

Stratigraphy of
Mid-Cretaceous Formations at
Drilling Sites in
Weston and Johnson Counties,
Northeastern Wyoming

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Stratigraphy of Mid-Cretaceous Formations at Drilling Sites in Weston and Johnson Counties, Northeastern Wyoming

By E. A. MEREWETHER

PALEONTOLOGY AND STRATIGRAPHY OF MID-CRETACEOUS ROCKS—
NORTHEASTERN WYOMING

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*A description and comparison of the
dissimilar formations of early
Late Cretaceous age in core holes and
outcrops on the eastern and western
flanks of the Powder River Basin*



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PALEONTOLOGY AND STRATIGRAPHY OF MID-CRETACEOUS ROCKS—
NORTHEASTERN WYOMING

STRATIGRAPHY OF MID-CRETACEOUS FORMATIONS
AT DRILLING SITES IN WESTON AND JOHNSON COUNTIES,
NORTHEASTERN WYOMING

By E. A. MEREWETHER

ABSTRACT

The sedimentary rocks of early Late Cretaceous age in Weston County, Wyo., on the east flank of the Powder River Basin, are assigned, in ascending order, to the Belle Fourche Shale, Greenhorn Formation, and Carlile Shale. In Johnson County, on the west flank of the basin, the lower Upper Cretaceous strata are included in the Frontier Formation and the overlying Cody Shale. The Frontier Formation and some of the laterally equivalent strata in the Rocky Mountain region contain major resources of oil and gas. These rocks also include commercial deposits of bentonite.

Outcrop sections, borehole logs, and core studies of the lower Upper Cretaceous rocks near Osage, in Weston County, and Kaycee, in Johnson County, supplement comparative studies of the fossils in the formations. Fossils of Cenomanian, Turonian, and Coniacian Age are abundant at these localities and form sequences of species which can be used for the zonation and correlation of strata throughout the region.

The Belle Fourche Shale near Osage is about 115 m (meters) thick and consists mainly of noncalcareous shale, which was deposited in offshore-marine environments during Cenomanian time. These strata are overlain by calcareous shale and limestone of the Greenhorn Formation. In this area, the Greenhorn is about 85 m thick and accumulated in offshore, open-marine environments during the Cenomanian and early Turonian. The Carlile Shale overlies the Greenhorn and is composed of, from oldest to youngest, the Pool Creek Member, Turner Sandy Member, and Sage Breaks Member. In boreholes, the Pool Creek Member is about 23 m thick and consists largely of shale. The member was deposited in offshore-marine environments in Turonian time. These rocks are disconformably overlain by the Turner Sandy Member, a sequence about 50 m thick of interstratified shale, siltstone, and sandstone. The Turner accumulated during the Turonian in several shallow-marine environments. Conformably overlying the Turner is the slightly calcareous shale of the Sage Breaks Member, which is about 91 m thick. The Sage Breaks was deposited mostly during Coniacian time in offshore-marine environments.

In Johnson County, the Frontier Formation consists of the Belle Fourche Member and the overlying Wall Creek Member, and is overlain by the Sage Breaks Member of the Cody Shale. Near Kaycee, the Belle Fourche Member is about 225 m thick and is composed mostly of interstratified shale, siltstone, and sandstone. These strata are mainly of Cenomanian age and were deposited largely in shallow-marine environments. In this area, the Belle

Fourche Member is disconformably overlain by the Wall Creek Member, which is about 30 m thick and grades from interlaminated shale and siltstone at the base of the member to sandstone at the top. The Wall Creek accumulated during Turonian time in shallow-marine environments. These beds are overlain by the Sage Breaks Member of the Cody. Near Kaycee, the Sage Breaks is about 65 m thick and consists mainly of shale which was deposited in offshore-marine environments during Turonian and Coniacian time.

Lower Upper Cretaceous formations on the east side of the Powder River Basin can be compared with strata of the same age on the west side of the basin. The Belle Fourche Shale at Osage is represented near Kaycee by most of the Belle Fourche Member of the Frontier. The Greenhorn at Osage contrasts with beds of similar age in the Belle Fourche at Kaycee. An upper part of the Greenhorn Formation, the Pool Creek Member of the Carlile Shale, and the basal beds of the Turner Sandy Member of the Carlile, in Weston County, are represented by a disconformity at the base of the Wall Creek Member of the Frontier in southern Johnson County. A middle part of the Turner in the vicinity of Osage is the same age as the Wall Creek Member near Kaycee. A sequence of beds in the upper part of the Turner and in the overlying Sage Breaks in Weston County is the same age as most of the Sage Breaks Member of the Cody in southern Johnson County.

INTRODUCTION

This report describes the lower Upper Cretaceous strata at boreholes and nearby outcrops in Johnson and Weston Counties, Wyo. (fig. 1) and will supplement the paleontologic studies of W. A. Cobban (mollusca), W. G. E. Caldwell and B. R. North (foraminifera), F. E. May and B. L. Whitney (dinoflagellates), and D. J. Nichols (palynomorphs). Outcrops, cores, and geophysical logs of the formations were investigated during 1975-79. The cores and logs were obtained from boreholes in NE1/4SW1/4 sec. 6, T. 42 N., R. 81 W., near Kaycee (Kaycee 7 1/2 minute quadrangle) in Johnson County, and in SW1/4NW1/4, sec. 30, T. 46 N., R. 63 W., near Osage (Osage 7 1/2 minute quadrangle) in Weston County (fig. 1). Molluscan fossils from outcrops

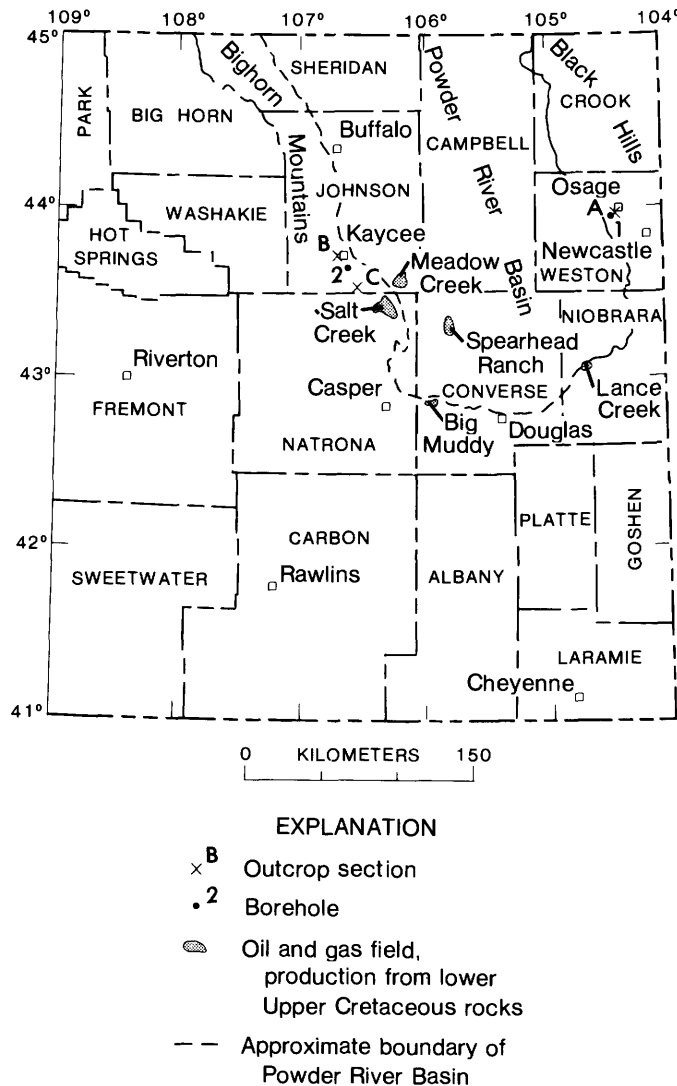


FIGURE 1.—Index map of Wyoming, showing the Powder River Basin and locations of outcrop sections A, B, and C, boreholes 1 and 2, and selected oil and gas fields.

near the drilling sites are listed in the following pages and are represented by some of the species named on figure 2. Fossils obtained from the core are described in other chapters of this volume by the paleontologists named above.

The core of the lower Upper Cretaceous formations was supplied mainly by J. D. Tucker and S. J. Grant. Geophysical logs of the boreholes were furnished by R. A. McCullough. R. W. Brown and B. M. Madsen performed X-ray analyses of samples from the core. G. E. Claypool, V. E. Shaw, J. P. Baysinger, Nancy Conklin, and T. L. Yager determined the organic composition of shale samples. The grain-size distribution of samples of sandstone was provided by M. B. Sawyer and E. T. Cavanaugh, using an image-analyzing com-

puter. Thin sections of sandstone were prepared by K. L. Gardner and examined by J. C. Webb, J. M. Nishi, M. J. Pinel, and E. T. Cavanaugh photographed samples of sandstone with a scanning electron microscope. Molluscan fossils from the region were prepared for study by R. E. Burkholder and identified by W. A. Cobban and N. F. Sohl. These contributions, from employees of the U.S. Geological Survey, are gratefully acknowledged.

In this investigation, samples from cores of shale and sandstone, and the clay fraction of the sandstone, were analyzed for constituent minerals by X-ray diffraction. The organic composition and thermal maturity of some of the rocks were determined by several methods (Merewether and Claypool, 1980). Organic-carbon content was obtained from the difference between total carbon, measured by combustion, and carbonate carbon, measured by acidification of a separate part of the sample. Hydrocarbon content and related characteristics were determined by thermal-evolution analysis (Claypool and Reed, 1976). The vitrinite reflectance reported herein is a mode of the reflectance values, in percent, for populations of vitrinite particles in oil.

The nomenclature used in this report for the size and sorting of the grains in sandstone and siltstone was described by Folk (1974). Micrographs, taken with a scanning electron microscope, and thin sections were used mainly to study the mineralogy of these rocks. Statistical descriptions of the grain sizes in samples of sandstone were obtained from an image-analyzing computer (Sawyer, 1977). For each sample, the diameters of 300 disaggregated grains were measured electronically, and the volume percentages of grains, in categories defined by grain diameter, were calculated. The computer program assumed that all grains are spherical and did not consider the variation in density of the grains in most rocks. As a consequence, data from the computer are not absolutely comparable with results from conventional procedures of sieving and weighing grains unless the grains are spherical and monomineralic.

STRATIGRAPHY

The strata of early Late Cretaceous age in Wyoming vary in lithology, thickness, and depositional environment, and commonly enclose one or more unconformities. They consist mainly of shale, siltstone, sandstone, conglomerate, and bentonite, but they locally include coal in western Wyoming and limestone in eastern Wyoming. At outcrops in Lincoln County, in southwestern Wyoming, the lower Upper Cretaceous Frontier Formation is about 670–790 m thick (Veatch, 1907, p. 65–69) and was deposited in marine and non-

Stage	Informal substage	Western Interior molluscan fossil zones; numbers represent zones identified at outcrop sections (figs. 2, 9, and 14)	K-Ar ages (million yrs.) (Obradovich and Cobban, 1975)	Osage area, Weston County ¹	Kaycee area, Johnson County	Central Natrona County		
Santonian	Lower	25 <i>Clioscaphites saxitonianus</i> 24 <i>Scaphites depressus</i>	86.8	Niobrara Formation (lower part) ?	Niobrara Member (lower part)	Niobrara Member (lower part)		
	Coniacian	Upper		23 <i>Scaphites ventricosus</i>	Sage Breaks Member	?	?	
Middle		22 <i>Inoceramus deformis</i>		Cody Shale (lower part)		Sage Breaks Member	Sage Breaks Member	
Lower		21 <i>Inoceramus erectus</i> 20 <i>Inoceramus waltersdorfensis</i>				Wall Creek Member	Wall Creek Member	
Turonian	Upper	19 <i>Prionocyclus quadratus</i> 18 <i>Scaphites nigricollensis</i> 17 <i>Scaphites whitfieldi</i> 16 <i>Scaphites warreni</i> 15 <i>Prionocyclus macombi</i>		88.9	Turner Sandy Member	Wall Creek Member	Wall Creek Member	
		Middle			14 <i>Prionocyclus hyatti</i> 13 <i>Collignoniceras woollgari regulare</i> 12 <i>Collignoniceras woollgari woollgari</i>			?
	Lower				11 <i>Mammites nodosoides</i> 10 <i>Watinoceras coloradoense</i>	Frontier Formation	Greenhorn Formation	?
		Cenomanian			Upper			9 <i>Sciponoceras gracile</i> 8 <i>Dunveganoceras albertense</i> 7 <i>Dunveganoceras pondi</i>
Middle	6 <i>Plesiacanthoceras wyomingense</i> 5 <i>Acanthoceras amphibolum</i> 4 <i>Acanthoceras alvaradoense</i> 3 <i>Acanthoceras muldoonense</i> 2 <i>Acanthoceras granerosense</i> 1 <i>Calycoceras gilberti</i>			Belle Fourche Shale	Belle Fourche Member			
	Lower					No molluscan fossil record		
			94					

¹Age of basal contact of Niobrara Formation from Evetts (1976, p.121).

FIGURE 2.—Correlation chart of the lower Upper Cretaceous formations at selected localities in northeastern Wyoming. Pattern represents a hiatus in the sequence of beds.

marine environments during Cenomanian, Turonian, and Coniacian time. Near the Black Hills (fig. 1), a sequence of approximately the same age is about 370 m thick and was deposited in marine environments.

The sedimentary rocks of early Late Cretaceous age in Weston County, on the east side of the Powder River Basin (fig. 1), are included in, from older to younger, the Belle Fourche Shale, Greenhorn Formation, and Carlile Shale (fig. 2). They conformably overlie the Mowry Shale of Early Cretaceous age and are disconformably overlain by the Upper Cretaceous Niobrara Formation. Near the town of Osage, the lower Upper Cretaceous sequence is about 370 m thick and is com-

posed of shale, siltstone, sandstone, limestone, and bentonite. These rocks were deposited in offshore-marine and nearshore-marine environments and contain invertebrate fossils of Cenomanian, Turonian, Coniacian, and Santonian age.

