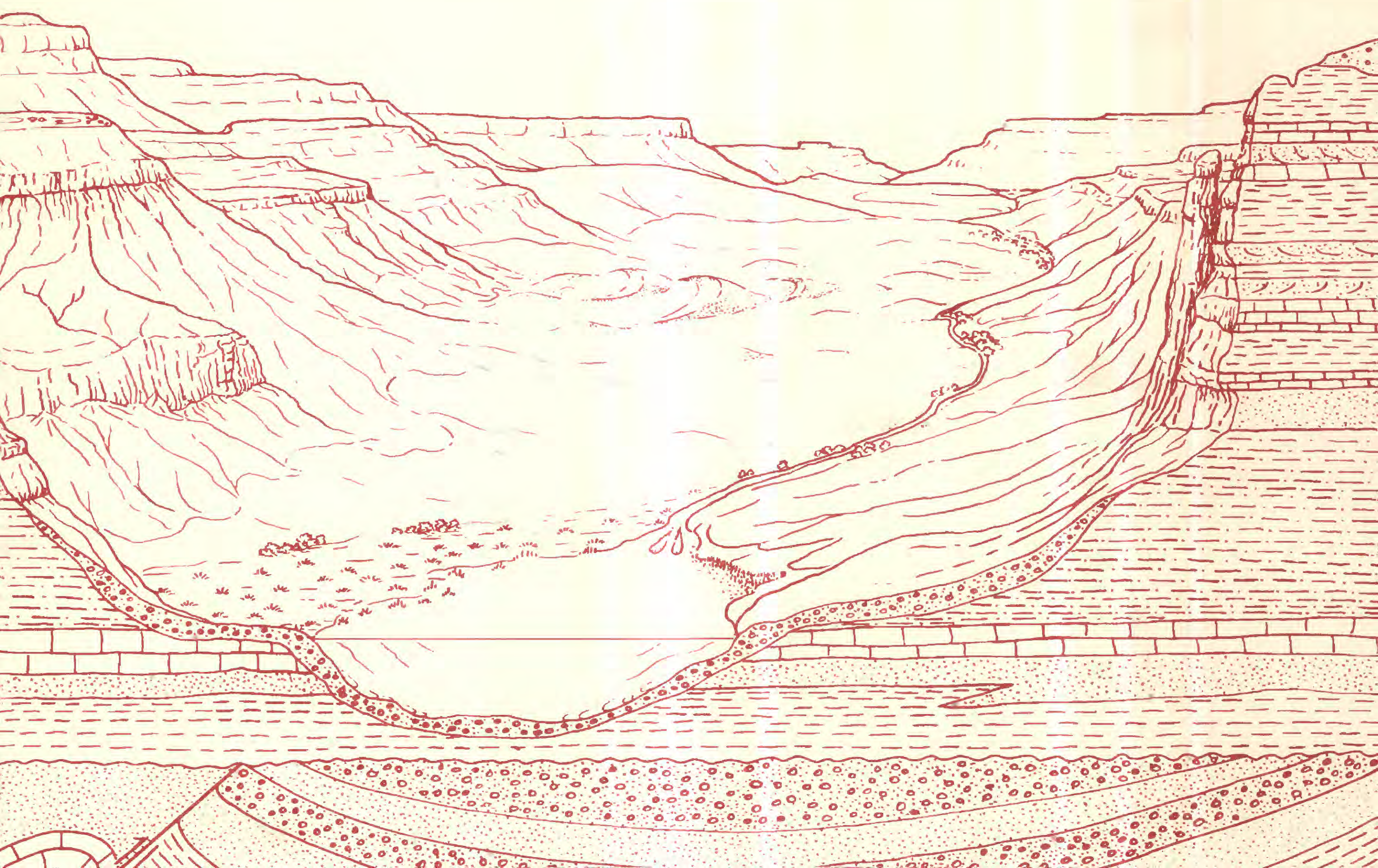
Stratigraphy and Tectonic Implications of Upper Cretaceous Rocks in the Powder River Basin, Northeastern Wyoming and Southeastern Montana

U.S. GEOLOGICAL SURVEY BULLETIN 1917–T



AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that may be listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" may no longer be available.

Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices listed below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Earth Science Information Center
101 Twelfth Ave., Box 12
Fairbanks, AK 99701

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey offices, all of which are authorized agents of the Superintendent of Documents.

- **ANCHORAGE, Alaska**–Rm. 101, 4230 University Dr.
- **LAKEWOOD, Colorado**–Federal Center, Bldg. 810
- **MENLO PARK, California**–Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**–USGS National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**–Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**–U.S. Post Office Bldg., Rm. 135, West 904 Riverside Ave.
- **WASHINGTON, D.C.**–Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the following U.S. Geological Survey offices:

- **FAIRBANKS, Alaska**–New Federal Bldg, 101 Twelfth Ave.
- **ROLLA, Missouri**–1400 Independence Rd.
- **STENNIS SPACE CENTER, Mississippi**–Bldg. 3101

Chapter T

Stratigraphy and Tectonic Implications of Upper Cretaceous Rocks in the Powder River Basin, Northeastern Wyoming and Southeastern Montana

By E.A. MEREWETHER

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins—both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1917

EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1996

For sale by
U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Merewether, E. A. (Edward Allen), 1930–

Stratigraphy and tectonic implications of Upper Cretaceous rocks in the Powder River Basin, northeastern Wyoming and southeastern Montana / by E.A. Merewether.

p. cm. — (Evolution of sedimentary basins—Powder River Basin ; ch. T) (U.S. Geological Survey bulletin ; 1917)

Includes bibliographical references (p. –).

Supt. of Docs. no.: I 19.3: 1917T

1. Geology, Stratigraphic—Cretaceous. 2. Geology—Powder River Basin (Wyo. and Mont.) 3. Powder River Basin (Wyo. and Mont.) I. Title. II. Series. III. Series: U.S. Geological Survey bulletin ; 1917.

QE75.B9 no. 1917–T
[QE688]
557.3 s—dc20
[551.7′ 7′09787] 95–20660
CIP

CONTENTS

FIGURES

TABLES

Stratigraphy and Tectonic Implications of Upper Cretaceous Rocks in the Powder River Basin, Northeastern Wyoming and Southeastern Montana

By E.A. Merewether

Abstract

Sedimentary rocks of Late Cretaceous age (98.5–65.4 Ma) in the Powder River Basin of northeastern Wyoming and southeastern Montana include siliciclastic, carbonate, pyroclastic, and coaly strata that crop out along the eastern, southern, and western margins of the basin and have been penetrated in the subsurface of the basin by many boreholes drilled for oil and gas. Siliciclastic beds predominate and are composed mainly of quartz, potassium feldspar, plagioclase, mixed-layer clay minerals, mica-illite, chlorite, kaolinite, and fragments of older rocks (sedimentary, metamorphic, and igneous).

These Upper Cretaceous strata conformably overlie Lower Cretaceous beds and are conformably overlain by Paleocene beds; however, they enclose several widespread unconformities. The strata thicken southward in the basin from about 1,300 m (4,300 ft) in Powder River County, Montana, to about 3,000 m (9,800 ft) in Converse County, Wyoming.

The rocks were deposited in continental, nearshore-marine, and offshore-marine environments on the west side of a north-trending epeiric sea, and they record at least six cycles of marine transgression and regression, some of which correspond to eustatic events. Most of the sediments were derived from erosion of areas in central and northwestern Wyoming, eastern Idaho, and western Montana. Paleocurrent directions determined from outcrops of sandstone in the Powder River Basin are northeast, southeast, and southwest. In the northwestern and northeastern parts of the basin the average rate of sedimentation during the Late Cretaceous was about 8.1 cm (3.2 in.)/1,000 years and 5.8 cm (2.3 in.)/1,000 years, respectively, whereas in the southern part of the basin the average rate of sedimentation was 12.1–13.6 cm (4.8–5.4 in.)/1,000 years.

The Powder River Basin is a large structural depression, having an area of about 57,000 km^2 (22,000 mi^2), that formed early in Tertiary time as a result of compression of a foreland in the Western Interior of North America. At the end of the Cretaceous, the total tectonic subsidence of the base of the Upper Cretaceous sequence was about 523 m (1,716 ft) near the northwestern margin of the basin, about 306 m (1,004 ft) near the northeastern edge, about 681 m (2,234 ft) on the southeastern flank, and about 761–762 m (2,497–2,500 ft) on the southwestern flank. The higher rates of tectonic subsidence (>9 cm [3.5 in.]/1,000 years) were determined from stratigraphic units mostly in the southern part of the basin.

Subsidence in the basin region during the Late Cretaceous was occasionally interrupted by regional or local uplift, particulary in the middle and late Turonian, early Campanian, late Campanian, and late early to early late Maastrichtian. Nearby areas in central and southeastern Wyoming evidently were rising during the middle and late Turonian, early and late Campanian, and early and latest Maastrichtian.

The greater thickness, higher sedimentation rate, and higher subsidence rate of several Upper Cretaceous stratigraphic units in the southern part of the basin probably are consequences of structural location. They apparently reflect the subsidence of downwarps or downthrown blocks, as well as the uplift of adjoining areas to the south in central and southeastern Wyoming.

INTRODUCTION

Sedimentary rocks of Late Cretaceous age (98.5–65.4 Ma) in the Powder River Basin of northeastern Wyoming and southeastern Montana (fig. 1) are composed

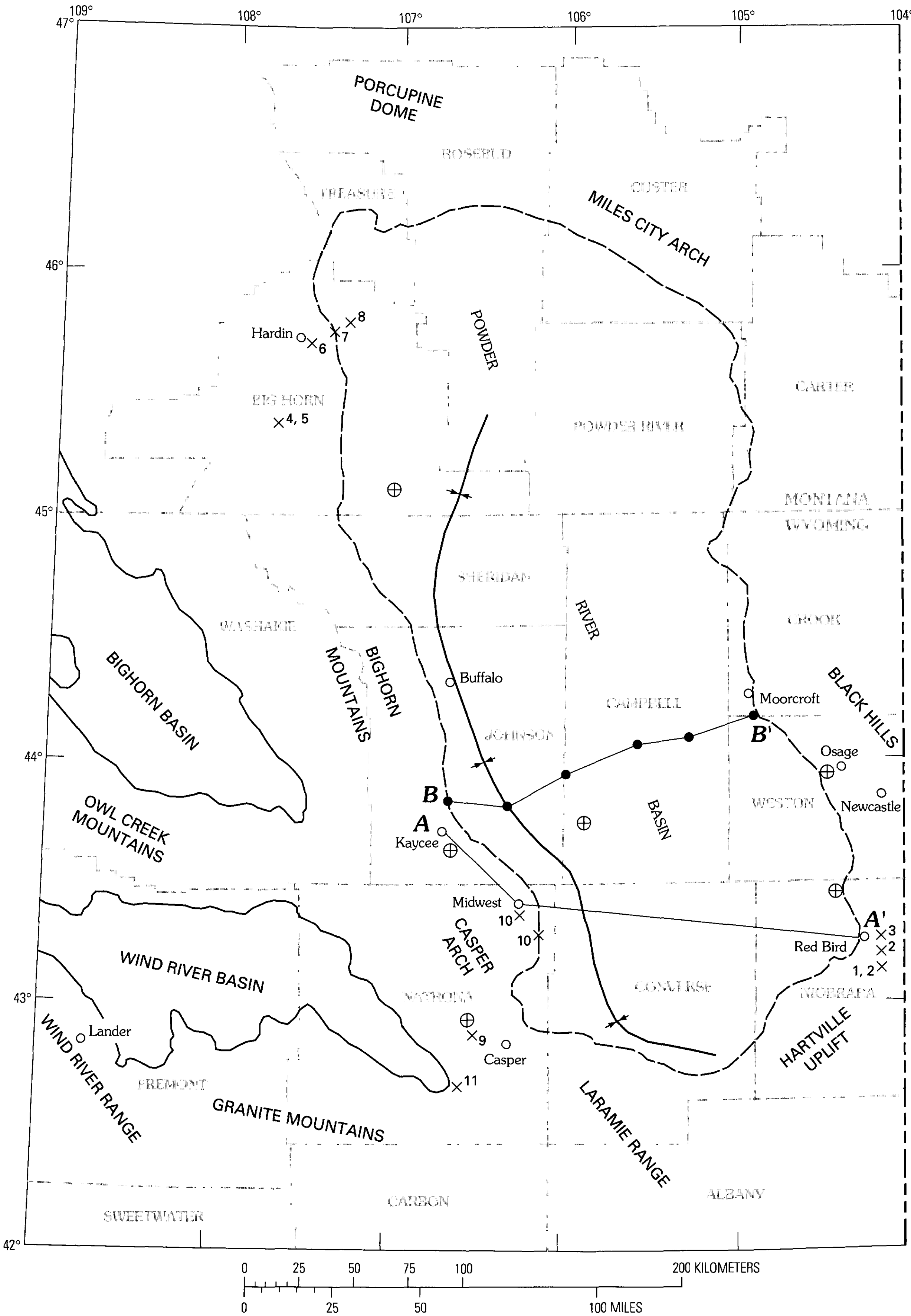

109°
108°
107°
106°
105°
104°
47°
46°
45°
44°
43°
42°
PORCUPINE DOME
ROSEBUD
TREASURE
CUSTER
MILES CITY ARCH
Hardin
6
7
8
POWDER
BIG HORN
4, 5
CARTER
POWDER RIVER
MONTANA
WYOMING
SHERIDAN
RIVER
CROOK
WASHAKIE
BIGHORN MOUNTAINS
BIGHORN BASIN
Buffalo
Moorcroft
BLACK HILLS
CAMPBELL
JOHNSON
B'
Osage
B
WESTON
Newcastle
A
Kaycee
BASIN
OWL CREEK MOUNTAINS
Midwest
10
10
A'
3
2
1, 2
Red Bird
CASPER ARCH
WIND RIVER BASIN
NATRONA
CONVERSE
NIOBRARA
9
Casper
Lander
WIND RIVER RANGE
HARTVILLE UPLIFT
FREMONT
11
GRANITE MOUNTAINS
LARAMIE RANGE
CARBON
ALBANY
SWEETWATER
0
25
50
75
100
200 KILOMETERS
0
25
50
100 MILES

Figure 1 (facing page). Map showing outline (dashed line) and troughline (line with facing arrows) of Powder River Basin (where blanketed by Tertiary strata) and locations of major structural features, important boreholes (⊕) and outcrops (x), and lines of profile *A–A′* (fig. 5) and cross section *B–B′* (fig. 6), southeastern Montana and northeastern Wyoming. Outcrop locations are referred to by number and are described in table 1.

of siliciclastic, carbonate, pyroclastic, and coaly beds that were deposited in marine and continental environments along the west side of a north-trending epeiric seaway (fig. 2). These rocks thicken southward from about 1,300 m (4,300 ft) in Powder River County, Montana, to about 3,000 m (9,800 ft) in Converse County, Wyoming, (fig. 3) (W.D. Grundy and C.T. Pierson, written commun., 1991).

On the southeastern flank of the Powder River Basin in eastern Niobrara County, Wyoming, outcropping strata of Late Cretaceous age are, in ascending order, the Mowry Shale, Belle Fourche Shale, Greenhorn Formation, Carlile Shale, Niobrara Formation, Pierre Shale, Fox Hills Sandstone, and Lance Formation (fig. 4, table 1). Laterally equivalent strata on the northwestern flank of the basin in Big Horn County, Montana, are, from oldest to youngest, the Mowry Shale, Belle Fourche Formation, Greenhorn Formation, Cody Shale, Judith River Formation, Bearpaw Shale, Fox Hills Sandstone, and Hell Creek Formation. Rocks of the same age in the southwestern part of the basin are, from oldest to youngest, the Mowry Shale, Frontier Formation, Cody Shale, Mesaverde Formation, Lewis Shale, Fox Hills Sandstone, and Lance Formation.

The information shown in figure 4 for the southwestern area pertains to scattered outcrops in southeastern Natrona County. Figure 4 also displays information for comparable strata on the southwestern flank of the Bighorn Basin in northwestern Wyoming. In the Powder River Basin, Upper Cretaceous beds conformably overlie Lower Cretaceous beds, either at or slightly below the base of the Mowry Shale, and are conformably overlain by Tertiary (Paleocene) strata of the Fort Union Formation.

The Powder River Basin, as defined by the extent of associated sedimentary rocks of Tertiary age, is a region of about 57,000 km^2 (22,000 mi^2) in northeastern Wyoming and southeastern Montana (fig. 1). Adjoining the basin are the Big Horn Mountains and Casper arch to the west, the Black Hills to the east, Porcupine Dome and the Miles City arch to the north, and the Laramie Mountains and Hartville uplift to the south. The Powder River Basin is an intermontane, compressional foreland basin that formed in the early Tertiary during the Laramide orogeny. Upper Cretaceous rocks crop out along the eastern, southern, and western margins of the basin and have been penetrated in the subsurface of the region by many boreholes drilled for oil and gas.

The Upper Cretaceous formations and members in the Powder River Basin are lithostratigraphic units, most of which intertongue laterally in outcrops and in the subsurface (figs. 5, 6) (Merewether and others, 1977a, b, c; Fox, 1993a, b, c, d). In the basin region, Upper Cretaceous beds of marine origin have been assigned ages and correlated by using collections of molluscan fossils (Gill and Cobban, 1966a) and a sequence of molluscan index fossils (fig. 7) (Obradovich and Cobban, 1975), as well as by using absolute radiometric ages (Obradovich, 1988, 1993) and borehole logs of widespread and distinctive beds of bentonite (Asquith, 1970). Absolute ages were determined from beds of bentonite (Obradovich and Cobban, 1975; Obradovich, 1988, 1993), which are associated with 14 fossil zones in the sequence (fig. 7); absolute ages were extrapolated to the remaining 53 zones. Consequently, absolute ages assigned to most of the zones are approximate, and thus many of the sedimentation rates and subsidence rates derived from those ages for this report also are approximate.

Rates of deposition and subsidence were calculated using BasinWorks, a commercial computer program for subsidence analysis and geohistory. In this program, rates of deposition and subsidence are derived from radiometric ages, lithology, present-day stratigraphic thickness, paleowater depth, eustasy, and compaction parameters.

Radiometric ages used for the global sea-level cycles of Haq and others (1987) are probably not always compatible with those supplied by Obradovich (1988, 1993) for the chronostratigraphy in this report (figs. 5, 7). Consequently, any eustatic event depicted by Haq and others (1987) and recorded by strata in the Powder River Basin may have been assigned two ages.

Acknowledgments.—This report is mainly a compilation of published and unpublished information from studies of Upper Cretaceous strata by many scientists during the past century. Their investigations concerned outcrops, drill cores, and borehole logs of rocks in the Powder River Basin and adjoining areas. Unpublished stratigraphic data from about 8,000 boreholes in the basin were supplied by N.M. Denson, D.L. Macke, and R.R. Schumann and were placed in computers through the efforts of R.R. Wahl, C.K. Simmerman, D.K. Higley, and B.L. Crysdale. Molluscan fossils of marine origin from outcrops on the perimeter of the basin were identified and interpreted by W.A. Cobban and N.F. Sohl. W.A. Cobban and the late J.R. Gill collected many fossils and provided much useful stratigraphic information. Foraminifers in samples of two cores of mid-Cretaceous formations were identified and interpreted by B.R. North and W.G.E. Caldwell, Department of Geology, University of Western Ontario, London, Ontario, Canada. Relative and radiometric ages of the beds (fig. 7) were determined from a time scale prepared by Obradovich and Cobban (1975) and modified by Lanphere and Jones (1978), Fouch and others (1983), and

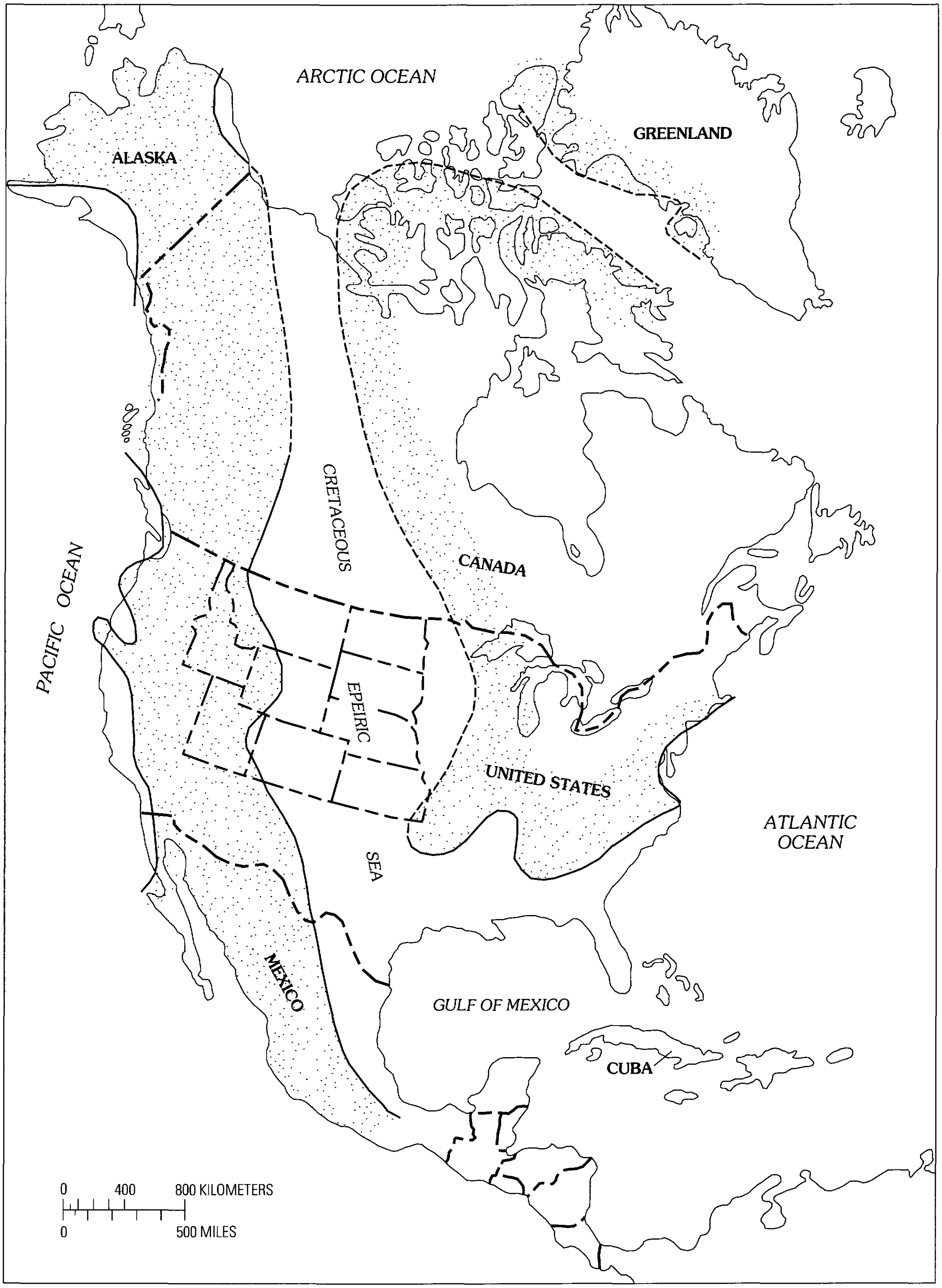


Figure 2. Map showing probable distribution of land (stippled) and sea during late Campanian time in North America. Modified from Gill and Cobban (1973).

Obradovich (1988, 1993). The major contributions of the above-named scientists of the U.S. Geological Survey and the University of Western Ontario are gratefully acknowledged.

