier." DeChadenedes (1975) located nonmarine, deltaic, and marine facies of these rocks in the eastern part of the overthrust belt and the western part of the Green River Basin from the area of La Barge, Wyo., south to the Wyoming-Utah State line. The stratigraphy and structure of the oil- and gas-producing La Barge area, at the north end of the Moxa arch (fig. 1), were described by McDonald (1976). Names applied to members of the Frontier at Coalville, Utah, by Hale (1960) and Ryer (1976) were used in the Green River Basin and overthrust belt of Wyoming by Myers (1977). The members of the Frontier at Cumberland Gap are, in ascending order, Chalk Creek, Coalville, Allen Hollow, Oyster

[1]Company names are for descriptive purposes only and do not constitute endorsement by the U.S. Geological Survey.

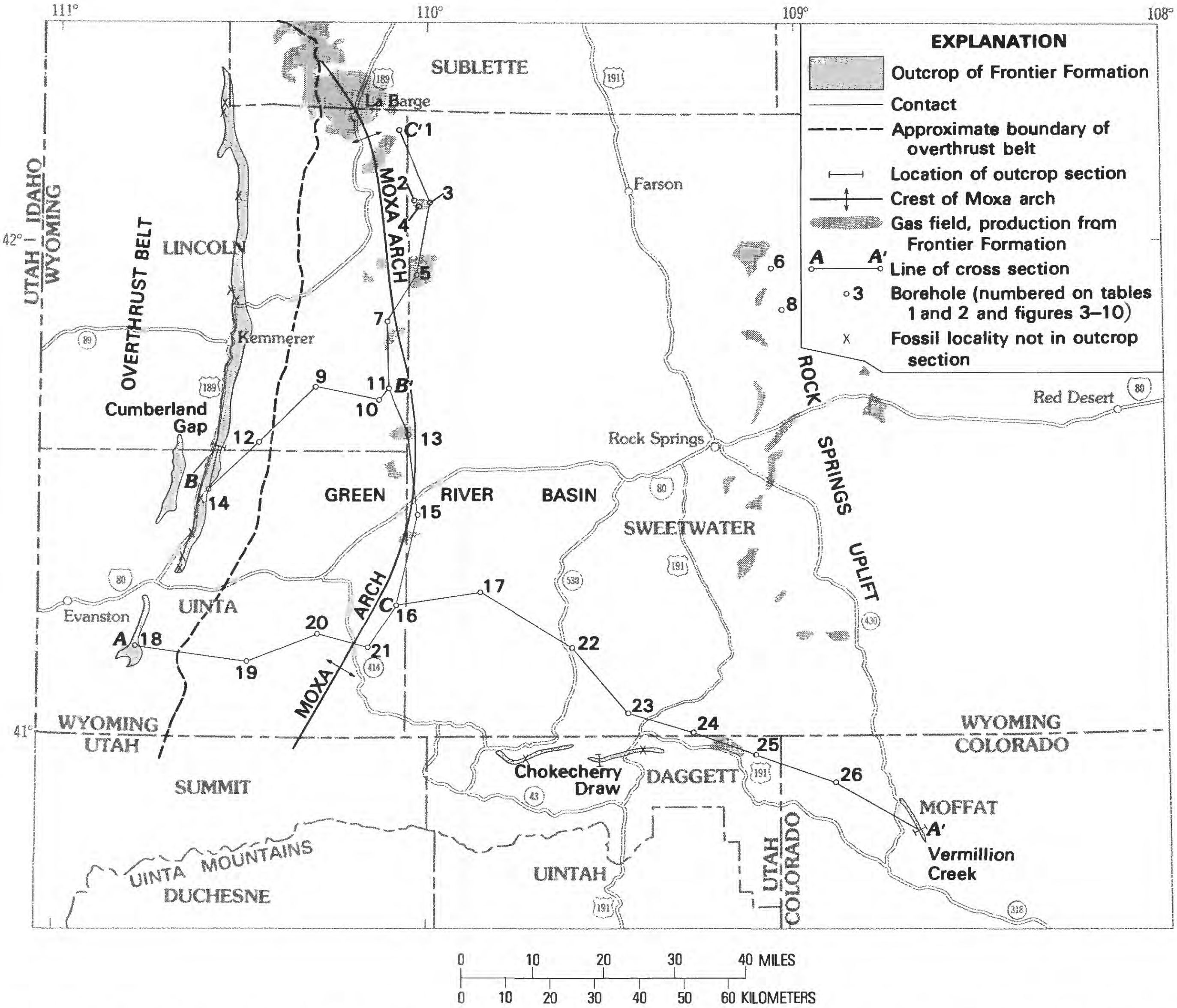


FIGURE 1.—Map of southwestern Wyoming, northeastern Utah, and northwestern Colorado, showing outcrops of Frontier Formation, the crest of the Moxa arch, and location of selected gas fields, boreholes, outcrop sections, and fossil localities. Modified from Love and others (1955), Stokes and Madsen (1961), and Tweto (1979).

Ridge Sandstone, and Dry Hollow (fig. 2). Myers (1977) studied outcrops, cores, and borehole logs of the Frontier and described the depositional environments and areal distribution of units within the formation. Myers (1977, figs. 4 and 18) also located sediment-source areas and shorelines for his "second Frontier sandstone" (Chalk Creek and Coalville Members) and "first Frontier sandstone" (Oyster Ridge Sandstone and Dry Hollow Members). The outcrops at Cumberland Gap (Cobban and Reeside, 1952) also were analyzed in Ryer's (1977a, b) interpretations of the depositional history of the Frontier at Coalville, Utah. Wach (1977) described the stratigraphy, structure, and hydrocarbon potential of sandstone units in the upper part of the Frontier along the Moxa arch. Outcropping units and members of the formation near the eastern edge of the overthrust belt in southwestern Wyoming have been mapped by Rubey and others (1975), and investigated by M'Gonigle (1979, 1980) and Schroeder (1978, 1980). Depositional environments and reservoir properties of upper parts of the Frontier on the Moxa arch, near the confluence of Lincoln, Sublette, and Sweetwater Counties, Wyo., were determined from cores and borehole logs by Hawkins (1980). The petrography and depositional environments of much of the Frontier on the Moxa arch were described and related by Winn and Smithwick (1980).

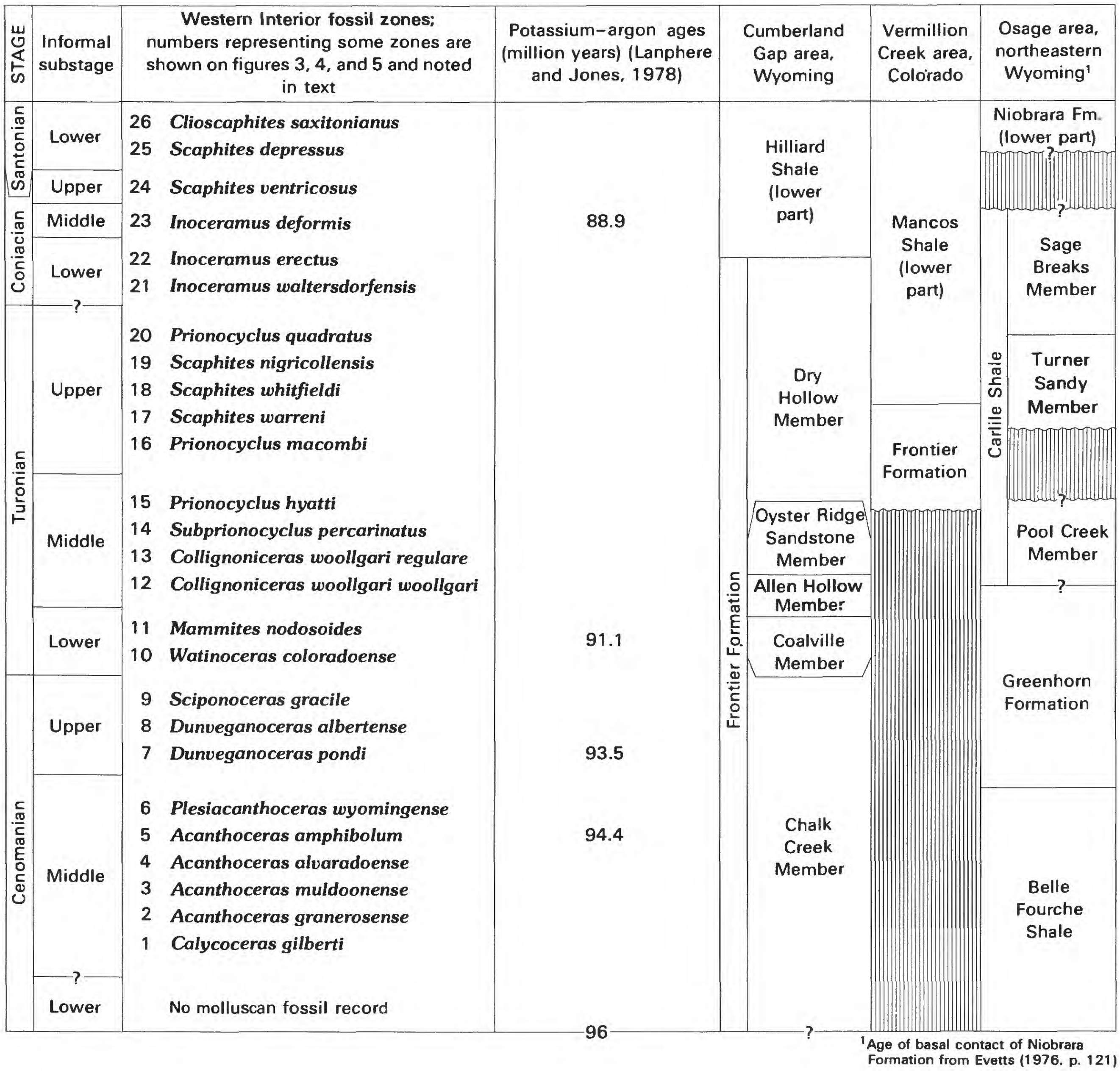


FIGURE 2.—Correlation of the lower Upper Cretaceous formations at selected localities in Wyoming and Colorado. Patterned area represents hiatus in sequence of beds.

STRATIGRAPHY

The Frontier Formation in southwestern Wyoming and adjacent parts of Utah and Colorado is composed of shale, siltstone, sandstone, and minor conglomerate, bentonite, and coal. These rocks were deposited in offshore-marine, nearshore-marine, and nonmarine environments during early Late Cretaceous time. Molluscan fossils in the marine beds are of Turonian and early Coniacian age (fig. 2). Strata in the formation crop out as a succession of north-trending ridges and valleys on the east side of the overthrust belt (fig. 1) and can be traced southeast and east beneath the surface of the Green River Basin to outcrops on the north flank of the Uinta Mountains in Utah and Colorado, and to outcrops in south-central Wyoming. The Frontier is locally more than 610 m (2,000 ft) thick in the overthrust belt and thins southeastward to less than 60 m (200 ft) near the Uinta Mountains.

OVERTHRUST BELT

The outcrops of Frontier in the eastern part of the overthrust belt have been displaced eastward at least 20 km (12 mi) by faulting (De Chadenedes, 1975; Royse and others, 1975). The section at Cumberland Gap (fig. 1) on the easternmost thrust plate was designated (Ryer, 1977c) as the reference section for the Frontier and its Chalk Creek, Coalville, Allen Hollow, and Oyster Ridge Sandstone Members. The Frontier Formation is 596 m (1,955.4 ft) thick (Cobban and Reeside, 1952, p. 1924) and this thickness includes the Dry Hollow Member at the top (Myers, 1977, p. 274) (fig. 2). All of these members are adopted here by the U.S. Geological Survey except for the Dry Hollow, a geographic name that is preempted for a Tertiary latite in central Utah. This sequence conformably overlies the Lower Cretaceous Aspen Shale and is conformably overlain by the Upper Cretaceous Hilliard Shale. The sediments in the Frontier near Cumberland Gap accumulated during a period of about 7 million years (fig. 2) at a rate (compacted) of about 86 m/m.y. (meters per million years).

The Chalk Creek Member of the Frontier is 295 m (967.0 ft) thick at Cumberland Gap and about 427 m (1,400 ft) thick north of Kemmerer (Myers, 1977, p. 276). The member is composed mainly of gray beds of nonmarine origin and consists of mudstone, siltstone, sandstone, and minor coal and bentonite (Cobban and Reeside, 1952, p. 1926–1929). Myers (1977, p. 276) proposed that the Chalk Creek had been deposited largely in fluvio-deltaic environments and that the member originated on an upper delta-plain at outcrops near Cumberland Gap and on a lower delta-plain at the outcrops north of Kemmerer. DeChadenedes (1975, fig. 1) and Myers (1977, fig. 4) depicted deltas in the Chalk Creek in the vicinity of Cumberland Gap and La Barge (fig. 1).

The Chalk Creek is largely of Cenomanian and earliest Turonian age and apparently is correlative with the Belle Fourche Shale and part of the Greenhorn Formation of northeastern Wyoming (fig. 2). The member conformably overlies the Lower Cretaceous Aspen Shale and is overlain conformably by the marine Coalville Member which contains molluscan fossils of early Turonian age. However, the basal part of the Chalk Creek in some areas could be Early Cretaceous, as proposed by Ryer (1977b) for the member in northeastern Utah. Strata typical of the lower part of the Chalk Creek seemingly intertongue with the upper part of the Aspen Shale at outcrops on the east side of the overthrust belt (J. W. M'Gonigle and T. A. Ryer, oral commun., 1980) and in the subsurface along the Moxa arch.

The Coalville Member at Cumberland Gap is 77 m (251.0 ft) thick and consists of three sequences of shale and overlying fine-grained sandstone of marine origin (Cobban and Reeside, 1952, p. 1926). However, Myers (1977, p. 279) reported that the Coalville at other localities is about 30.6–45.7 m (100–150 ft) thick and includes coal beds and fossil oysters of fresh-water and brackish-water origin. Apparently, the member was deposited in nonmarine and shallow-marine environments on deltas and along the interdeltaic coast during a regional marine transgression. DeChadenedes (1975, fig. 1) and Myers (1977, fig. 4) indicated depocenters for the member near La Barge and Cumberland Gap (fig. 1).

The Coalville Member at Cumberland Gap is of early Turonian age and is equivalent laterally to an upper part of the Greenhorn Formation in northeastern Wyoming (fig. 2). Molluscan fossils in the member were reported by Cobban and Reeside (1952, p. 1926). A supplementary collection of fossils from south of Cumberland Gap includes the following species:

USGS D9302, SW¼ sec. 2, T. 17 N., R. 117 W., Uinta County, Wyo., from calcareous concretions in sandy shale between sandstone units in the upper part of the Coalville Member.

Idonearca sp.
Mytiloides mytiloides (Mantell)
Mytiloides aff. *M. opalensis* (Boese)
Ostrea sp.
Plicatula sp.
Camptonectes sp.
Pleuriocardia n. sp.
Cyprimeria? sp.
Mammites nodosoides (Schlotheim)
Pugnellus fusiformis Meek
Rostellinda cf. *R. plicata* Dall
Rostellinda dalli (Stanton)

The Allen Hollow Member, which conformably overlies the Coalville Member, is 91.4 m (300.0 ft) thick and consists of dark-gray, calcareous and noncalcareous shale and bentonite at Cumberland Gap (Cobban and Reeside, 1952; Myers, 1977). Myers (1977, p. 280) reported that the Allen Hollow ranges in thickness from about 27.4 m (90.0 ft) at outcrops southwest of La Barge to about 115.8 m (380.0 ft) at outcrops near Kemmerer. The member was deposited in offshore-marine environments and, according to Myers (1977, fig. 8), intertongues with the overlying Oyster Ridge Sandstone Member north of Kemmerer (fig. 1).

Outcrops of the Allen Hollow yield mollusks and foraminifers of late early Turonian and early middle Turonian age (fig. 2, zones 11–12). Rocks of the same age in northeastern Wyoming are assigned to the upper part of the Greenhorn Formation and the basal part of the Carlile Shale (fig. 2). Fossils from the Allen Hollow, in addition to the collections of Cobban and Reeside (1952, p. 1925), include the following species:

USGS D9301, SW¼ sec. 34, T. 17 N., R. 117 W., Uinta County, Wyo., from calcareous siltstone in the upper part of the Allen Hollow Member.