The lower Upper Cretaceous rocks in Johnson County, on the west side of the Powder River Basin (fig. 1), include the Frontier Formation and the overlying Sage Breaks Member of the Cody Shale (fig. 2). These strata conformably overlie the Lower Cretaceous Mowry Shale and are conformably overlain by the Niobrara Member of the Cody Shale. Near the town of Kaycee, the lower Upper Cretaceous sequence

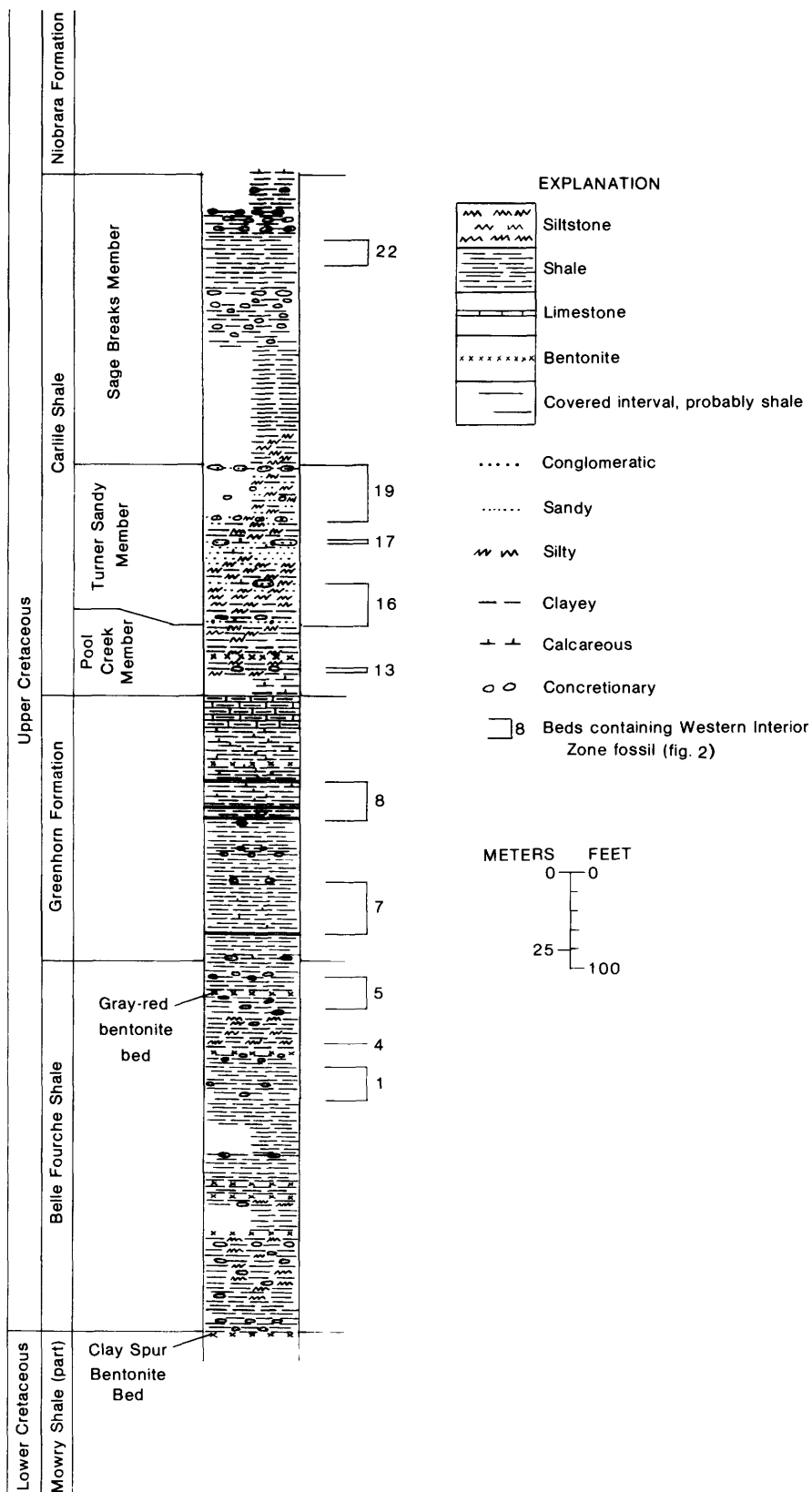


FIGURE 3.—Outcrop section A of the lower Upper Cretaceous formations near Osage, secs. 16, 17, 19, 20, and 30, T. 46 N., R. 63 W., Weston County. Data included from Robinson and others (1964).

is about 315 m thick and consists of shale, siltstone, sandstone, minor conglomerate, and bentonite. These rocks were deposited largely in nearshore-marine environments and contain molluscan fossils of Cenomanian, Turonian, and Coniacian Age.

BELLE FOURCHE SHALE

The Belle Fourche Shale was named by Collier (1922, p. 83) from outcrops near the Belle Fourche River in southwestern Crook County, on the west flank of the Black Hills (fig. 1). In Weston County, near Osage, the formation is about 115 m thick and is composed mainly of interstratified shale and bentonite. Most of the beds are soft. Consequently, the Belle Fourche seldom crops out and generally forms strike valleys. These strata conformably overlie the well-indurated Mowry Shale of Early Cretaceous age and are overlain by the ridge-forming Greenhorn Formation of Late Cretaceous age. The Belle Fourche Shale accumulated during Cenomanian time; the upper part of the formation near Osage contains invertebrate fossils of middle Cenomanian age (fig. 2). These rocks were deposited in offshore-marine environments.

The Belle Fourche Shale is about 118 m thick at the outcrop section near Osage (fig. 3), and 115–122 m thick in boreholes in the area. The formation is about 113 m thick near Newcastle, southeast of Osage, and as much as 260 m thick in western Crook County (Robinson and others, 1964, p. 53–60), northwest of Osage. Robinson and others (1964, p. 53) concluded that this variation in thickness is caused by the lateral gradation of noncalcareous rocks in the upper part of the Belle Fourche into calcareous shale which is locally assigned to the overlying basal Greenhorn.

At outcrops in Weston County, the Belle Fourche is composed largely of noncalcareous shale, silty shale, and bentonite. Small amounts of calcareous shale and siltstone occur near the top of the formation. Units of dark-gray shale in the Belle Fourche are commonly more than 6 m thick. The units of siltstone are light gray to dusky yellow to pale brown, platy, and less than 1 m thick. Beds of very light gray to grayish-orange bentonite, as much as 1 m thick, are abundant. Ferruginous concretions are common in the Belle Fourche, and sideritic concretions are especially plentiful in the basal 20 m of the formation.

Cores of the uppermost 25 m of the formation from borehole 1 in SW1/4 NW1/4 sec. 30, T. 46 N., R. 63 W. (fig. 1) include interlaminated shale and lesser siltstone (fig. 4). These rocks are very light gray to dark gray, largely noncalcareous, and contain small horizontal burrows and molluscan fossils. The laminae are commonly discontinuous, even, and parallel; discon-

tinuous, wavy, and nonparallel; and microcross-laminated. Some of the core has flaser bedding, lenticular bedding, and small slump structures. Samples from depths of about 258 m and 267 m were analyzed by X-ray diffraction. They contain quartz, sodic plagioclase, potassium feldspar, dolomite, pyrite, mica-illite, and chlorite. The laminae at a depth of 258 m also contain montmorillonite and calcite. At 267 m, the laminae include smectite or mixed-layer clay, and kaolinite. The organic composition of these samples (table 1) was described and interpreted by Merewether and Claypool (1980). In the borehole, the Belle Fourche includes potential source rocks for hydrocarbons, but the sampled beds are thermally immature (in an early stage of the hydrocarbon-generation process).

In the vicinity of Osage, the upper part of the Belle Fourche, which is about 40 m thick, contains invertebrate fossils of middle Cenomanian age (fig. 2). Species in selected collections from these beds are:

USGS D9911, SW1/4 sec. 17, T. 46 N., R. 63 W., from a ferruginous concretion layer 7 m below the top of the Belle Fourche Shale.

Acanthoceras amphibolum Morrow
Inoceramus rutherfordi Warren
Borissiakoceras sp.

USGS D9920, SW1/4 sec. 17, T. 46 N., R. 63 W., from a ferruginous concretion layer 13 m below the top of the Belle Fourche Shale.

Acanthoceras amphibolum Morrow
Inoceramus rutherfordi Warren

USGS D9924, NW1/4 sec. 17, T. 46 N., R. 63 W., from a ferruginous concretion layer 27 m below the top of the Belle Fourche Shale.

Inoceramus arvanus Stephenson
Ostrea beloiti Logan
Acanthoceras alvaradoense Moreman?

USGS D9923, NW1/4 sec. 17, T. 46 N., R. 63 W., from a ferruginous concretion layer 35 m below the top of the Belle Fourche Shale.

Exogyra columbella Meek
Borissiakoceras compressum Cobban

USGS D9910, SW1/4 sec. 17, T. 46 N., R. 63 W., from a claystone concretion layer 38 m below the top of the Belle Fourche Shale.

Inoceramus eulessanus Stephenson
Exogyra columbella Meek
Acanthoceras sp.
Borissiakoceras compressum Cobban

The Belle Fourche consists of clay-rich strata and contains fossils and burrows of marine origin. Apparently, these rocks were deposited in shallow-water, offshore-marine environments, where mild current action alternated with slack water. Interstratified sandstone and shale of the same age but of near-shore-marine origin crop out near Kaycee (fig. 1), about 180 km west of the Osage area (Merewether and others, 1976).

TABLE 1.—Organic composition of lower Upper Cretaceous shale at boreholes 1 and 2, Powder River Basin, as determined by thermal evolution analysis, combustion, and reflectance

[From Merewether and Claypool, 1980. N.d., not determined]

Borehole No.	Stratigraphic unit	Sample depth (m)	Organic carbon (weight percent)	Total pyrolytic hydrocarbon (weight percent)	Volatile hydrocarbon (ppm by weight)	Ratio of pyrolytic hydrocarbon to organic carbon (percent)	Temperature of maximum pyrolytic yield (°C)	Modal vitrinite reflectance at random orientation (percent)
1	Sage Breaks Member of Carlile Shale.	29.0	1.28	0.17	33	13.6	459	N.d.
1	----do-----	59.4	2.23	.60	35	26.9	455	0.45
1	----do-----	80.8	1.38	.25	30	17.9	469	.50
1	Turner Sandy Member of Carlile Shale.	112.2	1.13	.08	9	7.5	467	.40
1	----do-----	130.2	.97	.14	44	14.7	464	.65
1	Pool Creek Member of Carlile Shale.	146.3	1.06	.11	24	10.6	461	N.d.
1	----do-----	157.0	4.29	1.90	200	44.3	446	.50
1	Greenhorn Formation.	163.4	2.17	.76	56	35.1	451	N.d.
1	----do-----	199.7	2.80	1.08	96	38.7	451	N.d.
1	----do-----	244.5	2.97	.99	65	33.2	454	.45
1	Belle Fourche Shale.	257.6	1.61	.39	32	24.0	458	N.d.
1	----do-----	266.7	1.16	.19	23	16.1	472	.45
2	Sage Breaks Member of Cody Shale.	48.8	.7	.11	65	16.0	477	.45
2	Wall Creek Member of Frontier Formation.	82.6	.5	.071	38	14.3	487	.55
2	Belle Fourche Member of Frontier Formation.	86.6	3.2	.32	79	10.0	466	.45
2	----do-----	137.2	.4	.058	44	14.5	471	.50
2	----do-----	222.8	1.2	.14	69	11.6	475	.50
2	----do-----	277.1	2.4	.35	71	14.5	476	.50

GREENHORN FORMATION

Darton (1909, p. 54-55) introduced the name Greenhorn Limestone into the northern Black Hills and Cobban (1951, p. 2183) changed the name to Greenhorn Formation in this area. In Weston County, near Osage, the formation is about 85 m thick and consists of interstratified calcareous and noncalcareous shale and siltstone, limestone, and bentonite. The indurated strata in the upper part of the formation form a conspicuous *quarta*, which extends along the western flank of the Black Hills. In that region, the Greenhorn overlies and intertongues with the Belle Fourche Shale (Robinson and others, 1964, fig. 5) and is overlain by

the Carlile Shale. In the Osage area, the formation contains invertebrate fossils of middle and late Cenomanian and early Turonian age and was deposited in offshore, open-marine environments.

The Greenhorn Formation is about 86 m thick at borehole 1 and ranges in thickness from 80 to 90 m in other boreholes in the area. At outcrops near Osage, the formation is 75-84 m thick. Robinson and others (1964, p. 65-66) reported thicknesses of 90 m for the Greenhorn near Newcastle, and 27 m for the formation farther northwest in northwestern Crook County.

At outcrops in Weston County, limestone of the Greenhorn Formation is generally light gray to medium gray to grayish orange, slightly silty or sandy,

laminated to thin bedded, and fossiliferous. Units of limestone are as much as 50 cm (centimeters) thick. The limestone at the top of the formation has abundant horizontal burrows which contain spreite and are about 1 cm in diameter and as much as 30 cm long. The shale is medium gray to grayish black, noncalcareous to very calcareous, and forms units as much as 10 m thick. Some of the shale encloses ferruginous and septarian limestone concretions and is fossiliferous.

A core of the Greenhorn from borehole 1 (figs. 1 and 5) is composed mainly of interlaminated medium dark-gray to dark-gray shale and very light gray to light-gray siltstone. In general, these rocks grade from slightly calcareous near the base of the formation to very calcareous near the top. Most of the laminae are discontinuous, even, and parallel, but in the upper part of the formation some are discontinuous, wavy, and nonparallel. They commonly contain small horizontal burrows, fragments of molluscan fossils, and fish bones.