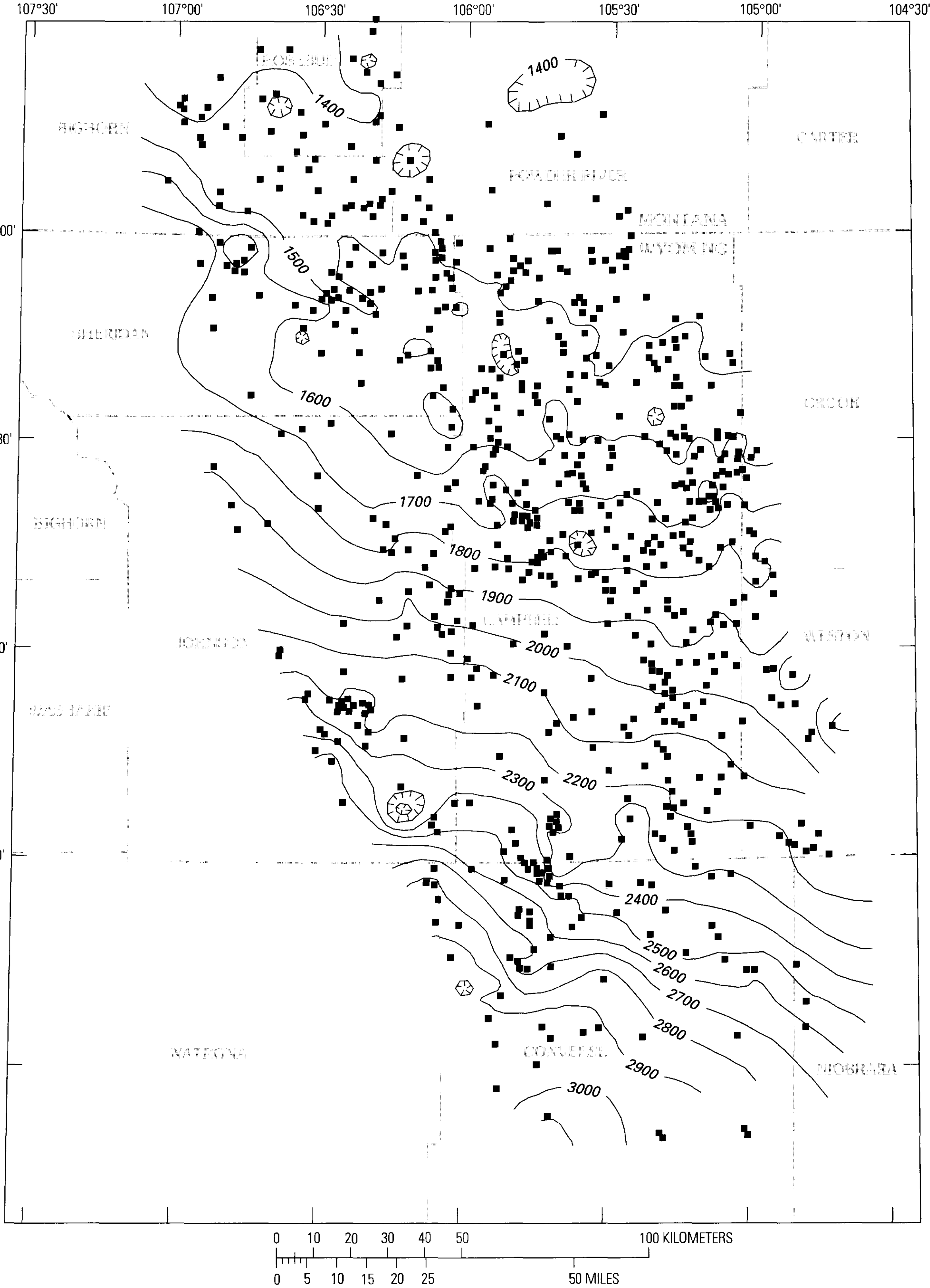


Figure 3. Map showing thickness of sedimentary rocks of Late Cretaceous age in region of Powder River Basin, northeastern Wyoming and southeastern Montana. Contour interval 100 m (328.1 ft). Black squares indicate locations of selected boreholes. Modified from W.D. Grundy and C.T. Pierson (written commun., 1991).

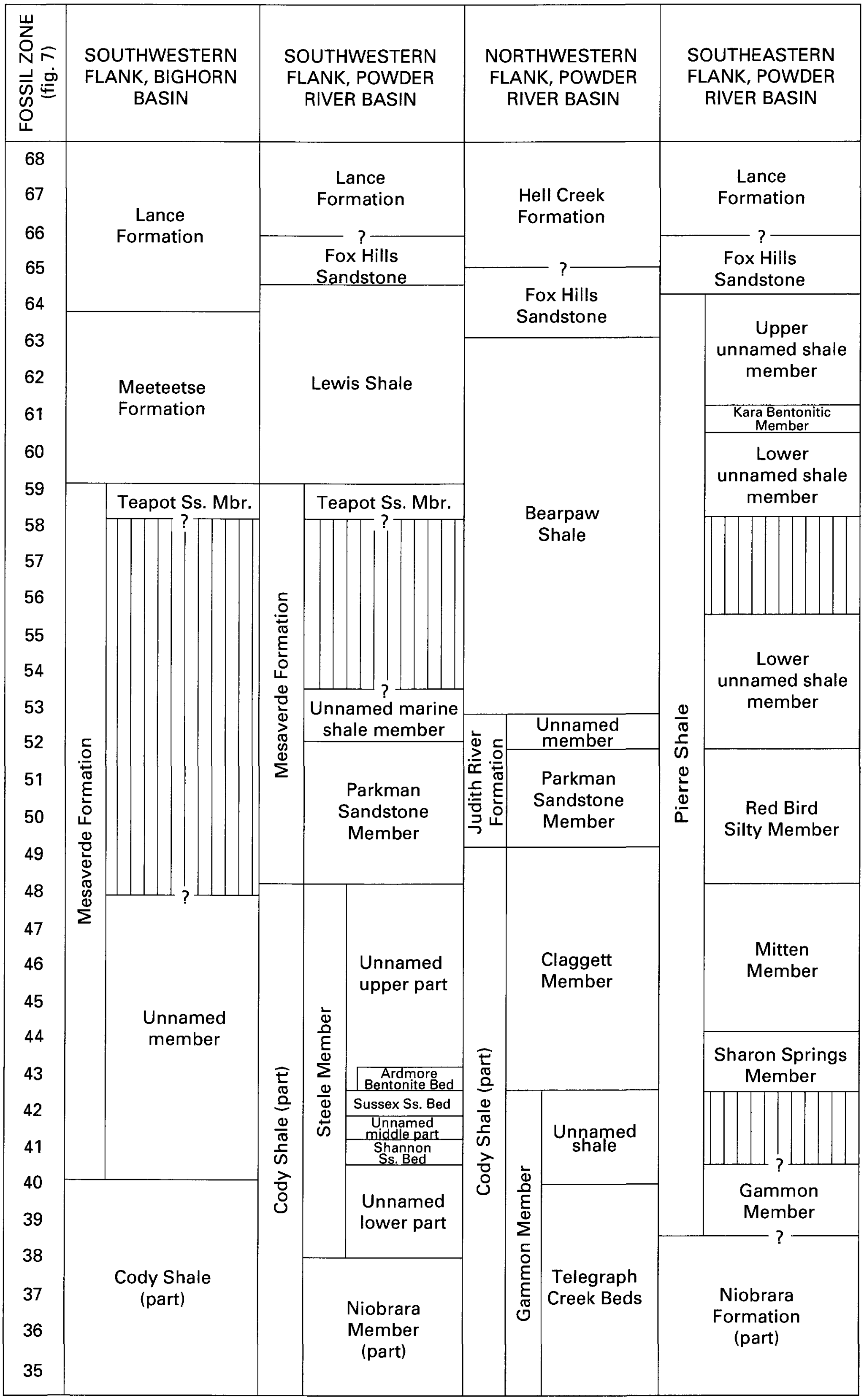
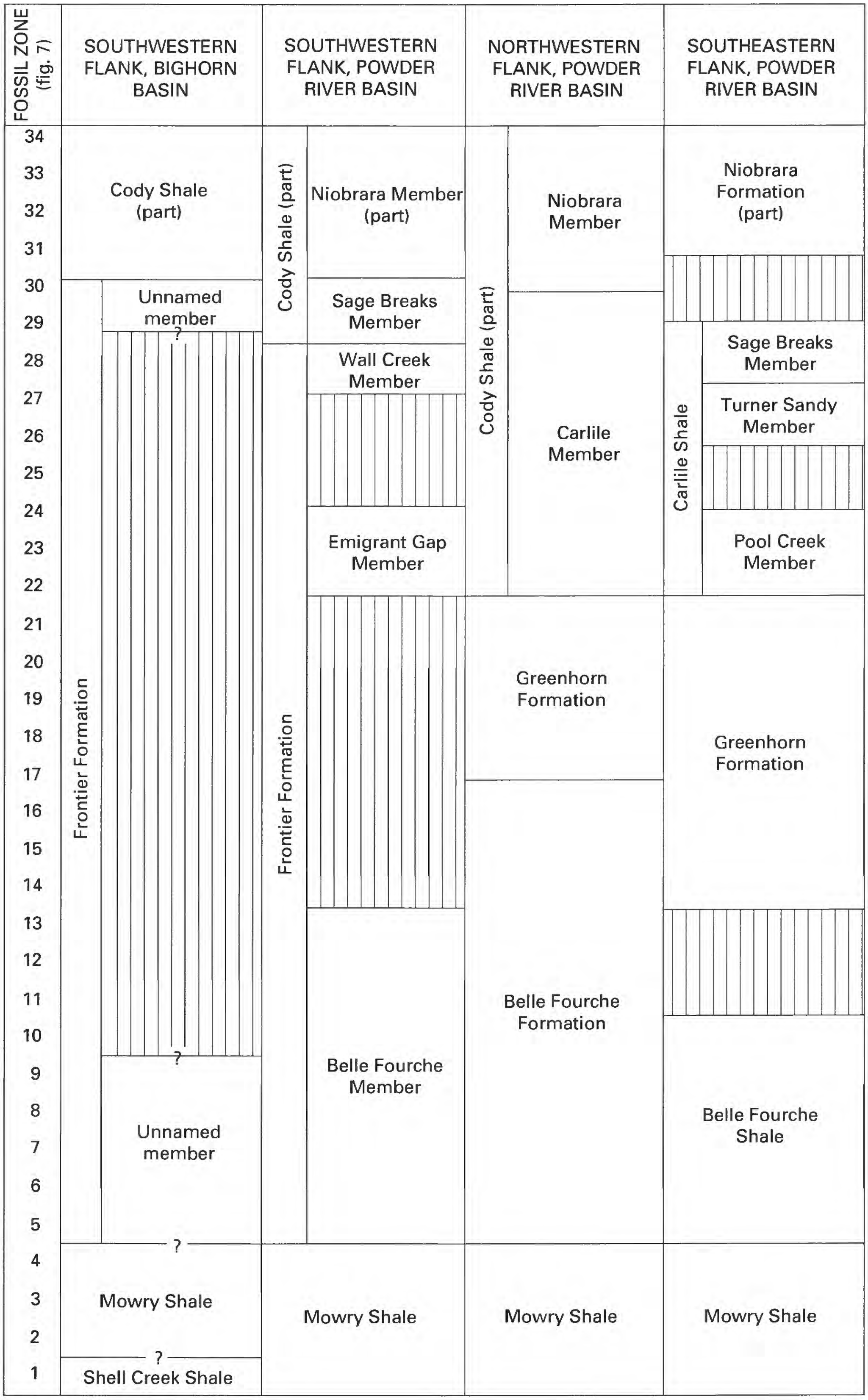


Figure 4 (above and facing page). Stratigraphic nomenclature for Upper Cretaceous rocks in Bighorn and Powder River Basins, Wyoming and Montana. Lined pattern represents a hiatus in the stratigraphic record and the faunal succession.


FOSSIL ZONE (fig. 7)
SOUTHWESTERN FLANK, BIGHORN BASIN
SOUTHWESTERN FLANK, POWDER RIVER BASIN
NORTHWESTERN FLANK, POWDER RIVER BASIN
SOUTHEASTERN FLANK, POWDER RIVER BASIN
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Cody Shale (part)
Frontier Formation
Unnamed member
?
?
Unnamed member
?
Mowry Shale
?
Shell Creek Shale
Cody Shale (part)
Niobrara Member (part)
Sage Breaks Member
Wall Creek Member
Emigrant Gap Member
Frontier Formation
Belle Fourche Member
Mowry Shale
Cody Shale (part)
Niobrara Member
Carlile Member
Greenhorn Formation
Belle Fourche Formation
Mowry Shale
Niobrara Formation (part)
Carlile Shale
Sage Breaks Member
Turner Sandy Member
Pool Creek Member
Greenhorn Formation
Belle Fourche Shale
Mowry Shale

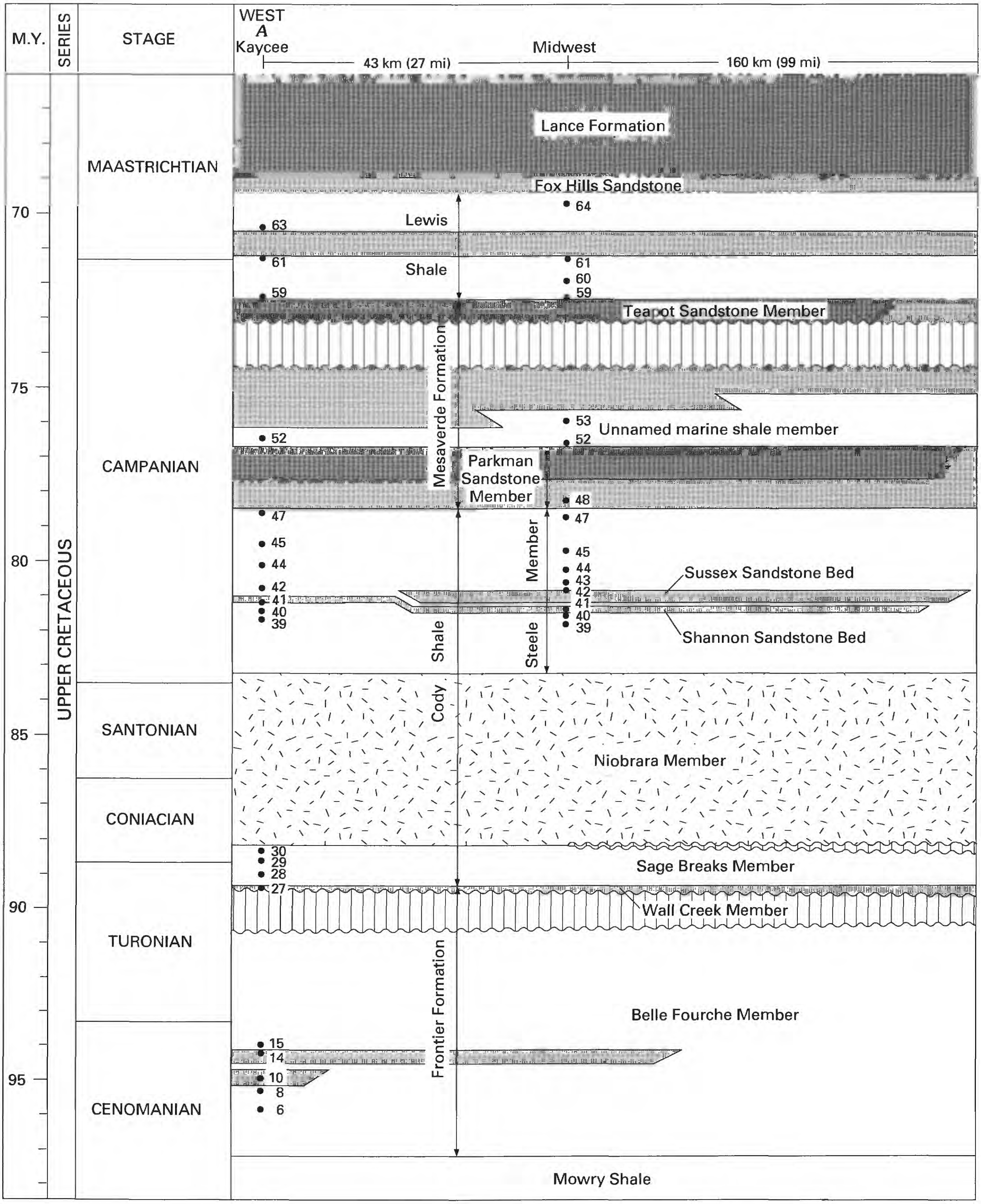


Figure 5 (above and following page). Chronostratigraphic profile of Upper Cretaceous rocks from outcrops near Kaycee, Midwest, and Red Bird, northeastern Wyoming. Line of profile is shown in figure 1.

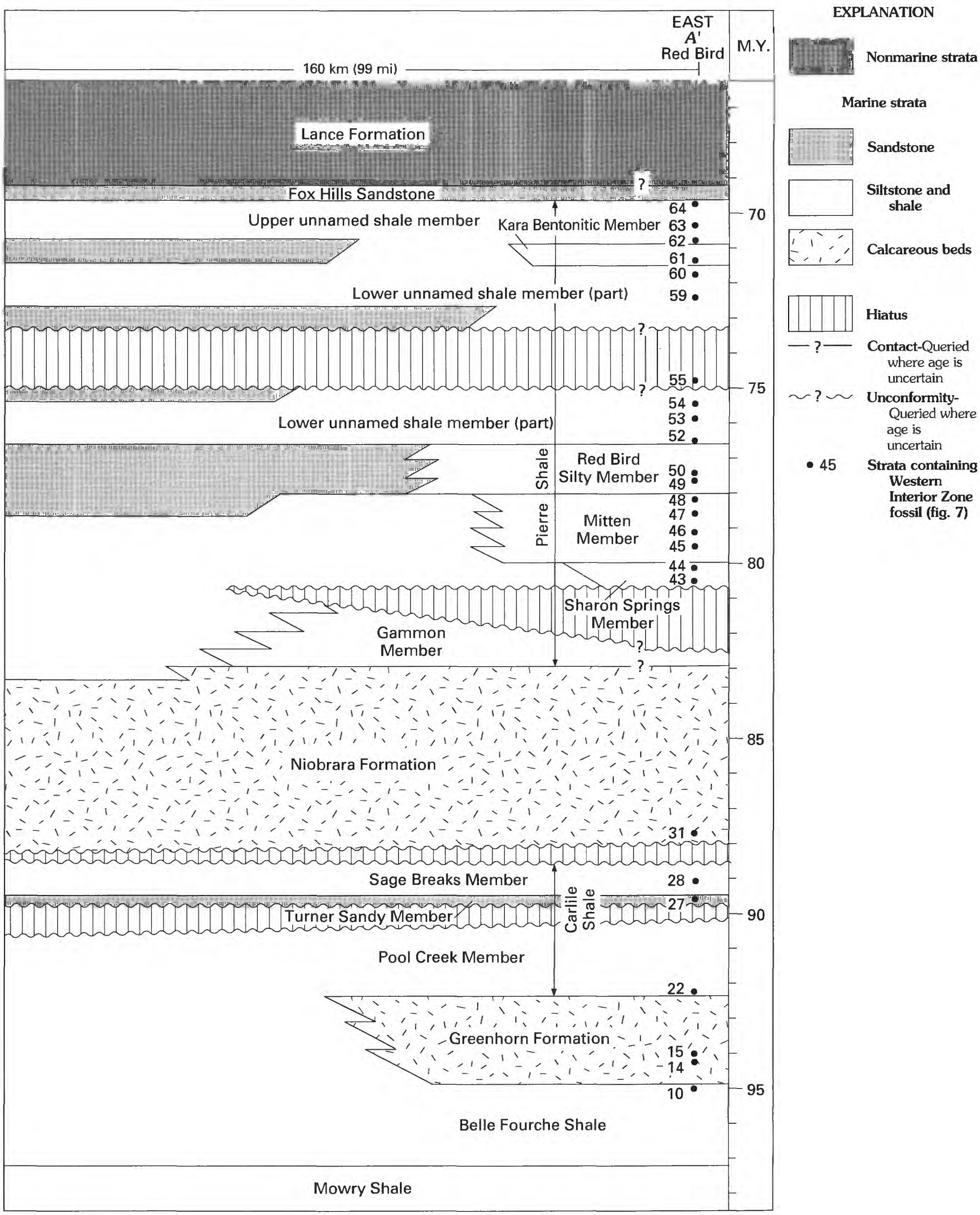

EAST
A'
Red Bird
M.Y.
160 km (99 mi)
Lance Formation
Fox Hills Sandstone
Upper unnamed shale member
Kara Bentonitic Member
Lower unnamed shale member (part)
Lower unnamed shale member (part)
Red Bird Silty Member
Mitten Member
Pierre Shale
Sharon Springs Member
Gammon Member
Niobrara Formation
Sage Breaks Member
Turner Sandy Member
Carlile Shale
Pool Creek Member
Greenhorn Formation
Belle Fourche Shale
Mowry Shale
70
75
80
85
90
95
64
63
62
61
60
59
55
54
53
52
50
49
48
47
46
45
44
43
31
28
27
22
15
14
10
EXPLANATION
Nonmarine strata
Marine strata
Sandstone
Siltstone and shale
Calcareous beds
Hiatus
Contact-Queried where age is uncertain
Unconformity-Queried where age is uncertain
Strata containing Western Interior Zone fossil (fig. 7)

Table 1. Representative outcrop sections in the Powder River Basin, Wyoming and Montana.

Sec. no.	Stratigraphic units	State	County	Location	References
1	Belle Fourche Shale and Greenhorn Formation	Wyoming	Niobara	Sec. 11, 14, T. 36 N., R. 62 W.	E.A. Merewether and W.A. Cobban (unpublished data)
2	Carlile Shale	Wyoming	Niobara	Sec. 23, T. 36 N., R. 62 W., Sec. 36, T. 37 N., R. 62 W.	E.A. Merewether and W.A. Cobban (unpublished data)
3	Pierre Shale	Wyoming	Niobara	Sec.13,14,24, T. 38 N., R. 62 W.	Gill and Cobban (1966a)
4	Mowry Shale	Montana	Big Horn	Sec. 35, T. 6 S., R. 32 E.	Knechtel and Patterson (1956)
5	Belle Fourche and Greenhorn Formations and Carlile Member of Cody Shale	Montana	Big Horn	Sec. 36, T. 6 S., R. 32 E.	Knechtel and Patterson (1956)
6	Niobrara Member of Cody Shale	Montana	Big Horn	Sec. 25, 36, T. 1 S., R. 33 E. Sec. 1, 11, 15, T. 2 S., R. 33 E.	Knechtel and Patterson (1956)
7	Gammon and Claggett Members of Cody Shale	Montana	Big Horn	Sec. 11–13, T. 1 S., R. 34 E. Sec. 18, T. 1 S., R. 35 E.	Knechtel and Patterson (1956)
8	Judith River Formation and Bearpaw Shale	Montana	Big Horn	Sec. 7–10, T. 1 S., R. 35 E.	Knechtel and Patterson (1956)
9	Frontier Formation	Wyoming	Natrona	Sec. 4, T. 33 N., R. 81 W.	Cavanaugh (1976)
10	Cody Shale	Wyoming	Natrona	Sec. 3, 4, T. 38 N., R. 78 W. Sec. 3, T. 39 N., R. 79 W.	Gill and Burkholder (1979)
11	Mesaverde Formation, Lewis Shale, and Fox Hills Sandstone	Wyoming	Natrona	Sec. 15, 16, T. 31 N., R. 82 W.	Rich (1962); J.R. Gill (1972, written commun.)