Inoceramus sp.
Ostrea sp.
Cyprimeria sp.
Cymbophora emmonsi (Meek)
Corbulid
Collignoniceras woollgari (Mantell)
Placenticeras sp.
Cryptorhytis? *utahensis* Meek
Tritonidea? *huerfanensis* Stanton
Rostellinda dalli (Stanton)
Rostellinda plicatula Dall

USGS D9304, SW¼ sec. 2, T. 17 N., R. 117 W., Uinta County, Wyo., from calcareous concretions in the lower part of the Allen Hollow Member.

Phelopteria gastrodes (Meek)
Mytiloides mytiloides (Mantell)
Ostrea sp.
Pleuriocardia n. sp.
Cyprimeria sp.

USGS D9303, SW¼ sec. 2, T. 17 N., R. 117 W., Uinta County, Wyo., from calcareous concretions in the lower part of the Allen Hollow Member, below D9304.

Mytiloides mytiloides (Mantell)
Ostrea sp.
Pleuriocardia n. sp.
Cymbophora emmonsi (Meek)

USGS D9307, NE¼ sec. 31, T. 19 N., R. 116 W., Lincoln County, Wyo., from shaly sandstone and sandy shale at the base of the Allen Hollow Member.

Nemodon sp.
Mytiloides mytiloides (Mantell)
Crassostrea soleniscus (Meek)
Anomia subquadrata Stanton
Brachidontes multilinigera (Meek)
Cymbophora emmonsi (Meek)
Pugnellus fusiformis Meek

The Oyster Ridge Sandstone Member, which grades into the underlying shale of the Allen Hollow, consists of interstratified shale, siltstone and sandstone, and minor conglomerate and bentonite. These rocks crop out as a prominent north-trending hogback near the western edge of the Green River Basin and are 40.8 m (134.0 ft) thick at Cumberland Gap. Myers (1977, p. 282) indicated that the sandstone of the Oyster Ridge ranges in thickness from 15.2 m to more than 61.0 m (50.0 to more than 200.0 ft) in this region. The member commonly is composed of one or more upward-coarsening, very fine grained to medium-grained sandstone units overlain by shale and channel-filling sandstone, which were deposited mainly in progradational delta-front, delta-plain, shoreface, and foreshore environments (Myers, 1977). These strata, according to Myers (1977, fig. 18), were derived largely from a delta in the vicinity of Kemmerer and from another west of La Barge.

Some of the marine beds in the Oyster Ridge Sandstone Member contain molluscan fossils of middle Turonian age. As a consequence, this member can be correlated with part of the Pool Creek Member of the Carlile Shale in northeastern Wyoming (fig. 2). Fossils in the Oyster Ridge Sandstone Member reported by Cobban and Reeside (1952, p. 1924), include *Ostrea soleniscus* Meek at the top of the member and *Collignoniceras woollgari* (Mantell) and *Ostrea* aff. *O. anomioides* Meek near the middle of the member.

The Dry Hollow Member, at the top of the Frontier, overlies the Oyster Ridge Sandstone and is composed of mudstone, siltstone, sandstone, conglomerate and coal. At Cumberland Gap, the Dry Hollow is 92.0 m (303.0 ft) thick (Cobban and Reeside, 1952, p. 1923–1924). Most of the member was deposited in delta-front and delta-plain environments, but the uppermost sandstone and shale are of shallow-water marine origin. This marine unit, which generally overlies a coal bed, is about 13.0 m (43.0 ft) thick at Cumberland Gap and as much as 36.6 m (120.0 ft) thick elsewhere in the region (Myers, 1977, p. 285). McDonald (1976, fig. 20) indicated that the "first Frontier sandstone," at the top of the formation in the La Barge area, was derived from a delta near the Frontier outcrops west of La Barge. Myers (1977, fig. 18) proposed that the two main sources of the shallow-marine and deltaic sediments in the Oyster Ridge and Dry Hollow Members were at Kemmerer and near outcrops of the Frontier west of La Barge.

At Cumberland Gap, the marine Oyster Ridge Sandstone Member of middle Turonian age is overlain by units of, from oldest to youngest, brackish-water shale, nonmarine strata, and marine beds (Cobban and Reeside, 1952, p. 1923–1924). Myers (1977, figs. 2 and 19) assigned the units to the Dry Hollow Member and indicated that the Oyster Ridge Sandstone and Dry Hollow Members in the region are conformable. However, Hale (1962, p. 219) had proposed that the contact of the members is a disconformity, which represents some of middle and late Turonian time. Beds in the upper part of the Dry Hollow, about 30 m (98.4 ft) below the top, contain mixed assemblages of marine and nonmarine dinoflagellates (J. W. M'Gonigle and D. J. Nichols, written commun., 1981). The lowest of these beds is of Turonian age; a bed about 4 m (13 ft) higher in the sequence is of Coniacian age. Furthermore, early Coniacian mollusks of marine origin had been collected by Cobban and Reeside (1952, p. 1923) from the top of the Dry Hollow. Presumably, most of the member is Turonian but about the upper one-third of the member is early Coniacian. The Oyster Ridge Sandstone Member and about the lower two-thirds of the Dry Hollow are of Turonian age and, according to Myers (1977, p. 275), seem to be gradational and conformable. However, if the strata in the upper part of the Oyster Ridge Sandstone Member and in the lower part of the Dry Hollow are of middle Turonian age and are overlain by late Turonian to early Coniacian beds of the Dry Hollow, the disconformity and hiatus suggested by Hale (1962) could be within the lower two-thirds of the Dry Hollow. J. W. M'Gonigle (written commun., 1981) mapped a chert-bearing conglomeratic unit in the lower part of the Dry Hollow south of Cumberland Gap.

The Dry Hollow Member corresponds in age to part of the Carlile Shale of northeastern Wyoming (fig. 2). Collections of molluscan fossils from marine strata in the member at several localities are as follows:

USGS D11053, SE¼ sec. 13, T. 16 N., R. 118 W., Uinta County, Wyo., from crossbedded, fine-grained sandstone at the top of the Dry Hollow Member.

Inoceramus erectus Meek

USGS D11056, SW¼ sec. 1, T. 26 N., R. 116 W., Lincoln County, Wyo., from sandstone near the top of the Dry Hollow Member.

Lopha sannionis (White)
Crassostrea sp.
Gyrodes depressa Meek

USGS D11058, NW¼ sec. 12, T. 22 N., R. 116 W., Lincoln County, Wyo., from sandstone near the top of the Dry Hollow Member.

Inoceramus erectus Meek
Crassostrea sp.
Pleuriocardia curtum (Meek)

Marine sandstone of the Dry Hollow Member, in the uppermost Frontier, is overlain comformably by marine shale of the Hilliard. Cobban and Reeside (1952) reported that a sandstone about 60 m (about 200 ft) above the base of the Hilliard near Cumberland Gap contains the early Coniacian fossil *Inoceramus erectus* Meek. These marine rocks of the uppermost Frontier and basal Hilliard are equivalent in age to part of the Sage Breaks Member of the Carlile Shale in northeastern Wyoming (fig. 2).

UINTA MOUNTAINS

The outcropping Frontier at the southern edge of the Green River Basin, on the north flank of the Uinta Mountains (fig. 1), is generally about 60 m (200 ft) thick and is composed of marine and nonmarine shale, siltstone, sandstone, and minor coal and bentonite (C. M. Molenaar, written commun., 1980). Molenaar (written commun., 1980) suggested that these rocks were deposited in deltaic and shallow-marine environments. Molluscan fossils in the formation are of middle and late Turonian age (fig. 2, zones 15–18). Reeside (1955) recognized a major hiatus at the contact of the Frontier and the underlying Lower Cretaceous Mowry Shale near the Uinta Mountains in northwestern Colorado. The thickness and age of the Frontier indicate that the disconformable basal contact of the formation on the southern margin of the Green River Basin represents strata of Cenomanian and early Turonian age in the lower part of the Frontier at Cumberland Gap. Marine sandstone units at the top of the Frontier near the Uinta Mountains intertongue with the overlying marine shale (the Hilliard Shale in Wyoming and the Mancos Shale in Colorado). The outcropping Frontier in these areas is about the same age as the middle of the Carlile Shale in northeastern Wyoming (fig. 2).

Selected collections of fossils from the Frontier and the overlying shale near the Uinta Mountains are as follows:

USGS D9282, NW¼ sec. 30, T. 10 N., R. 100 W., Moffat County, Colo., from calcareous concretions in the Mancos Shale, about 4 m (13 ft) above the Frontier Formation.

Inoceramus perplexus Whitfield
Scaphites whitfieldi Cobban

USGS D9284, SW¼ sec. 30, T. 3 N., R. 22 E., Daggett County, Utah, from concretions in the lower part of the uppermost sandstone in the Frontier Formation.

Inoceramus perplexus Whitfield
Baculites yokoyamai Tokunaga and Shimizu
Prionocyclus novimexicanus (Marcou)

USGS D9288, NE¼ sec. 34, T. 3 N., R. 21 E., Daggett County, Utah, from siltstone about 12 m (39 ft) below the top of the Frontier Formation.

Inoceramus dimidius White
Cymbophora sp.

USGS D9281, NW¼ sec. 30, T. 10 N., R. 100 W., Moffat County, Colo., from siltstone 12 m (39 ft) below the top of the Frontier Formation.

Inoceramus aff. *I. cuvieri* Sowerby
Corbula sp.
Gyrodes sp.
Rosellinda? sp.

USGS D9280 NW¼ sec. 30, T. 10 N., R. 100 W., Moffat County, Colo., from interlaminated shale and siltstone in the lowermost 3 m (10 ft) of the Frontier Formation.

Inoceramus sp.
Prionocyclus hyatti (Stanton)

MOXA ARCH

In the subsurface along the Moxa arch (fig. 1), the Frontier Formation consists mainly of marine and nonmarine shale, siltstone, and sandstone. DeChadenedes (1975) determined from borehole logs that the formation ranges in thickness from less than 150 m (500 ft) near the Wyoming-Utah State line, to more than 335 m (1,100 ft) in northeastern Lincoln County, Wyo. The disconformity at the base of the Frontier at outcrops on the northern flank of the Uinta Mountains, extends northward and divides the formation in the Green River Basin into two stratigraphic units. On the Moxa arch, the lower unit seems to be largely marine siltstone and shale, and it thickens irregularly northward from less than 10 m (32.8 ft) at the Wyoming-Utah State line to at least 170 m (557.8 ft) near La Barge. The thinning to the south was caused mostly by regional mid-Cretaceous tectonism and erosion. Truncated strata at the top of this unit presumably are successively younger from south to north; from an early Cenomanian age near the Uinta Mountains to a probable early Turonian age near La Barge. Some of the thickening apparently is caused by intertonguing of the lowermost Frontier and uppermost Mowry.

The part of the Frontier above the disconformity, between the Uinta Mountains and La Barge, is mostly sandstone that was informally named the "second Frontier sandstone" by DeChadenedes (1975) and Myers (1977). Wach (1977, figs. 5 and 9) indicated that the thickness of his "2nd Frontier sandstone," which includes units of sandstone, siltstone, and shale, increases by onlap northward along the arch. He suggested that some of these rocks were derived from deltas near Kemmerer and La Barge. Cored beds in the "second Frontier sandstone" of McDonald (1973), DeChadenedes (1975), and Myers (1977) reportedly were deposited in deltaic and shallow-marine environments. Hawkins (1980) proposed that some of these strata accumulated in barrier island, back-barrier, and coastal-plain environments. According to Winn and Smithwick (1980), sandstone units in the upper part of the Frontier, along the axis of the arch, were deposited as offshore storm bars and on a wave-dominated delta as distributary-mouth bars, fluvial point-bars and related sediments. A younger sandstone unit, which is the uppermost Frontier in the vicinity of La Barge, was informally named the "first Frontier sandstone" (DeChadenedes, 1975; McDonald, 1976; Myers, 1977).

Cores of the upper part of the Frontier and the lower part of the Hilliard Shale, from the east flank of the Moxa arch in northwestern Sweetwater County, Wyo., contain molluscan fossils of middle Turonian to early Coniacian age. Strata of the same age in northeastern Wyoming are assigned to the Carlile Shale (fig. 2). The species in the cores are named as follows:

USGS D11363, SE¼ sec. 5, T. 24 N., R. 111 W., Sweetwater County, Wyo. In borehole 2 (table 1) at a depth of 2,836.9–2,837.2 m (9,307.0–9,308.0 ft) from shale in the lower part of the Hilliard Shale, about 10.4 m (34 ft) above the top of the Frontier Formation.

Scaphites uintensis Cobban?
Inoceramus sp.

Remarks: The age of *S. uintensis* is early Coniacian (fig. 2, probably zone 22).

USGS D11207, SE¼ sec. 9, T. 24 N., R. 111 W., Sweetwater County, Wyo. In borehole 4 (table 1) at a depth of 2,917.6 m (9,571.75 ft) from siltstone in the Frontier, about 6.1 m (20 ft) below the top of the formation.

Lopha sannionis (White)
Pleuriocardia pauperculum (Meek)

Remarks: The range of *L. sannionis* is late Turonian to middle Coniacian (fig. 2, zones 18–23).

NE¼ sec. 3, T. 24 N., R. 111 W., Sweetwater County, Wyo. In borehole 3 (table 1) at depths of 2,948.1 m (9,672 ft) and 2,949.8 m (9,677.5 ft), from sandstone in the Frontier, about 63.1–64.8 m (207–212.5 ft) below the top of the formation.

Ostrea cf. *O. anomioides* Meek

Remarks: The range of this fossil probably is middle Turonian to early Coniacian (fig. 2, zones 13–22).