Samples of the core from depths of about 163 m, 176 m, 200 m, and 244 m were analyzed by X-ray diffraction. All of these rocks contain quartz, calcite, clay, and pyrite, although the proportion of calcite to other minerals appears to be larger in the samples from 163 m and 176 m. The laminae at depths of 200 m and 244 m also contain mica-illite, chlorite, kaolinite, sodic plagioclase, potassium feldspar, and dolomite. At 163 m, the rock includes mica-illite, chlorite, smectite or mixed-layer clay, sodic plagioclase, potassium feldspar, and dolomite.

The organic composition of samples from depths of 163 m, 200 m, and 245 m was reported by Merewether and Claypool (1980). Hydrogen-rich organic matter, which was derived largely from aquatic plants, is comparatively abundant in the sampled strata (table 1). These rocks could generate oil and gas if their organic components were not thermally immature.

The Greenhorn Formation in the Osage area contains abundant molluscan fossils of late Cenomanian and early Turonian age (fig. 2). Representative collections are:

USGS D5935, NE1/4 sec. 20, T. 46 N., R. 63 W., from calcareous shale 11 m below the top of the Greenhorn Formation.

Mytiloides mytiloides (Mantell)

Pseudoperma bentonensis (Logan)

USGS D5934, S1/2 sec. 17, T. 46 N., R. 63 W., from very thin, light-brown calcarenite 27 m below the top of the Greenhorn Formation.

Inoceramus cf. *I. mesabiensis* Bergquist

Metococeras defordi Young

USGS D5932, S1/2 sec. 17, T. 46 N., R. 63 W., from very thin, light-brown calcarenite 34 m below the top of the Greenhorn Formation.

Phellopteria sp.

Inoceramus pictus Sowerby

Calycoceras sp.

Metococeras defordi Young

USGS D5929, S1/2 sec. 17, T. 46 N., R. 63 W., from soft, limonitic concretions 40 m below the top of the Greenhorn Formation.

Dunveganoceras albertense (Warren)

USGS D5928, S1/2 sec. 17, T. 46 N., R. 63 W., from soft, limonitic concretions 59 m below the top of the Greenhorn Formation.

Inoceramus pictus Sowerby

Calycoceras? canitaurinum (Haas)

USGS D9898, SE1/4 sec. 7, T. 46 N., R. 63 W., from light-brown limestone concretion near base of Greenhorn Formation.

Inoceramus prefragilis Stephenson

Calycoceras? canitaurinum (Haas)

Dunveganoceras pondi Haas

In Weston County, the Greenhorn is composed largely of fossiliferous, calcareous, and argillaceous strata. Evidently, the formation was deposited in open-marine environments of low current energy, far from shore. Interstratified shale and sandstone of Greenhorn age but of nearshore-marine origin crop out near Kaycee and Casper on the southwest flank of the Powder River Basin (Merewether and others, 1979) (fig. 1).

CARLILE SHALE

The name Carlile Shale was first used in the Black Hills region by Darton (1909, p. 54-55). In the vicinity of Osage, the Carlile is about 165 m thick and includes, in ascending order, the Pool Creek Member, Turner Sandy Member, and Sage Breaks Member (fig. 2). Knechtel and Patterson (1962, p. 921) named the Pool Creek Member from outcrops along Pool Creek on the northeast flank of the Black Hills. The Pool Creek consists mostly of interlaminated shale and siltstone, and is calcareous at the base and noncalcareous at the top. These strata are disconformably overlain by the Turner Sandy Member, which is composed of interstratified shale, siltstone, and sandstone. The sandy beds of the Turner are conformably overlain by the slightly calcareous shale of the Sage Breaks. The Turner Sandy Member and Sage Breaks Member were named by Rubey (1930, p. 4) from outcrops near Osage.

Most of the Carlile is soft and forms a topography of little relief; however, beds of concretionary siltstone and sandstone in the Turner commonly crop out as small hogbacks and questas. In Weston County, the Carlile overlies the Greenhorn Formation and is disconformably overlain by the Niobrara Formation. The Carlile at Osage contains invertebrate fossils of Turonian, Coniacian, and Santonian Age and was

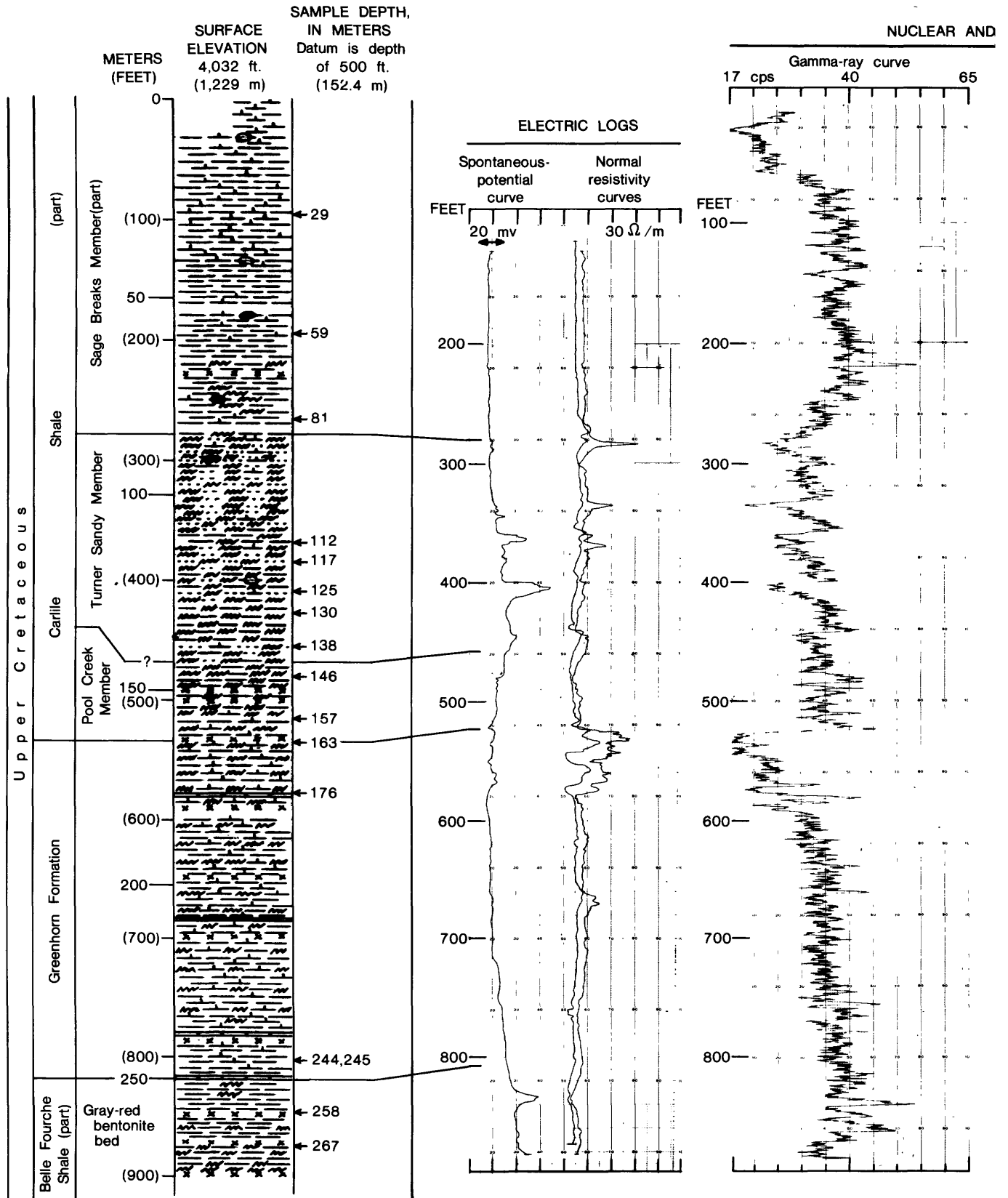
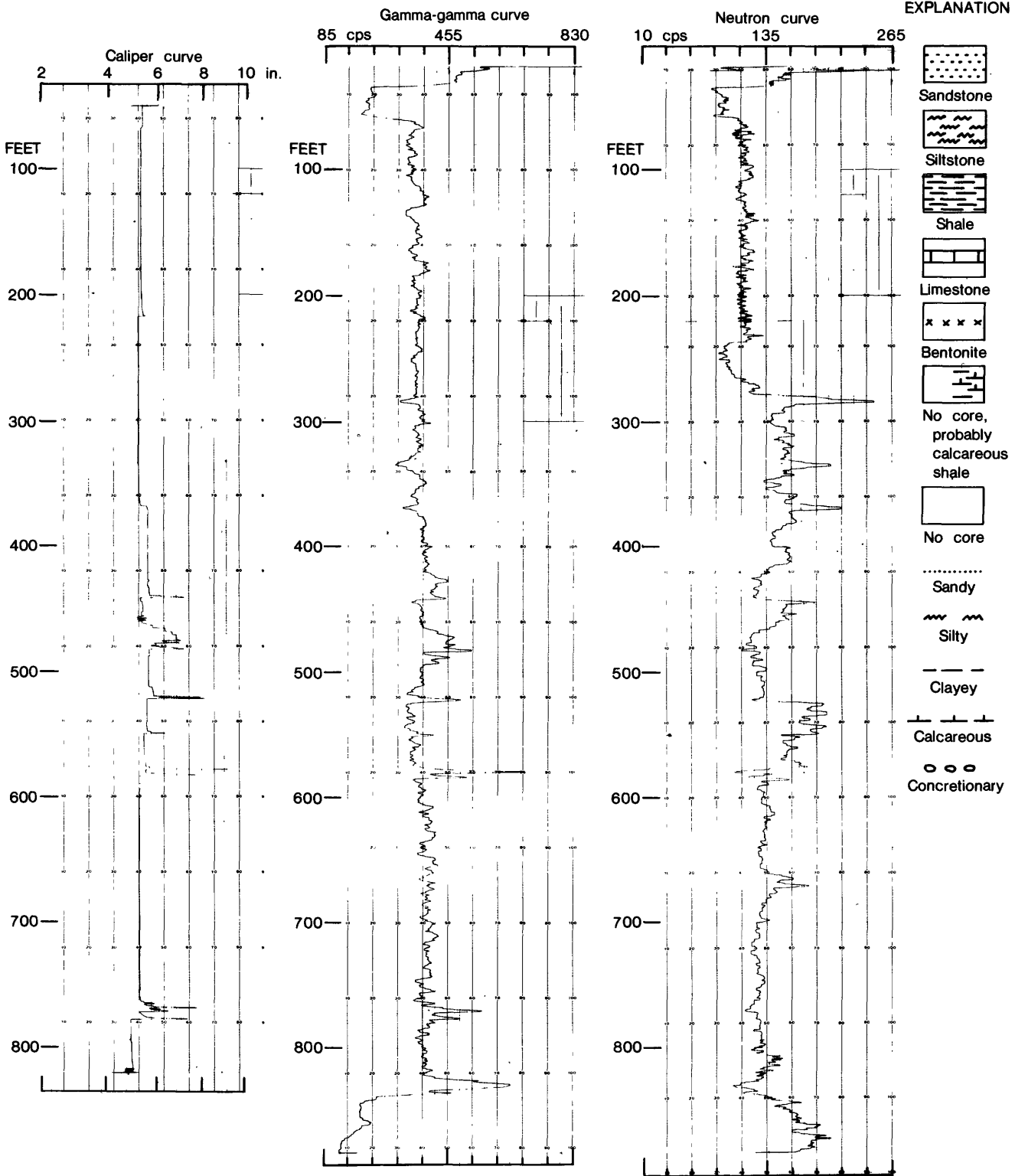


FIGURE 4.—Lithologic and geophysical logs of lower Upper Cretaceous formations near

CALIPER LOGS

NUCLEAR LOGS



Osage, from borehole 1, SW1/4NW1/4 sec. 30, T. 46 N., R. 63 W., Weston County.

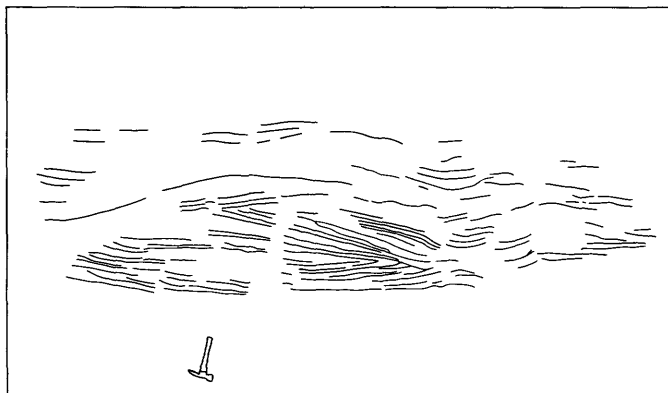


FIGURE 5.—Drawing showing crossbedding in the middle of the Turner Sandy Member near Osage. The hammer is 28 cm long. Direction of view is southeast.

deposited in offshore-marine and nearshore-marine environments.

POOL CREEK MEMBER

The Pool Creek Member is about 23 m thick at borehole 1 (fig. 4) and 20–28 m thick in nearby oil wells. At outcrops along the west side of the Black Hills, the member is about 30 m thick near Newcastle, about 28 m thick near Osage, and about 15 m thick near the border of Weston and Crook Counties (fig. 1) (Robinson and others, 1964, p. 72–74).

At outcrops in the vicinity of Osage (fig. 3), the Pool Creek consists of dark-gray, silty shale and minor light-gray bentonite, and has conspicuous layers of light-gray, calcareous concretions near the middle. The units of shale are as much as 12 m thick, and the beds of bentonite are as much as 34 cm thick. Locally, the lithology of the uppermost Pool Creek contrasts strongly with the lithology of the overlying basal sandstone of the Turner Sandy Member. The Pool Creek correlates with the unnamed member of the Frontier in central Natrona County (fig. 2).