STRATIGRAPHY

Strata of Cenomanian through Campanian age (figs. 4, 7) can be traced in the subsurface, by using borehole logs, from near the eastern edge of the basin, where the strata were deposited in marine environments, to the western edge of the basin, where they accumulated in marine and continental environments (fig. 6, table 2). Beds of Maastrichtian age throughout the basin were deposited in both continental and marine environments. For all of these strata average sedimentation rates for two locations in the northern part of the basin are 5.8 and 8.1 cm (2.3 and 3.2 in.)/1,000 years, and rates for three locations in the southern part of the basin range from 12.1 to 13.6 cm (4.8–5.4 in.)/1,000 years. Gill and Cobban (1973) determined that the average rate of sedimentation for Upper Cretaceous strata (excluding the Mowry Shale and laterally equivalent beds) in Wyoming is about 19 cm (7.5 in.)/1,000 years. The value of Gill and Cobban seemingly includes some high rates, perhaps from the thicker, nearshore-marine and nonmarine sequences in western Wyoming.

The stratigraphic nomenclature used in this report for Upper Cretaceous beds in Big Horn County, in the northwestern part of the Powder River Basin (fig. 4), differs from that of Richards (1955), Knechtel and Patterson (1956), and Gill and Cobban (1973). Descriptions of outcrops in the area by W.A. Cobban, S.H. Patterson, and P.W. Richards are presented in reports by Richards (1955) and by Knechtel and Patterson (1956). The published nomenclatures are modified herein because lithologic units in the sequence resemble named units in Carter and Crook Counties near the Black Hills (fig. 1) and because fewer names simplify regional stratigraphic correlations and interpretations.

For the northwestern part of the basin, rocks assigned to the "Frontier formation" and to the overlying lower member of the "Cody shale" by Richards (1955) and to the "Belle Fourche shale member of the Cody shale" by Knechtel and Patterson (1956) are herein assigned to the Belle Fourche Formation. Beds that Knechtel and Patterson called the "Greenhorn calcareous shale member of the Cody shale" are herein referred to as the Greenhorn Formation. Rocks formerly assigned to the "Carlile and Niobrara shale members" of the Cody Shale are here called the Carlile and Niobrara Members of the Cody Shale. The "Telegraph Creek shale member" and the overlying "unnamed sandy shale member" of the Cody (Knechtel and Patterson, 1956) as well as the Telegraph Creek Formation (Gill and Cobban, 1973), are herein referred to as the Telegraph Creek Beds and the unnamed shale of the Gammon Member of the Cody Shale. The overlying shale has been called the "Claggett Shale" (Gill and Cobban, 1966, 1973) but is herein called the Claggett Member of

Table 2. Boreholes used to construct cross section in the southern part of the Powder River Basin, northeastern Wyoming.
[Line of section *B–B'* is shown in figure 1; cross section is shown in figure 6]

Borehole	Operator	Lease name	County	Location
1	Anderson Oil Company	Wonderful Wyoming 1	Johnson	Sec. 36, T. 45 N., R. 82 W.
2	Shell Oil Corporation	Montgomery 13X–11B	Johnson	Sec. 11, T. 44 N., R. 79 W.
3	Sun Oil Company	Champlin Federal 1	Campbell	Sec. 27, T. 46 N., R. 76 W.
4	Royal Resources Corporation	Romaker 1–22	Campbell	Sec. 22, T. 47 N., R. 73 W.
5	British-American Oil Producing Company	Government Kimes 1	Campbell	Sec. 5, T. 47 N., R. 70 W.
6	R.M. Hill	Bridwell Federal 1–6	Weston	Sec. 6, T. 48 N., R. 67 W.

the Cody Shale. Beds assigned to the "Parkman sandstone member" and the "upper unnamed member" of the "Judith River formation" by Knechtel and Patterson (1956) and called the "Parkman Sandstone" by Gill and Cobban (1966, 1973) are called herein the Parkman Sandstone Member and the unnamed member of the Judith River Formation. Younger Cretaceous strata have been assigned, in ascending order, to the Bearpaw Shale, Fox Hills Sandstone, and Hell Creek Formation (Gill and Cobban, 1966, 1973).

The gross mineral composition of samples of the Upper Cretaceous rocks is summarized in tables 3 and 4 and was determined mainly by X-ray diffraction. Several samples of mudrock were also investigated by means of combustion and acidification procedures to determine amounts of organic carbon. Sampled mudrocks consist

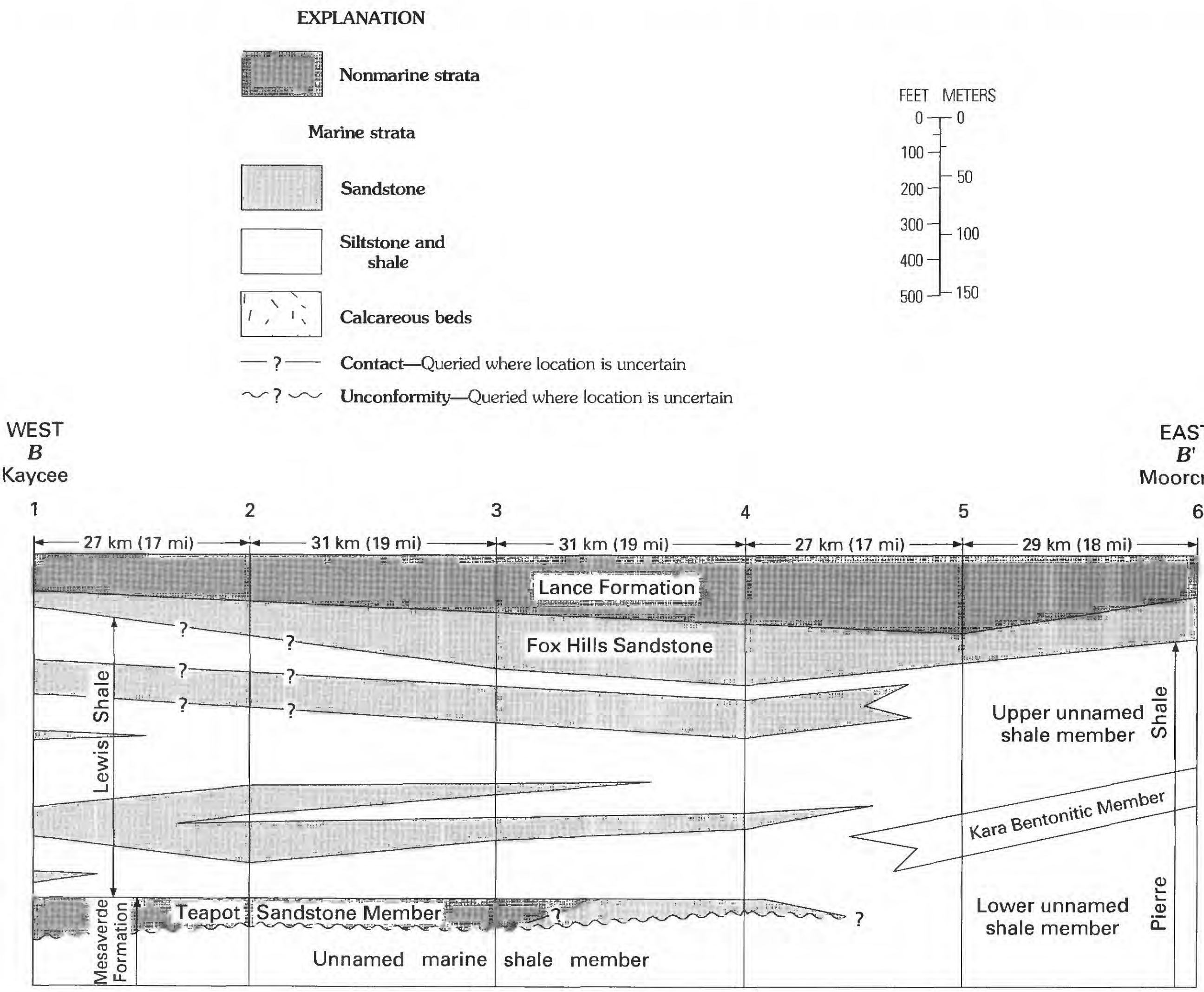
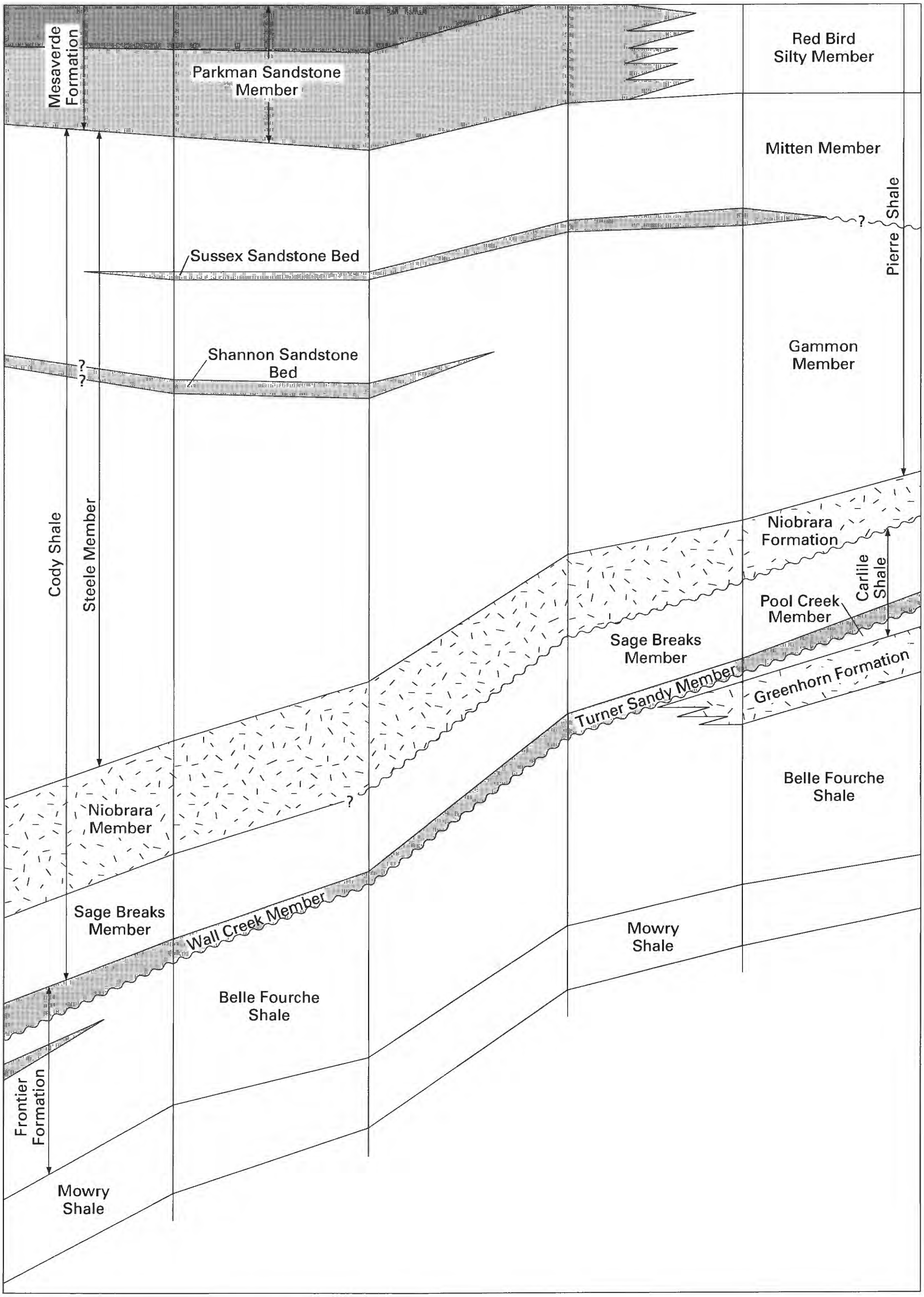


Figure 6 (above and following page). Stratigraphic cross section of Upper Cretaceous rocks in subsurface from near Kaycee to near Moorcroft, northeastern Wyoming. Datum is coeval tops of Parkman Sandstone Member of Mesaverde Formation and of Red Bird Silty Member of Pierre Shale. Line of section is shown in figure 1; wells used to construct cross section are described in table 2.


Mesaverde Formation
Parkman Sandstone Member
Red Bird Silty Member
Mitten Member
Pierre Shale
Sussex Sandstone Bed
Shannon Sandstone Bed
Gammon Member
Cody Shale
Steele Member
Niobrara Formation
Carlile Shale
Pool Creek Member
Sage Breaks Member
Turner Sandy Member
Greenhorn Formation
Belle Fourche Shale
Niobrara Member
Sage Breaks Member
Wall Creek Member
Mowry Shale
Belle Fourche Shale
Frontier Formation
Mowry Shale

Ma	SERIES	STAGE	INFORMAL SUBSTAGE	FOSSIL ZONE
65	PALEOCENE (part)			
66	UPPER CRETACEOUS	Maastrichtian	Upper	
67	UPPER CRETACEOUS	Maastrichtian	Upper	*68 *Triceratops*
68	UPPER CRETACEOUS	Maastrichtian	Upper	67 *Discoscaphites cheyennensis*
	UPPER CRETACEOUS	Maastrichtian	Upper	66 *Discoscaphites roanensis*
69	UPPER CRETACEOUS	Maastrichtian	Upper	
	UPPER CRETACEOUS	Maastrichtian	Upper	65 *Hoploscaphites aff. H. nicolleti*
	UPPER CRETACEOUS	Maastrichtian	Lower	*64 *Baculites clinolobatus*
70	UPPER CRETACEOUS	Maastrichtian	Lower	63 *Baculites grandis*
	UPPER CRETACEOUS	Maastrichtian	Lower	62 *Baculites baculus*
71	UPPER CRETACEOUS	Maastrichtian	Lower	61 *Baculites eliasi*
	UPPER CRETACEOUS	Campanian	Upper	60 *Baculites jenseni*
72	UPPER CRETACEOUS	Campanian	Upper	59 *Baculites reesidei*
	UPPER CRETACEOUS	Campanian	Upper	58 *Baculites cuneatus*
73	UPPER CRETACEOUS	Campanian	Upper	*57 *Baculites compressus*
74	UPPER CRETACEOUS	Campanian	Upper	56 *Didymoceras cheyennense*
	UPPER CRETACEOUS	Campanian	Upper	*55 *Exiteloceras jenneyi*
75	UPPER CRETACEOUS	Campanian	Upper	54 *Didymoceras stevensoni*
76	UPPER CRETACEOUS	Campanian	Upper	*53 *Didymoceras nebrascense*
	UPPER CRETACEOUS	Campanian	Middle	52 *Baculites scotti*
77	UPPER CRETACEOUS	Campanian	Middle	51 *Baculites reduncus*
	UPPER CRETACEOUS	Campanian	Middle	50 *Baculites gregoryensis*
78	UPPER CRETACEOUS	Campanian	Middle	49 *Baculites perplexus* (late form)
	UPPER CRETACEOUS	Campanian	Middle	48 *Baculites gilberti*
79	UPPER CRETACEOUS	Campanian	Middle	47 *Baculites perplexus* (early form)
	UPPER CRETACEOUS	Campanian	Middle	46 *Baculites sp.* (smooth)
	UPPER CRETACEOUS	Campanian	Middle	45 *Baculites asperiformis*
80	UPPER CRETACEOUS	Campanian	Middle	44 *Baculites mclearni*
	UPPER CRETACEOUS	Campanian	Middle	*43 *Baculites obtusus*

Ma	SERIES	STAGE	INFORMAL SUBSTAGE	FOSSIL ZONE
	UPPER CRETACEOUS	Campanian	Lower	42 *Baculites sp.* (weak flank ribs)
81	UPPER CRETACEOUS	Campanian	Lower	41 *Baculites sp.* (smooth)
	UPPER CRETACEOUS	Campanian	Lower	40 *Scaphites hippocrepis III*
	UPPER CRETACEOUS	Campanian	Lower	*39 *Scaphites hippocrepis II*
82	UPPER CRETACEOUS	Campanian	Lower	
83	UPPER CRETACEOUS	Campanian	Lower	38 *Scaphites hippocrepis I*
84	UPPER CRETACEOUS	Santonian	Upper	*37 *Desmoscaphites bassleri*
	UPPER CRETACEOUS	Santonian	Upper	36 *Desmoscaphites erdmanni*
85	UPPER CRETACEOUS	Santonian	Upper	35 *Clioscaphites choteauensis*
	UPPER CRETACEOUS	Santonian	Mid	34 *Clioscaphites vermiformis*
86	UPPER CRETACEOUS	Santonian	Low	*33 *Clioscaphites saxitonianus*
87	UPPER CRETACEOUS	Coniacian	Upper	32 *Scaphites depressus*
	UPPER CRETACEOUS	Coniacian	Middle	31 *Inoceramus involutus*
88	UPPER CRETACEOUS	Coniacian	Middle	*30 *Inoceramus deformis*
	UPPER CRETACEOUS	Coniacian	Low	29 *Inoceramus erectus*
89	UPPER CRETACEOUS	Turonian	Upper	28 *Prionocyclus quadratus*
	UPPER CRETACEOUS	Turonian	Upper	27 *Scaphites whitfieldi*
	UPPER CRETACEOUS	Turonian	Upper	26 *Prionocyclus wyomingensis*
90	UPPER CRETACEOUS	Turonian	Upper	*25 *Prionocyclus macombi*
	UPPER CRETACEOUS	Turonian	Middle	*24 *Prionocyclus hyatti*
91	UPPER CRETACEOUS	Turonian	Middle	23 *Prionocyclus percarinatus*
92	UPPER CRETACEOUS	Turonian	Middle	22 *Collignoniceras woollgari*
	UPPER CRETACEOUS	Turonian	Lower	21 *Mammites nodosoides*
93	UPPER CRETACEOUS	Turonian	Lower	*20 *Vascoceras birchbyi*
	UPPER CRETACEOUS	Turonian	Lower	*19 *Pseudaspidoceras flexuosum*
	UPPER CRETACEOUS	Cenomanian	Upper	18 *Nigericeras scotti*
	UPPER CRETACEOUS	Cenomanian	Upper	*17 *Neocardioceras juddii*
	UPPER CRETACEOUS	Cenomanian	Upper	16 *Burroceras clydense*
94	UPPER CRETACEOUS	Cenomanian	Upper	*15 *Euomphaloceras septemseriatum*
	UPPER CRETACEOUS	Cenomanian	Upper	14 *Metoicoceras mosbyense*
	UPPER CRETACEOUS	Cenomanian	Upper	13 *Dunveganoceras problematicum*
	UPPER CRETACEOUS	Cenomanian	Upper	*12 *Dunveganoceras pondi*
	UPPER CRETACEOUS	Cenomanian	Middle	11 *Plesiacanthoceras wyomingense*
95	UPPER CRETACEOUS	Cenomanian	Middle	*10 *Acanthoceras amphibolum*
	UPPER CRETACEOUS	Cenomanian	Middle	9 *Acanthoceras bellense*
	UPPER CRETACEOUS	Cenomanian	Middle	8 *Acanthoceras muldoonense*
	UPPER CRETACEOUS	Cenomanian	Middle	7 *Acanthoceras granerosense*
	UPPER CRETACEOUS	Cenomanian	Middle	*6 *Conlinoceras tarrantense*
96	UPPER CRETACEOUS	Cenomanian	Lower	
	UPPER CRETACEOUS	Cenomanian	Lower	5 No molluscan fossil record
97	UPPER CRETACEOUS	Cenomanian	Lower	4 *Neogastroplites maclearni*
	UPPER CRETACEOUS	Cenomanian	Lower	3 *Neogastroplites americanus*
98	UPPER CRETACEOUS	Cenomanian	Lower	2 *Neogastroplites muelleri*
	UPPER CRETACEOUS	Cenomanian	Lower	*1 *Neogastroplites cornutus*
	UPPER CRETACEOUS	Cenomanian	Lower	*0 *Neogastroplites haasi*

Figure 7 (preceding page). Ages and fossil sequence for Upper Cretaceous strata in Western Interior of United States. Asterisk (*) indicates sequential location of rocks radiometrically dated. Compiled from Obradovich and Cobban (1975) and Obradovich (1988, 1993).

mostly of quartz, potassium feldspar, plagioclase, dolomite, illite, kaolinite, chlorite, and mixed-layer clay minerals (generally illite, beidellite, and montmorillonite). Mineral components of the sandstone units were ascertained using X-ray records, thin sections, and micrographs. Sampled sandstones are composed mainly of quartz, potassium feldspar, plagioclase, mica, illite, and lithic fragments. Many of the sandstone units are litharenites.

The latitudes of the region of the basin during the Cretaceous were between 45° and 50° N., slightly north of the present latitudes of about 42° and 47° N. (Couillard and Irving, 1975). From studies of fossil plants, Upchurch and Wolfe (1987) concluded that Cretaceous land areas in the high-middle paleolatitudes (about 45°–65° N.) were seasonal in precipitation and daylength and temperatures were higher than at present. Mean annual temperatures probably were less than 20°C (<68°F) in Aptian through early Cenomanian time and were 13°C–20°C (55.4°F–68°F) during middle Cenomanian through late Maastrichtian time. Upchurch and Wolfe (1987) determined that paleoclimates were subhumid at low-middle paleolatitudes but wetter at higher paleolatitudes, which would have included the region of the Powder River Basin. Wolfe and Upchurch (1986) and J.A. Wolfe (oral commun., 1986, 1989) also proposed that the climate in the region of the Powder River Basin during the late Maastrichtian was warm (25°C–37°C, 77°F–98.6°F) and subhumid (rainfall 80–90 cm [31–35 in.]/year). Parrish and Barron (1986) indicated that the mid-Cretaceous climate at mid-latitudes on continents of the Northern Hemisphere was seasonal and characterized by high rates of precipitation. According to Burgess (1971) and Breithaupt (1985), fossil flora and fauna of several Upper Cretaceous units in the region of the basin are typical of subtropical to warm temperate, coastal-lowland and nearshore-marine environments.

From global reconstructions of Cretaceous climates, Barron (1989) proposed that severe winter storms extended into the northern part of the epeiric sea of North America, but that few hurricanes affected the seaway during Albian and Cenomanian time. He also suggested that severe winter storms and hurricanes were common in the seaway during the Campanian and Maastrichtian. Numerical simulations of aqueous currents in the epicontinental sea by Ericksen and Slingerland (1990) indicate that the circulation was generally storm dominated and that tides in the region of the Powder River Basin were microtidal. Winter storms crossing the seaway from west to east generated dominantly south flowing, shore-parallel geostrophic currents. During much of the Late Cretaceous, the open-marine waters of the epeiric sea apparently were slightly acidic, a condition that caused the slow dissolution first of aragonite and thereafter of calcite in invertebrate exoskeletons on the seafloor (Gill and Cobban, 1966a).

ROCKS OF CENOMANIAN AND EARLY TURONIAN AGE

MOWRY SHALE

Darton (1904a, p. 400; 1906, p. 53) named the Mowry Shale from outcrops at the western margin of the Powder River Basin, about 18 km (11 mi) northwest of Buffalo, Wyoming (fig. 1). These distinctive rocks of early Cenomanian age (Cobban and Kennedy, 1989a) extend throughout most of Wyoming and Montana and crop out along the western, southern, and eastern margins of the Powder River Basin. The formation is composed mainly of interstratified soft light-greenish-gray bentonite and dark-gray, siliceous mudstone and siltstone. The mudstone and siltstone generally weather to hard, brittle, light-gray chips. The uppermost bed of the Mowry consists of bentonite, locally called the Clay Spur Bentonite Bed (Robinson and others, 1964), and is commonly 1–2 m (3–7 ft) thick.