STRATIGRAPHIC INTERPRETATIONS

Strata in the Frontier have been traced, with borehole logs and cores (table 1), from outcrops on the north side of the Uinta Mountains through the Green River Basin and across thrust faults to outcrops in the overthrust belt. Stratigraphic cross sections indicate striking increases in the thickness of the formation from east to west, along the north flank of the Uinta Mountains (fig. 3) and from the Moxa arch to the overthrust

TABLE 1.—*Location of selected boreholes and outcrop sections in the Green River Basin, Wyoming, Utah, and Colorado (fig. 1)*

Borehole No.	Operator	Lease name	Location sec.	Location T.	Location R.	County	State
1	Southland Royalty Co.-----	Stead Canyon East 1-----	18	26 N.	111 W.	Lincoln-----	Wyoming.
2	C & K Petroleum, Inc.-----	Lincoln Road 4----------	5	24 N.	111 W.	Sweetwater--	Do.
3	--do----------------------	Lincoln Road 2----------	3	24 N.	111 W.	---do-------	Do.
4	--do----------------------	Lincoln Road 1----------	9	24 N.	111 W.	---do-------	Do.
5	Davis Oil Co. & Southland-Royalty Co.	Storm Shelter 1-A-------	29	23 N.	111 W.	---do-------	Do.
6	K. D. Luff, Inc.----------	Amoco 2-27--------------	27	23 N.	103 W.	---do-------	Do.
7	Carter Oil Co.------------	Opal 1------------------	34	22 N.	112 W.	Lincoln-----	Do.
8	K. D. Luff, Inc.----------	Amoco Champlin 1-23-----	23	22 N.	103 W.	Sweetwater--	Do.
9	Amoco Production Co.------	Dry Muddy Creek 1-------	16	20 N.	114 W.	Lincoln-----	Do.
10	--do----------------------	Wilson Ranch 1----------	25	20 N.	113 W.	---do-------	Do.
11	C & K Petroleum, Inc.-----	Chrisman 1--------------	18	20 N.	112 W.	---do-------	Do.
12	Belco Petroleum Corp.-----	Hams Fork 2-------------	30	19 N.	115 W.	---do-------	Do.
13	Mountain Fuel Supply Co.--	Bruff 1-----------------	22	19 N.	112 W.	---do-------	Do.
14	Marathon Oil Co.----------	Albert Creek 1----------	36	18 N.	117 W.	Uinta-------	Do.
15	Mountain Fuel Supply Co.--	Church Buttes 16--------	14	17 N.	112 W.	Sweetwater--	Do.
16	Max Pray Co.--------------	Government-Akridge 1----	19	15 N.	112 W.	Uinta-------	Do.
17	Brinkerhoff Drilling Co.--	Henry 1-----------------	7	15 N.	110 W.	Sweetwater--	Do.
18	Sundance Oil Co.----------	Big Piney Federal 1-----	24	14 N.	119 W.	Uinta-------	Do.
19	Sun Oil Co.---------------	Black's Fork 1----------	34	14 N.	116 W.	---do-------	Do.
20	Oil Development Co. of Texas.	Leavitt Creek 1---------	8	14 N.	114 W.	---do-------	Do.
21	Pure Oil Co.--------------	Butcher Knife Springs 1--	21	14 N.	113 W.	---do-------	Do.
22	Lone Star Producing Co.---	Currant Creek Federal 1--	20	14 N.	108 W.	Sweetwater--	Do.
23	--do----------------------	Government IX-3---------	3	12 N.	107 W.	---do-------	Do.
24	Mountain Fuel Supply Co.--	Richards Mountain 1------	19	12 N.	105 W.	---do-------	Do.
25	Pure Oil Co.--------------	USA 1-29----------------	29	3 N.	25 E.	Daggett-----	Utah.
26	Champlin Petroleum Co.----	CPC 1 Federal----------- 31-19 (11-102).	19	11 N.	102 W.	Moffat------	Colorado.
Outcrop section							
Cumberland Gap------------			31 & 32	19 N.	116 W.	Lincoln-----	Wyoming.
Chokecherry Draw----------			34	3 N.	21 E.	Daggett-----	Utah.
Vermillion Creek----------			30	10 N.	101 W.	Moffat------	Colorado.

belt (fig. 4), and from south to north along the axis of the Moxa arch (fig. 5). Near the Uinta Mountains, the thickness increases westward from 43.0 m (141.0 ft) at Vermillion Creek in Colorado to about 570.0 m (1,870.0 ft) at borehole 18 in Wyoming (fig. 3). Similarly, the thickness of the Frontier increases southwestward from about 135.6 m (445.0 ft) at borehole 11 on the Moxa arch to 596.0 m (1,955.4 ft) at Cumberland Gap (fig. 4). Along the Moxa arch, the thickness of the formation increases irregularly northward from about 19.8 m (65.0 ft) at borehole 16 to about 224.3 m (736.0 ft) at borehole 1 (fig. 5).

The Frontier in borehole 18 and at Cumberland Gap is part of a thrust plate that was displaced eastward at least 20 km (12 mi; DeChadenedes, 1975; Royse and others, 1975) and thrust over strata in the Green River Basin. This foreshortening of the region caused much of the apparent increase in the rate of westerly thickening for the Frontier (figs. 3 and 4). Furthermore, the outcropping Frontier in the thrust plate is locally as much as 4.5 km (about 14,800 ft) higher than the formation in the subsurface beneath the plate. Consequently, the Frontier is not continuous between the Moxa arch and the overthrust belt as shown on figures 3 and 4.

Hale (1962, fig. 2) depicted the thickening of the Frontier and the truncation of progressively younger strata in the lower part of the formation, from the Moxa arch westward through the eastern part of the overthrust belt. Thomaidis (1973, pl. 1) depicted northward thickening of the lower part of the Frontier along the Moxa arch. Northward thickening in most of the Cretaceous strata on the arch was reported by Stearns and others (1975, p. 11 and pl. 1).

The disconformity at the base of the Frontier on the

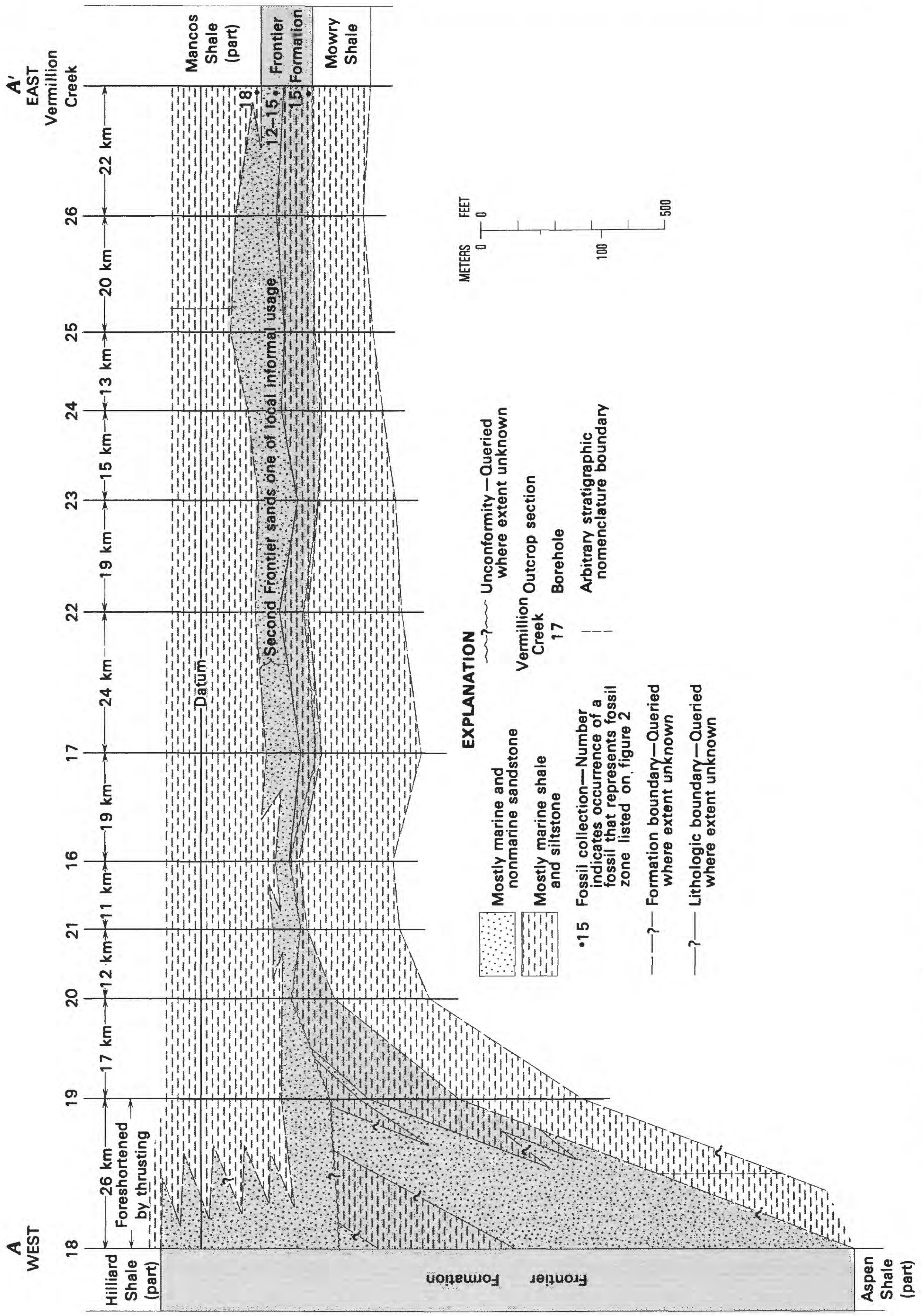


FIGURE 3.—Stratigraphic diagram of the Frontier Formation and Mowry Shale at boreholes and outcrop in northwestern Colorado, northeastern Utah, and southwestern Wyoming along line of section *A–A′*. Location of boreholes and outcrop shown on figure 1 and table 1. Datum is bed in Hilliard Shale and laterally equivalent rocks. Thrust faulting has displaced the mid-Cretaceous strata in borehole 18 eastward at least 20 km, to depicted present location about 26 km west of borehole 19.

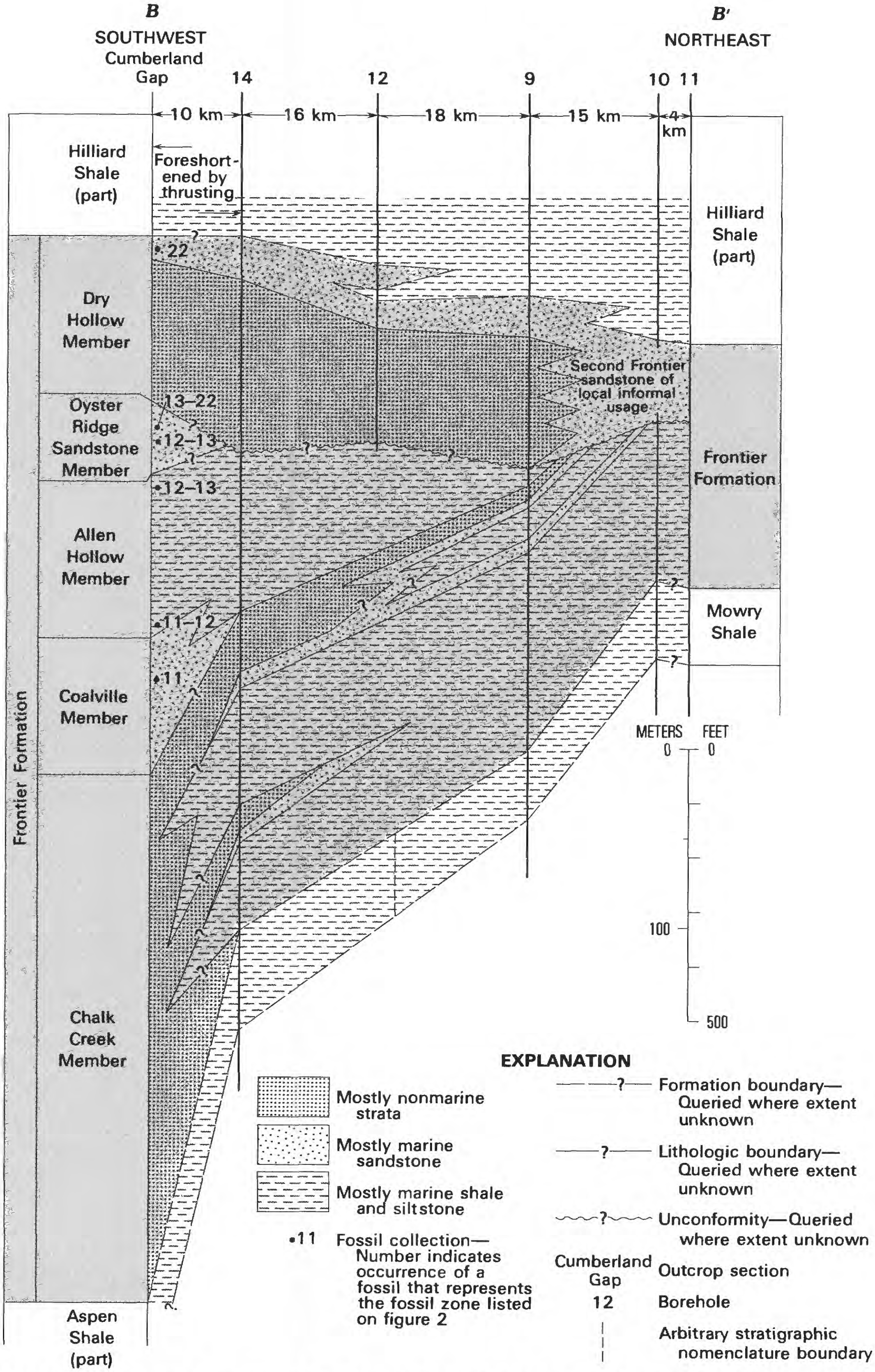


FIGURE 4.—Stratigraphic diagram of the Frontier Formation and Mowry Shale at boreholes and outcrop on the Moxa arch and the overthrust belt, southwestern Wyoming along line of section *B–B'*. Location of boreholes and outcrop shown on figure 1 and table 1. Thrust faulting has displaced the mid-Cretaceous strata at Cumberland Gap eastward at least 20 km, to the present location about 10 km north of and about 4.5 km higher than the mid-Cretaceous rocks in borehole 14.

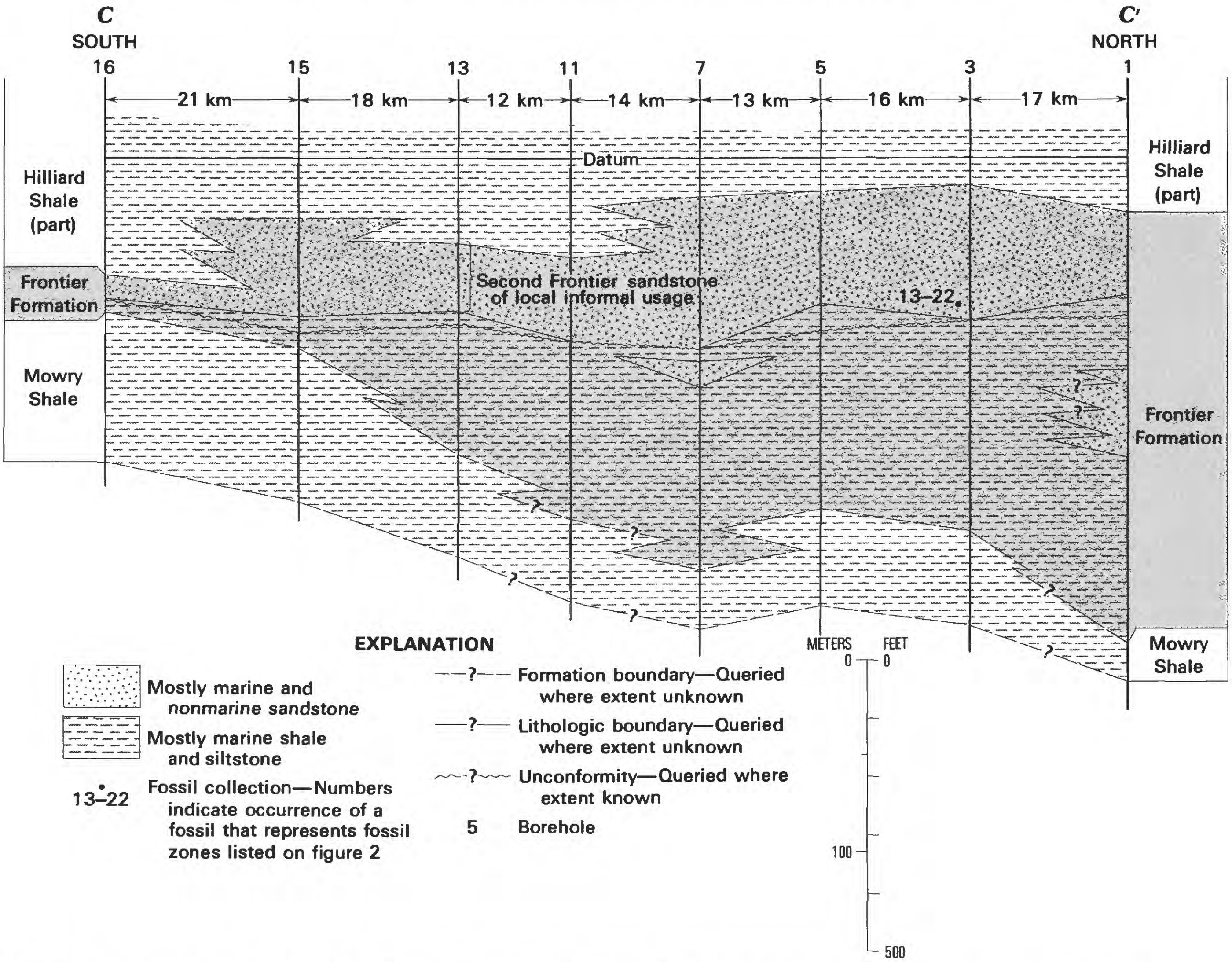


FIGURE 5.—Stratigraphic diagram of the Frontier Formation and Mowry Shale at boreholes on the Moxa arch, southwestern Wyoming along line of section *C–C′*. Location of boreholes shown on figure 1 and table 1. Datum is bed in Hilliard Shale.

north flank of the Uinta Mountains extends northward and is within the formation in the Green River Basin (fig. 5). Below the disconformity, the lower part of the Frontier in the southern part of the basin is probably of early Cenomanian age and locally is less than 10 m (32.8 ft) thick. On the Moxa arch near La Barge, the lower part of the formation is of Cenomanian and probably early Turonian age, and is at least 170 m (557.8 ft) thick. Laterally equivalent strata at Cumberland Gap in the overthrust belt may be of Cenomanian to middle Turonian age and are at least 500 m (1,640.5 ft) thick (fig. 4). Evidently, the truncation of the lower part of the Frontier along the disconformity decreases northward along the Moxa arch and westward between the arch and the overthrust belt, reflecting a mid-Cretaceous uplift in the vicinity of the Uinta Mountains (Weimer, 1962, p. 129).