Core of the Pool Creek Member from borehole 1 (fig. 4) consists largely of interlaminated dark-gray shale and light-gray siltstone. In the lower one-half of the member, most of the rocks are calcareous. The laminae in the core are generally discontinuous and are either wavy and nonparallel or even and parallel. Many laminae contain small horizontal burrows, although only a minor part of the Pool Creek is bioturbated. Molluscan fossils and fish bones are common.

Samples of the core from depths of 146 m and 157 m were analyzed to determine their mineral composition and organic-carbon content. Both samples contain quartz, mica-illite, smectite or mixed-layer clay, chlorite, sodic plagioclase, potassium feldspar,

dolomite, and pyrite. Kaolinite was recognized in the sample from a depth of 146 m. The laminae at about 157 m contain minor calcite. Merewether and Claypool (1980) described the organic composition of some of these strata (table 1). The constituent organic matter is suitable for conversion to oil and gas. However, the sampled rocks have been only slightly altered by burial metamorphism and are, therefore, in an early stage of the petroleum-forming process.

In Weston County, the Pool Creek contains molluscan fossils of middle Turonian age. A representative collection of fossils from the vicinity of Osage is:

USGS D9896, NW1/4 sec. 35, T. 46 N., R. 63 W., from calcareous concretions about 14 m below the top of the Pool Creek Member.

Inoceramus cuvieri Sowerby

Pseudomelania hendricksoni Henderson

Scaphites larvaeformis Meek and Hayden

Collignonicerias woollgari regulare Haas

Tragodesmoceras carlilense Cobban

The Pool Creek Member near Osage consists mainly of interlaminated shale and siltstone, and contains small horizontal burrows and fossils of marine origin. The member probably accumulated in offshore-marine environments of comparatively low current energy. Sandstone and shale of approximately the same age but of nearshore-marine origin crops out west of Casper in southeastern Natrona County (fig. 1) and is assigned to the unnamed member of the Frontier Formation (Merewether and others, 1979).

TURNER SANDY MEMBER

The Turner Sandy Member is about 55 m thick in borehole 1 and ranges in thickness from 49 m to 59 m at other boreholes in the area. At outcrops, the member is about 50 m thick near Osage, approximately 57 m thick near the boundary of Weston and Crook Counties (Robinson and others, 1964, p. 72–73), and about 56 m thick in the vicinity of Newcastle.

In Weston County, the Turner is composed of interstratified shale, siltstone, and sandstone. These rocks disconformably overlie the Pool Creek Member and are conformably overlain by the Sage Breaks Member of the Carlile. At outcrops near Osage (fig. 3), the lower one-half of the Turner includes, from older to younger, a thin basal sandstone, a unit which grades from shale at the base to sandstone at the top, and another similar gradational unit. The upper one-half of the member consists of siltstone, shale, and minor sandstone. The shale in the Turner is mainly dark gray, silty, and noncalcareous, and the siltstone is largely medium gray, argillaceous or sandy, and noncalcareous. The units of

shale are as much as 8 m thick. Most of the sandstone in the member is light gray to grayish orange, very fine grained, silty, and calcareous; however, the basal sandstone is locally medium grained and contains sparse, coarse grains, granules, and pebbles of quartz and chert. The sand grains are dominantly angular to subrounded and generally are not well sorted. A few beds of sandstone appear to have good porosity. Units of sandstone are as much as 5 m thick. The siltstone and sandstone are commonly in sequences of very thin to thin, discontinuous beds and show scour and fill bedding, tabular crossbedding, trough crossbedding (fig. 5), and ripple marks. Paleocurrent directions, obtained from crossbeds and ripple marks, are southwest, northeast, and southeast, but the dominant direction seems to be southeast. Burrows, which are plentiful in the outcropping siltstone and sandstone, are parallel and perpendicular to the strata and include *Ophiomorpha*, *Thalassinoides*, *Rhizocorallium* and, tentatively, *Rosselia*, *Cruziana*, and *Skolithos*. Fragments of fossil wood in the basal sandstone are extensively bored. At outcrops, the Turner contains conspicuous calcareous siltstone and sandstone concretions, which are commonly fossiliferous.

The core of the Turner Sandy Member is composed of interstratified and intergradational light-gray sandstone, light-gray to medium-gray siltstone, and medium-gray to dark-gray shale (fig. 4). Shale is a minor component of the core and most of it is interlaminated with siltstone or sandstone. Generally, the laminae of shale and siltstone are discontinuous and are either wavy and nonparallel or even and parallel. Flaser and lenticular bedding are common near the base of the member. Some strata are cross-laminated and others are bioturbated. The shale and siltstone commonly enclose small, smooth burrows (including *Siphonites*) which parallel the bedding planes. Most of the sandstone is very fine grained, thinly laminated to very thinly bedded, and horizontally stratified, and contains burrows. Some sandstone units are fine grained with sparse, medium to very coarse grains, some are slightly calcareous, and some are cross-stratified or bioturbated. Many of the cored beds in the Turner contain molluscan fossils.

The organic composition of the shale at depths of about 112 m and 130 m in borehole 1 (table 1) was described by Merewether and Claypool (1980). Evidently, the organic matter in these strata was derived mainly from land plants and is thermally immature. Although the organic-carbon content of the sampled beds is comparatively low, the shale in the Turner could be a source rock for natural gas.

Samples of the core, which were analyzed by X-ray diffraction, consist of sandstone from depths of about

117 m, 125 m, and 138 m, and shale from depths of about 112 m and 130 m. Most of these rocks contain quartz, mica-illite, kaolinite, chlorite, potassium and sodium feldspars, and dolomite. The samples of sandstone also contain calcite, and the rocks from 112 m, 117 m, 130 m, and 138 m contain pyrite. Micrographs of the sandstone, taken with a SEM, depict authigenic minerals, including quartz, feldspar (fig. 6), kaolinite, chlorite, and pyrite.

Thin sections of the sandstone from depths of about 117 m, 125 m, and 138 m show angular to subrounded grains of quartz, chert, and feldspar, and minor amounts of detrital chalcedony, biotite, and other minerals. Many of the grains of quartz, chert, and feldspar are angular because they are corroded and have been partially replaced by clay and calcite (fig. 7). Most of the sand grains appear to have been subrounded at the time of deposition.

Samples of sandstone from depths of about 117 m, 125 m, and 138 m in borehole 1 were analyzed to determine the size and sorting of the constituent grains. In the sample from a depth of 117 m, the sand has a mean grain size of 1.91 phi (medium sand), a standard deviation of 0.47 phi (well sorted), and a skewness of +0.24 (fine skewed), and a kurtosis of 2.62 (very leptokurtic). At a depth of 125 m, the sand has a mean grain size of 2.76 phi (fine sand), a standard deviation of 0.54 phi (moderately well sorted), a skewness of -0.30 (coarse skewed); and a kurtosis of 2.22 (very leptokurtic). The sand in the sample from 138 m has a mean grain size of 1.78 phi (medium sand), a standard deviation of 0.47 phi (well sorted), a skewness of +0.66 (strongly fine skewed), and a kurtosis of 3.52 (extremely leptokurtic).

To summarize, these samples of Turner sandstone consist of clay, silt, and very fine to coarse sand grains. The amount of clay in the samples, estimated from X-ray analyses, is probably less than 10 percent. At depths of 117 m and 138 m, the sand is largely medium grained and is well sorted and angular to subrounded. The sand at 125 m is mostly fine grained, is moderately well sorted, and is angular to subrounded. The grain-size distribution for the sand in these three samples is asymmetric and very leptokurtic. Although the sand is moderately well sorted and well sorted, which is evidence of submature, mature, and supermature sedimentary textures, the rocks may contain a significant amount of clay, which characterizes immature textures. However, micrographs taken with a SEM show that much of the clay is authigenic. Furthermore, the roundness and presumably the sorting of the grains has been affected by post depositional dissolution. Therefore, these textures probably were mature or supermature before diagenesis.



FIGURE 6.—Authigenic crystal of feldspar (f) on a corroded crystal of quartz (q), from sandstone in the Turner Sandy Member at a depth of 125 m in borehole 1.

In the area of Osage, outcrops of the Turner contain invertebrate fossils of late Turonian age. Representative collections of these fossils are:

USGS D9915, NW1/4 sec. 20, T. 46 N., R. 63 W., from calcareous sandstone concretions about 5 m below the top of the Turner Sandy Member.

Inoceramus incertus Jimbo
Inoceramus lusatae Andert
Scaphites corvensis Cobban
Bostrychoceras n. sp.
Prionocyclus quadratus Cobban
Eutrephoceras sp.

Perissoptera cf. *P. prolabiata* (White)

USGS D9914, NE1/4 sec. 20, T. 46 N., R. 63 W., from calcareous sandstone concretions about 17 m below the top of the Turner Sandy Member.

Inoceramus n. sp.
Inoceramus lusatae Andert
Baculites yokoyamai Tokunaga and Shimizu
Scaphites sp.
Prionocyclus sp.
Bellifusus willistoni (Logan)

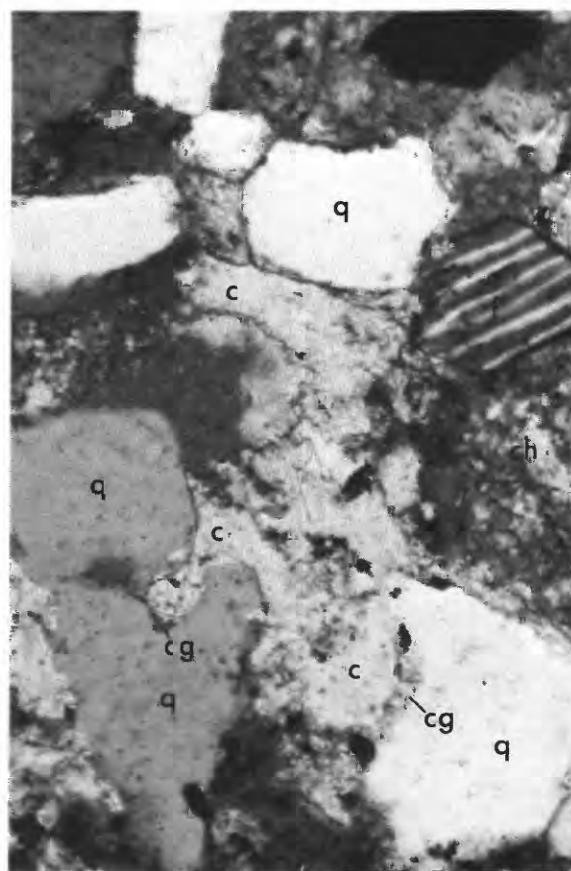


FIGURE 7.—Corroded grains (cg) of quartz (q), chert (ch), and feldspar (f), cemented by calcite (c) in a thin section of sandstone from the Turner Sandy Member, at a depth of 117 m in borehole 1.

USGS D9899, NW1/4 sec. 18, T. 46 N., R. 63 W., from sandstone concretions about 24 m below the top of the Turner Sandy Member.

Inoceramus perplexus Whitfield
Pleurocardia sp.
Scaphites whitfieldi Cobban

USGS D9912, NW1/4 sec. 20, T. 46 N., R. 63 W., from calcareous sandstone concretions about 40 m below the top of the Turner Sandy Member.

Inoceramus dimidius White
Scaphites warreni Meek and Hayden
Prionocyclus wyomingensis Meek

USGS D9917, NW1/4 sec. 20, T. 46 N., R. 63 W., from sandstone concretions about 1.5 m above the base of the Turner Sandy Member.

Inoceramus dimidius White
Prionocyclus sp.

USGS D10121, NW1/4 sec. 31, T. 47 N., R. 64 W., from sandstone about 1 m above the base of the Turner Sandy Member.

Inoceramus n. sp.
Scaphites warreni Meek and Hayden
Prionocyclus macombi Meek

The Turner Sandy Member in the vicinity of Osage is composed of interstratified shale, siltstone, and sandstone, and contains horizontal and vertical burrows and invertebrate fossils of marine origin. Some shale units grade upward into sandstone units, which are overlain by more shale. Much of the sandstone is moderately well sorted to well sorted and consists of angular to subrounded, very fine and fine grains of quartz, chert, and feldspar. The sandstone is laminated to thin bedded and locally has scour-and-fill bedding and crossbedding. In Weston County, the Turner was deposited in shallow-marine environments (probably at depths of less than 60 m) in the distal part of a high-destructive, tide-dominated delta (Merewether and others, 1979). Some of these strata accumulated in the form of nearshore and offshore bars.

SAGE BREAKS MEMBER

In boreholes near Osage, the Sage Breaks is commonly 91–94 m thick. The part of the member penetrated at borehole 1 is about 85 m thick. Robinson and others (1964, p. 71–73) reported thicknesses of about 78 m at outcrops between Osage and Newcastle, and about 83 m at outcrops on the northwestern flank of the Black Hills.

In Weston County, outcrops of the Sage Breaks are composed largely of dark-gray, noncalcareous shale which contains several conspicuous layers of closely spaced concretions (fig. 3). The concretions are commonly light gray to grayish orange, calcareous, and septarian, and are as much as 45 cm thick and 1.8 m long. The Sage Breaks is conformable and gradational with the underlying Turner and is disconformably overlain by the Niobrara Formation.

Where cored in borehole 1, the Sage Breaks Member consists mainly of medium-dark-gray, slightly calcareous, thinly laminated shale (fig. 4). Most of the shale in the basal 12 m of the member is slightly silty, and much of the shale in the uppermost 45 m of the member is pyritic. The core contains sparse concretions, a few small horizontal burrows, and many invertebrate fossils. A bed of bentonite about 8 cm thick was found about 18 m above the base of the Sage Breaks.