Robinson and others (1964) reported that the outcropping lower part of the Mowry on the eastern edge of the basin in northern Weston County (fig. 1) includes a basal unit, 3–6 m (10–20 ft) thick, of soft shale and sandstone (named the "Nefsy Shale Member of the Graneros Shale" by Collier, 1922) and, at about 5.5 m (18 ft) above the base of the formation, a unit of sandstone as thick as 1.5 m (5 ft). At outcrops near the western edge of the basin the Mowry includes thin beds of siltstone and sandstone in Big Horn County (fig. 8) (Knechtel and Patterson, 1956) and units of sandstone as thick as 4 m (14 ft) in northern Johnson County (Mapel, 1959).

The formation along the western margin of the basin was divided by Davis and others (1989) into northeast-trending lithologic units that, from northwest to southeast, are composed mainly of laminated and moderately bioturbated silty mudstone, interlaminated mudstone and fining-upward laminae of siltstone and mudstone, homogeneous mudstone, and radiolarian-bearing mudstone. Trace fossils are common in the Mowry throughout the basin region.

At scattered locations in the Powder River Basin the Upper Cretaceous Mowry Shale conformably overlies the Lower Cretaceous Thermopolis Shale, Muddy Sandstone, Skull Creek Shale, or Newcastle Sandstone, and it is conformably overlain by the Upper Cretaceous Belle Fourche

Table 3. Composition of some Upper Cretaceous mudrocks in the Powder River Basin, Wyoming and Montana.

Formation (Member)	County	No. of samples	Qtz	Potassium feldspar	Plagioclase	Calcite	Dolomite	Illite	Kaolinite	Chlorite	Mont-morillonite	Mixed-layer clay	Pyrite	Organic-C (wt. percent)	Reference
Lewis Shale	Natrona	3	X	X	X		X	X	X	X		X			Schultz and others (1980)
Bearpaw Shale	Big Horn	1	X	X	X		X	X	X	X		X			Schultz and others (1980)
Pierre Shale (upper unnamed shale)	Niobrara	3	X		X		X	X	X	X		X			Schultz and others (1980)
Bearpaw Shale	Big Horn	1	X	X	X		X	X	X	X		X			Schultz and others (1980)
Mesaverde (unnamed marine shale)	Natrona	1	X	X	X	X	X	X	X	X		X		X	Schultz and others (1980)
Pierre Shale (Red Bird Silty)	Niobrara	2	X		X		X	X	X	X		X			Schultz and others (1980)
Cody Shale (upper part of Steele)	Natrona	2	X	X	X		X	X	X	X		X			Schultz and others (1980)
Pierre Shale (Mitten)	Carter	2	X		X			X	X			X			Schultz and others (1980)
Pierre Shale (Mitten)	Niobrara	2	X		X			X	X			X			Schultz and others (1980)
Pierre Shale (Sharon Springs)	Niobrara	1	X		X		X	X	X	X		X	X	X	Schultz and others (1980)
Cody Shale (lower part of Steele)	Natrona	4	X	X	X		X	X	X	X	X				Schultz and others (1980)
Pierre Shale (Gammon)	Carter	2	X		X		X	X	X	X		X		0.6–0.8	Schultz and others (1980)
Cody Shale (Sage Breaks)	Johnson	1	X	X	X		X	X		X		X		0.7	Merewether and others (1976)
Carlile Shale (Sage Breaks)	Weston	3	X	X	X	X	X	X	X	X			X	1.3–2.2	Merewether (1980)
Frontier (Wall Creek)	Johnson	1	X	X	X		X	X		X		X		0.5	Merewether and Claypool (1980)
Carlile Shale (Turner Sandy)	Weston	2	X	X	X		X	X	X	X			X	1.0–1.1	Merewether (1980)
Carlile Shale (Pool Creek)	Weston	2	X	X	X		X	X	X	X		X	X	1.1–4.3	Merewether (1980)
Frontier (Belle Fourche)	Johnson	2	X	X	X	X	X	X	X	X	X	X		0.4–3.2	Merewether and Claypool (1980)
Frontier (Belle Fourche)	Johnson	19	X	X	X			X	X	X	X	X		1.0–2.0	Merewether and Gautier (unpub. data)
Greenhorn	Weston	4	X	X	X	X	X	X	X	X			X	2.2–3.0	Merewether (1980)
Belle Fourche Shale	Weston	2	X	X	X		X	X	X	X		X	X	1.2–1.6	Merewether (1980)
Mowry Shale	--[1]	29	X	X	X				X		X	X			Davis (1970)
Mowry Shale	Powder River	20												1.9–4.4	Dean and Arthur (1989)

[1]Converse, Crook, Johnson, Natrona, Niobrara, and Sheridan.

Table 4. Composition of some Upper Cretaceous sandstones in the Powder River Basin, Wyoming and Montana.

Formation (Member: Bed)	County	No. of samples	Qtz	K feldspar	Plag.	Biotite or musc.	Calcite	Dolomite	Siderite	Pyrite	Illite
Hell Creek	Rosebud	10	X	X	X						
Lance	Campbell	10	X	X	X						
Lance	Niobrara	10	X	X	X						
Lewis Shale	Converse		X	X	X	X					
Lewis Shale	Campbell		X	X	X	X					
Mesaverde (Teapot Sandstone)	Natrona	2	X	X	X	X					
Mesaverde (Teapot Sandstone)	Natrona	2	X	X	X						X
Mesaverde (Teapot Sandstone)	Converse		X	X	X	X					
Mesaverde (Parkman Sandstone)	Natrona		X	X	X	X					
Mesaverde (Parkman Sandstone)	Natrona	2	X	X	X			X			X
Mesaverde (Parkman Sandstone)	Natrona		X	X	X	X					
Judith River (Parkman Sandstone)	Big Horn	1	X	X	X			X			X
Cody Shale (Steele: Sussex Sandstone).	Campbell		X	X	X						
Cody Shale (Steele: Sussex Sandstone)	Campbell		X		X		X	X	X	X	X
Cody Shale (Steele: Shannon Sandstone)	Campbell, Johnson, Natrona		X	X	X		X	X	X	X	
Frontier (Wall Creek)	Johnson	2	X	X		X	X				X
Frontier (Wall Creek)	Converse	1	X		X		X				X
Frontier (Wall Creek)	Converse	1	X		X		X				X
Carlile Shale (Turner Sandy)	Weston	3	X	X	X	X	X	X		X	X
Frontier (Belle Fourche)	Johnson	3	X	X	X	X	X	X			
Frontier (Belle Fourche)	Natrona	5	X	X	X	X					

Shale, Belle Fourche Formation, or Belle Fourche Member of the Frontier Formation (fig. 4). An outcropping unit of soft shale (Nefsy Shale Member of Collier, 1922) that separates the Newcastle or the Muddy from siliceous strata of the Mowry has been assigned to either the Thermopolis or the Mowry, which complicates comparison of reported thicknesses for the Mowry.

Along the eastern margin of the basin the Mowry (including a soft basal shale as thick as 6 m [20 ft]) is about 70 m (230 ft) thick at outcrops near the corner common to Wyoming, Montana, and South Dakota (Cobban, 1952; Robinson and others, 1964). It apparently thins southward and is about 49 m (160 ft) thick in boreholes in Niobrara County (fig. 9A).

Near the western edge of the basin the Mowry is about 122 m (400 ft) thick at outcrops (Knechtel and Patterson, 1956) and about 88 m (290 ft) thick in boreholes (fig. 9B) in southern Big Horn County, and to the south it is 152–160 m (500–525 ft) thick (including a soft basal shale about 60 m [200 ft] thick) at outcrops near Buffalo in Johnson and Sheridan Counties (Hose, 1955; Mapel, 1959). In boreholes in southwestern Campbell County (fig. 9C) and east-central Natrona County (fig. 9D) the formation is about 73 m (240 ft) thick and 79 m (260 ft) thick, respectively.

Small-scale isopach maps of the Mowry in Wyoming and eastern Montana by Davis (1970), Nixon (1973), and Burtner and Warner (1984) show the formation thinning eastward in the northern part of the Powder River Basin and thinning irregularly southeastward in the southern part of the basin. The thickness in the subsurface of the basin, according to Fox and Higley (1987a), ranges from about 99 m (325 ft) in northern Johnson County to about 44 m (145 ft) in northeastern Converse County. Their map indicates that the least thicknesses are on the eastern flank of the basin and that the formation does not thin uniformly eastward or southeastward across the basin.

The Mowry Shale in the Powder River Basin contains abundant fossilized scales and bones of fish, as well as fossilized reptilian bones (Massare and Dain, 1989), Radiolaria (Rubey, 1929), Foraminifera (Skolnick, 1958; Ellis, 1963), and mollusks. According to Massare and Dain (1989), reptilian remains in the upper part of the Mowry in Weston County represent an ichthyosaur, an elasmosaur, a pliosaur, and a crocodile. Marine mollusks of Late Cretaceous (early Cenomanian) age (fig. 7) have been collected from outcrops of lower, middle, and upper parts of the Mowry at scattered localities near the perimeter of the basin (Reeside and Cobban, 1960; Robinson and others, 1964; L.M. Pratt and F.B. Zelt, written commun., 1985).

Chlorite	Kaoli-nite	Glauco-nite	Mixed-layer clay	Lithic fragments				Rock type	Reference	Formation (Member: Bed)
				Sed.	Vol.	Plutonic	Meta.			
				X	X				Connor (1992)	Hell Creek
				X	X		X		Connor (1992)	Lance
						X			Connor (1992)	Lance
		X		X				Subarkosic	Runge and others (1973)	Lewis Shale
		X		X			X		Runge and others (1973)	Lewis Shale
X				X				Graywacke	Pryor (1961)	Mesaverde (Teapot Sandstone)
	X		X						Schultz and others (1980)	Mesaverde (Teapot Sandstone)
X	X	X		X				Litharenite	Isbell and others (1976)	Mesaverde (Teapot Sandstone)
X				X				Litharenite	Hubert and others (1972)	Mesaverde (Parkman Sandstone)
X	X		X						Schultz and others (1980)	Mesaverde (Parkman Sandstone)
							X		Dogan (1984)	Mesaverde (Parkman Sandstone)
X	X		X						Schultz and others (1980)	Judith River (Parkman Sandstone)
X	X	X		X		X	X	Litharenite	Berg (1975)	Cody Shale (Steele: Sussex Sandstone).
X	X	X		X				Litharenite	Higley (1992	Cody Shale (Steele: Sussex Sandstone)
X	X	X		X		X	X	Litharenite	Hansley and Whitney (1990)	Cody Shale (Steele: Shannon Sandstone)
	X			X					Merewether (1980)	Frontier (Wall Creek)
X				X					Tillman and Almon (1979)	Frontier (Wall Creek)
X				X					Tillman and Almon (1979)	Frontier (Wall Creek)
X	X			X					Merewether (1980)	Carlile Shale (Turner Sandy)
	X			X					Merewether (1980)	Frontier (Belle Fourche)
				X	X		X	Litharenite	Cavanaugh (1976)	Frontier (Belle Fourche)

The Mowry Shale of the Powder River Basin, which was deposited in the offshore environments of a south-trending boreal sea, grades into nearshore sandstone of the Dakota Group in South Dakota, Nebraska, and Colorado, and of the Bear River Formation in Utah and Idaho (fig. 2) (McGookey and others, 1972; Williams and Stelck, 1975). From the distribution of mineral components, Davis (1970) concluded that the dominant source area for sediments of the Mowry was in northwestern Wyoming and that a diffuse sedimentary source was east of the Powder River Basin. Nixon (1973) indicated that sediments in the lower part of the formation were derived from northwestern Wyoming and southwestern South Dakota and that sediments in the upper part originated in northwestern Wyoming. Davis and Byers (1989) concluded that sandstone in the upper part of the Mowry in north-central Wyoming was derived from western Montana.

Byers and Larson (1979) interpreted the Mowry near the southwestern margin of the Powder River Basin as representing deposition mainly in a quiet, anaerobic, comparatively deep water (>150 m, 490 ft) environment, although they interpreted the uppermost part of the formation along the western flank of the basin as indicating deposition in a quiet, marginally aerobic environment in water 15–150 m (50–490 ft) deep. Burtner and Warner (1984) summarized a succession of depositional environments for the Mowry in central Wyoming, from anoxic conditions for the base of the formation to oxic conditions for the top. According to Davis and others (1988), the sea "was not a fresh water body but was either of normal marine salinity or contained brackish water with greater than one-half normal salinity." Davis and others (1989) indicated that the Mowry on the western flank of the Powder River Basin accumulated on a submarine slope in dysaerobic to anaerobic water. The sediments were deposited from bottom flows (distal storm flows or turbidity flows) in the northwestern part of the basin and by pelagic settling on the southwestern flank of the basin.

The formation in western and central Wyoming, according to Byers and Larson (1979), records an eastward-prograding shoreline. In terms of sequence stratigraphy (Van Wagoner and others, 1990), the Mowry could include, in ascending order, a retrogradational parasequence set (transgressive systems tract) and an aggradational to progradational parasequence set (most of a highstand systems tract).

BELLE FOURCHE SHALE AND FORMATION

Collier (1922) named the Belle Fourche Shale from outcrops along the Belle Fourche River in southwestern Crook County near the eastern margin of the Powder

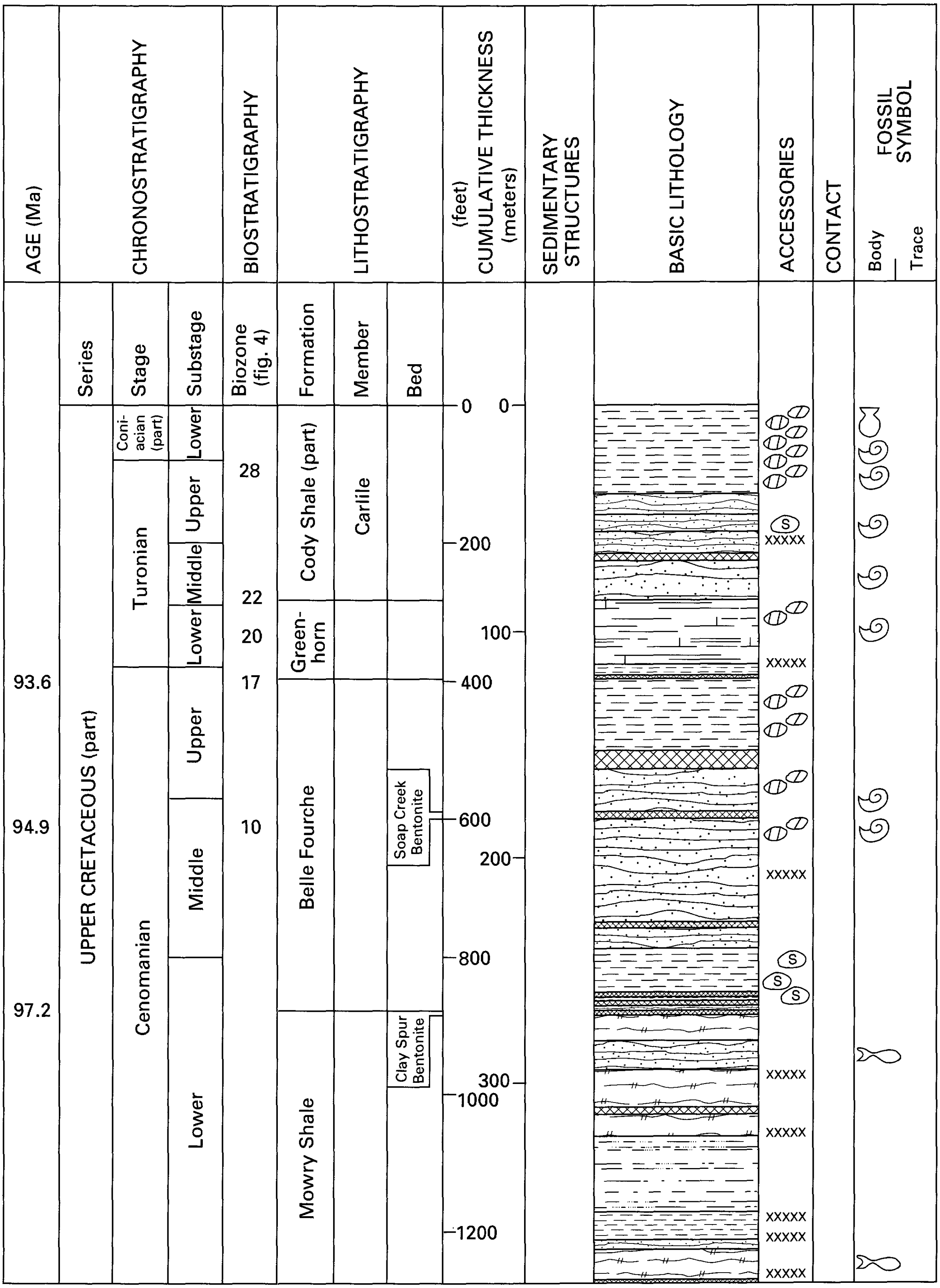
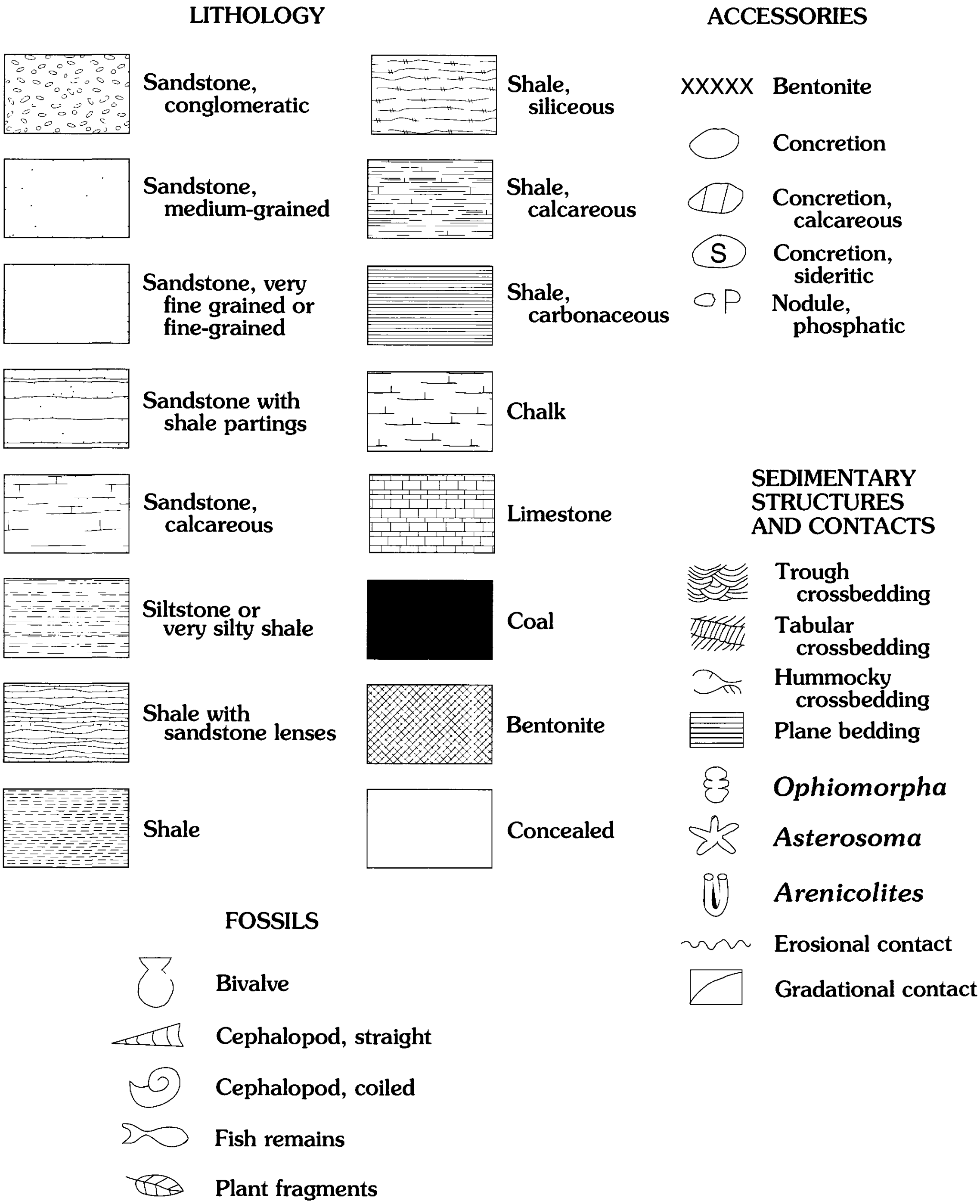
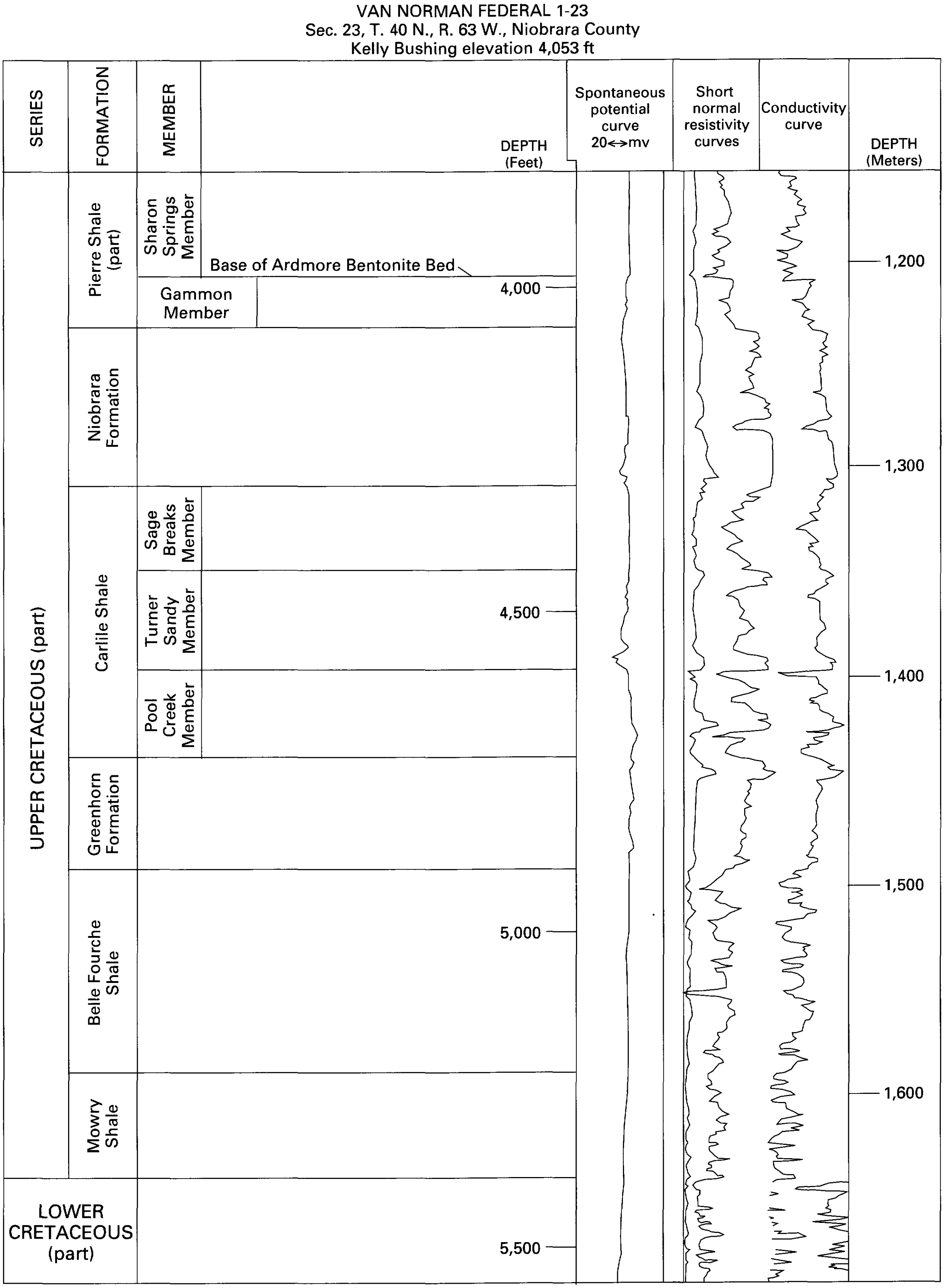


Figure 8 (above and facing page). Outcrop sections of Mowry Shale, Belle Fourche Formation, Greenhorn Formation, and Carlile Member of the Cody Shale, southern Big Horn County, Montana (sections 4, 5, table 1). Modified from Knechtel and Patterson (1956).