The upper part of the Frontier, above the disconformity, thickens irregularly northward and westward in the Green River Basin, mainly by the accretion of sandstone units at the top of the formation (Wach, 1977). This part ranges in thickness from less than 60 m (196.9 ft) at the south edge of the basin, to at least 80 m (262.5 ft) near La Barge, and probably to about 90 m (295.3 ft) at Cumberland Gap.

Fossiliferous rocks of middle and late Turonian age (fig. 2, zones 15–18), which overlie the disconformity near the Uinta Mountains, can be followed in the subsurface northward to boreholes 2, 3, and 4 near the crest of the Moxa arch (fig. 1). Cores of some of these strata and overlying beds, from the upper part of the Frontier and the lower part of the Hilliard Shale in boreholes 2, 3, and 4, contain mollusks of middle Turonian to early Coniacian age (fig. 2, zones 13–22). The fossiliferous rocks near the Uinta Mountains and on the Moxa arch are about the same age and are of deltaic and marine origin. They are probably also laterally equivalent to part of the Dry Hollow Member of the Frontier, which is of Turonian to early Coniacian age and of nonmarine and shallow-marine origin, at Cumberland Gap in the overthrust belt (fig. 2).

Sandstone units at the top of the Frontier, near the Uinta Mountains and in boreholes on the Moxa arch south of La Barge, were assigned to the "second Frontier sandstone" and correlated with strata of the Chalk Creek and Coalville Members in the overthrust belt by DeChadenedes (1975, p. 152–156) and Myers (1977, fig. 4). Similarly, Winn and Smithwick (1980, p. 139–140) indicated that the Frontier on the arch is of Cenomanian age and is laterally equivalent to the Chalk Creek and Coalville. The Chalk Creek is mainly of Cenomanian age and the Coalville is of early Turonian age at Cumberland Gap (fig. 2). However, the "second Frontier sandstone" (Myers, 1977, fig. 4) in boreholes 2, 3, and 4 on the Moxa arch can be traced southwestward in the subsurface to outcrops of the Dry Hollow Member (Turonian through early Coniacian age) at Cumberland Gap. Although the boreholes between the Moxa arch and the overthrust belt are widely spaced and the Frontier at Cumberland Gap has been displaced eastward, the "second Frontier sandstone" apparently is an eastern extension of part of the Dry Hollow Member. Furthermore, the fossils in the "second Frontier sandstone" (Myers, 1977, fig. 4) in boreholes 2, 3, and 4 are middle Turonian to early Coniacian in age and correspond in age to fossils in the Oyster Ridge Sandstone and Dry Hollow Members at Cumberland Gap. From this evidence, the shallow-marine and deltaic strata of the "second Frontier sandstone" (Myers, 1977, fig. 4) on the Moxa arch are interpreted to be seaward facies of nonmarine beds in the Dry Hollow Member.

Deltas that supplied the sediments in the lower part of the Frontier, in the Chalk Creek and overlying Coalville Members and in laterally equivalent strata, may have been located near Cumberland Gap and west of La Barge on the east side of the overthrust belt (DeChadenedes, 1975, fig. 1; Myers, 1977, fig. 4). Moreover, an upper part of the Chalk Creek Member, the Coalville Member, and a lower part of the overlying Allen Hollow Member were deposited during a regional marine transgression in the Cenomanian and early Turonian (Merewether, 1982). The upper part of the Allen Hollow and the overlying Oyster Ridge Sandstone and Dry Hollow Members in the overthrust belt and laterally equivalent beds in the western part of the Green River Basin were derived mainly from deltas in the vicinity of Kemmerer and La Barge (Wach, 1977, fig. 9; Myers, 1977, fig. 18). These rocks, excepting an upper part of the Dry Hollow, were deposited during a regional marine regression, mainly in the middle Turonian (Merewether, 1982). The hiatus at the base of the Frontier on the northern flank of the Uinta Mountains and within the formation along the Moxa arch, represents uplift and truncation of the Mowry near the Uinta Mountains and the lower part of the Frontier in the Green River Basin during early to middle Turonian time. Subsequently, shallow-marine and deltaic beds in the upper part of the Frontier on the arch and in the Frontier along the Uinta Mountains were deposited over the erosional surface during a middle Turonian transgression, prograded seaward in a late middle and earliest late Turonian regression, and accumulated thereafter during a late Turonian transgression. This latter transgression, which was regional and generally continued into the Coniacian, is represented by an upper part of the Dry Hollow Member of the Frontier and a lower part of the overlying Hilliard Shale.

CORE-SAMPLE DESCRIPTIONS

Cores of beds in the Frontier and basal Hilliard from four boreholes along the Moxa arch, two boreholes on the north flank of the Rock Springs uplift, and one borehole in the overthrust belt (fig. 1, table 2), were examined and sampled for analyses. The cored strata in the Frontier are in the middle and upper parts of the formation and were deposited in offshore, shoreface, delta-front, and delta-plain environments (table 2) during Turonian time. The cored beds in the Frontier on the Moxa arch are within the "second Frontier sandstone" of DeChadenedes (1975) and Myers (1977) and probably grade westward into parts of the Dry Hollow Member of the Frontier at Cumberland Gap.

BOREHOLE 1

Core sample S–1 was obtained from a cross-stratified, fine-grained sandstone in the Frontier at a depth of 2,600.5 m (8,531.5 ft) in borehole 1 (figs. 1 and 6, table 2). The sandstone is of marine origin and was deposited in a shoreface or delta-front environment. Sample S–1 is composed of about 82 percent sand, 11 percent silt, and 7 percent clay by weight (table 3). The sand has a modal grain size of 160 micrometers (μm) and a maximum grain size of 340 μm (table 4). Porosity and permeability of the sample are about 10.4 percent and 0.97 millidarcies (mD), respectively. In thin section (fig. 7*A*), the rock has clay-filled, intergranular microporosity, minor intergranular mesoporosity, and consists of detrital grains of quartz, chert, rock fragments, and feldspars that are cemented by quartz, calcite, and clay

TABLE 2.—*Location, depth, lithology, and depositional environment of core samples from the Frontier Formation and the lower part of the Hilliard Shale in southwestern Wyoming*

Core sample No.	Borehole No. (fig. 1)	Depth Meters	Depth Feet	Lithology	Depositional environment
S-1	1	2,600.5	8,531.5	Sandstone---	Shoreface?
L4	2	2,837.0	9,307.5	Shale-------	Offshore marine.
L4-1	2	2,890.1	9,481.5	Sandstone---	Delta-front?
L4-2	2	2,898.8	9,510.3	----do------	Do.
L2-1	3	2,914.7	9,562.3	----do------	Delta-plain.
L2-1A	3	2,916.7	9,569.0	Shale-------	Do.
L2-2	3	2,922.8	9,589.0	Sandstone---	Do.
L2-2A	3	2,928.3	9,607.0	Shale-------	Do.
L2-3	3	2,933.8	9,625.0	Sandstone---	Delta-front.
L2-4	3	2,939.9	9,645.0	----do------	Do.
L2-5	3	2,948.1	9,672.0	----do------	Do.
A2-1	6	2,408.6	7,902.0	Shale-------	Offshore-marine?
A-1A	8	2,130.9	6,991.0	----do------	Delta-front?
A-1	8	2,133.1	6,998.0	Sandstone---	Do.
C-1	11	3,383.9	11,101.7	----do------	Delta-front or shoreface.
C-1A	11	3,386.7	11,110.8	Shale-------	Do.
C-2	11	3,394.5	11,136.3	Sandstone---	Delta-plain.
C-2A	11	3,405.8	11,173.5	Shale-------	Do.
F-1	18	1,609.4	5,280.0	----do------	Offshore marine.

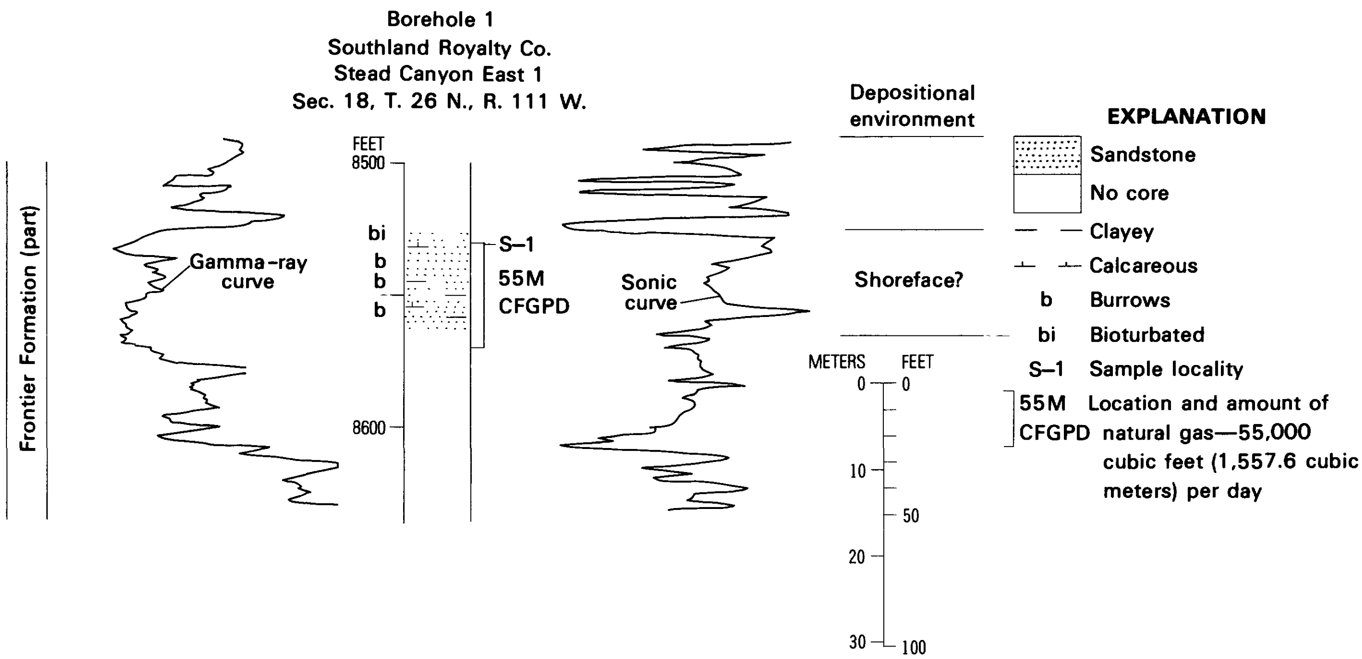


FIGURE 6.—Logs of cored and sampled strata in the Frontier Formation in borehole 1 on the Moxa arch, Wyoming (fig. 1).

(table 5). Choquette and Pray (1970) defined microporosity and mesoporosity as size terms for pores having diameters of less than 1/16 mm and 1/16–4 mm, respectively. In Folk's (1974) classification, the sandstone sample is a litharenite. Analysis of the sample by X-ray diffraction indicates the presence of mixed-layer illite-smectite, mica-illite, kaolin, and 7-Å (angstrom) trioctahedral clay (table 6). The sample also contains 0.03 percent organic carbon. Analysis by atomic absorption, spectrophotometry (rapid rock-analysis; Shapiro, 1975) indicates smaller amounts of magnesium oxide (MgO) and titanium oxide (TiO_2) in sample

TABLE 3.—*Grain sizes of core samples of sandstone from the Frontier Formation of southwestern Wyoming*

Core sample No.	Weight-percentage composition (mm = micrometers) Sand (>62 mm)	Silt (2-62 mm)	Clay (<2 mm)	Total
S-1	82.3	11.4	6.8	100.5
L4-1	73.0	9.7	17.8	100.5
L4-2	90.8	5.3	4.8	100.9
L2-1	82.7	11.1	6.2	100.0
L2-2	79.7	12.8	7.7	100.2
L2-3	85.1	7.9	8.2	101.2
L2-4	76.9	10.5	13.0	100.4
L2-5	74.9	12.3	12.5	99.7
A-1	84.7	10.8	4.7	100.2
C-1	78.9	13.3	8.2	100.4
C-2	77.4	15.6	6.9	99.9

S–1 than in most of the other samples (table 7). Analysis by emission spectrography shows smaller amounts of TiO_2, phosphate (P_2O_5), cobalt (Co), copper (Cu), chromium (Cr), nickel (Ni), scandium (Sc), and zinc (Zn), and a larger amount of manganese (Mn) in sample S–1 than in most of the samples (table 8). Sample S–1 was obtained from a depth of 2,600.5 m (8,531.5 ft) in the upper part of a sandstone that contains natural gas at depths of 2,600.0–2,612.2 m (8,530.0–8,570.0 ft.) (fig. 6). The reported initial potential flow of gas from this unit is 1,557.6 m^3 (cubic meters; 55,000 ft^3) per day. In the gas-bearing beds, the porosity ranges from 5.5 to 20.5 percent and the permeability ranges from 0.03 to 3.1 mD.

BOREHOLE 2

Core samples L4–1 and L4–2 were obtained from crossbedded, fine-grained sandstone in the Frontier from depths of 2,890.1 m (9,481.5 ft) and 2,898.8 m (9,510.3 ft), respectively, in borehole 2 (figs. 1 and 8, table 2). The sandstone beds apparently were deposited in delta-front environments. Sample L4–1 contains about 18 percent clay, 10 percent silt, and 73 percent sand (table 3), and has a modal grain size of 130 μm (table 4). This sandstone sample has a porosity of as much as 16.8 percent and a permeability of as much as 6.8 mD. The rock has clay-filled, intergranular microporosity (table 4) and consists mostly of detrital quartz and chert, which are cemented by clay and quartz (table 5). In Folk's (1974) classification, this sandstone is a sublitharenite. The clay is composed of mica-illite and a 7–Å trioctahedral clay and lesser amounts of mixed-layer illite-smectite and chlorite (table 6). Sample L4–1 contains 0.04 percent organic carbon (table 6). It contains larger amounts of Fe_2O_3, FeO, and Cu, and smaller amounts of P_2O_5 than most of the samples (tables 7 and 8).

Sample L4–2 has a modal grain size of 160 μm (table 4) and consists of about 91 percent sand, 5 percent silt, and 5 percent clay (table 3). The sample of sandstone has a porosity of 13.8–15.7 percent and a permeability of as much as 5.0 mD. In thin section, the rock has intergranular and intragranular mesoporosity and clay-filled, intergranular microporosity, (table 4) and is composed largely of detrital quartz, chert, and rock fragments, which are cemented by clay and quartz (fig. 7*B*; table 5). This sandstone is a sublitharenite (Folk, 1974). Clays in the sample include mixed-layer illite-smectite and mica-illite (table 6). The organic carbon content is 0.06 percent. Rapid rock analysis of L4–2 shows small amounts of alumina (Al_2O_3), calcium oxide (CaO), TiO_2, and P_2O_5, in comparison with the other samples (table 7). Spectrographic analysis of sample L4–2 indicates relatively small amounts of all the oxides and elements reported on table 8.

Samples L4–1 and L4–2 were collected from the top and base, respectively, of a sandstone that contains natural gas at depths of 2,890.8–2,897.8 m (9,484–9,507 ft) in borehole 2 (fig. 8). In the gas-bearing sequence, porosity is 6.3–18.4 percent and permeability is 0.07–5.8 mD. The reported initial potential flow of gas from this rock is 11,526.2 m^3 (407,000 ft^3) per day.