Core of the Sage Breaks, from depths of about 29 m, 59 m, and 81 m in borehole 1, was sampled to determine the mineral composition and organic-carbon content of some of the shale. X-ray diffraction analysis indicates that the samples contain quartz, mica-illite, chlorite, kaolinite, calcite, dolomite, sodium and potassium feldspars, and pyrite. The organic matter in the samples (table 1) was described by Merewether and Claypool (1980). They concluded that the Sage Breaks

in the Osage area includes potential source rocks for oil and gas but that the member is thermally immature.

Outcrops of the Sage Breaks in Weston County rarely contain megafossils, although molluscan fossils of middle Coniacian age were collected from the upper part of the member in the vicinity of Osage (figs. 2 and 3). Representative collections of these fossils are:

USGS D10152, SE1/4 sec. 19, T. 46 N., R. 63 W., from small calcareous concretions about 26 m below the top of the Sage Breaks Member.

Calcareous worm tube

Inoceramus inconstans Woods

Inoceramus sp.

Baculites mariasensis Cobban

USGS D10150, SW1/4 sec. 12, T. 46 N., R. 64 W., from soft dark-gray shale about 28 m below the top of the Sage Breaks Member.

Inoceramus deformis Meek

Inoceramus inconstans Woods

Pseudoperna congesta (Conrad)

The Sage Breaks Member near Osage is composed of thinly laminated, noncalcareous, and calcareous shale, and contains sparse horizontal burrows and many molluscan fossils. These rocks were deposited in offshore-marine environments of little current energy, which apparently were a great distance from the shore. Laterally equivalent units of nearshore-marine sandstone crop out in Fremont County (fig. 1) in central Wyoming.

FRONTIER FORMATION

The rocks of early Late Cretaceous age on the west flank of the Powder River Basin (fig. 1) are included in the Frontier Formation and the lower part of the overlying Cody Shale (fig. 2). They were first assigned to those formations by Hares (1916, p. 238) and Hares and others (1946). The Frontier conformably overlies the Lower Cretaceous Mowry Shale and is conformably overlain by the Cody Shale. In Johnson County, near Kaycee, the Frontier consists of the Belle Fourche Member, which was identified in this area by Merewether and Cobban (1973, p. 38), and the overlying Wall Creek Member, which was named by Wegemann (1911, p. 45). The Wall Creek in Johnson County rests disconformably on the Belle Fourche (Merewether and others, 1976, p. 35) and, at the top, interfingers with the lower part of the Cody Shale (Haun, 1958, p. 84). Lithologic and geophysical logs of the Frontier Formation in borehole 2 (fig. 1) were depicted by Merewether and others (1976, fig. 4). In Natrona County, near Casper, the Frontier is composed of, from older to younger, the Belle Fourche Member, unnamed member, and Wall Creek Member (fig. 2). The lower

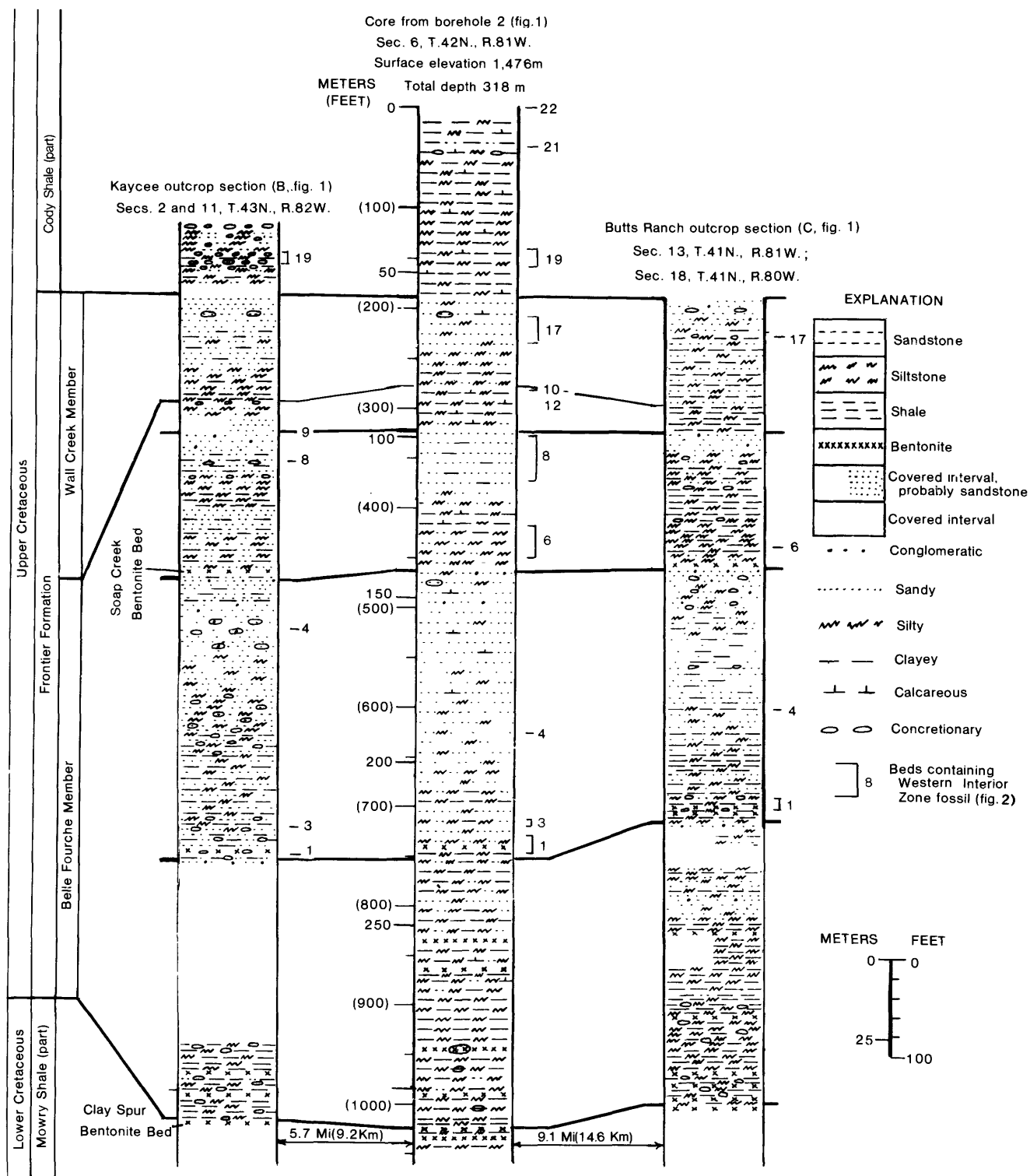


FIGURE 8.—Stratigraphic sections of the lower Upper Cretaceous Frontier Formation near Kaycee, Johnson County.

and upper contacts of the unnamed member are discontinuities.

The Frontier in the Kaycee area consists of about 255 m of interstratified shale, siltstone, sandstone,

minor conglomerate, and bentonite (fig. 8) (Merewether and others, 1976). Outcrops of these rocks commonly form a series of questas and strike valleys. In the vicinity of Kaycee, the Frontier contains molluscan

fossils of Cenomanian and Turonian age, and evidently was deposited largely in nearshore-marine environments.

BELLE FOURCHE MEMBER

In holes drilled for oil and gas near Kaycee, the Belle Fourche Member is 211–227 m thick. The member is about 228 m thick at borehole 2 and is about 223 m thick at outcrops in the area.

In the southern part of Johnson County, the Belle Fourche locally consists of four units of mainly shale and siltstone, and three intervening units of mostly sandstone. At outcrops, the shale in the member is largely dark gray or brownish gray, silty, and non-calcareous. Most of the outcropping siltstone is medium dark gray, clayey or sandy, and noncalcareous. The shale and siltstone are generally soft but commonly contain calcareous and ferruginous concretions. Sideritic concretions are abundant in a basal unit about 30 m thick that consists of interstratified shale, siltstone, and bentonite. The sandstone in the Belle Fourche is mainly very light gray to medium gray, very fine and fine grained, silty, noncalcareous, and moderately porous. Most of the grains are angular to subrounded and are moderately well sorted to well sorted. Grains of quartz, chert, glauconite, mica, and pyrite, and fine fragments of coaly material have been observed in hand specimens. Most of the sandstone is laminated to thin bedded, and the strata are largely either discontinuous and nonparallel or bioturbated.

The oldest of the three informal units of sandstone in the Belle Fourche Member is about 145 m below the top of the member and was designated the Third Wall Creek sand by Richardson (1957). In ledges and cliffs 3–4 km southwest of borehole 2 (fig. 1), this sandstone is as much as 40 m thick and is light gray, fine to coarse grained, and poorly sorted. Some beds near the top are conglomeratic and contain shale pebbles. The unit consists of tabular and trough crossbeds in sets as thick as 1.2 m, which are evidence of southeast-flowing paleocurrents. The lower part of the sequence includes wavy bedding and load structures. No burrows were observed in the sandstone. At outcrops about 15 km southeast of the borehole, this unit is represented by interlaminated and interbedded shale, siltstone, and very fine grained sandstone. These rocks are horizontally bedded and crossbedded, and apparently contain no burrows.

The most conspicuous unit of sandstone in the Belle Fourche is about 57 m below the top of the member and was named informally the Second Wall Creek sand by Richardson (1957). It is also informally called the "Second Wall Creek sandstone" or "Second Frontier

sandstone" (Barlow and Haun, 1966, p. 2185). In the vicinity of Kaycee, the sandstone is as much as 63 m thick and forms a prominent light-gray *questa*. This unit of sandstone, which is overlain by the Soap Creek Bentonite Bed (fig. 8) of Richards and Rogers (1951), can be divided into two parts. The lower part is about 48 m thick and grades from interlaminated shale, siltstone, very fine grained sandstone, and bentonite at the base, to fine-grained or medium-grained, crossbedded sandstone at the top. Cross-strata near the top of this sequence are in tabular sets as much as 30 cm thick. The lower part of the Second Wall Creek sand is mostly friable, but near the top it includes brownish-gray, calcareous concretions as large as 3 m in diameter. These concretions contain scattered pebbles of chert, fossilized fragments of burrowed wood, *Ophiomorpha*, and molluscan fossils.

The upper part of the Second Wall Creek sand consists mainly of interstratified very fine grained and fine grained sandstone and less dark-gray and brownish-gray shale. A thin bed of conglomerate occurs near the top of the sequence. This conglomerate is as much as 30 cm thick and contains pebbles of chert and igneous rocks as much as 8 cm long. Sandstone beds near the base of the sequence contain burrows, and those in the upper part of the unit are cross-stratified.

The uppermost unit of sandstone (not designated specifically by Richardson) in the Belle Fourche Member of the Kaycee area is about 14 m below the top of the member (fig. 8) and ranges in thickness from about 6 m to 23 m. These rocks are poorly cemented, although they contain hard, calcareous concretions, and the unit generally crops out as a weak ledge. Most of the sandstone is medium gray, very fine grained to fine grained, and poorly sorted, and contains burrows and molluscan fossils. The upper part of the unit contains scattered coarser grains and pebbles as large as 4.5 cm long and locally includes beds of conglomerate as much as 1 m thick. The pebbles consist largely of chert and quartz. At some outcrops, the upper part of the unit is cross-stratified and provides evidence of southward-flowing paleocurrents.

In core from borehole 2 (figs. 1 and 8), most of the shale in the Belle Fourche Member is dark gray, silty, non-calcareous, and interlaminated with siltstone, which is generally medium gray, argillaceous or sandy, and noncalcareous. However, near the top of the Belle Fourche Member, these rocks are mainly calcareous. The laminae of shale and siltstone are discontinuous and are either even and parallel or wavy and nonparallel. Flaser and lenticular bedding are common except at the base and top of the member. Most of the shale and siltstone contains small horizontal burrows,

and some units are bioturbated. Where interstratified with sandstone, the shale and siltstone commonly contain *Siphonites*.

Samples of shale from depths of 87 m, 137 m, 223 m, and 277 m in borehole 2 were analyzed by X-ray diffraction. They contain quartz, plagioclase, potassium feldspar, mixed-layer clays, and mica-illite. The sample from a depth of 87 m also contains calcite, dolomite, sodium montmorillonite, and minor chlorite or kaolinite. At a depth of 137 m, the shale includes dolomite, kaolinite, and minor chlorite. The sample at 223 m includes sodium montmorillonite and less chlorite and kaolinite.

The organic composition of the sampled shale was described by Merewether and Claypool (1980) and is summarized in table 1. These strata are in an early stage of the hydrocarbon-forming process and most of them are potential source rocks for gas.

The sandstone in the core from borehole 2 (fig. 8) is mainly light gray, very fine grained, silty, and non-calcareous. Richardson's (1957) Third Wall Creek sand, the lowest prominent unit of sandstone at outcrops in the area, is represented in the core by interbedded and interlaminated siltstone, shale, bentonite, and very fine grained sandstone. These beds and laminae are largely discontinuous, wavy, and nonparallel, and commonly enclose small, horizontal burrows. They show flaser and lenticular bedding and slump structures.

The thick unit of sandstone (the Second Wall Creek sand) near the middle of the Belle Fourche Member can be divided into two parts in the core. The lower part, which is about 48 m thick, grades from interlaminated shale, siltstone, and very fine grained sandstone at the base, to thinly bedded, fine-grained and medium-grained sandstone at the top. These rocks contain laminae and abundant fragments of coaly material. Strata in this sequence are discontinuous, wavy, and nonparallel at the base (some flaser bedding), bioturbated near the middle, and cross-stratified near the top. The lower half of the sequence contains small, horizontal-to-vertical burrows and *Siphonites*. Near the top of the sequence, small, horizontal-to-vertical burrows and *Ophiomorpha* are common. The upper part of the sandstone unit, which is about 15 m thick, comprises even, parallel laminae and very thin beds of very fine grained sandstone. However, near the top of this sequence, some beds are fine grained and medium grained, and contain scattered coarse grains and small pebbles. Many of these strata are thinly laminated to very thinly bedded and are discontinuous, wavy, and nonparallel. Some of the upper part of the sandstone unit is bioturbated. Small, horizontal and vertical burrows are abundant. A *Rhizocorallium* was found near the base of this sequence, and sparse *Ophiomorpha* and *Siphonites* occur near the top.