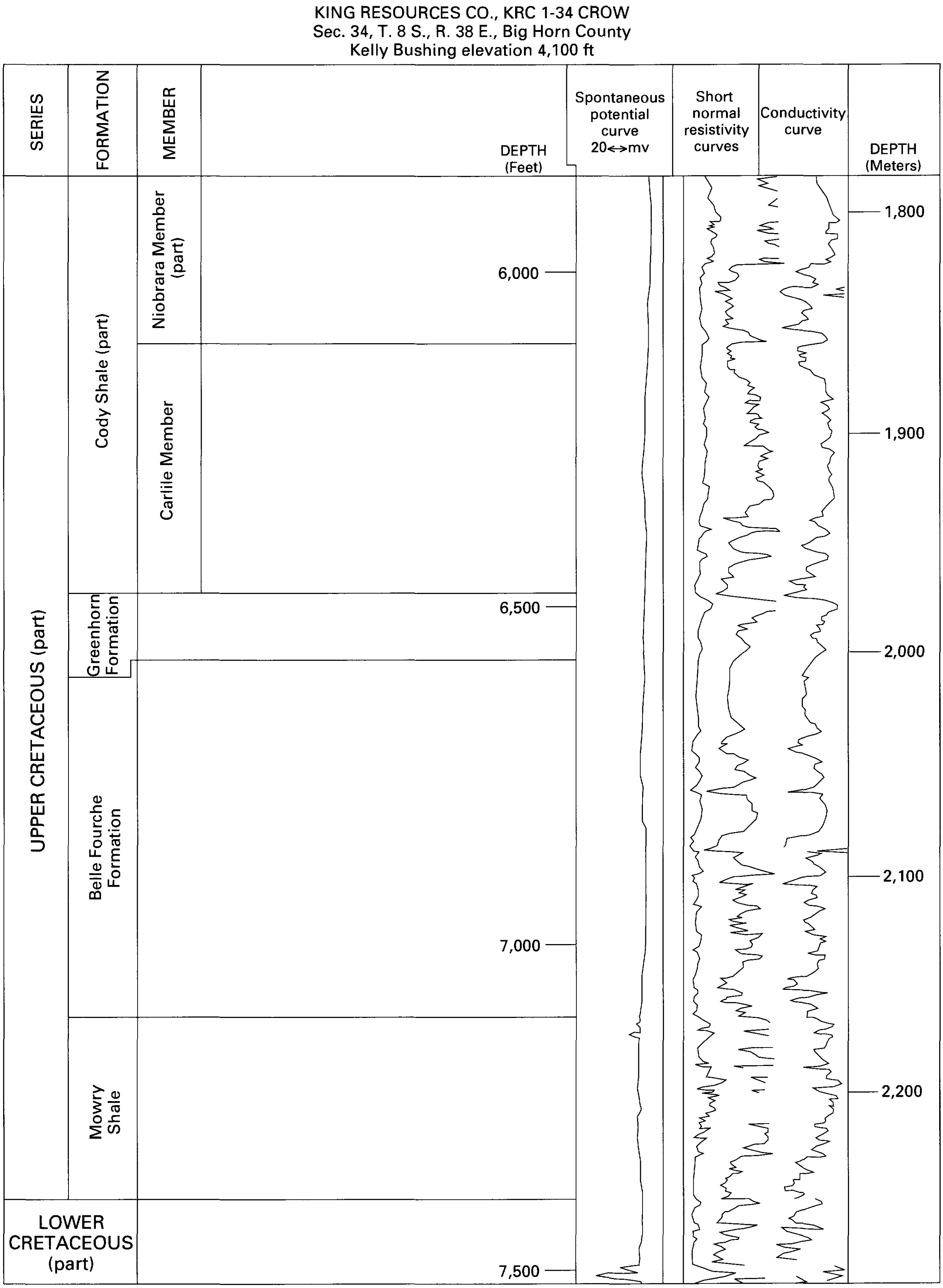
EXPLANATION (figs. 8, 10-12, 14, 16, 17, 19, 21, 25)



River Basin (fig. 1). This formation of Cenomanian age (figs. 4, 5) is recognized on the eastern flank of the basin and is composed of mainly noncalcareous dark-gray shale and lesser amounts of greenish-gray to reddish-brown bentonite (fig. 10). Several of the thicker beds of bentonite have been informally named and traced in outcrops along the edge of the basin (Moore, 1949; Knechtel and Patterson, 1956, 1962). Most of the Belle Fourche is poorly indurated, and the lower and middle parts seldom crop out. A basal unit of the formation, commonly 20–100 m (65–330 ft) thick, is characterized by abundant sideritic concretions. Minor amounts of siltstone, silty and sandy shale, and calcareous shale are in the upper part of the Belle Fourche (Robinson and others, 1964). Trace fossils are present throughout the formation. A core of the uppermost 25 m (82 ft) of the Belle Fourche, from a borehole

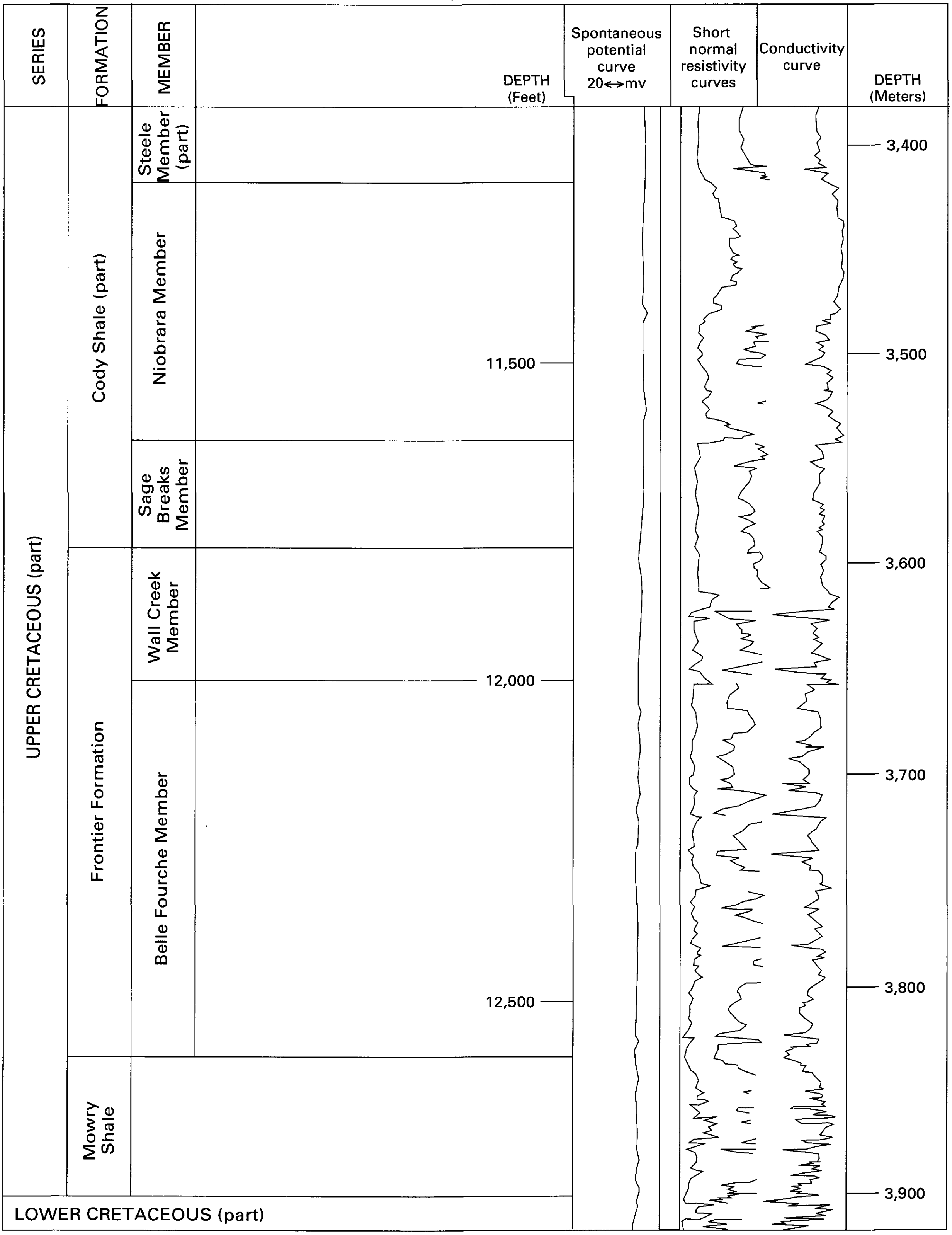

VAN NORMAN FEDERAL 1-23
Sec. 23, T. 40 N., R. 63 W., Niobrara County
Kelly Bushing elevation 4,053 ft
SERIES
FORMATION
MEMBER
DEPTH (Feet)
Spontaneous potential curve 20↔mv
Short normal resistivity curves
Conductivity curve
DEPTH (Meters)
UPPER CRETACEOUS (part)
Pierre Shale (part)
Sharon Springs Member
Base of Ardmore Bentonite Bed
Gammon Member
Niobrara Formation
Carlile Shale
Sage Breaks Member
Turner Sandy Member
Pool Creek Member
Greenhorn Formation
Belle Fourche Shale
Mowry Shale
LOWER CRETACEOUS (part)
4,000
4,500
5,000
5,500
1,200
1,300
1,400
1,500
1,600

A

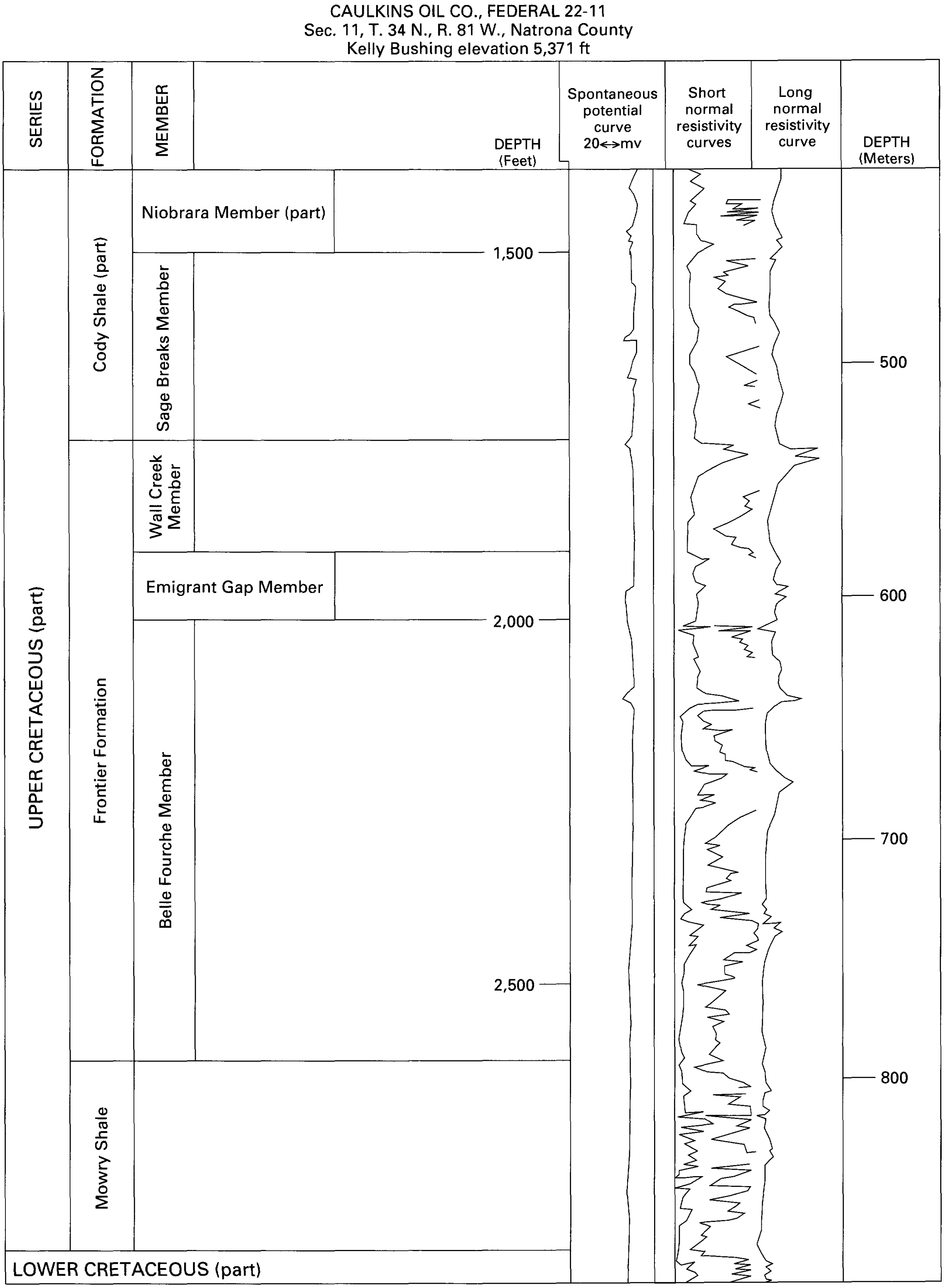

KING RESOURCES CO., KRC 1-34 CROW
Sec. 34, T. 8 S., R. 38 E., Big Horn County
Kelly Bushing elevation 4,100 ft
SERIES
FORMATION
MEMBER
DEPTH (Feet)
Spontaneous potential curve 20↔mv
Short normal resistivity curves
Conductivity curve
DEPTH (Meters)
UPPER CRETACEOUS (part)
LOWER CRETACEOUS (part)
Cody Shale (part)
Greenhorn Formation
Belle Fourche Formation
Mowry Shale
Niobrara Member (part)
Carlile Member
6,000
6,500
7,000
7,500
1,800
1,900
2,000
2,100
2,200

B

MIAMI OIL PRODUCERS, INC., CAMBLIN 1
Sec. 4, T. 43 N., R. 75 W., Campbell County
Kelly Bushing elevation 5,499 ft



C


CAULKINS OIL CO., FEDERAL 22-11
Sec. 11, T. 34 N., R. 81 W., Natrona County
Kelly Bushing elevation 5,371 ft
SERIES
FORMATION
MEMBER
DEPTH (Feet)
Spontaneous potential curve 20↔mv
Short normal resistivity curves
Long normal resistivity curve
DEPTH (Meters)
UPPER CRETACEOUS (part)
Cody Shale (part)
Niobrara Member (part)
Sage Breaks Member
Frontier Formation
Wall Creek Member
Emigrant Gap Member
Belle Fourche Member
Mowry Shale
LOWER CRETACEOUS (part)
1,500
2,000
2,500
500
600
700
800

D

Figure 9 (previous pages). Geophysical logs of Upper Cretaceous rocks in Powder River Basin. A, Mowry Shale to Sharon Springs Member of the Pierre Shale, Niobrara County, Wyoming. B, Mowry Shale to Niobrara Member of the Cody Shale, Big Horn County, Montana. C, Mowry Shale to Steele Member of the Cody Shale, Campbell County, Wyoming. D, Mowry Shale to Niobrara Member of the Cody Shale, Natrona County, Wyoming.

in SW1/4 NW1/4 sec. 30, T. 46 N., R. 63 W., Weston County, is composed of interlaminated shale and lesser siltstone that are very light gray to dark gray and mainly noncalcareous (Merewether, 1980). The laminae are discontinuous, even, and parallel; discontinuous, wavy, and nonparallel; and crosslaminated. Some of this shale and siltstone has flaser bedding, lenticular bedding, and small slump structures.

Along the eastern flank of the basin the Belle Fourche Shale conformably overlies the Mowry Shale and is conformably and disconformably overlain by the Greenhorn Formation. In Weston and Niobrara Counties, as well as on the northeastern flank of the Black Hills in South Dakota, the Belle Fourche probably is disconformably overlain by the Greenhorn (W.A. Cobban, oral commun., 1989). In other areas, the upper part of the Belle Fourche grades into and intertongues with the lower part of the Greenhorn, causing rather abrupt lateral changes in the thickness of both formations (Moore, 1949; Robinson and others, 1964).

Reports by Cobban (1952) and Robinson and others (1964) indicate that the formation at outcrops thins southward from about 230 m (750 ft) in northwestern Crook County to about 91 m (300 ft) in Niobrara County. At a borehole in Niobrara County (fig. 9A) the Belle Fourche is about 98 m (320 ft) thick. Southwestward across the basin, the Belle Fourche Shale grades laterally into mudrock, siltstone, and sandstone in the lower part of the Belle Fourche Member of the Frontier Formation (Merewether, 1980) (fig. 4).

At outcrops in the northwestern part of the basin in Big Horn County similar and partly equivalent strata formerly assigned to the Belle Fourche shale member of the Cody shale (Knechtel and Patterson, 1956) are herein assigned to the Belle Fourche Formation (fig. 4). This unit (fig. 8) is composed of shale, minor sandy shale, sparse thin beds of sandstone, and several beds of bentonite and is about 145 m (475 ft) thick (Richards, 1955; Knechtel and Patterson, 1956). At a borehole in Big Horn County (fig. 9B), the formation is about 162 m (530 ft) thick. The Belle Fourche in Big Horn County conformably overlies the Mowry Shale and is conformably overlain by the calcareous Greenhorn Formation.

The Belle Fourche contains microfossils and vertebrate fossils, as well as molluscan fossils in the middle and upper parts of the unit (Nace, 1941; Robinson and others, 1964; Merewether, 1980; Cobban, 1984, 1987, 1988a, b). Eicher (1967) determined that the foraminiferal fauna of the Belle Fourche in the northern part of the basin is sparse, limited in variety, and dominantly arenaceous, excepting the fauna in beds transitional with the overlying Greenhorn Formation. He also stated that the "foraminifera generally increase in abundance and variety upward," which indicates a gradual change in the water of the epeiric sea. In a core of the uppermost 18 m (60 ft) of the formation in northeastern Weston County, B.R. North and W.G.E. Caldwell (written commun., 1978, 1993) found agglutinated foraminifera and a few pelagic specimens that might reflect an abnormal marine environment.

Palynomorphs were identified by Okumura (1994) in core of an upper part of the Belle Fourche Shale (about 25 m [82 ft] thick) from Weston County. They include both continental and marine forms but are dominantly spores and pollen of continental origin.

Bones from ichthyosaurs and elasmosaurs have been found in the Belle Fourche in Weston County (Nace, 1941; Massare and Dain, 1989). Ammonites as old as earliest middle Cenomanian (fig. 7) have been collected from near the middle of the Belle Fourche at outcrops in Weston County. Molluscan fossils as young as very late Cenomanian have been found at the top of the outcropping Belle Fourche Formation in Big Horn County.

The concretionary strata of the lowermost Belle Fourche accumulated during early Cenomanian time in offshore-marine environments of a north-trending epeiric sea that extended from south-central Colorado to the Arctic Ocean (E.A. Merewether and D.L. Gautier, unpub. data). Fossiliferous middle and upper parts of the Belle Fourche were deposited during the middle and late Cenomanian (figs. 4, 5) in the offshore environments of an epicontinental sea that extended north from the present Gulf of Mexico to the Arctic Ocean. Laterally equivalent nearshore-marine strata on the east side of the seaway in South Dakota and Nebraska are within the Dakota Sandstone (Formation), whereas those on the west side of the seaway in Utah and Wyoming are within the Dakota Sandstone and the Frontier Formation (Merewether and Cobban, 1986a).

The Belle Fourche on the eastern flank of the Powder River Basin was interpreted by Weimer and Flexer (1985) as the offshore deposits of a slope and basin. According to Eicher (1967) and Eicher and Diner (1985), the sparse assemblages of arenaceous foraminifera in the Belle Fourche indicate restricted marine environments and poorly oxygenated water of less than normal marine salinity. Eicher (1967) also suggested that the general upward increase in the abundance and diversity of the foraminiferal specimens represents increasingly open marine environments. In a sequence-stratigraphic interpretation (Van Wagoner and others, 1990), the Belle Fourche could consist of, from oldest to youngest, a progradational

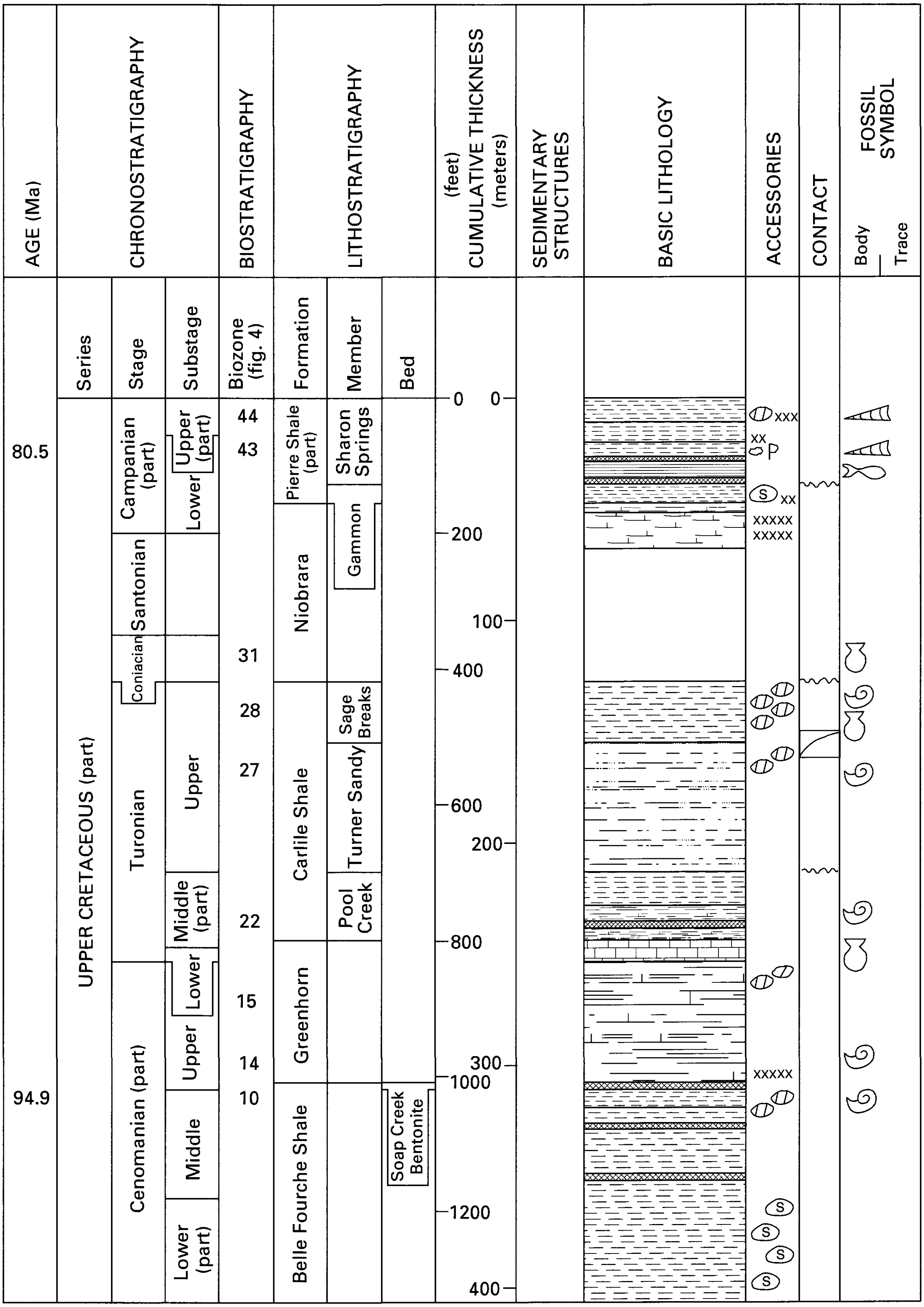


Figure 10. Outcrop sections of Belle Fourche Shale, Greenhorn Formation, Carlile Shale, Niobrara Formation, and lower part of Pierre Shale, northeastern Niobrara County, Wyoming (sections 1– 3, table 1). Explanation as in figure 8. Modified from Gill and Cobban (1966a) and U.S. Geological Survey (1974).

parasequence (part of a highstand systems tract), type-1 sequence boundary, progradational parasequence set (lowstand systems tract), and generally retrogradational parasequence set (transgressive systems tract).