Core of a lower part of the Hilliard Shale in borehole 2 (figs. 1 and 8) consists of fossiliferous shale that was deposited in an offshore-marine environment (table 2). Sample L4, from a depth of 2,837.0 m (9,307.5 ft), is composed mainly of quartz, dolomite, calcite, mica-illite, mixed-layer illite-smectite, kaolin, and chlorite (table 9). Clays comprise about 47 percent of the sample. The mean of vitrinite reflectance values for sample L4 is 0.67 percent, which probably indicates a thermally mature shale in an early stage of oil and gas generation (table 10).

BOREHOLE 3

Core samples L2–1 and L2–2 were collected from crossbedded and contorted-bedded, fine-grained sandstone at depths of 2,914.7 m (9,562.3 ft) and 2,922.8 m (9,589.0 ft), respectively, in borehole 3 (figs. 1 and 9, table 2). These rocks seem to be of nonmarine origin and probably were deposited on a delta plain. The samples consist of about 80–83 percent sand, 11–13 percent silt, and 6–8 percent clay (table 3). Modal grain size of the sand is 140 μm and maximum grain size is 452 μm in sample L2–1 and 301 μm in sample L2–2 (table 4). The porosity and permeability of sample L2–1 are about 12.4 percent and 0.14 mD, respectively. Sample L2–2 has a porosity value of about 17.0 percent and a permeability value of about 0.27 mD. In thin sections (fig. 7*C*), the rocks have clay-filled, intergranular microporosity and rare moldic and intergranular mesoporosity (table 4). They are composed mainly of rock fragments and detrital grains of quartz, chert, feldspar, and mica, which are cemented largely by clay, quartz, and

TABLE 4.—*Description of thin sections of sandstone from core samples of the Frontier Formation of southwestern Wyoming*

[μm, micrometers; ϕ, porosity; K, permeability; mD, millidarcies]

Core sample No.	Grain size (μm) Modal	Grain size (μm) Maximum	Estimated sorting	Estimated angularity	Fabric	Porosity and permeability
S-1	160	340	Well------	Subangular to to well rounded.	Granular mosaic-----	Mostly microporosity; clay-filled intergranular and secondary imtragranular mesoporosity. ϕ=10.4 percent, K=0.97 mD.
L4-1	130	300	Extremely well.	Subangular to rounded.	Bimodal, matrix- and framework-supported.	Microporosity; clay-filled intergranular. ϕ=as much as 16.8 percent, K=as much as 6.8 mD.
L4-2	160	390	Well------	Subrounded to well rounded.	Granular mosaic-----	Mesoporosity and microporosity; intergranular, intragranular, and clay-filled intergranular. ϕ=13.8-15.7 percent, K=as much as 5.0 mD.
L2-1	140	452	Moderately to well.	Subangular to subrounded.	Grain-supported-----	Mostly microporosity; clay-filled intergranular, rare moldic and intergranular. ϕ=12.4 percent, K=0.14 mD[1].
L2-2	140	301	Well------	---do--------	---do---------------	Mostly microporosity; clay-filled intergranular, rare moldic and intergranular. ϕ=17.0 percent, K=0.27 mD[1].
L2-3	140	600	--do------	Subangular to rounded.	Granular mosaic-----	Mostly microporosity; clay-filled intergranular, clay-filled moldic and rare intergranular. ϕ=12.3 percent, K=0.29-0.55 mD[1].
L2-4	80		--do------	Subangular to subrounded.	Matrix-supported----	Mesoporosity and microporosity; secondary intergranular, intragranular, clay-filled and clay-lined intergranular. ϕ=20-23 percent, K=0.43-0.48 mD[1].
L2-5	90	301	Moderately to well.	---do---------	Framework-supported.	Microporosity; clay-filled intergranular. ϕ=14.5-14.8 percent, K=0.51-0.58 mD[1].
A-1	100	241	Moderately well.	Rounded to subrounded.	Granular mosaic-----	Microporosity and rare mesoporosity; clay-filled intergranular and moldic. ϕ=14.6 percent, K=as much as 0.63 mD.
C-1	120	301	Well------	Subangular to subrounded.	---do---------------	Mostly microporosity, some mesoporosity; clay-filled intergranular, clay-filled moldic, intergranular and moldic. ϕ=12.8-14.8 percent, K=as much as 0.91 mD.
C-2	130	331	Moderately well.	---do---------	Cement-supported----	Microporosity and rare mesoporosity; clay-filled intergranular and clay-filled moldic porosity, rare moldic. ϕ=4.7-6.7 percent, K=as much as 0.95 mD.

[1]Porosity and permeability values provided by C & K Petroleum, Inc.

FIGURE 7 (facing page).—Photomicrographs of thin sections of sandstone in the Frontier Formation of southwestern Wyoming. *A*, Angular to subrounded grains of quartz (q) and chert (ch), cemented by calcite (cc) and authigenic clay (c), in core sample S-1 of borehole 1. *B*, Quartz overgrowths (qo) and subangular to well-rounded quartz grains (q) in core sample L4-2 of borehole 2. *C*, Subangular grains of quartz (q) and chert (ch), and intergranular calcite (cc), authigenic clay (c), and pores (p), in core sample L2-1 of borehole 3. *D*, Subangular grains of quartz (q) and chert (ch) and intergranular, authigenic clay (c) in core sample L2-3 of borehole 3.

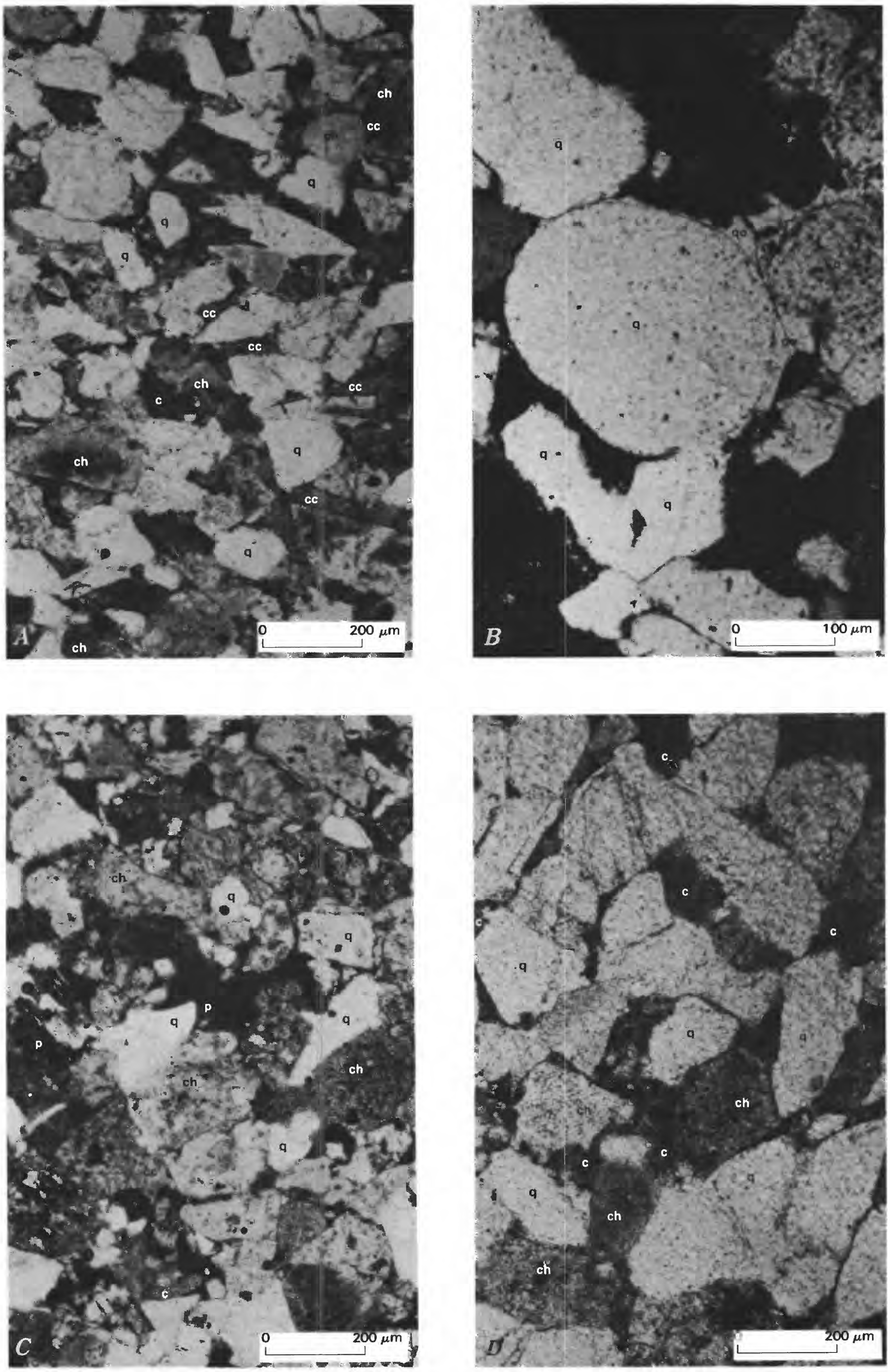

A
ch
cc
q
cc
c
0 200 µm
B
q
0 100 µm
C
ch
q
p
c
0 200 µm
D
c
q
ch
200 µm

TABLE 5.—*Composition (in percent) of thin sections of sandstone from core samples of the Frontier Formation of southwestern Wyoming*

[tr, less than 1 percent; leaders (---) indicate none reported]

	Core samples										
	S-1	L4-1	L4-2	L2-1	L2-2	L2-3	L2-4	L2-5	A-1	C-1	C-2
Detrital grains:											
Quartz	38	65	69	31	39	57	48	59	50	42	30
Plagioclase	1	---	---	1	tr	tr	3	---	2	2	2
Potassium feldspar	2	---	tr	tr	3	---	tr	---	tr	tr	1
Chert	19	5	12	35	21	18	10	6	12	13	20
Rock fragments	5	---	1	6	7	5	11	2	tr	8	12
Biotite	---	tr	---	tr	3	---	tr	tr	tr	tr	tr
Muscovite	tr	---	---	tr	tr	---	---	---	---	tr	tr
Glauconite	---	---	---	---	tr	---	tr	---	---	---	---
Dolomite	---	---	---	---	tr	---	---	---	---	---	---
Calcareous fossils	---	---	---	---	---	---	---	1	---	---	---
Detrital matrix	---	1	---	---	---	---	---	1	---	tr	---
Cements:											
Quartz	9	2	8	5	4	6	6	5	11	9	1
Calcite	11	tr	---	7	---	---	---	tr	---	---	26
Dolomite	---	---	---	---	---	---	tr	6	---	---	---
Pyrite	---	tr	---	---	---	---	tr	tr	tr	---	---
Kaolin	---	---	---	1	3	---	---	---	1	tr	---
Clays other than kaolin, undivided	14	26	9	13	19	13	22	20	23	25	7

TABLE 6.—*Estimated mineral and organic-carbon content of core samples of sandstone from the Frontier Formation of southwestern Wyoming*

[Mineral content determined by X-ray diffraction given as parts in ten; <1 = 5–9 percent; tr = <5 percent. Organic-carbon content (in weight percent) determined by combustion and acidification. Leaders (---) indicate none reported]

	Core samples										
	S-1	L4-1	L4-2	L2-1	L2-2	L2-3	L2-4	L2-5	A-1	C-1	C-2
Quartz	7+	7	9+	7+	7+	9	7+	6+	8+	8	6
Feldspar	tr	tr	tr	tr	<1	---	<1	tr	tr	tr	<1
Calcite	1	---	---	<1	---	---	---	1+	---	---	1+
Dolomite	---	---	---	tr	tr	---	---	---	---	---	---
Barite	---	---	---	tr	---	---	---	---	---	---	---
Hematite	---	---	---	tr	---	---	---	---	---	---	---
Marcasite	---	---	---	---	---	tr	---	---	---	---	---
Goethite	---	---	---	---	---	tr	---	---	---	---	tr
Siderite	---	---	---	---	---	---	tr	tr	tr	---	---
Pyrite	---	tr	tr	---	---	---	---	tr	tr	tr	---
Smectite	---	---	---	tr	---	---	---	---	---	---	---
Illite-smectite, mixed-layered	<1	<1	<1	<1	<1	1	1+	1+	tr	1	1
Mica-illite	tr	1	tr	tr	tr	tr	tr	tr	tr	tr	tr
Chlorite	---	tr	---	tr	tr	---	tr	tr	tr	tr	tr
7-angstrom trioctahedral clay	tr	1	---	tr	tr	---	tr	tr	tr	tr	<1
Kaolin	tr	---	---	tr	tr	---	tr	tr	tr	---	---
Organic carbon	0.03	0.04	0.06	0.14–.16	0.01	0.06	0.03	0.13–.16	0.04	0.06–.07	0.10

TABLE 7.—*Content of principal oxides (in weight percent) in core samples of sandstone from the Frontier Formation of southwestern Wyoming*

[Determined by atomic absorption and spectrophotometry (rapid rock-analysis, Shapiro, 1975)]

Oxide	Core samples										
	S-1	L4-1	L4-2	L2-1	L2-2	L2-3	L2-4	L2-5	A-1	C-1	C-2
SiO_2	86.1	87.3	96.2	85.2	84.4	95.2	90.2	82.1	95.4	91.0	71.9
Al_2O_3	3.7	4.8	2.1	5.2	7.2	3.2	5.9	4.3	2.5	6.2	6.5
Fe_2O_3	0.28	1.9	0.05	0.41	0.51	<0.01	0.07	0.35	0.04	0.20	0.36
FeO	<0.01	1.4	0.08	0.80	1.0	0.16	0.76	0.40	0.56	0.36	0.84
MgO	0.13	0.36	0.42	0.48	0.38	0.33	0.18	0.18	0.07	0.19	0.25
CaO	4.6	0.78	<0.01	3.3	0.58	<0.01	<0.01	4.9	0.35	0.09	8.8
Na_2O	0.21	0.22	0.16	0.20	1.1	0.13	0.32	0.18	0.15	0.28	0.66
K_2O	0.42	0.83	0.33	1.5	0.75	0.54	1.3	0.93	0.31	0.86	1.0
TiO_2	0.10	0.20	0.07	0.17	0.18	0.11	0.16	0.20	0.16	0.33	0.18
P_2O_5	0.03	0.05	0.02	0.11	0.18	0.02	0.05	0.13	0.12	0.17	0.11
MnO	0.05	<0.01	<0.01	0.10	0.05	0.05	0.03	0.03	<0.01	<0.01	0.10
CO_2	3.6	0.04	0.03	2.2	0.41	0.03	0.11	3.9	0.03	0.03	6.6
H_2O+	0.64	1.4	0.49	1.5	1.2	0.06	1.4	0.94	0.46	1.2	0.92
H_2O-	0.46	0.58	0.37	0.59	0.55	1.0	0.67	0.52	0.26	0.54	0.63
Total	100	100	101	101	99	101	101	99	100	101	99

calcite (table 5). Photomicrographs of the samples (fig. 10*A*, *B*), taken with a scanning electron microscope (SEM), show pore-lining authigenic quartz and clays. The sampled rocks are litharenites (Folk, 1974). X-ray diffraction analyses indicate minor amounts of mixed-layer illite-smectite, mica-illite, chlorite, kaolin, and 7-Å trioctahedral clay in the sandstones (table 6). Organic carbon content of these rocks is 0.14–0.16 percent (L2–1) and 0.01 percent (L2–2). In comparison with the other samples, L2–1 contains large amounts of MgO, potassium oxide (K_2O), and manganese oxide (MnO). Sample L2–2 contains relatively large amounts of Al_2O_3, sodium oxide (Na_2O), and P_2O_5 (table 7). Emission spectrographic analyses indicate comparatively large amounts of MgO, Co, Cr, lanthanum (La), Ni, vanadium (V), and Zn in both samples and relatively large amounts of iron oxide (Fe_2O_3), Na_2O, P_2O_5, Cu, and Sc in L2–2 (table 8).