The uppermost of the three prominent units of sandstone (not named by Richardson) in the Belle Fourche Member is about 23 m thick in the core (fig. 8). This unit, near its base, is composed of interlaminated shale, siltstone, and very fine grained sandstone. These rocks contain comparatively abundant, very fine to coarse fragments of coaly matter. Most of the laminae are discontinuous and are either wavy and nonparallel or even and parallel. Flaser bedding occurs rarely. Overlying the basal strata is a sequence of laminae and very thin beds of bioturbated, very fine grained and fine-grained sandstone. At the top of the unit, the sandstone is fine grained and coarse grained, and contains a few very coarse grains of chert and quartz. These strata are laminated to thin bedded and are discontinuous, wavy, and non-parallel. In this uppermost unit of sandstone, small horizontal burrows are common, and some beds are bioturbated. The unit contains sparse molluscan fossils.

Samples of sandstone from the core, from depths of 99 m, 143 m, and 150 m, were analyzed by X-ray diffraction and viewed with a SEM. All of the samples contain quartz, sodic plagioclase, potassium feldspar, clay minerals, and dolomite. The clay, which is mostly authigenic, is dominantly kaolinite at a depth of 99 m in the uppermost unit of sandstone in the Belle Fourche and largely sodium montmorillonite at depths of 143 m and 150 m, in the thick unit of sandstone near the middle of the member.

The petrology of some of the sandstone in the Frontier of Wyoming was summarized by Goodell (1962, p. 206-208). In thin sections, the sandstone in the Belle Fourche Member, at depths of 99 m, 104 m, 150 m, 164 m, and 242 m, is composed mainly of angular to subrounded grains of quartz, chert, and feldspar, and sparse biotite and chalcedony. Many grains are corroded (fig. 9) and have been partly replaced by clay at depths of 150 m and 242 m, and by dolomite and calcite at depths of 99 m, 104 m, and 164 m. The sample from a depth of 99 m contains a few euhedral and subhedral crystals of quartz which are probably sand grains with overgrowths. It can be inferred from thin sections that the grains were subangular to subrounded prior to diagenesis.

Sandstone in the core, from depths of about 99 m, 104 m, 150 m, 164 m, and 242 m, was analyzed to determine grain sizes. The thin sandstone at 242 m, which grades laterally into Richardson's (1957) Third Wall Creek sand, consists mostly of fine sand. For the sand grains in this sample, the mean size is 2.79 phi (fine sand), the standard deviation is 0.51 phi (moderately well sorted), skewness is -1.00 (strongly coarse skewed), and kurtosis is 3.88 (extremely leptokurtic). The samples from depths of 150 m and 164 m

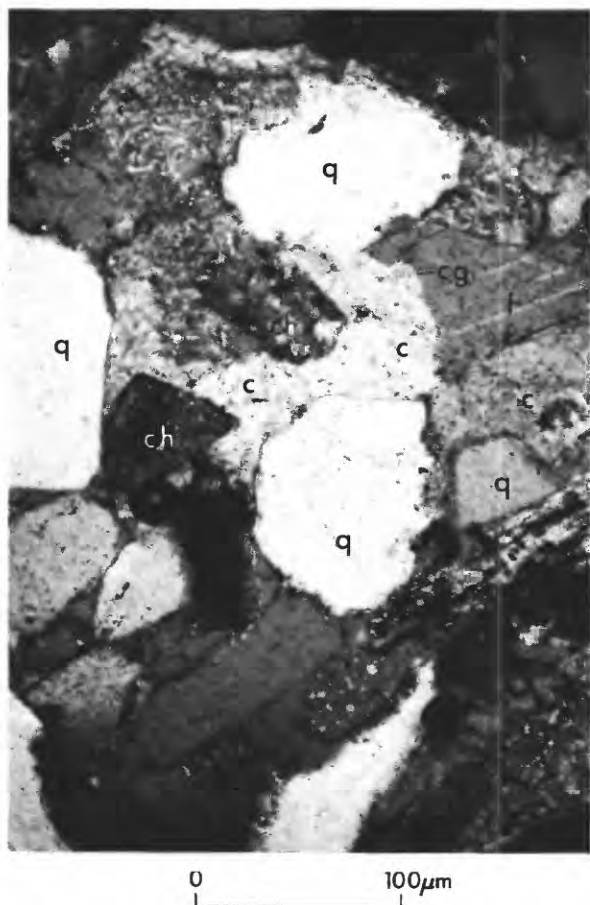


FIGURE 9.—Corroded grains (cg) of quartz (q), chert (ch), and feldspar (f) cemented by calcite (c) in a thin section of sandstone of the Belle Fourche Member, from a depth of 164.4 m in borehole 2.

are from the upper part of Richardson's (1957) Second Wall Creek sand, which is near the middle of the Belle Fourche Member. For the sand grains at 164 m, the mean size is 2.31 phi (fine sand), the standard deviation is 0.52 phi (moderately well sorted), skewness is +0.49 (strongly fine skewed), and kurtosis is 2.57 (very leptokurtic). The sand in the sample from 150 m has a mean diameter of 2.62 phi (fine sand), a standard deviation of 0.42 phi (well sorted), a skewness of -0.02 (nearly symmetrical), and a kurtosis of 2.45 (very leptokurtic). Samples of the uppermost unit of sandstone in the Belle Fourche were obtained from the core at depths of 99 m and 104 m. They were collected from the upper part of the unit. At 104 m, the sand grains have a mean diameter of 2.26 phi (fine sand), a standard deviation of 0.48 phi (well sorted), a skewness of +0.25 (fine skewed), and a kurtosis of 3.40 (extremely leptokurtic). At 99 m, the sand grains have a mean diameter of 1.87 phi (medium sand), a standard deviation of 0.64 phi (moderately well sorted), a skewness of +0.22 (fine skewed), and a kurtosis of 2.63 (very leptokurtic).

In summary, these samples include clay, silt, and very fine to medium grains of sand, but they are moderately well sorted to well sorted. Furthermore, four of the samples are dominantly fine grained and one is dominantly medium grained. The skewness varies between strongly coarse skewed and strongly fine skewed, but the kurtosis is more consistent, from very leptokurtic to extremely leptokurtic. Before post depositional alteration, these sandstone units probably contained little clay, were generally well sorted, and consisted mainly of subrounded grains. These rocks are interpreted to be texturally mature.

Outcrops of the Belle Fourche Member in southern Johnson County contain molluscan fossils of middle and late Cenomanian and earliest Turonian age. Representative collections of these fossils are:

USGS D9829, SW1/4 sec. 7, T. 42 N., R. 81 W., from small limestone concretions about 1 m below the top of the Belle Fourche Member.

Mytiloides subhercynicus (Seitz)?

Placenticerus? sp.

USGS D5725, SW1/4 sec. 2, T. 43 N., R. 82 W., from top of sandstone unit about 10 m below the top of the Belle Fourche Member.

Phelopteria sp.

Inoceramus pictus Sowerby

Ringicula? sp.

Sciponoceras gracile (Shumard)

Worthoceras vermiculum (Shumard)

Scaphites sp.

Neocardioceras? sp.

Placenticerus sp.

Metoicoceras sp.

USGS D5723, SW1/4 sec. 2, T. 43 N., R. 82 W., from septarian concretions in a sandstone unit, about 19 m below the top of the Belle Fourche Member.

Inoceramus pictus Sowerby

Sciponoceras sp.

Dunveganoceras albertense (Warren)

Metoicoceras muelleri Cobban

USGS D9789, SW1/4 sec. 15, T. 42 N., R. 81 W., from septarian concretions in sandstone unit, about 25 m below the top of the Belle Fourche Member.

Inoceramus ginterensis Pergament

Tarrantoceras sp.

Dunveganoceras albertense (Warren)

Metoicoceras sp.

USGS D9814, NW1/4 sec. 22, T. 42 N., R. 81 W., from sandstone concretions about 42 m below the top of the Belle Fourche Member.

Plesiacanthoceras wyomingense (Reagan)

USGS D9812, NW1/4 sec. 22, T. 42 N., R. 81 W., from limestone concretions in shale about 52 m below the top of the Belle Fourche Member.

Stomohamites sp.

Tarrantoceras sp.

Plesiacanthoceras wyomingense (Reagan)

USGS D6947, NE1/4 sec. 27, T. 42 N., R. 81 W., from sandy limestone concretions in siltstone, about 54 m below the top of the Belle Fourche Member.

- Inoceramus arvanus* Stephenson
Ostrea beloiti Logan
Acanthoceras amphibolum Morrow
 USGS D8465, SW1/4 sec. 2, T. 43 N., R. 82 W., from calcareous sandstone concretions in sandstone, about 71 m below the top of the Belle Fourche Member.
- Inoceramus pictus* Sowerby
Acanthoceras pepperense Moreman
 USGS D9817, SE1/4 sec. 35, T. 42 N., R. 81 W., from ferruginous, silty concretions about 105 m below the top of the Belle Fourche Member.
- Inoceramus* cf. *I. arvanus* Stephenson
Ostrea beloiti Logan
Acanthoceras cf. *A. alvaradoense* Moreman
 USGS D9801, W1/2 sec. 13, T. 42 N., R. 82 W., from ferruginous, silty concretions about 132 m below the top of the Belle Fourche Member.
- Ostrea* sp.
Turrilites (Euturrilites) scheuchzerianus Bosc
Acanthoceras muldoonense Cobban and Scott
 USGS D9807, NE1/4 sec. 10, T. 42 N., R. 82 W., from calcareous silty concretion about 133 m below the top of the Belle Fourche Member.
- Inoceramus eulessanus* Stephenson
Arrhoges? sp.
Acanthoceras muldoonense Cobban and Scott
Borissiakoceras compressum Cobban
 USGS D9850, SW1/4 sec. 13, T. 42 N., R. 82 W., from calcareous concretion about 135 m below the top of the Belle Fourche Member.
- Inoceramus macconnelli* Warren
Exogyra sp.
Calycoceras (Conlinoceras) tarrantense (Adkins)
 USGS D9805, SW1/4 sec. 12, T. 42 N., R. 82 W., from calcareous concretion about 142 m below the top of the Belle Fourche Member.
- Inoceramus eulessanus* Stephenson
Borissiakoceras compressum Cobban
Johnsonites sulcatus Cobban

Apparently, the Belle Fourche Member in southern Johnson County was deposited mainly in shallow-water, nearshore-marine environments near a wave-dominated, high-destructive delta (Merewether and others, 1979). Some of the sandstone bodies represent nearshore bars (Merewether and others, 1979, p. 80), which accumulated in response to southeast- and southwest-flowing currents (Towse, 1952, figs. 6 and 8). The uppermost beds of most sandstone units are locally composed of conglomeratic sandstone or conglomerate which probably was deposited on beaches and in tidal channels. However, Richardson's Third Wall Creek sand (1957), in the lower part of the Belle Fourche, is a thick, linear, southeast-trending body that appears to be a distributary channel deposit.

WALL CREEK MEMBER

The Wall Creek Member, which disconformably overlies the Belle Fourche Member near Kaycee, is 29–38 m thick at most outcrops and boreholes in the

area. However, where cored in borehole 2, the Wall Creek is about 27 m thick. In southern Natrona County (fig. 1), the Wall Creek disconformably overlies the unnamed member of the Frontier (fig. 2).

At outcrops in southern Johnson County (fig. 8), the Wall Creek grades from interlaminated shale, siltstone, and very fine grained sandstone at the base of the member to fine-grained, cross-stratified sandstone at the top of the member. The shale is mainly dark gray to olive gray, silty, and noncalcareous. Most of the siltstone is medium gray, clayey or sandy, and noncalcareous. In the lower part of the Wall Creek, these rocks generally contain small septarian concretions which are sparsely fossiliferous. The sandstone in the basal part of the member is medium gray to light brownish gray, horizontally laminated, and contains horizontal burrows. Near the top of the member, the sandstone is light gray to yellowish gray, irregular-bedded and planar crossbedded, and contains horizontal and vertical *Ophiomorpha* and other burrows. The crossbeds indicate southeast-flowing paleocurrents (Towse, 1952, fig. 10).

Where cored in borehole 2 (fig. 8), the Wall Creek Member consists of, in ascending order: interlaminated, dark-gray, silty shale and medium-gray, sandy siltstone; medium-gray, argillaceous and sandy siltstone; medium-gray, silty, very fine grained sandstone; and interstratified light-gray, very fine grained, slightly calcareous sandstone and minor medium-gray, silty shale. The laminae of shale and siltstone are mostly discontinuous, wavy, and nonparallel, and enclose small horizontal burrows. Some interlaminated shale, siltstone, and sandstone in the lower part of the member show flaser bedding. Much of the sandstone in the Wall Creek at borehole 2 consists of well-sorted, angular to subrounded grains and appears to have good porosity. Most of the sandstone contains fine fragments of coaly matter, and some contains rip-up clasts of shale. The silty sandstone is commonly bioturbated. In the upper part of the member, the slightly calcareous sandstone has microcross-laminations and discontinuous, wavy, nonparallel laminations, and it contains small horizontal burrows.

Shale in the Wall Creek at a depth of 82.5 m in borehole 2 was analyzed by X-ray diffraction. It consists mainly of quartz, plagioclase, potassium feldspar, dolomite, mica-illite, chlorite, and mixed-layer clays. The organic composition of the shale at a depth of 82.6 m is shown in table 1. Merewether and Claypool (1980) concluded that these strata are thermally immature but may be potential source rocks for natural gas.