BELLE FOURCHE MEMBER OF THE FRONTIER FORMATION

The name "Frontier Formation" was introduced by Knight (1902) for a sequence of interstratified sandstone, siltstone, shale, and coal of mid-Cretaceous age in southwestern Wyoming. Hares (1916) applied the name to conspicuous outcropping beds of sandstone and mudrock along the southwestern margin of the Powder River Basin. These siliciclastic rocks range in thickness from about 122 to 305 m (400–1,000 ft) and are thickest in the eastern half of Natrona County and in the southern half of Converse County. Towse (1952) reported that the Frontier is as thick as 300 m (983 ft) at an outcrop in east-central Natrona County. The formation was deposited during Cenomanian and Turonian time, mostly in shallow-marine environments. Fossil plants (spores and pollen from ferns and gymnosperms) and animals and the coal in the Frontier of central Wyoming indicate, according to Burgess (1971), nearshore-marine and nonmarine environments and a humid climate. Members of the Frontier in Natrona County (fig. 9D) are named, from oldest to youngest, the Belle Fourche Member (Merewether and others, 1979), the Emigrant Gap Member (newly named in this report), and the Wall Creek Member (Wegemann, 1911; Hares, 1916). In southern Johnson County the Frontier is composed generally of the Belle Fourche and Wall Creek Members. In northern Johnson County (Hose, 1955; Mapel, 1959) the Wall Creek Member grades laterally into a lower part of the Cody Shale, the Belle Fourche Member is raised in rank to the Belle Fourche Formation, and the name Frontier Formation is not used.

Outcrops of the Belle Fourche Member usually form low questas and intervening strike valleys and are composed mostly of medium-gray to dark-gray to brownish-gray, noncalcareous mudstone and silty shale; medium-gray to olive-gray, noncalcareous, clayey or sandy siltstone; and very light gray to medium-gray to brownish-gray, noncalcareous, silty, very fine grained to medium-grained and partly conglomeratic sandstone (Merewether and others, 1979). The member also includes very light gray to greenish-gray bentonite in abundant beds as thick as 2 m (7 ft). In Natrona and Johnson Counties the Belle Fourche consists of a basal unit of mudstone, commonly about 55 m (180 ft) thick, overlain by intertonguing units of sandstone, locally more than 40 m (130 ft) thick, and shale and siltstone, mostly 6–30 m (20–100 ft) thick (fig. 11). Most of the outcropping mudrocks in the member are soft to moderately indurated, although they contain calcitic and sideritic concretions, and they are rarely well exposed. Where cored at a borehole in south-central Johnson County (fig. 1), the shale is mostly dark gray, silty, and noncalcareous and is interlaminated with siltstone that is generally medium gray, argillaceous or sandy, and noncalcareous (Merewether and others, 1976; Merewether, 1980); near the top of the member shale and siltstone are mainly calcareous. Laminae of shale and siltstone are discontinuous and are either even and parallel or wavy and nonparallel. Flaser and lenticular bedding are common except in lowermost and uppermost parts of the Belle Fourche.

Most of the mudrocks contain trace fossils; several thin units in the lower part of the member are bioturbated (E.A. Merewether and D.L. Gautier, unpub. data). In southern Johnson County outcrops and core of the member contain *Planolites*, *Schaucylindrichnus (Terebellina)*, *Ophiomorpha*, *Rhizocorallium*, *Teichichnus*, *Asterosoma*, and probably *Zoophycos* and *Skolithos*. Several of these trace fossils represent the *Cruziana* ichnofacies and indicate shallow water (below low tide but generally within wave base).

At outcrops, the sandstone is either friable, concretionary, or well cemented. Units of sandstone commonly grade into underlying siltstone and are sharply overlain by shale or siltstone. Grain size in these units ranges from very fine and silty at the base to fine or medium and pebble bearing near the top. Most of the units are laminated to thin bedded, horizontally bedded near the base and crossbedded near the top, and they display wave or current ripples. Thick lenticular bodies of sandstone in the lower part of the Belle Fourche Member at outcrops in southern Johnson County, however, are composed of trough crossbedded and tabular-planar crossbedded strata (R.W. Tillman, written commun., 1990). In the core from Johnson County the laminae and beds are generally either discontinuous, wavy, and nonparallel or bioturbated.

In southeastern Natrona County a sandstone unit near the middle of the member and about 16 m (52 ft) thick is bioturbated and thin to medium bedded; hummocky cross-stratification is present in the lower part of the unit and megaripple crosslamination (trough crossbedding) is present in the upper part of the unit (Winn, 1986). Burrow forms in the sandstone in Natrona County include *Ophiomorpha*, *Thalassinoides*, *Asterosoma*, and *Arenicolites* (Merewether and Cobban, 1986b; Winn 1986).

The conglomeratic sandstone at the top of several units of sandstone in the member includes granules, pebbles, and cobbles of chert, quartzite, quartz, and igneous and sedimentary rocks. Haun (1953) reported pebbles and small cobbles of chert, andesite porphyry, quartz, and quartzite in outcropping sandstone of the Belle Fourche in the southern part of Johnson County. Barlow and Haun (1966) determined that the pebbles are larger and more

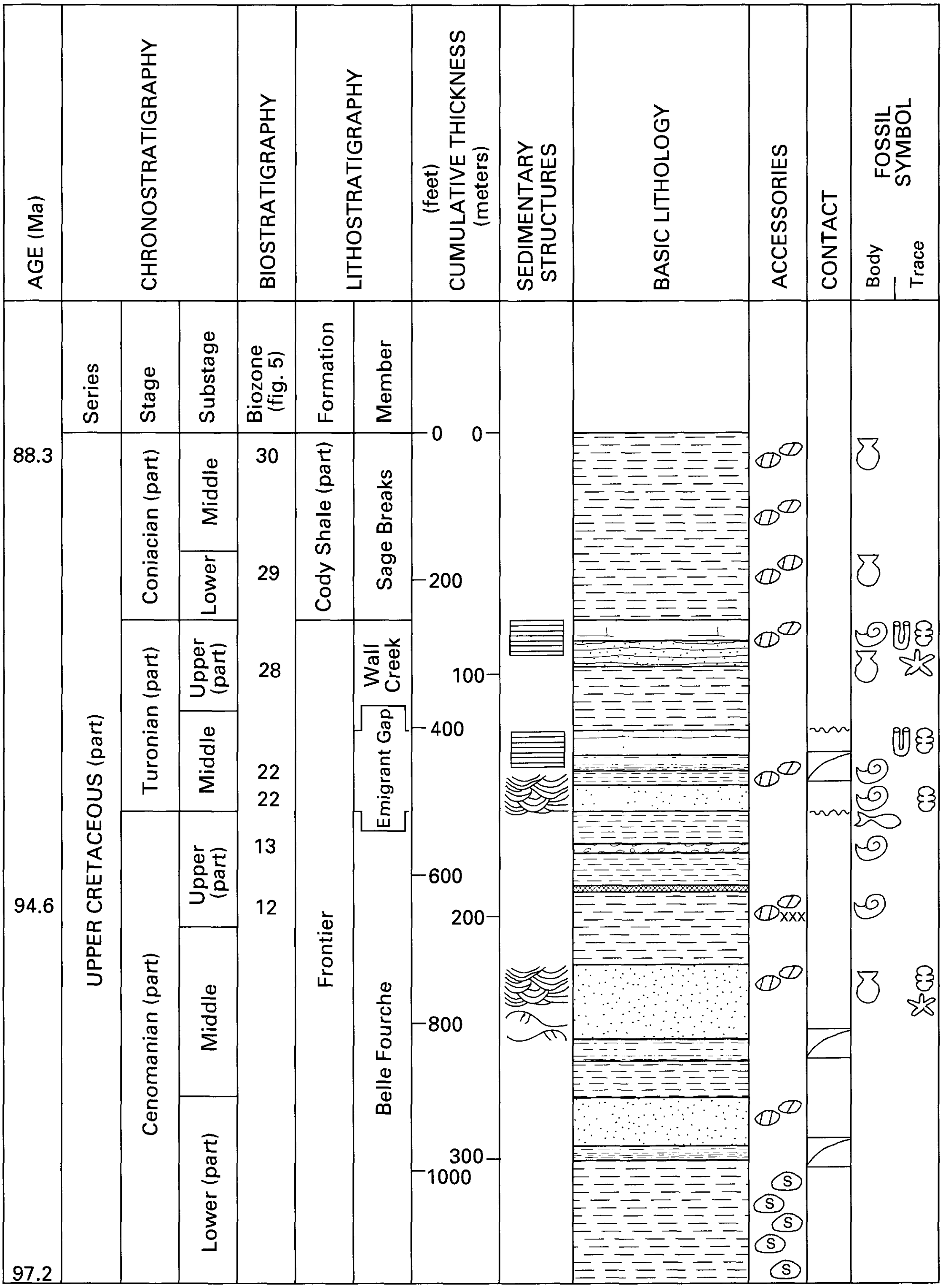


Figure 11. Outcrop sections of Frontier Formation and Sage Breaks Member of the Cody Shale, southeastern Natrona County, Wyoming (section 9, table 1). Explanation as in figure 8. Modified from Cavanaugh (1976), Winn (1986), and Merewether and Cobban (1986b).

abundant in beds in the upper part of the Belle Fourche Member than in the rest of the member. They also concluded that the pebbles are largest in south-central Johnson County and that they decrease in size northward in Johnson County and southward in Natrona County (fig. 1).

The Belle Fourche Member of the Frontier Formation conformably overlies the Mowry Shale and is disconformably overlain by either the Emigrant Gap Member or the Wall Creek Member of the Frontier (figs. 4, 5). In the southwestern part of the Powder River Basin, in southern Johnson County, Natrona County, and western Converse County the Belle Fourche is about 180–240 m (591–787 ft) thick. In boreholes in southwestern Campbell County (fig. 9C) and east-central Natrona County (fig. 9D) the member is about 174 m (570 ft) thick and 183 m (600 ft) thick, respectively. Some of these variations in thickness reflect differential erosion at the top of the member; the amount of truncation apparently was greatest in a west-southwest-trending area in southern Natrona County (Merewether and others, 1979).

Fossils of marine origin are common in the Belle Fourche Member. Foraminifers in the core from Johnson County generally increase in abundance and variety upward, from sparse arenaceous species near the base of the member to many arenaceous and calcareous species (benthic and pelagic) near the top (B.R. North and W.G.E. Caldwell, written commun., 1978, 1993). Palynomorphs from the core include dinocysts and acritarchs of marine origin as well as spores and pollen of terrestrial origin (Okumura, 1994). Ammonites and bivalves of middle and late Cenomanian and early Turonian age have been collected from outcrops and core of the middle and upper parts of the Belle Fourche (figs. 5, 11) (Merewether and others, 1976; Merewether, 1980; Cobban, 1987, 1988a, b). A lower part of the member, which is about 85 m (278 ft) thick in southern Johnson County, apparently contains only an ichnofauna, palynomorphs, and mainly arenaceous foraminifers (Eicher, 1967); it could be either early Cenomanian or middle Cenomanian. The age of the top of the Belle Fourche Member, as indicated by molluscan fossils, varies from early late Cenomanian (fig. 7, zone 13) in east-central Natrona County to early Turonian (fig. 7, zone 20 or 21) in southern and central Johnson County, and the top of the member probably reflects differential erosion. Sparse fossil corals (*Archohelia dartoni* Wells) that probably indicate shallow, warm, and relatively clear seawater were collected by M.C. Huff of Louisiana State University and by W.A. Cobban and E.A. Merewether of the U.S. Geological Survey from upper Cenomanian and lower Turonian rocks in the upper part of the member at three localities in Johnson County.

The strata of the Belle Fourche Member accumulated mainly in environments of the outer coastal plain and the shelf in water depths perhaps as great as 60 m (200 ft). Water depths have been estimated as less than 37 m (120 ft) (Haun, 1958) and less than 130 m (427 ft) (Merewether and others, 1979). Waters in this epeiric sea probably varied from fresh to saline (normal marine) and from aerobic to dysaerobic (E.A. Merewether and D.L. Gautier, unpub. data).

In core of the Belle Fourche Member in southern Johnson County the abundance of continental palynomorphs relative to marine palynomorphs increases upward from the base of the member at a depth near 318 m (1,042 ft) to beds in the thick "second Frontier sandstone" (Barlow and Haun, 1966) of the Belle Fourche at a depth of about 168 m (550 ft) (Okumura, 1994). These amounts of spores and pollen seemingly indicate an intermittently, but generally regressing shoreline during late early Cenomanian and most of middle Cenomanian time (about 97.2–94.9 Ma). Presumably, the shoreline was easternmost and nearest to southern Johnson County during late middle Cenomanian time while the "second Frontier sandstone" of Barlow and Haun (1966) was accumulating. Palynomorphs in the overlying rocks indicate a generally transgressing shoreline mainly during late Cenomanian and Turonian time.

Maps of units of sandstone in the member depict broad lobate bodies that trend and thin southward probably from areas of sediment input in southwestern Johnson and northwestern Natrona Counties (Barlow and Haun, 1966; Merewether and others, 1979). Paleocurrent directions from crossbeds and ripple marks in the member are dominantly southeast and southwest (Towse, 1952; Van Houten, 1962; Cavanaugh, 1976; Winn, 1986), corresponding to trends of the sandstone bodies; however, from a synchronous, mostly southwest trending sandstone body near the top of the Belle Fourche Member in southwestern Johnson County and northwestern Natrona County the average paleocurrent direction (63 measurements of crossbeds) is S. 24° E. In that area, the Belle Fourche, excepting the nonfossiliferous lower part of the member, was deposited in shallow-water environments probably near and within the distal part of a delta. Many of the sandstone units in the member could have accumulated in delta-front environments and spread southward by lateral accretion. Winn (1986) concluded that one of the sandstone units in Natrona County represents intermittent deposition on a shallow shelf by geostrophic storm flows.

Maps of the lithofacies of Cenomanian rocks in Wyoming and adjoining areas (Merewether and Cobban, 1986a) are consistent with the conclusions of Goodell (1962) and of Barlow and Haun (1966) and indicate that the sandstone units of the member prograded episodically southwest, south, and southeast from a source area in northwestern Wyoming and southwestern Montana. A plot of the relative abundance of continental and marine palynomorphs in core from southern Johnson County by Okumura (1994) suggests at least five regressions of the Cenomanian shoreline near that area. The shoreline was nearest the site of the corehole during about 95.4–94.8 Ma in the middle Cenomanian when a thick marine sandstone was deposited. Litharenite and sublitharenite in the member in southeastern Natrona County contain scattered fragments of sedimentary, volcanic, and metamorphic rocks (Cavanaugh, 1976) that probably were derived from highlands in northwestern Wyoming and adjoining parts of Montana and Idaho. In Johnson and Natrona Counties the member can be interpreted as, in ascending order, a progradational parasequence (part of a highstand systems tract), type-1 sequence boundary, another progradational parasequence set (lowstand systems tract), retrogradational parasequence set (transgressive systems tract), and a generally aggradational parasequence set (highstand systems tract) (Van Wagoner and others, 1990).

GREENHORN FORMATION

The name "Greenhorn Limestone" was introduced into the eastern part of the Powder River Basin by Darton (1901) and was subsequently changed to Greenhorn Formation by Cobban (1951a). Along the eastern edge of the basin, the formation was deposited during middle Cenomanian through early Turonian time (figs. 4, 5) and consists of calcareous and noncalcareous shale that commonly contains limestone concretions, and calcareous mudstone, limestone and minor sandstone and bentonite (fig. 10) (Robinson and others, 1964; Macdonald and Byers, 1988). The rocks grade from predominantly calcareous and noncalcareous shale at the base to calcareous shale, calcareous mudstone, and silty limestone at the top.

Similar strata in the northwestern part of the basin (fig. 8) have been called the "Greenhorn calcareous member" of the Cody Shale at outcrops (Richards, 1955; Knechtel and Patterson, 1956) and the Greenhorn Formation in the subsurface (Fox, 1993a) and are called herein the Greenhorn Formation (fig. 4). These strata accumulated during the late Cenomanian and early Turonian and are laterally equivalent to the upper part of the Greenhorn on the eastern flank of the basin (figs. 1, 4). In Big Horn County the formation consists of calcareous shale, which commonly contains calcareous concretions, and minor bentonite.

Along the eastern margin of the basin, outcrops of interbedded limestone and calcareous siliciclastic rocks in the upper part of the Greenhorn generally form a conspicuous ridge. The shale at outcrops comprises units as thick as 10 m (33 ft) and is dark gray, olive gray, and brownish gray; it encloses light-gray and yellowish-gray, septarian, limestone concretions that are as much as 2 m (6 ft) in diameter (Robinson and others, 1964). The outcrops also include light-gray, laminated or bioturbated mudstone; light-brownish-gray to light-gray, skeletal or burrow-mottled limestone; and yellowish-gray bentonite (Macdonald and Byers, 1988). The outcropping limestone is commonly clayey to sandy, laminated to thin bedded, and parallel and cross stratified and comprises beds as thick as 50 cm (20 in). Macdonald and Byers (1988) reported that the skeletal limestone locally displays ripple marks, groove marks, and scour surfaces and is composed mainly of inoceramid grainstone and foraminiferal grainstone. They also determined that the burrow-mottled limestone is composed of mudstone and wackestone that include various proportions of foraminifers and inoceramid prisms.

A core of the Greenhorn from Weston County (fig. 1) consists mostly of interlaminated, medium-dark-gray to dark-gray shale and very light gray to light-gray siltstone (Merewether, 1980). These laminae are mostly discontinuous, even, and parallel, indicating weak currents at the interface, although in the upper part of the formation some laminae are discontinuous, wavy, and nonparallel. According to Macdonald and Byers (1988), the core of the upper part of the Greenhorn also displays bioturbation, minor small-scale crosslamination, and lenticular bedding. Horizontal burrows, including *Planolites* and *Thalassinoides*, have been found in outcrops and in the core from Weston County (Merewether, 1980; Macdonald and Byers, 1988).

In Carter and Crook Counties (fig. 1), the Greenhorn Formation conformably overlies the Belle Fourche Shale and is conformably overlain by the Carlile Shale. In Weston and Niobrara Counties, as well as on the northeastern flank of the Black Hills in South Dakota, the Greenhorn appears, however, to disconformably overlie the Belle Fourche (W.A. Cobban, oral commun., 1989), indicating local mid-Cretaceous erosion or nondeposition. The location of the contact of the Belle Fourche and Greenhorn in the core from Weston County corresponds to the location of an abrupt and conspicuous decrease in the relative abundance of continental palynomorphs in the core (Okumura, 1994). Where the basal part of the Greenhorn grades laterally into the upper part of the Belle Fourche, the thickness of both formations changes rapidly (Robinson and others, 1964).

On the northern flank of the Black Hills the Greenhorn thins westward from 110 m (360 ft) near the northeastern corner of Wyoming to 55 m (180 ft) in south-central Carter County (Cobban, 1952). In Big Horn County the Greenhorn Formation is 18–30 m (60–100 ft) thick (Knechtel and Patterson, 1956) (fig. 9B), although the basal beds are younger than those of the Greenhorn near the Black Hills (fig. 4). At outcrops in northwestern Weston County the formation is about 24 m (80 ft) thick, and it thickens southeastward to about 90 m (295 ft) in east-central Weston County (Robinson and others, 1964). In the east-central part of the Powder River Basin, in Crook and Campbell Counties, the formation thins southwestward from about 152 m (500 ft) to about 107 m (350 ft), and in the southeastern part of the basin, in Weston, Converse, and Niobrara Counties, it thins southeastward from about 122 m (400 ft) to about 46 m (150 ft) (Weimer and Flexer, 1985). Southwestward across the basin, lower parts of the Greenhorn grade into siliciclastic strata in the upper part of the Belle Fourche Member of the Frontier Formation, and upper parts of the Greenhorn are represented in the Frontier by a hiatus (fig. 4).

Fossils are locally abundant in outcrops of the Greenhorn Formation, and they commonly include ammonites, bivalves, foraminifers, palynomorphs, and the bones and teeth of fish (Cobban, 1951a; Robinson and others, 1964; Cobban, 1984; Macdonald and Byers, 1988; Okumura, 1994). In core from Weston County, ammonites and bivalves (mainly *Inoceramus* and *Mytiloides*) were found in almost all beds between the base and the top of the formation (Cobban, 1984). Foraminifers in the core are abundant, varied, and mainly pelagic (B.R. North and W.G.E. Caldwell, written commun., 1978, 1993). Palynomorphs in the core include both marine and continental forms but are dominantly marine and mostly dinocysts (Okumura, 1994). The age of the base of the formation, as determined from molluscan fossils (figs. 4, 5), varies from middle Cenomanian in Weston County, to late Cenomanian in Crook County, to probably late Cenomanian in Big Horn County. The top of the formation in the Rocky Mountain region is of earliest middle Turonian age.

The mainly calcareous rocks of the Greenhorn accumulated in the open-marine environments of a north-trending epicontinental sea that connected the Gulf of Mexico and the Arctic Ocean. These rocks are widespread in the Western Interior, and they seemingly record most of a middle Cenomanian to early Turonian eustatic rise (Hancock, 1975; Hancock and Kauffman, 1979). In the sequence stratigraphy of Van Wagoner and others (1990), the Greenhorn is mainly a retrogradational parasequence set in a transgressive systems tract, but near its top it includes part of a progradational parasequence in a highstand systems tract. The Greenhorn, as interpreted by Weimer (1984) and Weimer and Flexer (1985), accumulated on a lower slope and an adjacent basin in which water depths were 185–305 m (600–1,000 ft). Macdonald and Byers (1988) proposed that the lower part of the formation near the eastern edge of the basin was "deposited by hemipelagic settling of clays and planktonic foraminifera in a relatively deep (more than 150 m, or 500 ft), quiet marine environment" and that the upper part of the formation "was deposited by hemipelagic settling, bottom currents, and storm-generated or storm-enhanced currents***in a sea less than 150 m (500 ft) deep." They concluded that the lower part of the Greenhorn represents mainly anaerobic environments, whereas the upper part represents dysaerobic and aerobic conditions. The abundance of benthic mollusks and trace fossils in the core of the Greenhorn from Weston County (Cobban, 1984) indicates, however, that in at least one area all depositional environments of the formation were aerobic.