Core samples L2–3, L2–4, and L2–5 are also from borehole 3 (figs. 1 and 9, table 2), but were obtained from very fine grained and fine-grained sandstone at depths of 2,933.8–2,948.1 m (9,625.0–9,672.0 ft). These marine rocks probably were deposited in delta-front environments (table 2) and are composed of about 75–85 percent sand, 8–12 percent silt, and 8–13 percent clay (table 3). Modal grain sizes are 140 µm (L2–3), 80 µm (L2–4), and 90 µm (L2–5) (table 4).

In sample L2–3, the porosity is about 12.3 percent and the permeability is 0.29–0.55 mD. This sandstone in thin section (fig. 7*D*) has clay-filled, intergranular and clay-filled, moldic microporosity, rare mesoporosity (table 4), and consists largely of detrital quartz, chert, and rock fragments, which are cemented by clay and quartz (table 5). The rock is a litharenite (Folk, 1974). Clay minerals in the sandstone, as determined by X-ray diffraction analysis, include mixed-layer illite-smectite and minor mica-illite (table 6). The sample contains 0.06 percent organic carbon (table 6) and, in comparison with the other samples, smaller amounts of Fe_2O_3, CaO, Na_2O, P_2O_5, Co, La, Mn, Ni, Sc, ytterbium (Yb), and Zn (tables 7 and 8).

A sequence of mainly sandstone beds, represented by samples L2–2 and L2–3 (fig. 8), contains natural gas at depths of 2,923.1–2,938.4 m (9,590–9,640 ft). In these rocks, the porosity is 1.5–19.9 percent and the permeability is 0.07–1.2 mD. The reported initial potential flow of gas is 28,320 m^3 (1 million ft^3) per day. C & K Petroleum, Inc. reported slightly above-normal reservoir pressure and a pressure gradient of 12.04 kilopascal/m (0.533 psi/ft) for a sandstone in this sequence.

The porosity and permeability of sample L2–4 are 20–23 percent and 0.43–0.48 mD, respectively. In thin section, the sandstone has intergranular and intragranular mesoporosity, clay-filled and clay-lined, intergranular microporosity (table 4), and is composed mainly of detrital quartz, chert, rock fragments, and feldspar, which are cemented by clay and quartz (table 5). Minor amounts of zircon, leucoxene, and apatite also are present in the sample (D. L. Gautier, written commun., 1981). In Folk's (1974) classification, the rock is

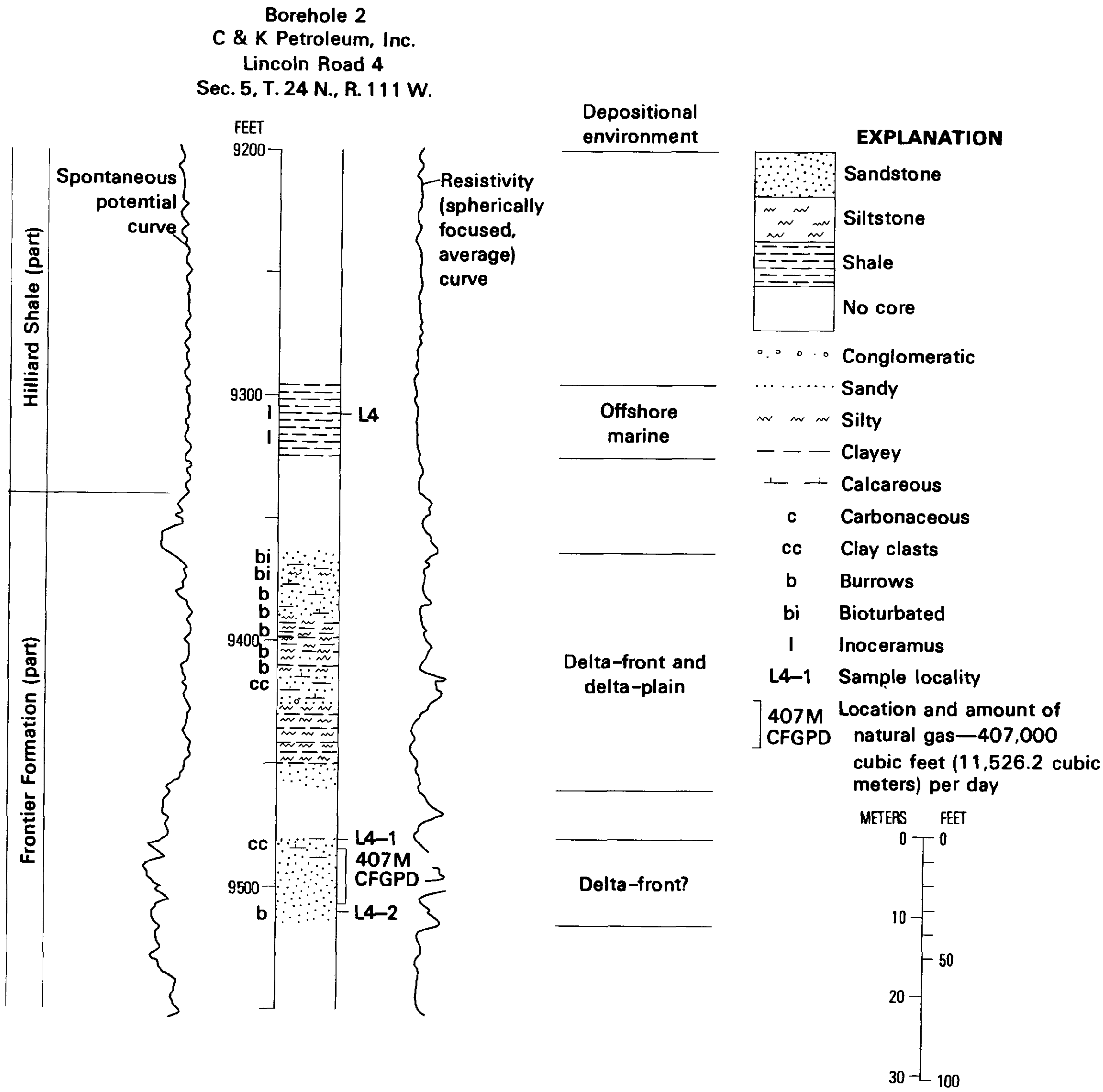


FIGURE 8.—Logs of cored and sampled strata in the Frontier Formation and Hilliard Shale in borehole 2 on the Moxa arch, Wyoming (fig. 1).

a litharenite. The clay consists of mixed-layer illite-smectite and lesser amounts of mica-illite, chlorite, kaolin, and 7–Å trioctahedral clay (table 6). Organic-carbon content is 0.03 percent. The sample contains relatively large amounts, compared with the other samples, of K_2O, barium (Ba), and boron (B) (tables 7 and 8).

Sample L2–5 has a porosity of 14.5–14.8 percent and a permeability of 0.51–0.58 mD. In thin section, the sandstone has clay-filled, intergranular microporosity (table 4) and consists largely of detrital quartz, chert, and rock fragments, cemented by clay, calcite, and quartz (table 5). The rock is a sublitharenite (Folk, 1974). Mixed-layer illite-smectite is the most abundant clay mineral, although mica-illite, chlorite, kaolin, and 7–Å trioctahedral clay are present also (table 6). The organic carbon content is 0.13–0.16 percent. Spectrographic analysis indicates a comparatively large amount of Ba, strontium (Sr), yttrium (Y), Yb, and zirconium (Zr) in this sample (table 8).

Samples L2–1A and L2–2A from depths of 2,916.7 m (9,569.0 ft) and 2,928.3 m (9,607.0 ft), respectively, in borehole 3 consist of shale that was deposited in delta-plain environments (table 2). Sample L2–1A is composed mainly of mica-illite, mixed-layer illite-smectite, and quartz, but includes small amounts of kaolin, chlorite, and pyrite (table 9). The sample also contains 0.64 percent organic carbon, 0.04 mg/g (milligrams per

TABLE 8.—*Approximate content of selected oxides and elements in core samples of sandstone from the Frontier Formation of southwestern Wyoming, determined by emission spectrographic analysis*

	Core samples										
	S-1	L4-1	L4-2	L2-1	L2-2	L2-3	L2-4	L2-5	A-1	C-1	C-2
	Oxides (in weight percent) recalculated from elements										
AL_2O_3	2.8	3.6	1.6	4.7	6.4	2.3	6.8	4.2	1.4	4.2	5.3
Fe_2O_3	.29	2.6	.11	1.3	1.7	.13	1.2	.99	.54	.96	1.2
MgO	.11	.27	.043	.38	.33	.061	.28	.20	.10	.23	.27
CaO	1.7	.097	.025	1.5	.29	.045	.14	2.5	.17	.29	4.1
Na_2O	.071	.066	.024	.13	.69	.036	.31	.12	.045	.19	.32
K_2O	.18	.30	.16	.41	.34	.23	.71	.40	.088	.37	.45
TiO_2	.017	.092	.016	.11	.095	.025	.11	.12	.050	.15	.07
P_2O_5	<.16	<.16	<.16	.19	.28	<.16	.18	.25	.23	.21	.19
MnO	.048	.004	.001	.028	.011	.001	.006	.027	.002	.003	.085
	Selected elements (in parts per million)										
Ba	200	300	160	410	270	270	460	430	92	350	310
B	20	38	13	39	42	21	57	45	23	52	45
Co	<1.0	2.2	<1.0	5.0	4.1	<1.0	1.0	<1.0	1.1	1.7	2.5
Cu	3.1	8.6	3.0	6.0	47	5.0	5.2	4.7	7.8	7.3	4.9
Cr	1.8	5.6	2.2	11	9.6	3.9	6.6	5.5	3.2	12	7.7
La	14	14	11	28	32	<10	17	27	11	15	19
Mn	370	28	6.1	220	88	10	46	210	16	26	660
Ni	<1.5	4.5	<1.5	5.9	4.4	<1.5	3.4	2.3	1.6	4.0	3.5
Sc	<1.0	2.1	<1.0	2.1	2.5	<1.0	2.2	2.1	<1.0	2.1	3.7
Sr	170	37	24	170	120	28	110	310	13	78	290
V	8.1	19	5.9	31	27	9.7	23	18	5.6	21	28
Y	3.9	4.5	<1.5	6.5	8.8	3.1	7.2	9.8	3.9	6.7	11
Yb	.17	.57	<.15	.48	.56	<.15	.68	.68	.22	.49	1.1
Zn	<15	31	<15	50	55	<15	20	20	<15	27	35
Zr	31	82	16	64	48	22	61	91	89	77	100

TABLE 9.—*Estimated mineral content by X-ray diffraction of core samples of shale from the Frontier Formation and Hilliard Shale of southwestern Wyoming*

[Leaders (—) indicate none detected]

	Core samples							
	L4	L2-1A	L2-2A	A2-1	A-1A	C-1A	C-2A	F-1
	Mineral content (approximate weight percent)							
Quartz	34	33	51	33	51	40	35	46
Pyrite	3	2	2	7	---	1	4	4
Feldspar	3	---	---	5	---	---	2	4
Calcite	6	---	---	---	---	---	2	---
Dolomite	7	---	---	---	---	---	4	---
Clay minerals	47	65	47	56	49	59	53	46
	Clay minerals (estimated percent of total clay)							
Mica-illite and mixed-layer illite-smectite	85	95	70	90	75	100	95	90
Kaolin and chlorite	15	5	30	10	25	---	5	10

TABLE 10.—*Organic composition, vitrinite reflectance, and hydrocarbon potential of core samples of shale from the Frontier Formation and Hilliard Shale of southwestern Wyoming*

[C, carbon; mg/g, milligrams per gram; CO_2, carbon dioxide; °C, degrees Celsius; leaders (---) indicate not analyzed]

	Core samples							
	L4	L2-1A	L2-2A	A2-1	A-1A	C-1A	C-2A	F-1
Organic C (weight percent)	---	0.64	2.12	1.27	0.27	4.42	0.92	1.71
Volatile hydrocarbon, S_1 (mg/g)	---	0.04	0.04	0.08	0.01	0.28	0.12	0.25
Pyrolytic hydrocarbon, S_2 (mg/g)	---	0.25	1.84	0.83	0.07	4.48	0.37	5.84
Estimated capacity for oil generation	---	Nil	Slight	Nil	Nil	Large	Nil	Large.
Pyrolytic CO_2, S_3 (mg/g)	---	0.20	0.24	0.16	0.09	0.49	0.45	0.33
Temperature of maximum pyrolytic yield (°C)	---	462	466	455	456	474	462	430
Hydrogen index (mg hydrocarbon/g C)	---	40	87	65	24	101	40	341
Oxygen index (mg CO_2/g C)	---	32	11	13	36	11	49	19
Type of organic matter	---	Terrestrial humic.	Marine sapropelic?	Marine sapropelic.	Terrestrial humic.	Marine sapropelic.	Terrestrial humic.	Marine sapropelic.
Transformation ratio (S_1/S_1+S_2)	---	0.14	0.02	0.09	0.14	0.06	0.24	0.04
Mean vitrinite reflectance (percent)	0.67	0.80	0.72	0.74	0.75	1.04	1.14	0.48
Estimated thermal maturity	Mature	Mature	Mature	Mature	Mature	Mature	Mature	Immature.

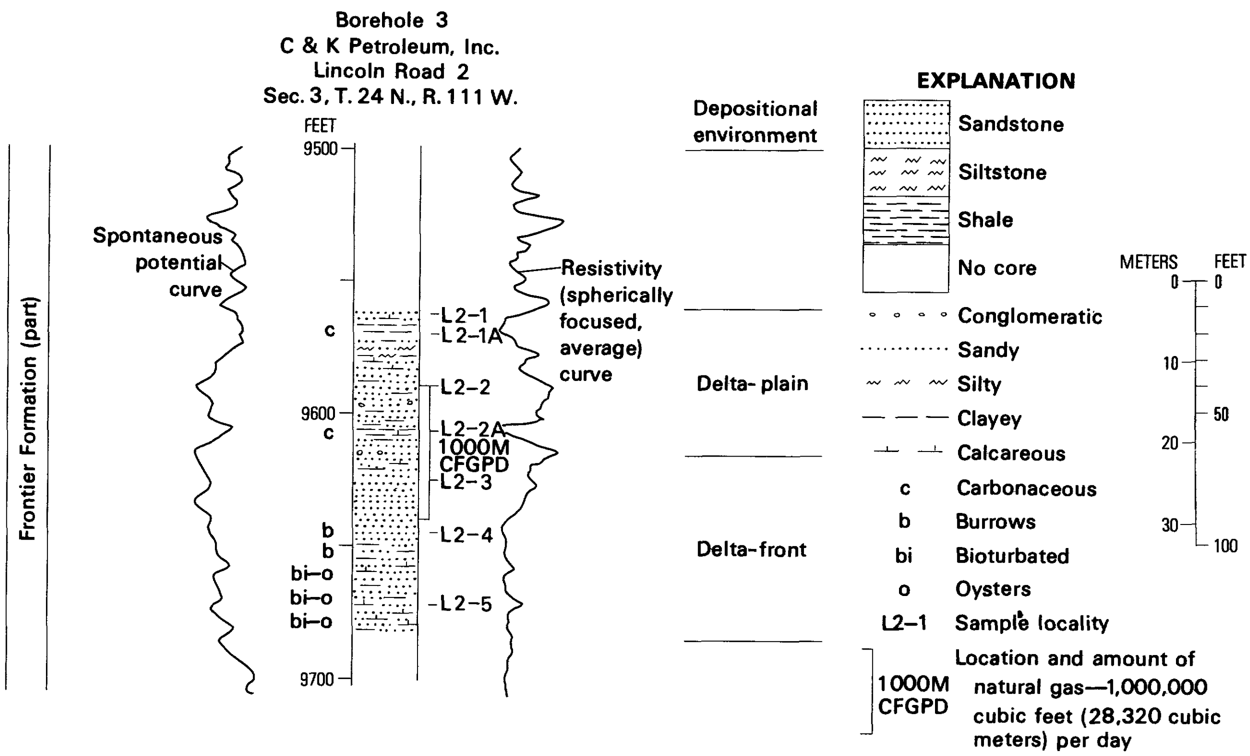


FIGURE 9.—Logs of cored and sampled strata in the Frontier Formation in borehole 3 on the Moxa arch, Wyoming (fig. 1).

gram) volatile hydrocarbon (S_1), and 0.25 mg/g pyrolytic hydrocarbon (S_2, table 10). Total hydrocarbon yield or the original hydrocarbon-generating capacity (volatile hydrocarbon, S_1, plus pyrolytic hydrocarbon, S_2) is 0.29 mg/g, which indicates that L2–1A is a poor source rock for oil and gas (G. E. Claypool, written commun., 1980). The hydrogen index (40) and oxygen index (32) reflect terrestrial humic organic matter in the sample (table 10). Thermal alteration of the shale, indicated (table 10) by the temperature of maximum pyrolytic yield (462°C), the transformation ratio or production index ($S_1/(S_1+S_2)=0.14$), and vitrinite reflectance (0.80 percent), is sufficient for oil generation, although this shale is a poor source rock for hydrocarbons.