Sandstone in the member, at a depth of 58 m in borehole 2, is composed largely of quartz, calcite,

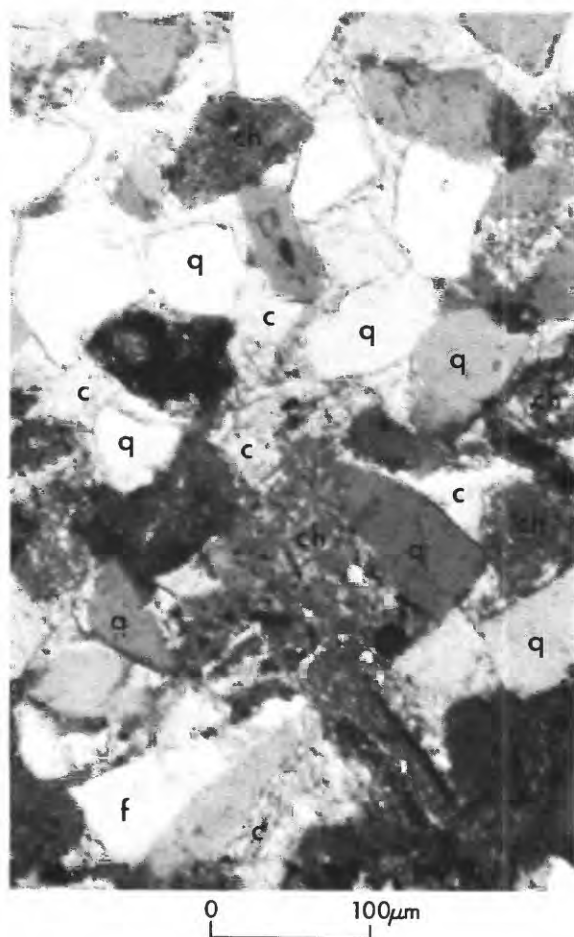


FIGURE 10.—Angular to subrounded grains of quartz (q), chert (ch), and feldspar (f), cemented by calcite (c), in a thin section of sandstone of the Wall Creek Member, from a depth of 57.9 m in borehole 2.

potassium feldspar, kaolinite, and mica-illite. Clay minerals make up 5–10 percent of the sampled bed and are mainly authigenic. SEM micrographs of the rock show subangular sand grains, interlaminated crystals of kaolinite, and moderate porosity (Merewether and others, 1976, fig. 8).

Thin sections of the sandstone at depths of 58 m and 63 m show angular to subrounded grains of quartz, chert, feldspar, and minor biotite. The grains of quartz and feldspar are commonly corroded and have been partly replaced by calcite (fig. 10). Most of the sand was probably subrounded when deposited.

Samples of sandstone from depths of 58 m and 63 m were analyzed to determine the size and sorting of the constituent grains. The sand at a depth of 63 m is mainly fine grained (mean size 2.54 phi) and well sorted (standard deviation 0.48 phi). For this sample, the skewness is -0.03 (nearly symmetrical) and the kurtosis is 2.86 (very leptokurtic). A sandstone near the

top of the Wall Creek, at a depth of 58 m, is also largely fine grained (mean size 2.37 phi) and well sorted (standard deviation 0.43 phi). However, the skewness is 0.34 (strongly fine skewed) and the kurtosis is 3.03 (extremely leptokurtic). When deposited, the sand contained little clay, was well sorted, and consisted mostly of subrounded grains. The sampled sandstone of the Wall Creek may be either texturally mature or texturally supermature.

The Wall Creek Member in the vicinity of Kaycee contains invertebrate fossils of late Turonian age which are typified by *Scaphites whitfieldi* Cobban. Representative collections of the fossils are:

USGS D9792, NW1/4 sec. 1, T. 42 N., R. 82 W., from a sandstone concretion about 7 m below the top of the Wall Creek Member.

Inoceramus perplexus Whitfield

Scaphites whitfieldi Cobban

Prionocyclus novimexicanus (Marcou)

USGS D8489, SW1/4 sec. 7, T. 41 N., R. 80 W., from small septarian concretions about 10 m below the top of the Wall Creek Member.

Inoceramus perplexus Whitfield

Prionocyclus novimexicanus (Marcou)

In the southern part of Johnson County, the Wall Creek Member grades from interlaminated siltstone and shale at the base of the member to cross-stratified, well-sorted sandstone at the top of the member. These rocks contain burrows and molluscan fossils of marine origin and are interpreted to have been deposited in shallow water near the western margin of a high-destructive, tide-dominated delta (Merewether and others, 1979, p.89–91). The sandstone of the member near Kaycee probably accumulated as a submarine off-shore bar.

CODY SHALE

Hares and others (1946) applied the name Cody Shale to the thick body of gray shale that conformably overlies the Frontier Formation on the west flank of the Powder River Basin. In the lower part of the Cody, the basal unit of noncalcareous shale and the overlying unit of calcareous shale were called the Sage Breaks Member and Niobrara Member, respectively, by Merewether and others (1977).

SAGE BREAKS MEMBER

In the southwestern part of the Powder River Basin, the lower part of the Sage Breaks Member of the Cody interfingers with the upper part of the Wall Creek Member of the Frontier (Haun, 1958, p. 84). On the western flank of the basin in Johnson County, the Sage Breaks is conformably overlain by the Niobrara.

The Sage Breaks Member, which consists mainly of soft, gray shale and many septarian concretions, rarely crops out and generally forms a topography of little relief. In boreholes in the vicinity of Kaycee, the member is generally 65–70 m thick. The lower part of the Sage Breaks, where cored in borehole 2, is about 57 m thick. Outcrops of the member near Kaycee are composed of dark-gray, silty shale and lesser medium-gray to dark-gray, clayey or slightly sandy siltstone (fig. 8). These rocks enclose many layers of septarian calcareous concretions and limestone concretions, which are as much as 1 m in diameter and are sparsely fossiliferous.

Core of the Sage Breaks from borehole 2 is composed largely of silty shale and argillaceous siltstone, which are medium gray to dark gray and locally slightly calcareous. Scattered grains of mica and pyrite were identified in hand specimens of the core.

Most of the Sage Breaks is thinly laminated to laminated. The laminae are mainly discontinuous and either wavy and parallel or even and parallel; however, some are wavy and nonparallel. Core from the lower part of the member has minor flaser and lenticular bedding. Many laminae are bioturbated or enclose small horizontal burrows and *Siphonites*. They also contain fossil mollusks and foraminifera.

A sample of core from a depth of about 49 m, in the lower part of the Sage Breaks, was analyzed by X-ray diffraction and by thermal evolution and combustion procedures. The sampled shale contains quartz, plagioclase, potassium feldspar, dolomite, mica-illite, chlorite, and mixed-layer clays. The organic composition of the shale (Merewether and Claypool, 1980) (table 1) indicates that the member has some potential as a source rock for natural gas.

Outcrops of the Sage Breaks Member near Kaycee contain sparse invertebrate fossils of latest Turonian through middle Coniacian age. Representative collections of these fossils are:

USGS D9795, NW1/4 sec. 6, T. 42 N., R. 81 W., from shale about 8 m below the top of the Sage Breaks Member.

Inoceramus deformis Meek

USGS D9826, SW1/4 sec. 6, T. 42 N., R. 81 W., from large septarian concretions about 10 m below the top of the Sage Breaks Member.

Inoceramus cf. *I. lusatae* Andert

Anisomyon sp.

Eutrephoceras sp.

USGS D8492, SW1/4 sec. 6, T. 42 N., R. 81 W., from small septarian concretions about 19 m below the top of the Sage Breaks Member.

Inoceramus erectus Meek (early form)

USGS D8468, NE1/4 sec. 11, T. 43 N., R. 82 W., from septarian concretions about 44 m below the top of the Sage Breaks Member.

Eutrephoceras sp.

Proplacenticeras stantoni (Hyatt)

USGS D8467, NE1/4 sec. 11, T. 43 N., R. 82 W., from limestone concretions about 53 m below the top of the Sage Breaks Member.

Inoceramus perplexus Whitfield

Baculites yokoyamai Tokunaga and Shimizu

Scaphites corvensis Cobban

Prionocyclus quadratus Cobban

USGS D9804, SW1/4 sec. 6, T. 42 N., R. 81 W., from septarian concretions about 56 m below the top of the Sage Breaks Member.

Inoceramus sp.

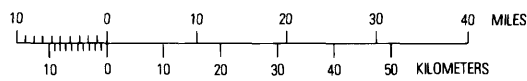
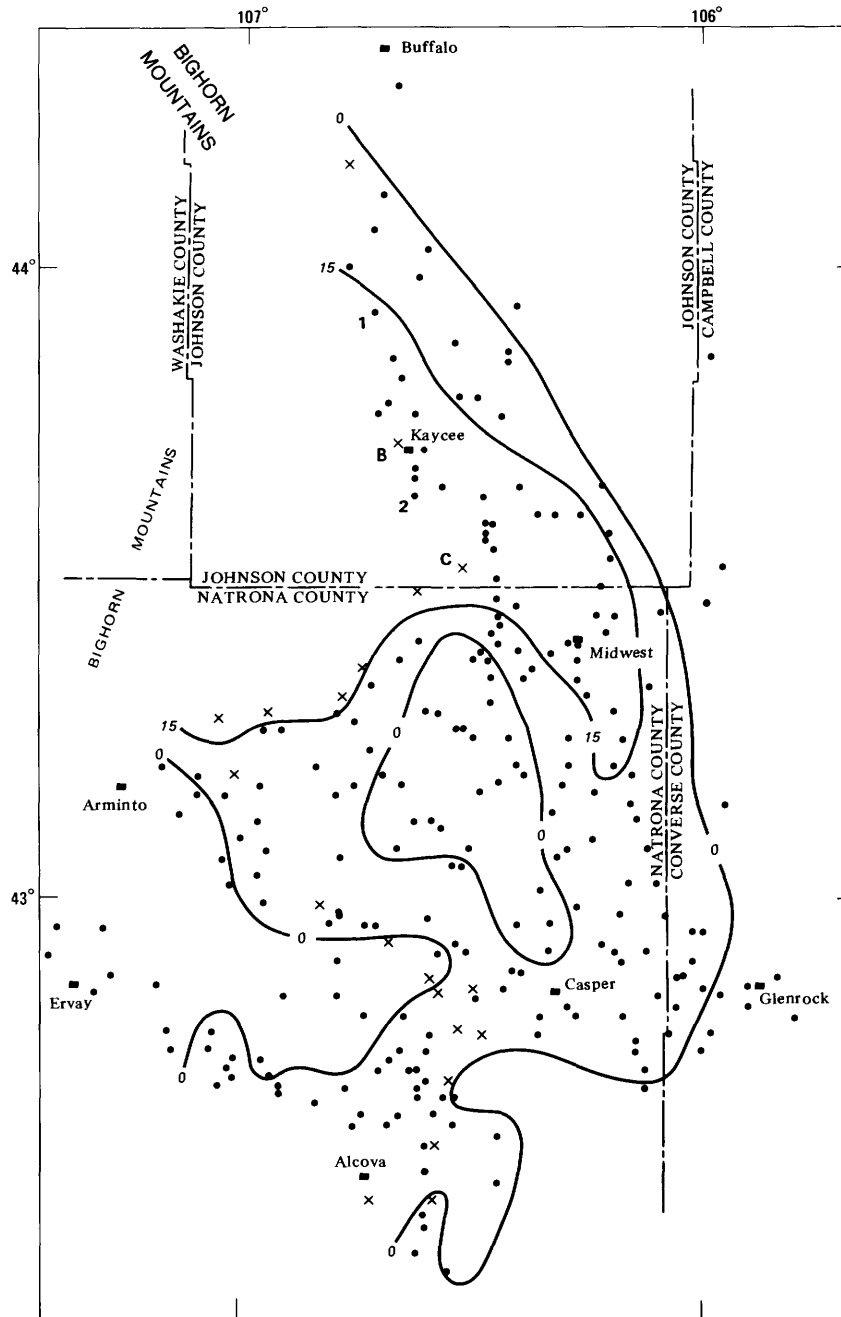
Prionocyclus quadratus Cobban

In southern Johnson County, near Kaycee, the Sage Breaks Member consists mainly of silty shale and contains burrows and molluscan fossils of marine origin. These strata accumulated in offshore-marine to open-marine environments of comparatively low current energy during a local marine transgression. Units of shallow-marine sandstone, which are laterally equivalent to parts of the Sage Breaks Member, crop out near Osage, Casper, Rawlins, and Riverton (fig. 1).

DEPOSITIONAL ENVIRONMENTS AND GEOLOGIC HISTORY

The lower Upper Cretaceous formations in northeastern Wyoming are distinctive and represent a variety of depositional environments. Isopach maps of these strata (Merewether and others, 1979) provide evidence that the region resembled the wide-shelf sedimentary model of Asquith (1974, fig. 4) during much of early Late Cretaceous time. His model consists of fluvial, paludal, barrier-island, shelf, slope, and basin environments which parallel the shoreline and have a collective width of 322–644 km.

The Belle Fourche Shale near Osage, on the eastern flank of the Powder River Basin, is about 115 m thick and consists mainly of shale and siltstone. These rocks accumulated in offshore-marine environments, probably on the slope between the shelf and the basin, during early and middle Cenomanian time (fig. 2, zones 1–5). They were deposited during a period of about 2.0 million years (fig. 2) at a vertical sedimentation rate (after compaction) of about 57.5 m per million years. On the western flank of the basin near Kaycee, about 180 km west of Osage, strata of early and middle Cenomanian age make up most of the Belle Fourche Member of the Frontier Formation. This sequence is about 170 m thick and includes shale, siltstone, and sandstone. These rocks were deposited in shallow-marine and nonmarine environments of the shelf, in the distal part of a high-destructive, wave-dominated delta (fig. 11). The rate of vertical sedimentation (after compaction) for this part of the Belle Fourche Member was about 85 m per million years.