REGIONAL HIATUS FOR LATE CENOMANIAN AND EARLY TURONIAN TIME

In Natrona and Converse Counties strata of late Cenomanian age at the top of the Belle Fourche Member are disconformably overlain by beds of middle Turonian age in the Emigrant Gap Member (Merewether and Cobban, 1986b; Cobban, 1990). This disconformity apparently also is present in an isolated outcrop near the southern border of western Johnson County but has not been confirmed in other areas of the Powder River Basin. It has been recognized at outcrops in central and northwestern Wyoming and in southwestern Montana (Merewether, 1983; Merewether and Cobban, 1986a). Part of the late Cenomanian and all of the early Turonian are represented by the disconformity and the associated hiatus in the southwestern part of the basin and by calcareous beds of the Greenhorn along the northwestern and eastern margins of the basin. The erosion and nondeposition recorded by the hiatus were likely caused by a regional uplift during late early Turonian to early middle Turonian time. Nevertheless, several attributes of the disconformity and the associated beds resemble those of the type-1 sequence boundary of Van Wagoner and others (1990).

ROCKS OF MIDDLE TURONIAN AGE

POOL CREEK MEMBER OF THE CARLILE SHALE AND STRATA IN THE CARLILE MEMBER OF THE CODY SHALE

Darton (1909) was the first to use the name Carlile Shale for the sequence of siliciclastic beds between carbonate rocks of the underlying Greenhorn Formation and of the overlying Niobrara Formation near the Black Hills (fig. 10). These beds were deposited in marine environments, and they contain molluscan fossils of middle Turonian through middle Coniacian age (Robinson and others, 1964; Merewether, 1980; Cobban, 1984). At outcrops along the eastern margin of the Powder River Basin, the Carlile thins southward from 168–198 m (550–650 ft) on the northern flank of the Black Hills (Cobban, 1952) to 113–128 m (370–420 ft) in eastern Niobrara County (fig. 9A) (Robinson and others, 1964). The formation has been divided into three parts (fig. 4), in ascending order, the Pool Creek Member (Knechtel and Patterson, 1962), the Turner Sandy Member (Rubey, 1930), and the Sage Breaks Member (Rubey, 1930). The contact of the Pool Creek and Turner is a widespread disconformity. Rocks of similar composition and age along the northwestern flank of the basin (fig. 8) were called the "Carlile shale member of the Cody shale" by Richards (1955) and Knechtel and Patterson (1956) but are herein called the Carlile Member of the Cody Shale. The Carlile of Big Horn County is composed mainly of shale, is about 86 m (281 ft) thick at outcrops, and is as thick as 119 m (390 ft) in the subsurface (fig. 9B); it apparently does not enclose a regional disconformity.

The Pool Creek has been recognized along the eastern flank of the basin where scattered outcrops of the member contain marine fossils of middle Turonian age. In that area, the Pool Creek consists generally of soft and concretion-bearing, dark-gray shale and silty shale and sparse laminae of limestone and bentonite (Cobban, 1951a). Laminae of sandstone and thin beds of crossbedded sandstone have been found in a few areas. Lower and middle parts of the member commonly contain light-gray limestone concretions. A core of the Pool Creek from Weston County is composed of interlaminated dark-gray shale and light-gray siltstone that in the lower half of the member are mostly calcareous. The laminae in the core are generally discontinuous and are either wavy and nonparallel or even and parallel. Many of the laminae contain small burrows, and a minor part of the core is bioturbated. Small horizontal burrows *(Planolites?)* are common, and a specimen of *Schaucylindrichnus (Terebellina)* was found.

The Pool Creek Member conformably overlies the Greenhorn Formation and is disconformably overlain by the Turner Sandy Member of the Carlile Shale. Cobban (1952) indicated that the member on the northern flank of the Black Hills is 23–47 m (75–155 ft) thick. Robinson and others (1964) reported that the Pool Creek at outcrops is about 12 m (40 ft) thick in northern Weston County and 30 m (100 ft) thick in east-central Weston County. It is perhaps 43 m (140 ft) thick in eastern Niobrara County (fig. 9A). An isopach map of the Pool Creek in the subsurface (Weimer and Flexer, 1985) shows that the member is thin to absent in parts of Crook, Weston, Campbell, Converse, and Niobrara Counties and that it is as thick as 43 m (140 ft) in south-central Niobrara County. Stratigraphic cross sections for the basin (Merewether and others, 1977a, b, c; Fox, 1993a, b, c, d) indicate that the Pool Creek was partly to completely removed by mid-Cretaceous erosion.

Outcrops and core of the Pool Creek contain foraminifers, palynomorphs, and macrofossils. B.R. North and W.G.E. Caldwell (written commun., 1978, 1993) indicated that the foraminifera in the core consist of several agglutinated species. Okumura (1994) determined that most of the palynomorphs are marine and that most of the marine palynomorphs are cavates, which are most abundant nearshore. The core also contains molluscan fossils and the fossilized bones and scales of fish. Ammonites and bivalves of early middle Turonian age are abundant in the lower part of the Pool Creek along the eastern flank of the basin (figs. 4, 7), and fossils of late middle Turonian age are in the upper part of the member at outcrops on the northern margin and near the southern terminus of the Black Hills (Cobban, 1951a; Robinson and others, 1964; Cobban, 1984).

Mudrocks of the Pool Creek are the same age as the shallow-marine shale, siltstone, and sandstone that comprise the Emigrant Gap Member of the Frontier Formation in central Natrona County (fig. 4); formerly the Pool Creek graded southwestward into those rocks. Mudrocks of early middle Turonian age also are present in the Carlile Member of the Cody Shale on the northwestern flank of the basin. In the northeastern part of the basin, the Pool Creek accumulated probably on the outer part of a depositional shelf and on the adjoining slope. These beds display reverse grading and apparently are progradational. In terms of sequence stratigraphy (Christie-Blick, 1990; Van Wagoner and others, 1990) the member includes most of the progradational parasequence in a highstand systems tract. Weimer and Flexer (1985) proposed that the Pool Creek was deposited in water 90–180 m (300–600 ft) deep and was subsequently truncated by subaerial erosion during a fall of sea level.

EMIGRANT GAP MEMBER OF THE FRONTIER FORMATION

Siliciclastic strata described as the "unnamed member of the Frontier Formation" by Merewether and others (1979) and as the "member of Emigrant Gap" by Merewether and Cobban (1986a, b) are herein named the Emigrant Gap Member. This stratigraphic unit was named from a historically significant pass called Emigrant Gap, about 16 km (10 mi) west of the city of Casper in eastern Natrona County. Outcrops of the member near Emigrant Gap, in NW1/4 sec. 4, T. 33 N., R.81 W., comprise the type section (fig. 11); they have been described by Cavanaugh (1976), Merewether and Cobban (1986b), and Winn (1986). The Emigrant Gap Member occupies a large protuberant area in western and central Wyoming that extends eastward from central Fremont County to northwestern Carbon County and central Converse County. Rocks of the same age have been located in northwestern and southwestern Wyoming. The Emigrant Gap Member crops out in a few areas in Natrona County, near the southwestern margin of the Powder River Basin, and extends eastward in the subsurface (fig. 9D), perhaps to central Converse County. It also crops out in a small area along the southern border of western Johnson County. In Natrona County the member consists of mudstone, shale, siltstone, and sandstone, and it contains middle Turonian mollusks of marine origin.

At outcrops the sandstone in the member commonly forms minor ridges, and the other rocks are mostly concealed in intervening low areas. The sandstone is light gray to medium gray to brownish gray, very fine to medium grained and locally conglomeratic, calcareous, and concretionary. Cavanaugh (1976) classified the sandstone as litharenite and sublitharenite. In southeastern Natrona County, west of Casper, a medium-grained pebble-bearing sandstone at the base of the member sharply overlies shale in the Belle Fourche Member. Many of the pebbles are composed of chert and phosphate (Cavanaugh, 1976; Bitter, 1986). This sandstone is as thick as 18 m (60 ft); most of it is trough crossbedded, and an upper part is horizontally bedded (Merewether and others, 1979; Winn, 1986). Several bedding surfaces display flow casts.

Overlying the basal pebble-bearing sandstone is a medium-gray silty mudstone that encloses scattered silty limestone concretions. The mudstone grades upward into medium-gray to brownish-gray siltstone that contains scattered chert pebbles. Overlying the siltstone, at the top of the member, is a very fine and fine-grained sandstone as thick as 12 m (40 ft); it is made up of beds as thick as 15 cm (5.9 in) interstratified with lesser amounts of shale. In this sandstone, bed thickness and grain size increase upward, and beds display horizontal and rippled laminations and hummocky crosslaminations (Winn, 1986). *Ophiomorpha*, *Thalassinoides*, *Arenicolites*, and other burrows have been found in these strata.

The Emigrant Gap Member is disconformable with both the underlying Belle Fourche and the overlying Wall Creek Members of the Frontier Formation. In the southwestern part of the Powder River Basin the Emigrant Gap ranges in thickness from as much as 43 m (140 ft) in east-central Natrona County to a wedge edge in northern and southern parts of the county.

Fossils of marine origin and middle Turonian age (figs. 7, 11) have been collected from the member (Cobban and Kennedy, 1989b; Cobban, 1990). Fish teeth and ammonites of early middle Turonian age are in the basal sandstone, and ammonites of the same age are in the overlying concretion-bearing mudrocks (Cobban, 1990). Sparse mollusks of late middle Turonian age are in sandstone at the top of the member. An early middle Turonian ammonite, probably from sandstone, was found by W.A. Cobban (personal commun., 1989) near the south-central border of Johnson County.

Paleocurrent directions measured by Cavanaugh (1976), Winn (1986), and myself at outcrops of sandstone in the member in Natrona County range from south to northeast but are dominantly east. The member in that area records deposition on an erosional surface, later deposition during an apparently local marine transgression, subsequent deposition during a marine regression, followed by a period of erosion. Lithologic units of the Emigrant Gap Member can be assigned to, in ascending order, a progradational parasequence (lowstand systems tract), retrogradational parasequence (transgressive systems tract), and progradational parasequence (highstand systems tract) (Van Wagoner and others, 1990).

Winn (1986) proposed that the member in east-central Natrona County filled a west-trending trough or embayment that had been eroded into the underlying Belle Fourche Member. Moreover, he suggested that most of the sequence accumulated in marine environments during a relative sea-level rise and that the uppermost unit of sandstone prograded eastward and was deposited on a lower delta front beyond the distributary system.

REGIONAL HIATUS FOR MIDDLE AND LATE TURONIAN TIME

Middle Turonian strata are disconformably overlain by upper Turonian rocks along the eastern margin of the Powder River Basin where the Pool Creek Member is overlain by the Turner Sandy Member of the Carlile Shale, in the southern part of the basin in the subsurface, near the southwestern boundary of the basin where the Emigrant Gap Member is overlain by the Wall Creek Member of the Frontier Formation, within the Frontier near the western edge of the basin in a small area in southwestern Johnson County, and elsewhere in Wyoming (Merewether and Cobban, 1985, 1986a). The disconformity has not been confirmed, however, in the northwestern part of the Powder River Basin.

The depths of the disconformity in core holes in Weston and Johnson Counties, Wyoming, correspond to the depths of rather abrupt changes in the relative abundance of continental and marine palynomorphs in the cores (Okumura, 1994). The disconformity is apparently associated with an increase in the abundance of marine palynomorphs and with a marine transgression.

In sequence stratigraphy (Van Wagoner and others, 1990), this disconformity probably is a major, type-1, sequence boundary. Mid-Cretaceous erosion and the removal of middle Turonian beds in most of Johnson County and some adjoining areas (Merewether and Cobban, 1986a) has obscured the original lateral extent of this disconformity and the magnitude of the corresponding middle and late Turonian hiatus. This period of erosion and nondeposition could have been associated with the major lowstand of sea level at 90 Ma depicted by Haq and others (1987). Weimer and Flexer (1985) concluded that the disconformity at the top of the Pool Creek Member of the Carlile Shale developed when "the shelf across the Powder River Basin was subaerially exposed and subjected to extensive erosion."

ROCKS OF LATE TURONIAN AGE

TURNER SANDY MEMBER OF THE CARLILE SHALE AND STRATA IN THE CARLILE MEMBER OF THE CODY SHALE

The Turner Sandy Member of the Carlile Shale was named by Rubey (1930) from outcrops in Weston County at the western margin of the Black Hills. Outcrops of sandstone and siltstone in the Turner commonly form persistent low ridges that are flanked by swales and valleys in the mudrocks of the underlying Pool Creek and overlying Sage Breaks Members. The Turner consists of shale, siltstone, and minor sandstone (fig. 10) and generally contains macrofossils of marine origin and late Turonian age (figs. 4, 5). Most of the shale is dark gray, silty, and noncalcareous; it comprises units as thick as 8 m (26 ft). The siltstone is mainly medium gray, argillaceous or sandy, and noncalcareous. Most of the sandstone is light gray to grayish orange, very fine grained, silty, and calcareous, although the thin lenticular sandstone at the base of the member in Weston County is locally medium grained and contains scattered granules and pebbles as long as 3 cm (1.2 in.) of chert and quartz (Merewether, 1980). Units of sandstone are rarely as thick as 5 m (16 ft).

Overlying the basal sandstone of the member in Weston County are, from oldest to youngest, a gradational sequence that coarsens upward from shale to sandstone, another similar gradational sequence, and interstratified units of siltstone, shale, and minor sandstone in the upper half of the Turner. The beds of siltstone and sandstone commonly are very thin to thin, discontinuous, and tabular planar crossbedded, and they display scour-and-fill structures and ripple marks. From studies of outcrops and cores, Weimer and Flexer (1985) described the stratification of three categories of sandstone, in ascending order: (1), parallel-laminated, low-angle cross-stratified or scour-and-fill bedding; (2), interstratified sandstone and laminae of siltstone or shale, ripple-laminated or horizontal-laminated; and (3), mainly bioturbated, rarely with a thin cross-stratified unit at the top. Rice and Keighin (1989) concluded that two types of oil-producing units of sandstone are present in the Turner: cross-stratified, medium-grained, sandstone bodies as thick as 4 m (13 ft) that fill narrow, elongate, erosional depressions and widespread, planar-laminated to hummocky cross-stratified, very fine grained sandstone bodies as thick as 12 m (39 ft) that enclose laminae of shale in the lower part and are bioturbated in the upper part. Trace fossils in outcrops of siltstone and sandstone include *Ophiomorpha*, *Thalassinoides*, and *Rhizocorallium*, and possibly *Rosselia*, *Cruziana*, and *Skolithos* (Merewether, 1980). In outcrops and cores of sandstone, Weimer and Flexer (1985) found *Skolithos*, *Planolites*, *Teichichnus*, and *Asterosoma*, whereas Rice and Keighin (1989) found the *Skolithos* ichnofacies.

Core of the Turner from Weston County (Merewether, 1980) consists of fossil-bearing, interstratified and intergradational, medium-gray to dark-gray shale, light-gray to medium-gray siltstone, and light-gray sandstone. The shale is a minor component, and most of it is interlaminated with siltstone or sandstone. The laminae of shale and siltstone are generally discontinuous and are either wavy and nonparallel or even and parallel. Near the base of the member flaser and lenticular bedding are common. Some of the shale and siltstone is crosslaminated, and some is bioturbated. Most of the sandstone in the core is very fine grained, thinly laminated to very thinly bedded, and horizontally stratified; however, some of the sandstone is fine grained with sparse, medium to very coarse grains, some is slightly calcareous, and some is cross-stratified or bioturbated. The core contains many small burrows *(Planolites?)* and a few specimens of *Schaucylindrichnus (Terebellina)*.

The Turner Sandy Member disconformably overlies the Pool Creek Member and is conformably overlain by the Sage Breaks Member. Near the eastern edge of the Powder River Basin the Turner thins southward from 56–79 m (185–260 ft) at outcrops on the northern flank of the Black Hills (Cobban, 1952) to 45–49 m (146–160 ft) at outcrops and boreholes in eastern Niobrara County (fig. 9A). An isopach map of the member on the eastern flank of the basin by Weimer and Flexer (1985) indicates, however, that the thickness varies from about 24 m (80 ft) to as much as 90 m (300 ft). Weimer and Flexer concluded that the Turner is thicker in northeast-trending "valley-like" areas that are "a few miles" wide and "tens of miles" long.

The Turner Sandy Member contains fossilized palynomorphs, foraminifera, and mollusks of marine origin. The mollusks are abundant and include assorted ammonites and bivalves that represent all fossil zones of the late Turonian except the earliest (Cobban, 1951a, b, 1984; Merewether, 1980). Lenses of conglomeratic sandstone and concretions in the basal part of the member (about 1.5 m [5 ft] thick) have yielded ammonites, *Inoceramus*, fish teeth, and fragments of fossil wood. In the core from Weston County B.R. North and W.G.E. Caldwell (written commun., 1978, 1993) found arenaceous foraminifers in the lower part of the Turner and sparse pelagic and benthic species in the upper part. R.D. Bergad (written commun., 1989) found saccate pollen, trilete spores, marine microplankton, and microforaminifera in the core from Weston County. Research by Okumura (1994) indicates that the palynomorphs in the core are mostly marine and that the marine palynomorphs are mainly cavates.

The Turner was deposited in shallow-water marine environments on a shelf and, particularly where the member is sandy, as distal parts of a delta lobe. The regional extent of sandy beds in the Turner and in the contiguous equivalent Wall Creek Member of the Frontier forms an irregular lobate body that extends east-northeastward across the Powder River Basin from Natrona County to Weston County (Merewether and others, 1979). From a study of palynomorphs and other microfossils, R.D. Bergad (written commun., 1989) concluded that the Turner in Weston County was deposited in a nearshore-marine environment close to an area of lowland vegetation.

Several paleocurrent directions from crossbeds in the Turner in northern Weston County have an average value of S. 38° E. The average direction from a few crossbeds in southeastern Weston County is S. 65° E and in east-central Niobrara County about N. 60° E. Weimer and Flexer (1985) suggested that the lower part of the Turner was deposited in "brackish to marine (tidal flat to estuary)" environments and that it filled valleys in the underlying Pool Creek Member and in the Greenhorn Formation. Rice and Keighin (1989) concluded that the units of cross-stratified medium-grained sandstone in the member fill elongate (as long as 10 km [6 mi]), narrow (less than 1.5 km [0.9 mi] wide), east-trending erosional depressions. They proposed that the sand was reworked on an inner shelf by eastward-flowing currents during a marine transgression and after a eustatic fall. Rice and Keighin (1989) also described units of very fine grained sandstone that are planar laminated and hummocky cross-stratified and are bioturbated near the top. These units are widespread (70 km^2 [27 mi^2]) and indicate upward-shoaling and deposition below fairweather wave base on a stormwave-dominated outer shelf (Rice and Keighin, 1989). Biostratigraphic data from much of Wyoming (Merewether and Cobban, 1986a) indicate that basal beds of the Turner and Wall Creek Members onlap the basal disconformity toward the southwest and west and were deposited during a eustatic rise (Haq and others, 1987). In sequence stratigraphy (Van Wagoner and others, 1990), the Turner includes a progradational parasequence in a lowstand systems tract and overlying retrogradational parasequence set in a transgressive systems tract.

WALL CREEK MEMBER OF THE FRONTIER FORMATION

Wegemann (1911) proposed the name "Wall Creek Sandstone Lentil of the Benton Shale," and Hares (1916) assigned the name to the uppermost sandstone of the Frontier Formation along the western margin of the Powder River Basin. Subsequently, Merewether and others (1979) modified the definition of the member to include the sandstone, as well as an underlying unit of siltstone and shale. Outcrops of the Wall Creek in the southern half of Johnson County, in Natrona County, and in the southern part of Converse County generally form conspicuous ridges. The late Turonian age of the Wall Creek Member in the basin was determined by means of molluscan fossils; however, the age varies slightly because the basal part of the member onlaps an erosional surface and the upper part of the member interfingers with a lower part of the overlying Cody Shale (Haun, 1958).

Units of sandstone in the member generally grade into underlying siltstone and are abruptly overlain by shale or siltstone. The sandstone is light to medium to brownish gray, and the units commonly grade from very fine grained and horizontally bedded at the base to fine grained and crossbedded near the top. Winn (1991) concluded that the member in the west-central part of the basin is composed of three or four, approximately tabular, coarsening-upward sandstone units that are cross stratified, horizontally laminated, and ripple laminated at the top. He also indicated that the sandstone units are 6–15 m (20–49 ft) thick "and grade from bioturbated muddy sand upward to less burrowed, coarser beds." In that part of the basin, bioturbation and burrowing are common, and ichnofossils include *Asterosoma*, *Teichichnus*, and *Thalassinoides*, fewer *Terebellina* and *Planolites*, and rare *Ophiomorpha* (Winn, 1991).

Core of the Wall Creek from Johnson County (Merewether and others, 1976) is composed of, in ascending order, interlaminated silty shale and sandy siltstone, argillaceous and sandy siltstone, silty, very fine grained sandstone, and interstratified, very fine grained, slightly calcareous sandstone and minor silty shale. Most of the laminae of shale and siltstone are discontinuous, wavy, and nonparallel and enclose small horizontal burrows (*Planolites?*). Some of the interlaminated shale, siltstone, and sandstone in the lower part of the member has flaser bedding. The silty sandstone in the lower part is commonly bioturbated. In the upper part of the member, slightly calcareous sandstone contains microcrosslaminations, discontinuous, wavy, nonparallel laminations, and small horizontal burrows.

At scattered outcrops in southeastern Natrona County (fig. 11) the sandstone at the base of the Wall Creek contains pebbles as long as 5 cm (2 in) and is crossbedded (Merewether and Cobban, 1986b). Phosphatic nodules and clasts of phosphate-cemented sandstone were found in the basal beds by Bitter (1986). Sandstone in the lower part of the member at one location is mostly fine grained, thin to medium bedded, and bioturbated, although some is megaripple-crosslaminated and flat to hummocky laminated. The sandstone in the upper part of the member coarsens upward and is bioturbated, crossbedded, hummocky and horizontally laminated and is interbedded with thick, almost massive, channel-filling sandstone (Winn, 1986). Outcrops of the Wall Creek in southeastern Natrona County exhibit *Ophiomorpha*, *Asterosoma*, and *Arenicolites* (Cavanaugh, 1976), *Thalassinoides* and *Skolithos* (Winn, 1986), and *Planolites*.

Cores of the Wall Creek Member from northwestern Converse County, as described by Tillman and Almon (1979), represent a vertical sequence of four upward-coarsening units, each of which is composed of very fine grained to coarse-grained sandstone, shaley and sandy siltstone, and minor shale. The shale is commonly interlaminated with siltstone (flaser bedding) and with sandstone. Siltstone in the sequence is generally bioturbated. The sandstone is either horizontally laminated to crossbedded and partly rippled or reworked. The cores contain the trace fossils *Asterosoma*, *Teichichnus*, *Chondrites*, and "donut burrows" *(Schaucylindrichnus* or *Terebellina?).*

In the southwestern part of the basin, the Wall Creek Member disconformably overlies either the Emigrant Gap Member or the Belle Fourche Member (figs. 9C, D) and is conformably overlain by the Cody Shale. The thickness of the Wall Creek in that area ranges from about 3 to 85 m (10–280 ft). The member is thickest, more than 61 m (200 ft), in an irregular area in east-central Natrona County and west-central Converse County and in smaller areas near the southeastern corner of Johnson County. In outcrops near the western edge of the basin in Johnson County the sandstone of the Wall Creek grades northward into laterally equivalent siltstone and shale of the Cody Shale.