Sample L2–2A consists largely of mica-illite, mixed-layer illite-smectite, kaolin, chlorite, and quartz (table 9). The sample also contains 2.12 percent organic carbon, 0.04 mg/g volatile hydrocarbon, and 1.84 mg/g pyrolytic hydrocarbon (table 9). For L2–2A, the total hydrocarbon yield is 1.88 mg/g, which represents a marginal source rock for oil (G. E. Claypool, written commun., 1980). From the hydrogen index (87) and oxygen index (11), the type of organic matter in the sample is interpreted to be dominantly marine sapropelic. The temperature of maximum pyrolytic yield (466°C) and the vitrinite reflectance (0.72 percent) indicate that the sampled bed is thermally mature with regard to oil generation.

BOREHOLE 6

Sample A2–1 consists of marine shale in the Frontier Formation from a depth of 2,408.6 m (7,902.0 ft) in borehole 6, on the north flank of the Rock Springs uplift (fig. 1, table 1). The shale is composed mostly of mica-illite, mixed-layer illite-smectite, quartz, and lesser amounts of pyrite, feldspar, kaolin, and chlorite (table 9). Organic carbon comprises 1.27 percent of the sample (table 10). The total hydrocarbon yield of A2–1 is 0.91 mg/g, of which 0.08 mg/g is volatile hydrocarbon and 0.83 mg/g is pyrolytic hydrocarbon. These values indicate a poor source rock for oil (G. E. Claypool, written commun., 1980). Marine sapropelic organic matter in the shale is indicated (table 10) by the hydrogen index (65) and the oxygen index (13). The temperature of maximum pyrolytic yield (455°C) and the vitrinite reflectance (0.74 percent) for sample A2–1 are evidence of an early stage of thermal alteration and oil generation (table 10).

The Frontier Formation and overlying Cretaceous and Tertiary strata in the Superior Oil Corp. Pacific Creek-Federal 1 well (sec. 27, T. 27 N., R. 103 W.), about 39 km (24.2 mi) north of borehole 6, were investigated by Law and others (1980). A core sample of marine shale, from the upper part of the Frontier at a depth of 6,249 m (20,503 ft), contains about 0.8 percent organic carbon, largely in the form of humic-kerogen (Law and others, 1980, p. 29 and fig. 7). A vitrinite reflectance value of 1.0–1.1 percent for the sample indicates sufficient thermal alteration of the humic material for the generation of gas in the Frontier.

BOREHOLE 8

Core sample A–1 was obtained from a very fine grained sandstone containing sparse burrows, at a depth of 2,133.1 m (6,998.0 ft) in borehole 8 on the north flank of the Rock Springs uplift (figs. 1 and 11, table 2). The sandstone probably was deposited in a delta-front environment. Sample A–1 has a modal grain size of 100 μm and consists of about 85 percent sand, 11 percent silt, and 5 percent clay (table 3). The sample has a porosity of about 14.6 percent and a permeability of as much as 0.63 mD. Thin sections of the rock show clay-filled, intergranular microporosity and rarely show moldic porosity. This sandstone sample is composed mainly of quartz, chert, and feldspar, which are cemented by clay and quartz (tables 4 and 5). According to Folk's (1974) classification, the rock is a sublitharenite. In sample A–1, the clay includes mixed-layer illite-smectite, mica-illite, chlorite, kaolin, and 7-Å trioctahedral clay, and the organic-carbon content is 0.04 percent (table 6). Rapid rock analysis shows comparatively small amounts of MgO, Na_2O, K_2O, and MnO in the sample (table 7). Spectrographic analysis indicates relatively small amounts of Al_2O_3, K_2O, Ba, La, Sc, Sr, V, and Zn (table 8). The sandstone units in the Frontier at borehole 8 apparently do not contain natural gas, even though the porosity ranges from 0.6 to 15.0 percent and the permeability ranges from less than 0.01 to 11.0 mD in the cored sandstone.

Sample A–1A from a depth of 2,130.9 m (6,991.0 ft) in borehole 8 consists of shale of shallow-marine or brackish-water origin (table 2). The shale is composed largely of mica-illite, mixed-layer illite-smectite, kaolin, chlorite, and quartz (table 9). The sample also contains (table 10) organic carbon (0.27 percent), and yields volatile hydrocarbon (0.01 mg/g) and pyrolytic hydrocarbon (0.07 mg/g). Total hydrocarbon content is 0.08 mg/g, which is insufficient for a source rock for oil or gas (G. E. Claypool, written commun., 1980). The hydrogen index (24) and oxygen index (36) for A–1A seem to represent terrestrial humic organic matter in the rock (table 10). With regard to oil generation, the shale is thermally mature, as indicated by the temperature of maximum pyrolytic yield (456°C), the transformation ratio (0.14), and vitrinite reflectance (0.75 percent).

BOREHOLE 11

Samples C–1 and C–2 were collected from cores of cross-stratified, very fine grained to fine-grained sandstone at depths of 3,383.9 m (11,101.7 ft) and 3,394.5 m (11,136.3 ft), respectively, in borehole 11 (figs. 1 and 12, table 2). These rocks probably were deposited in deltaic environments. Core sample C–1 has a modal grain size of 120 μm and is composed of about 79 percent sand, 13 percent silt, and 8 percent clay (tables 3 and 4). Porosity is 12.8–14.8 percent and permeability is as much as 0.91 mD. The sandstone has mostly clay-filled, intergranular microporosity and some intergranular and moldic mesoporosity, and consists mainly of detrital quartz, chert, rock fragments, and feldspar, cemented by clay and quartz (table 5). The thin sections also include minor amounts of tourmaline, zircon, leucoxene, and magnetite or ilmenite (D. L. Gautier, written commun., 1981). In Folk's (1974) classification, the sandstone is a litharenite. Viewed with a scanning electron microscope, pores in sample C–1 contain (fig. 10*C*) mixed-layer illite-smectite. Clays in the sample include mixed-layer illite-smectite and lesser amounts of mica-illite, chlorite, and 7–Å trioctahedral clay (table 6). Organic-carbon content is 0.06–0.07 percent. The sample also contains relatively large amounts of TiO_2, P_2O_5, B, and Cr (tables 7 and 8). Gas was not found in this sandstone unit.

Sample C–2 is composed of about 77 percent sand, 16 percent silt, and 7 percent clay, and has a modal grain size of 130 μm (tables 3 and 4). Porosity and permeability of the sample are about 4.7–6.7 percent and as much as 0.95 mD, respectively. In thin section, the rock shows secondary moldic and intergranular mesoporosity and clay-filled, intergranular microporosity, and consists mostly of detrital quartz, chert, rock fragments, and feldspar. Authigenic minerals include calcite, clay, and quartz (tables 4 and 5). This sandstone is also a litharenite (Folk, 1974). Micrographs of sample C–2 (fig. 10*D*), taken with a scanning electron microscope, show corroded, angular grains of quartz cemented by clay. The clay in the sample is largely mixed-layer illite-smectite, but includes mica-illite, chlorite, and 7–Å trioctahedral clay (table 6). Organic carbon content is 0.10 percent. The sample contains comparatively large amounts of CaO, Na_2O, K_2O, MnO, B, Sc, Sr, V, Y, Yb, and Zr (tables 7 and 8). Sample C–2 was obtained from the upper part of a sandstone that produces natural gas at depths of 3,397.7–3,403.8 m (11,147–11,167 ft) in borehole 11 (fig. 12). These reservoir rocks reportedly yield gas at an initial potential flow rate of 70,885.0 m^3 (2.503 million ft^3) per day.

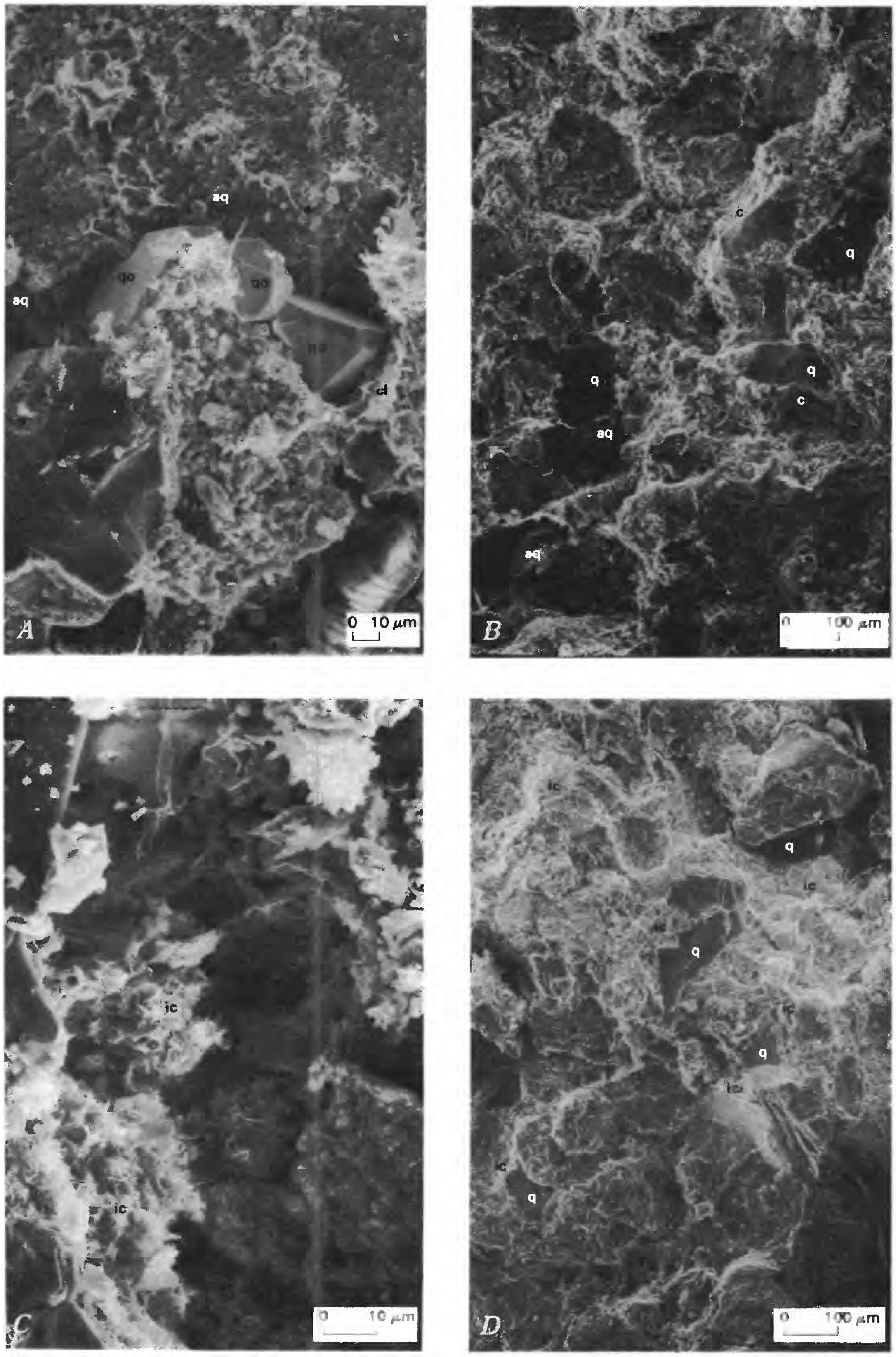
Sample C–1A, from a depth of 3,386.7 m (11,110.8 ft) in borehole 11 (fig. 12), is a carbonaceous shale, which was deposited in a deltaic environment (table 2). The shale consists mostly of mica-illite, mixed-layer illite-smectite, and quartz (table 9) but also contains 4.42 percent organic carbon (table 10). In this sample, the volatile hydrocarbon (0.28 mg/g), pyrolytic hydrocarbon (4.48 mg/g), and total hydrocarbon yield (4.76 mg/g) indicate a rich source rock for oil and gas (G. E. Claypool, written commun., 1980). Evidence of marine, sapropelic, organic matter in the sample (table 10) is provided by the hydrogen index (101) and the oxygen index (11). Oil and gas generation in this thermally mature shale is indicated (table 10) by the temperature of maximum pyrolytic yield (474°C) and vitrinite reflectance (1.04 percent).

Sample C–2A is shale of deltaic origin from a depth of 3,405.8 m (11,173.5 ft) in borehole 11 (table 2). It is composed mainly of mica-illite, mixed-layer illite-smectite, kaolin, chlorite, and quartz (table 9). The sample also contains 0.92 percent organic carbon, and yields 0.12 mg/g volatile hydrocarbon and 0.37 mg/g pyrolytic hydrocarbon (table 10). The shale evidently is a poor source rock for oil and gas (G. E. Claypool, written commun., 1980), as indicated by the total hydrocarbon yield (0.49 mg/g). Terrestrial humic matter in the sample is represented by the hydrogen index (40) and oxygen index (49). Thermal alteration, as represented by the temperature of maximum pyrolytic yield (462°C), the transformation ratio (0.24), and vitrinite reflectance (1.14 percent) for the shale, is suitable for the generation of oil and gas.