EXPLANATION

- 15 — Isopach line—Showing thickness in meters
- 2 Borehole—Number designates borehole shown on fig 1 and table 2
- × B Outcrop section or fossil locality—Letter designates outcrop section shown on figs 1 and 9

FIGURE 11.—Map showing approximate thickness of a representative unit of sandstone (fossil-zones 5 and 6) in the Belle Fourche Member of the Frontier Formation.

The Greenhorn Formation of the Osage area is about 85 m thick and is composed largely of calcareous shale and limestone. These beds accumulated mainly in the open-marine environment of the basin during the middle and late Cenomanian and early Turonian (fig. 2, zones 5–11). In the Kaycee area, strata of middle and late Cenomanian and earliest Turonian age (fig. 2, zones 5–10) form the upper part of the Belle Fourche Member of the Frontier. These strata are about 55 m thick. Younger beds of Turonian Age (fig. 2, zones 11–16) are missing from the sequence at Kaycee and are represented by the disconformity at the base of the Wall Creek Member. The upper part of the Belle Fourche Member was deposited on the shelf in shallow-marine environments, probably near the seaward terminus of a high-destructive, wave-dominated delta.

In Weston County, the Pool Creek Member of the Carlile Shale consists of about 23 m of shale and siltstone. These strata accumulated mostly in offshore environments on the slope during middle Turonian time (fig. 2, zones 12–14). No rocks of middle Turonian age occur near Kaycee, in southern Johnson County.

The Turner Sandy Member of the Carlile near Osage is about 50 m thick and is composed largely of shale, siltstone, and sandstone. It was deposited on a submarine shelf, largely in offshore and shoreface environments, during late Turonian time (fig. 2, zones 16–19). The sandstone probably accumulated as channel fillings, nearshore bars, and offshore bars, in the distal part of a tide-dominated, high-destructive delta (fig. 12).

The basal strata of the Turner Member at Osage (fig. 2, zone 16) have no age equivalents in the sequence of beds near Kaycee. However, strata near the middle of the Turner Member, which have an estimated total thickness of as much as 18 m, are approximately equivalent in age (fig. 2, zone 17) to the Wall Creek Member of the Frontier at Kaycee. The Wall Creek Member near Kaycee is about 30 m thick and consists of shale, siltstone, and sandstone of shallow-marine origin which accumulated on the shelf in offshore and shoreface environments. The sandstone was deposited as an offshore bar near a tide-dominated, high-destructive delta (fig. 12).

In the vicinity of borehole 1, in Weston County, the Sage Breaks Member of the Carlile is mostly slightly calcareous shale and is about 91 m thick. The member was deposited on the slope and in the basin, in offshore and open-marine environments, during latest Turonian, Coniacian, and early Santonian time (Evetts, 1976).

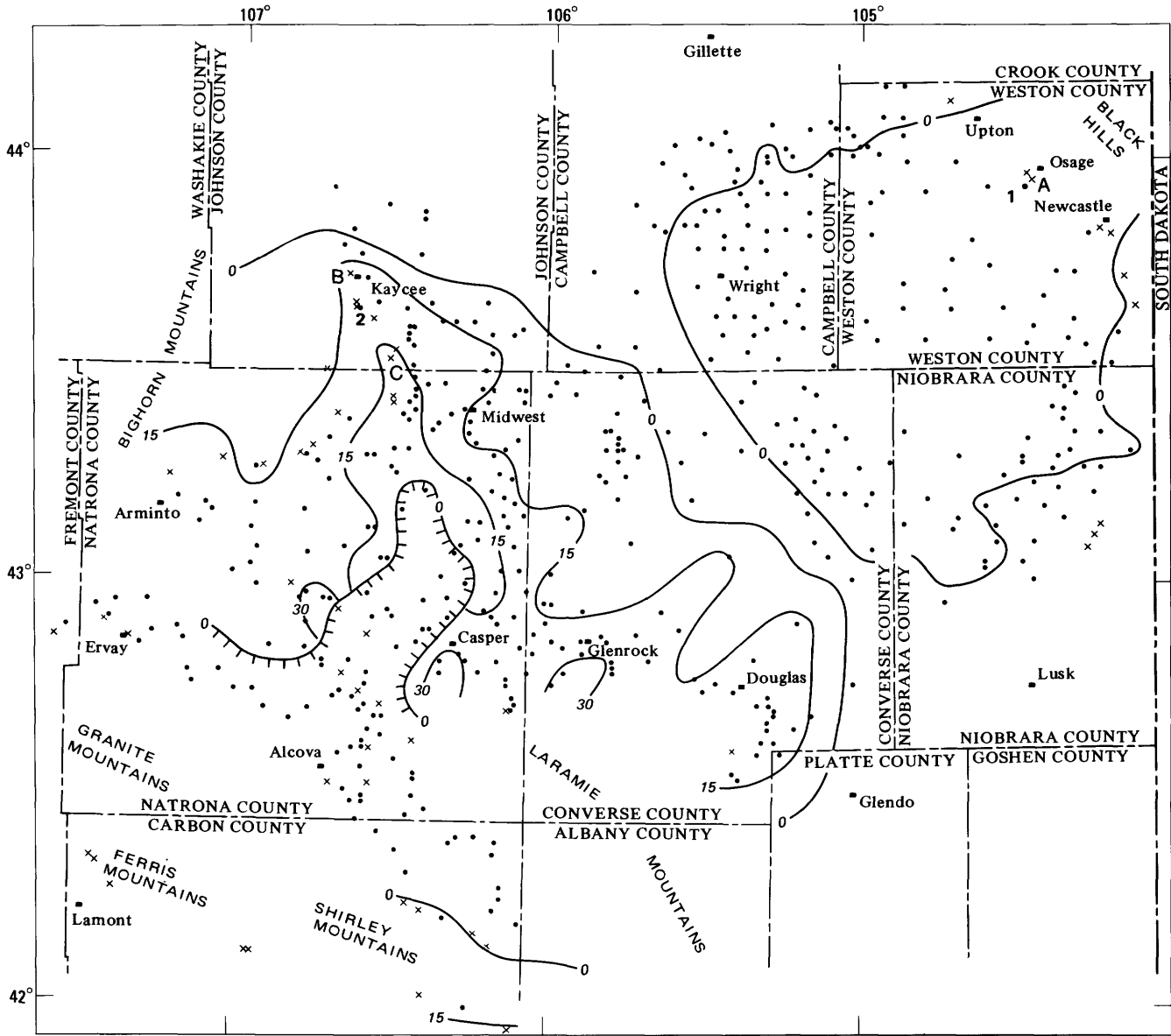
Near Osage, strata of latest Turonian through middle Coniacian age (fig. 2, zones 19–22), in the Turner and Sage Breaks Members, are as much as 85 m thick. This sequence of beds, which was deposited mainly on

the slope and in the basin, is about the same age as the Sage Breaks Member of the Cody Shale, where penetrated by borehole 2 in Johnson County. In borehole 2, the Sage Breaks is about 57 m thick and consists of silty shale. These laminae probably accumulated in offshore-marine environments on the shelf and slope.

In conclusion, the slope sediments of the Belle Fourche Shale and the basin sediments of the overlying Greenhorn Formation, in Weston County, are about the same age as the shelf sediments of deltaic origin in the Belle Fourche Member of the Frontier, in Johnson County (fig. 13). Furthermore, the two sequences have similar thicknesses. However, when some constituent stratigraphic units of the same age are compared, the thickness and rate of vertical sedimentation at the two localities are significantly different. The main source of these Cenomanian and lower Turonian sediments was a large delta which probably was in northwestern Wyoming and southwestern Montana (Goodell, 1962, p. 204; Merewether and others, 1979).

On the east flank of the Powder River Basin, the shale of the Belle Fourche and the overlying calcareous rocks of the Greenhorn are interpreted as evidence of a marine transgression during the Cenomanian and early Turonian. This transgression is also indicated by the areal distributions of successive sandstone units in the Belle Fourche Member of the Frontier, on the west flank of the basin (Merewether and others, 1979, figs. 7–9).

A marine regression in the early middle Turonian was accompanied by deposition of the basal beds of the Pool Creek Member and by the truncation of some lower Turonian and upper Cenomanian beds at the top of the Belle Fourche Member in the southwestern part of the Powder River Basin. During this regression, a large delta was developing in western Wyoming which, subsequently, prograded east and northeast to the southern part of the Powder River Basin (Towse, 1952, p. 2001; Cobban and Hook, 1979, fig. 3). Deposition of the middle Turonian Pool Creek and the unnamed member of the Frontier was followed by a regional uplift in the early late Turonian and the erosion of some Turonian and Cenomanian beds in northeastern Wyoming. During the subsequent marine transgression, this truncated surface was buried by shelf sediments, first by the basal Turner near Osage, later by the Wall Creek Member near Kaycee (fig. 12), and still later by the Wall Creek near Casper. The accumulation of the deltaic sediments of the Turner and Wall Creek continued through the late Turonian in this region while the delta front retreated toward the southwest. This transgression, which began in the early late Turonian and continued into the Coniacian in Wyoming, is also represented at Osage and Kaycee by



EXPLANATION

- 15 — Isopach line—Showing thickness in meters
- 2 Borehole—Number designates borehole shown on fig. 1 and table 2
- x B Outcrop section or fossil locality—Letter designates outcrop section shown on figs 1, 2 and 9
- ||||| Boundary of sandstone body where removed by erosion during the Turonian

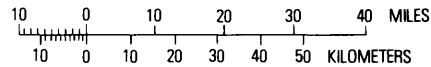


FIGURE 12.—Map showing approximate thickness of a representative unit of sandstone (fossil-zone 17) in the Wall Creek Member of the Frontier Formation and the Turner Sandy Member of the Carlile Shale.

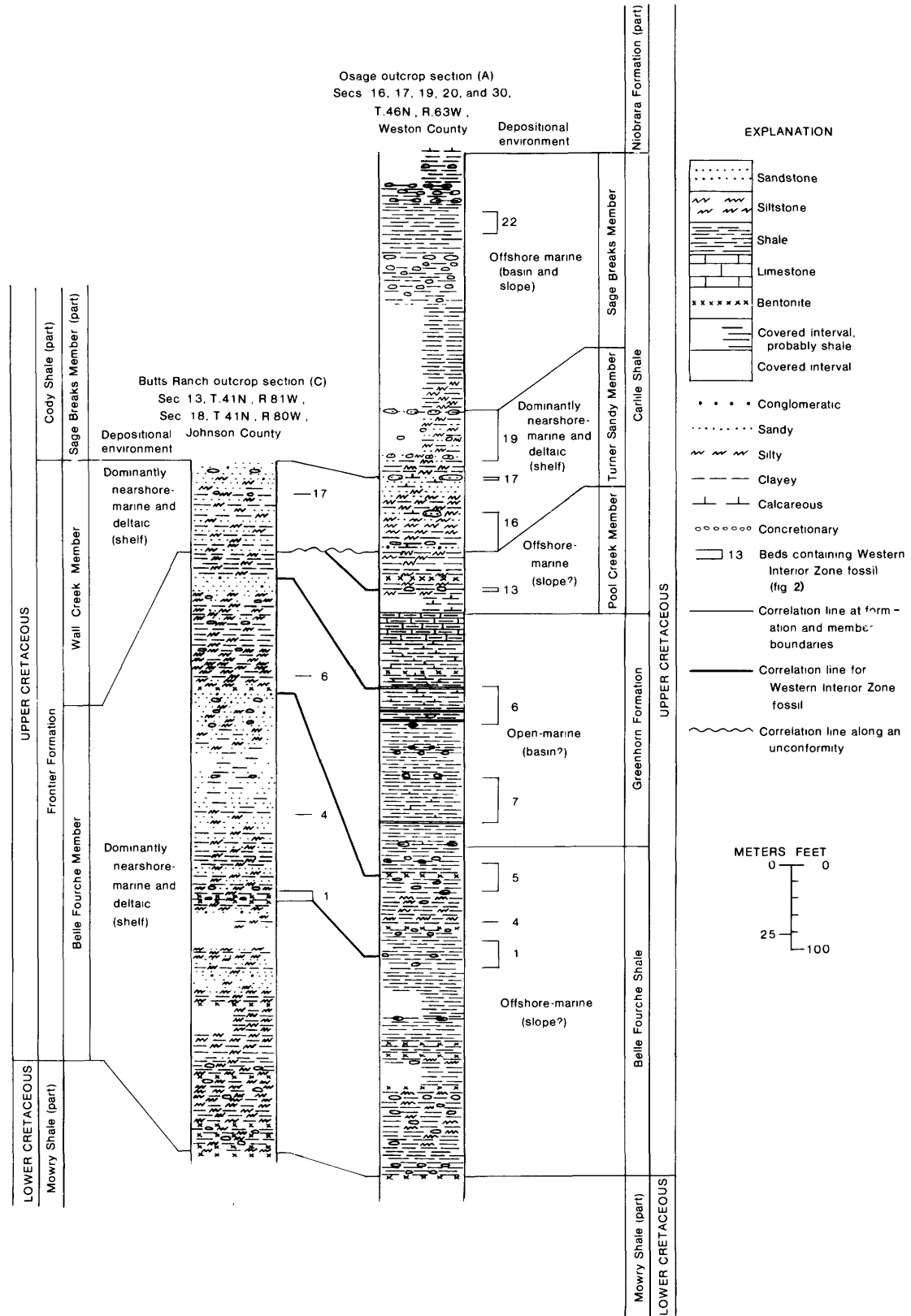


FIGURE 13.—Outcrop sections and depositional environments of lower Upper Cretaceous formations in Johnson and Weston Counties.

the slope deposits of the Sage Breaks. Another marine regression, during the early late Coniacian, caused the disconformity at the base of the Niobrara in the eastern and southern parts of the Powder River Basin. It was followed by another marine transgression and deposition of the Niobrara.

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