BOREHOLE 18

Core sample F–1 is from a depth of 1,609.4 m (5,280 ft) in borehole 18 in the eastern part of the overthrust belt (fig. 1, tables 1 and 2). The sample is shale of offshore-marine origin and is composed mostly of mica-illite, mixed-layer illite-smectite, kaolin, chlorite, quartz, feldspar, and pyrite (table 9). Analytical results for the organic material in the shale (table 10) include amounts of organic carbon (1.71 percent), volatile hydrocarbon (0.25 mg/g), and pyrolytic hydrocarbon (5.84

FIGURE 10 (facing page).—Photomicrographs of sandstone in the Frontier Formation of southwestern Wyoming, taken with a scanning electron microscope. *A*, Quartz overgrowths (qo) and pore-lining authigenic quartz (aq), mica-illite (i), and chlorite (cl) in core sample L2–1 of borehole 3. *B*, Grains of quartz (q) cemented by clays (c), and pore-lining authigenic quartz (aq) in core sample L2–2 of borehole 3. *C*, Mixed-layer illite-smectite (ic) lining a pore in core sample C–1 of borehole 11. *D*, Corroded grains of quartz (q) cemented largely by mixed-layer illite-smectite (ic) in core sample C–2 of borehole 11.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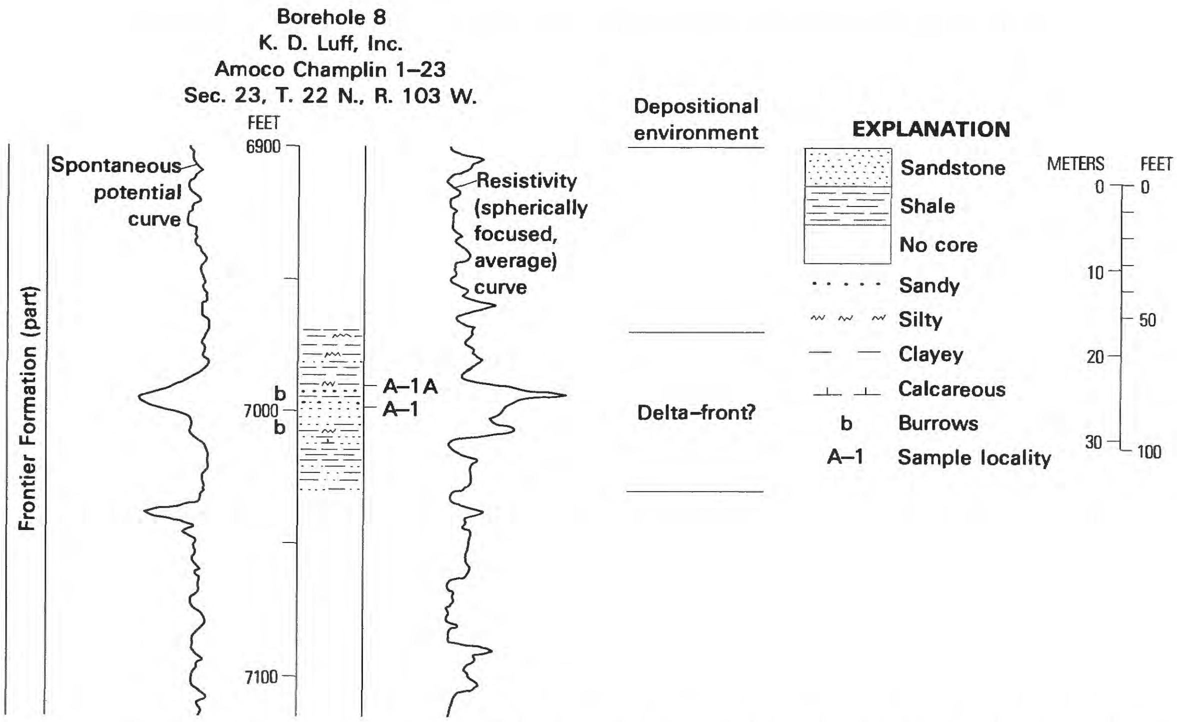

FIGURE 11.—Logs of cored and sampled strata in the Frontier Formation in borehole 8 on the Rock Springs uplift, Wyoming (fig. 1).

mg/g). The total hydrocarbon yield of 6.09 mg/g indicates that the sampled bed is a rich, potential source rock for oil (G. E. Claypool, written commun., 1980). Marine sapropelic matter in sample F–1 is represented by the hydrogen index (341) and oxygen index (19). The temperature of maximum pyrolytic yield (430°C), transformation ratio (0.04), and vitrinite reflectance (0.48 percent) are evidence that the shale is thermally immature with regard to oil generation.

SUMMARY AND INTERPRETATIONS

The samples of sandstone from cores of the Frontier Formation are composed of 73.0–90.8 percent sand, 5.3–15.6 percent silt, and 4.7–17.8 percent clay by weight (table 3). Modal grain sizes (table 4) range from 80 μm (very fine sand) to 160 μm (fine sand). The grains are moderately well sorted to extremely well sorted and are subangular to well rounded. These rocks consist largely of quartz, chert, feldspar, rock fragments, mica-illite, mixed-layer illite-smectite, chlorite, and 7–Å trioctahedral clay (tables 5 and 6). The sampled units of sandstone are litharenites and sublitharenites (Folk, 1974) and most of them were deposited in deltaic environments. Chert is most abundant in the sandstone of delta-plain origin.

The only samples that do not contain chlorite are S–1, L4–2, and L2–3 (table 6). These also contain less Fe_2O_3, TiO_2, B, Ni, Yb, and Zr than the other samples (table 8), which may indicate the lack of chlorite and relative deficiencies of heavy minerals. Furthermore, samples S–1 and L2–3 were obtained from gas-bearing strata (figs. 6 and 9) and sample L4–2 was obtained from slightly below gas-bearing beds (fig. 8). None of the samples of chloritic sandstone are from strata that contain gas, although samples L2–2 and C–2 are from slightly above gas-bearing beds.

Porosities of the sandstone samples range from 4.7 to 23.0 percent and permeabilities are from 0.14 to 6.80 mD. The samples generally have clay-filled, intergranular microporosity, although some have clay-filled, moldic microporosity and intergranular and moldic mesoporosity. Porosity has been reduced by compaction, including the mechanical deformation of ductile grains, and by precipitation of quartz, calcite, and authigenic clays, including mixed-layer illite-smectite, illite, chlorite, kaolin, and 7–Å trioctahedral clay. Authigenic clays commonly line and fill intergranular pores and block pore throats, thereby reducing porosity and permeability. Because of their characteristic microporosity, these sandstone units of the Frontier Formation are poor to fair reservoir beds for oil and gas. However, the permeability of the sandstone may be improved by fracturing treatments.

The composition of the sandstone samples, expressed as oxides of important rock-forming elements, was de-

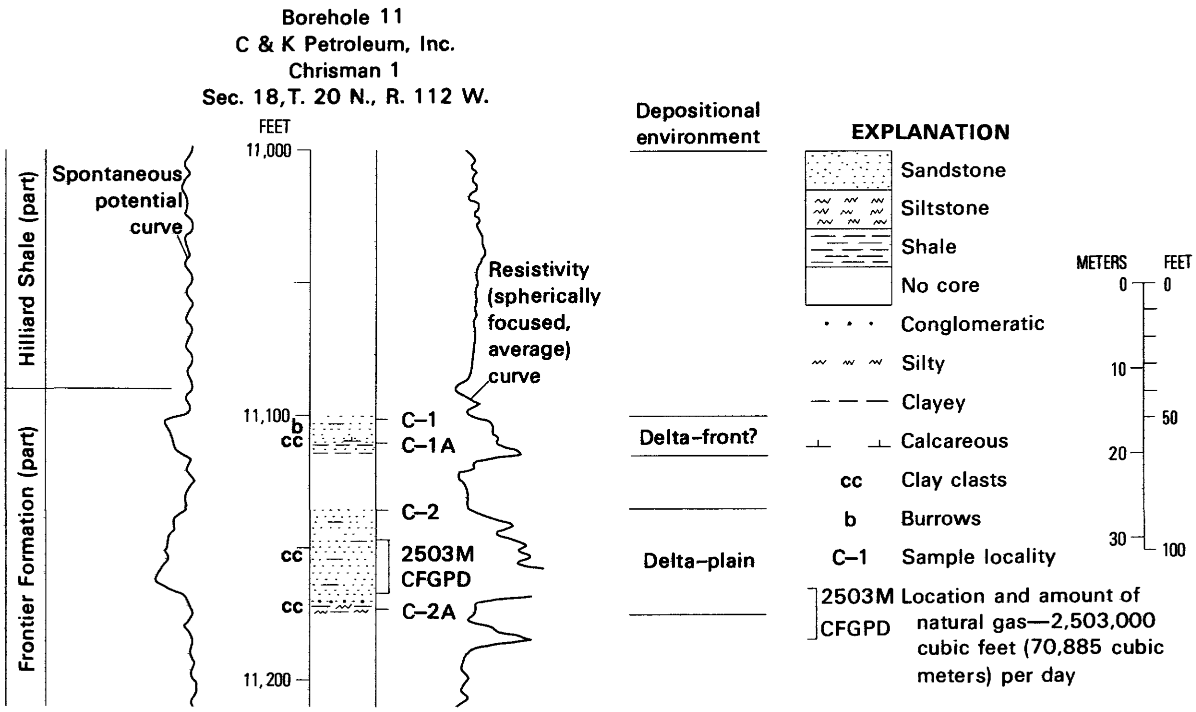

FIGURE 12.—Logs of cored and sampled strata in the Frontier Formation in borehole 11 on the Moxa arch, Wyoming (fig. 1).

termined by atomic absorption, spectrophotometry (rapid rock-analysis), and by semiquantitative emission spectroscopy (tables 7 and 8). These rocks, which are mainly of deltaic origin, contain about 72–96 percent SiO_2, 2–7 percent Al_2O_3, 0.1–3 percent Fe_2O_3 + FeO, 0.1–0.5 percent MgO, as much as 9 percent CaO, 0.1–1 percent Na_2O, and 0.3–1.5 percent K_2O. The samples of sandstone from the delta plain (L2–1, L2–2, and C–2), in comparison with the other sandstone samples, contain larger amounts of iron oxide, Co, Ni, and Zn.

Grain sizes and chemical data were compared statistically by means of correlation coefficients (r) by J. J. Connor (table 11). For the 11 samples of this study, r values of 0.52 and more are significant (the probability that these values do not arise by chance is 95 percent). Many elements are significantly and negatively correlated with the amounts of sand (r values of −0.52 to −0.83). The correlations indicate that most of the elements are concentrated in the silt and clay fractions of the samples. However, there is a positive correlation (r=0.64) between sand and Zn. Significant positive r values relate the silt fraction to Fe, Mg, Ca, Ti, Mn, B, Cr, Sc, Sr, V, Y, Zr, Al, and Na. The clay fraction has a significant positive correlation with Fe and Ba. Organic carbon is significantly related only to Cu (r=−0.62). Of the major rock-forming elements, the closely associated Fe and Mg (r=0.94), and Mg and Al (r=0.87) probably represent mica-illite, chlorite, mixed-layer illite-smectite, and biotite, mainly in the silt fraction of the samples. Calcium is correlative with Sr (r=0.85) and with Mn (r=0.95), which seems to indicate carbonate minerals in the silt fraction. Sodium correlates most strongly with Al (r=0.91) and probably represents sodic feldspar in the silt fraction. The correlation of K and Al (r=0.92) in the silt and clay fractions of these rocks largely represents potassium feldspar and mica-illite. Potassium and barium also are closely associated (r=0.95), perhaps indicating barium-bearing mica-illite in the silt and clay. Titanium is most directly related to B (r=0.94), Cr (r=0.89), and Fe (r=0.87), which probably are associated in heavy minerals such as tourmaline and ilmenite in the silt fraction. Phosphorus (P) correlates significantly only with Cu (r=0.68).

Shale samples from cores of the Frontier are composed mainly of quartz, mica-illite, mixed-layer illite-smectite, kaolin, and chlorite (table 9). However, they also contain 0.27–4.42 percent organic carbon, including 0.01–0.28 mg/g volatile hydrocarbon and 0.07–5.84 mg/g pyrolytic hydrocarbon (table 10). The organic matter in the samples was derived from terrestrial humic and marine sapropelic material.

Shale samples were obtained from boreholes 2, 3, and 11 (fig. 1 and table 1), which produce gas from the Frontier, and from boreholes 6, 8, and 18, in which the Frontier is nonproductive. Samples A2–1 and A–1A from boreholes 6 and 8, respectively, on the Rock

TABLE 11.—*Correlation coefficients for amounts of sand, silt, clay, organic carbon, and selected elements in eleven samples of sandstone of the Frontier Formation in southwestern Wyoming (statistically significant values are 0.52 and more)*

Silt	Clay	Organic C	Al	Fe	Mg	Ca	Na	K	Ti	P	Mn	Ba	B	Co	Cu	Cr	La	Ni	Sc	Sr	V	Y	Yb	Zn	Zr	
-0.62	-0.80	-0.01	-0.71	-0.83	-0.76	-0.44	-0.58	-0.66	-0.74	-0.05	-0.47	-0.63	-0.83	0.07	-0.27	-0.53	-0.40	-0.19	0.05	-0.53	-0.69	-0.56	-0.69	0.64	-0.75	Sand
	.03	.05	.64	.66	.72	.80	.77	.44	.61	.06	.76	.35	.72	.26	.33	.59	.50	.03	.79	.68	.63	.80	.47	.16	.76	Silt
		-.05	.42	.54	.41	-.07	.16	.50	.47	.00	.01	.55	.50	-.20	.10	.22	.12	.17	-.43	.14	.39	.07	.40	-.56	.36	Clay
			-.10	-.08	-.02	.37	-.28	.16	.14	-.43	.21	.30	.06	.14	-.62	.14	.08	-.03	.00	.25	.12	.19	.29	-.26	.22	Org. C
				.74	.87	.48	.91	.92	.71	-.16	.60	.83	.87	.39	.41	.76	.75	.67	.35	.76	.94	.79	.75	.17	.46	Al
					.94	.43	.72	.59	.87	.02	.46	.50	.86	.51	.55	.74	.57	.75	-.04	.45	.80	.65	.76	.41	.83	Fe
						.56	.82	.72	.86	-.25	.60	.65	.90	.69	.50	.82	.72	.93	.06	.62	.91	.75	.76	.80	.75	Mg
							.49	.35	.35	-.09	.95	.36	.45	.54	-.06	.29	.56	.05	.50	.85	.48	.61	.16	.11	.56	Ca
								.72	.68	.09	.57	.56	.82	.32	.60	.73	.71	.43	.52	.67	.82	.84	.64	.31	.51	Na
									.67	-.38	.44	.95	.83	.22	.13	.72	.62	.60	.11	.70	.89	.69	.80	-.48	.36	K
										-.01	.28	.63	.94	.21	.47	.89	.58	.51	-.78	.41	.80	.70	.72	-.40	.81	Ti
											-.16	-.30	-.27	.22	.68	-.18	.33	-.31	-.14	-.10	-.25	.09	-.23	.17	-.18	P
												.42	.45	.61	.00	.26	.60	.27	.67	.90	.55	.60	.22	.25	.46	Mn
													.75	.32	.04	.67	.65	.62	-.44	.70	.83	.56	.71	-.61	.29	Ba
														.06	.39	.85	.59	.50	.00	.59	.88	.82	.87	-.65	.77	B
															.42	.62	.83	.74	.11	.54	.63	.40	.27	.98	-.37	Co
																.54	.50	.24	.01	.00	.42	.25	.15	.64	.26	Cu
																	.65	.83	.02	.42	.89	.66	.72	.58	.59	Cr
																		.45	.04	.73	.77	.72	.50	.50	.29	La
																			-.10	.37	.85	.20	.42	.77	-.52	Ni
																				.47	.48	.64	.84	.26	.31	Sc
																					.69	.76	.47	-.03	.36	Sr
																						.78	.84	.75	.55	V
																							.85	-.02	.59	Y
																								-.24	.56	Yb
																									-.47	Zn

Springs uplift (fig. 1) contain inadequate hydrocarbons for the generation of oil and their organic constituents are insufficiently altered for the generation of gas (table 10). Similarly, the organic matter of sample F–1 from borehole 18 in the overthrust belt is thermally immature and has not generated oil or gas. Samples L4, L2–1A, L2–2A, from gas-producing boreholes on the Moxa arch, have marginal thermal maturity as source rocks for gas and samples L2–1A and L2–2A do not contain enough hydrocarbons to be source rocks for oil. Evidently, the gas in the reservoir rocks of boreholes 2 and 3 was derived from beds below the sampled shale units. The thermal maturation of samples C–1A and C–2A, which represent beds above and below a gas-bearing sandstone in borehole 11 on the Moxa arch (fig. 10), is suitable for the generation of oil and gas. Furthermore, the total hydrocarbon yield (4.76 mg/g) and type of organic matter (marine sapropelic) for C–1A are typical of a source rock for oil and gas. For sample C–2A, the total hydrocarbon yield (0.49 mg/g) is inadequate and the humic organic matter is inappropriate for the generation of oil, although this shale may have yielded gas. Presumably, some of the gas in the reservoir rocks of borehole 11 was generated in the sampled shale units (fig. 10).

In conclusion, interbedded sandstone, siltstone, and shale of deltaic and nearshore-marine origin and of middle Turonian to early Coniacian age comprise the upper part of the Frontier Formation, the "second Frontier sandstone" of DeChadenedes (1975) and Myers (1977), in much of southwestern Wyoming. On the Moxa arch and on the Rock Springs uplift, these strata commonly include lenticular reservoir beds and thermally mature source rocks for gas at depths of about 2,591–3,871 m (8,500–12,700 ft). The broad geographic distribution of these strata and the large variation in depths of the mature source rocks and gas-bearing sandstone reservoirs may indicate that the hydrocarbon resources in the upper part of the Frontier in the Green River Basin are extremely large. The lower part of the formation in the basin is a truncated unit of shale, siltstone, and sandstone that thickens to the north and west. Because outcrops and cores of these rocks are sparse and relevant petrologic data are lacking, conclusions concerning their composition, age, and depositional environment are tentative and interpretations regarding their oil and gas potential would be speculation.

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