The Wall Creek Member in the vicinity of the Powder River Basin includes fossil foraminifers, palynomorphs, and mollusks of marine origin. In the core from Johnson County the basal part of the Wall Creek contains arenaceous foraminifers, and the middle of the member includes pelagic and calcareous benthic species (B.R. North and W.G.E. Caldwell, written commun., 1978, 1993) that probably indicate a change in the composition of the seawater. The foraminifera in the cores from Converse County include an agglutinated fauna of low species diversity from shale about 40 m (130 ft) below the top of the Frontier and an open-marine fauna from shale overlying the Frontier (Tillman and Almon, 1979). Palynomorphs in core of the Wall Creek from Johnson County include spores and pollen from continental environments and dinocysts and acritarchs from marine environments (Okumura, 1994). The dinocysts are mostly cavates.

Many outcrops of the member in the region also contain ammonites and bivalves of late Turonian age (Cobban, 1951a, b,1990); however, lateral changes in these faunas indicate slight differences in the age of the enclosing Wall Creek. Near the border of Natrona and Converse Counties (Merewether, 1983, fig. 2) fossil bivalves in the member are of middle late Turonian age (fig. 7, zones 26 and 27). A few of these species also are present in southern Johnson County (Merewether and others, 1979), where the member contains ammonites of zone 27 (fig. 7). Younger molluscan fossils (fig. 7, zone 28) of latest late Turonian age were collected from the member in south-central Natrona County.

The Wall Creek Member and the laterally intergradational Turner Sandy Member consist of overlapping lobate bodies of mostly sandstone and siltstone that extend and thin northeastward across the Powder River Basin from about southern Natrona County to eastern Weston County. The percentage of sandstone in the members is greatest along the southwestern margin of the basin. Deposition of these rocks began in the early late Turonian (fig. 7, zone 26) on the eroded surface of a shelf and continued intermittently through the latest Turonian by onlapping toward the southwest and west during a widespread marine transgression.

Local deposition in the region during the late Turonian is indicated by the location and age of three chronostratigraphic bodies of siliciclastic rocks. Sandstone, siltstone, and shale of the oldest body (fig. 7, zone 26) crop out on the southwestern flank of the Black Hills and at the northern end of the Laramie Mountains. A younger, intermediate body of sandstone and siltstone (fig. 7, zone 27) crops out in the same areas, conformably overlying the oldest body, as well as along the southeastern flank of the Bighorn Mountains where it rests on the erosional surface and the older body is absent. At one location in that area, the intermediate sandstone and siltstone are conformably overlain by the youngest body of rocks (fig. 7, zone 28) in the Wall Creek of the basin. At outcrops in southeastern Natrona County the youngest body rests on the eroded surface, and the two older bodies in the member are missing (Merewether and Cobban, 1986b).

Cores of the Wall Creek from northwestern Converse County indicated to Tillman and Almon (1979) that the member was deposited in environments ranging from shallow-marine shelf, to submerged marine bars (reworked and nonreworked), to beaches, lagoons, and tidal flats. From studies of the outcropping Wall Creek in southeastern Natrona County, Winn (1986) concluded that part of the member accumulated in shelf and lower shoreface environments, some of which had complex currents as well as unidirectional geostrophic flow. He also proposed that a channel-bearing, upper part of the member was deposited "near the mouth of a distributary system" and in upper shoreface and foreshore environments.

The Wall Creek near the southwestern margin of the Powder River Basin was interpreted by Huff (1989) and Huff and Nummedal (1990) in terms of sequence stratigraphy (Van Wagoner and others, 1990). They proposed that the member includes simple parasequences, as well as complex parasequences, that accumulated during a transgression and a following regression. They also concluded that the member is composed of as many as five stacked backstepping parasequences deposited during an episodic transgression in the late Turonian. After another investigation in the southwestern part of the basin, Winn (1991) indicated that the Wall Creek was deposited over a sequence-bounding unconformity, that it is part of a transgressive systems tract, and that sediments of the member were transported by storm-generated flows and were deposited in thin sheets mostly in middle to outer shelf environments. He also suggested that most of the sediments were derived from an uplifted area mainly in central Idaho. The sediments in the laterally intergradational Wall Creek and Turner Sandy Members apparently were deposited in several shallow-marine environments of a delta lobe that trended northeastward (Merewether and Cobban, 1986a); mean transport direction of the sand was northeastward. Paleocurrent directions from outcrops of the member, however, are south in southern Johnson County and dominantly southwest in southern Natrona County. The paleocurrent indicators probably formed during intermittent, postdepositional reworking of the sand by storm-generated currents.

ROCKS OF LATE TURONIAN AND CONIACIAN AGE

SAGE BREAKS MEMBER OF THE CARLILE SHALE AND STRATA IN THE CARLILE MEMBER OF THE CODY SHALE

Rubey (1930) named the Sage Breaks as a member of the Niobrara Formation from outcrops of concretion-bearing, dark-gray shale near the eastern margin of the Powder River Basin in Weston County. Cobban (1951a) assigned the member to the Carlile Shale. The Sage Breaks in the region rarely crops out, and it generally forms gentle slopes, flats, and valleys. Where exposed it consists of medium-dark-gray to grayish-black, noncalcareous shale that encloses several conspicuous layers of closely spaced concretions (fig. 10). The concretions are mostly light gray to grayish orange, calcareous, and septarian and are as thick as 45 cm (18 in.) and as long as 1.8 m (5.9 ft). Marine macrofossils collected mainly from the concretions are of late Turonian and Coniacian age (figs. 4, 5) (Merewether, 1980).

Core of the Sage Breaks from Weston County is composed of medium-dark-gray, slightly calcareous, thinly laminated shale (Merewether, 1980). Most of the shale in the basal 12 m (39 ft) of the member is slightly silty, and much of the shale in the uppermost 45 m (148 ft) of the member is pyritic. The core of the Sage Breaks encloses a few concretions, small horizontal burrows, and many invertebrate fossils. Trace-fossils near the middle of the member probably are *Planolites* and *Schaucylindrichnus* or *Terebellina*.

Strata comprising the Sage Breaks Member conformably overlie the Turner Sandy Member of the Carlile and, in the southern part of the Powder River Basin, are disconformably overlain by the Niobrara Formation. The Sage Breaks is 60–95 m (195–305 ft) thick on the northern flank of the Black Hills (Cobban, 1952). At outcrops along the western margin of the Black Hills the Sage Breaks is 75–90 m (250–300 ft) thick (Robinson and others, 1964; Merewether, 1980). In eastern Niobrara County the Sage Breaks is about 38 m (125 ft) thick (fig. 9A). An isopach map of the member in the subsurface on the eastern flank of the basin (Weimer and Flexer, 1985) shows thicknesses that range from less than 30 m (100 ft) to more than 90 m (300 ft). The isopach map and stratigraphic cross sections (Merewether and others, 1977; Fox, 1993c) of the basin indicate a northwest-trending area in the subsurface of Niobrara, Converse, and Campbell Counties where much or all of the Sage Breaks has been removed by mid-Cretaceous erosion.

Fossils of marine origin have been collected from outcrops at a few localities along the eastern edge of the basin (Robinson and others, 1964; Evetts, 1976; Merewether, 1980) and from a core from Weston County (Cobban, 1984). Molluscan fossils from outcrops and core of the basal part of the Sage Breaks are of latest Turonian age (fig. 4, zone 28), and those from the upper part of the member are middle Coniacian (fig. 4, zone 30).

Outcrops in Weston County also contain foraminifera that are of late Turonian age in the lower part of the Sage Breaks, of Coniacian age in the upper part, and possibly of Santonian age at the top (Evetts, 1976). These foraminifera are either arenaceous or calcareous and are mainly benthonic. Planktonic species are increasingly abundant between the middle and the top of the Sage Breaks. B.R. North and W.G.E. Caldwell (written commun., 1978, 1993) found abundant benthic and pelagic foraminifera in the Sage Breaks including planktonic species near the top of the member. Palynomorphs in core of the Sage Breaks from Weston County are mainly of marine origin, and the marine forms are mostly cavates (Okumura, 1994).

A similar body of concretion-bearing shale crops out in northern Johnson County (Hose, 1955; Mapel, 1959) and in Big Horn County (Richards, 1955; Knechtel and Patterson, 1956) near the northwestern edge of the basin. These strata comprise an upper part of the Carlile Member of the Cody Shale, and they enclose molluscan fossils of latest Turonian to middle Coniacian age (Richards, 1955; Knechtel and Patterson, 1956).

The concretion-bearing shale of latest Turonian age in the basal part of the Sage Breaks Member near the Black Hills grades southwestward into marine sandstone at the top of the Frontier Formation in Natrona County. Shale of middle Coniacian age (fig. 7, zone 30) in the upper part of the member (Merewether, 1980) grades west-southwest into marine sandstone at the top of the Frontier in west-central Wyoming (Merewether and Cobban, 1986a). In sequence stratigraphy (Van Wagoner and others, 1990), the Sage Breaks is a retrogradational parasequence set in a transgressive systems tract.

Clay-rich sediments of the Sage Breaks were deposited in offshore-marine environments of a shelf and slope. Changes in the enclosed microfauna between the base and the top of the member indicate, according to Evetts (1976), "deepening" water "and increasing distance from the shoreline." Evetts proposed that a middle part of the member accumulated on a marine shelf in water probably less than 200 m (655 ft) deep and that the uppermost strata of the member accumulated on an upper slope in water 200–600 m (655–1,970 ft) deep. Weimer and Flexer (1985) concluded that the Sage Breaks was deposited on a slope in water 90–185 m (300–600 ft) deep.

SAGE BREAKS MEMBER OF THE CODY SHALE

The Cody Shale was named by Lupton (1916) from outcrops in northwestern Wyoming. The thick body mainly of gray shale that conformably overlies the Frontier Formation on the western flank of the Powder River Basin was assigned to the Cody by Hares and others (1946). In the southwestern part of the basin, the basal stratigraphic unit of the Cody was assigned to the Sage Breaks Member (figs. 4, 9C, D) by Merewether and others (1977a, b). This marine unit consists mostly of poorly indurated, noncalcareous, slightly silty shale (fig. 11), the lower part of which grades laterally into sandstone of the uppermost Frontier (Haun, 1958). Overlying the Sage Breaks is the Niobrara Member of the Cody. Land surfaces presently formed on the Sage Breaks Member generally have little relief, and outcrops of the member are sparse. The outcrops are composed of medium-dark-gray shale and silty shale and minor medium-gray siltstone and yellowish-gray bentonite. Enclosed in the shale and siltstone are layers of limestone concretions and septarian calcareous concretions as much as 1 m (3 ft) in diameter. The scattered outcrops in northern Natrona County and southern Johnson County contain macrofossils of latest Turonian to middle Coniacian age (figs. 4, 7).

Core of the Sage Breaks from south-central Johnson County consists of medium-gray to dark-gray, silty shale and argillaceous siltstone, some of which is slightly calcareous (Merewether and others, 1976). Most of these mudrocks are thinly laminated to laminated. The laminae are mainly discontinuous and either wavy and parallel or even and parallel; however, some are wavy and nonparallel. The lower part of the member includes minor flaser and lenticular bedding. Cores of lower parts of the Sage Breaks from northwestern Converse County are composed of silty shale and overlying shale that are either subhorizontally laminated, ripple laminated, or bioturbated (Tillman and Almon, 1979). Cores from Johnson and Converse Counties contain abundant burrows, probably *Planolites* and *Schaucylindrichnus* or *Terebellina*, and scattered foraminifera and mollusks.

Along the southwestern flank of the Powder River Basin, the Sage Breaks Member conformably overlies the Frontier Formation; the lower part of the Sage Breaks interfingers with the upper part of the Frontier (Haun, 1958). In that area, the Sage Breaks and the overlying Niobrara Member of the Cody Shale are apparently conformable, although they are disconformable in the south-central part of the basin. The Sage Breaks is absent at outcrops in southern Converse County, where the Frontier is disconformably overlain by the Niobrara. In the western part of the basin the thickness of the Sage Breaks ranges from as much as 94 m (310 ft) in south-central Johnson and west-central Converse Counties to 53 m (175 ft) and less in southern Campbell County (fig. 9C) where the member probably has been truncated.

Fossils in the Sage Breaks include palynomorphs of marine and continental origin and foraminifers and mollusks of marine origin. Most of the palynomorphs in the core from southern Johnson County are marine forms that consist mainly of cavates (Okumura, 1994). B.R. North and W.G.E. Caldwell (written commun., 1978, 1993) reported abundant calcareous and arenaceous foraminifera, which consist of benthonic species and a few planktonic species, in samples of the core from Johnson County. In the cores from Converse County the calcareous and arenaceous foraminifers are also benthonic and planktonic (D.H. Dailey, written commun., 1989). At outcrops the basal part of the Sage Breaks contains fossil bivalves and ammonites of latest Turonian age (figs. 4, 7, zone 28) in Johnson County and similar fossils of early Coniacian age (figs. 4, 7, zone 29) in southern Natrona County; the uppermost part of the member generally contains fossil bivalves of middle Coniacian age (figs. 4, 7, zone 30).

The Sage Breaks Member of the Cody Shale grades northward into strata in Big Horn County herein assigned to the Carlile and Niobrara Members of the Cody Shale. Laterally equivalent rocks in northern Johnson, Sheridan, and Big Horn Counties were formerly referred to as the "Carlile Shale Member" and the "Niobrara Shale Member" of the Cody (Knechtel and Patterson, 1956; Mapel, 1959). These synchronous mudrocks (fig. 8) are the same age as marine sandstone units of the Frontier Formation in central and west-central Wyoming (Merewether and Cobban, 1986a).

The shale and siltstone of the Sage Breaks were deposited in offshore-marine environments during a widespread marine transgression. In terms of sequence stratigraphy (Van Wagoner and others, 1990), they are probably a retrogradational parasequence set in a transgressive systems tract. From studies of the enclosed microfauna, D.H. Dailey (written commun., 1989) concluded that the member in northwestern Converse County accumulated on middle to outer parts of a shelf.

REGIONAL HIATUS MAINLY FOR CONIACIAN TIME

The disconformity at the top of the Carlile Shale has been recognized at outcrops on the southeastern flank of the Powder River Basin and at outcrops and in the subsurface near the southern end of the basin (Merewether and others, 1977b; Weimer and Flexer, 1985; Fox, 1993c). On the eastern and northern sides of the Black Hills, the disconformity is associated with a layer of phosphatic nodules (Tourtelot and Cobban, 1968). At outcrops in east-central Niobrara County (Merewether and Cobban, 1985) rocks of either latest Turonian or early Coniacian age in the Sage Breaks Member of the Carlile Shale are disconformably overlain by beds of late Coniacian or possibly Santonian age in the Niobrara Formation. Similarly, at outcrops in south-central Converse County sandy siltstone of latest Turonian age in the Wall Creek Member of the Frontier Formation is disconformably overlain by clayey limestone of late Coniacian or possibly Santonian age in the Niobrara Member of the Cody Shale (Merewether and Cobban, 1973).

The disconformity has not been recognized at outcrops near the northeastern and northwestern margins of the basin. In the subsurface the maximum amount of truncation at this disconformity is within an irregular elongate area that extends northwest from south-central Niobrara County through northeastern Converse County to southwestern Campbell County. Most of this area of greatest erosion is depicted by Weimer and Flexer (1985).

ROCKS OF LATE CONIACIAN, SANTONIAN, AND EARLY CAMPANIAN AGE

NIOBRARA FORMATION

The name "Niobrara group" was applied by Newton and Jenney (1880) to grayish-yellow outcrops of soft, calcareous strata of Cretaceous age on the periphery of the Black Hills. Thereafter, Darton (1901) referred to these rocks as the Niobrara Formation. Where exposed on the surface, this formation erodes easily and generally forms valleys and swales. Along the eastern flank of the Powder River Basin, the Niobrara consists of yellowish- to dark-gray clayey limestone, calcareous shale, and noncalcareous shale and many thin beds and laminae of light-gray to grayish-orange bentonite (fig. 10) (Robinson and others, 1964). The limestone and shale are thin bedded to thinly laminated and are mostly horizontally stratified. Weimer and Flexer (1985) reported that the Niobrara includes bioturbated chalk. The lower part of the formation contains a few limestone and septarian limestone concretions about 30 cm (12 in.) long.

The Niobrara in the subsurface of southern Campbell County, northeastern Converse County, and southern Weston County was divided by Weimer and Flexer (1985) into lower and upper units; the lower unit fills depressions formed by mid-Cretaceous erosion of the Sage Breaks. In Big Horn County, outcrops of mainly noncalcareous shale and less bentonite (fig. 12) were called the "Niobrara shale member of the Cody shale" by Richards (1955) and Knechtel and Patterson (1956) but are herein called the Niobrara Member of the Cody Shale. A few units of shale in the Niobrara of Big Horn County are sandy.

At outcrops in the northeastern part of the basin the Niobrara Formation is apparently conformable and gradational with the underlying Sage Breaks Member of the Carlile Shale; however, on borehole logs from that area, Fox (1993d) depicted a disconformity at the base of the Niobrara. The formation at outcrops and in the subsurface in the southern part of the basin clearly rests disconformably on the Carlile. Along the eastern flank of the basin, the Niobrara is conformably overlain by the Gammon Member of the Pierre Shale; the upper part of the Niobrara and the basal part of the Gammon interfinger (Gill and Cobban, 1966a).

The Niobrara on the northern flank of the Black Hills and "along the northwestern side of the Black Hills" is generally 46–61 m (150–200 ft) thick (Cobban, 1952; Robinson and others, 1964). In northeastern Niobrara Count, the Niobrara is 73–80 m (240–264 ft) thick (fig. 9A) (Horton, 1953). In the northwestern part of the basin, where the Niobrara Member of the Cody Shale is evidently older (fig. 4), the member is about 85–125 m (280–410 ft) thick (figs. 12, 13) (Richards, 1955; Knechtel and Patterson, 1956). Regional isopach maps of the formation and laterally equivalent strata by Crews and others (1976), Weimer and Flexer (1985), and Fox and Higley (1987c) show that these rocks thicken irregularly southwestward from about 20 m (65 ft) near the southeastern corner of Powder River County in the northeastern part of the basin to 152–198 m (500–650 ft) in the western and southwestern parts of the basin. The Niobrara Formation or Member is locally thicker in a generally northwest trending area in the southern part of the basin where it rests disconformably on strata of the Carlile Shale (Weimer and Flexer, 1985).

The Niobrara Formation and Member in the Powder River Basin contain marine fossils—the remains of foraminifera, coccoliths, bivalves, fish, and reptiles—that vary in age probably from late Coniacian to early Campanian (figs. 4, 7). The outcropping formation on the west side of the Black Hills is probably Santonian. Evetts (1976) indicated that the microfossils in the basal 3 m (10 ft) of the Niobrara in eastern Weston County are Santonian and include planktonic foraminifera and coccoliths. Robinson and others (1964) reported that outcrops along the western slopes of the Black Hills contain the bivalves Inoceramus and Ostrea congesta and the vertebrae of mosasaurs. The Niobrara in eastern Niobrara County was tentatively assigned to Coniacian, Santonian, and early Campanian time by Gill and Cobban (1966a, table 2). Outcrops of the formation in Niobrara and Converse Counties contain the bivalve Volviceramus involutus of late Coniacian or possibly Santonian age (Merewether and Cobban, 1985). In Big

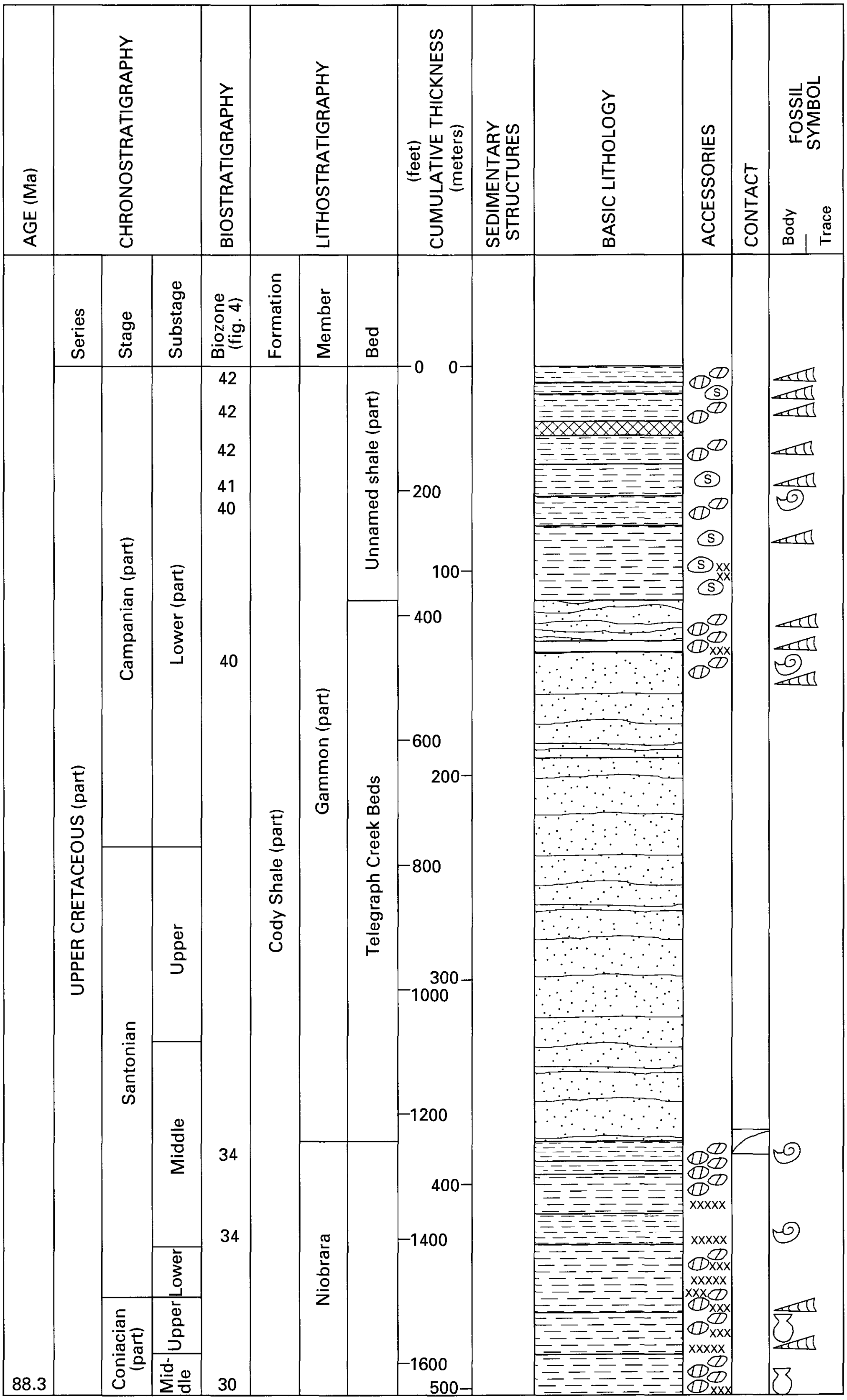


Figure 12. Outcrop sections of Niobrara Member and part of the Gammon Member of the Cody Shale, northern Big Horn County, Montana (sections 6, 7, table 1). Explanation as in figure 8. Modified from Knechtel and Patterson (1956).

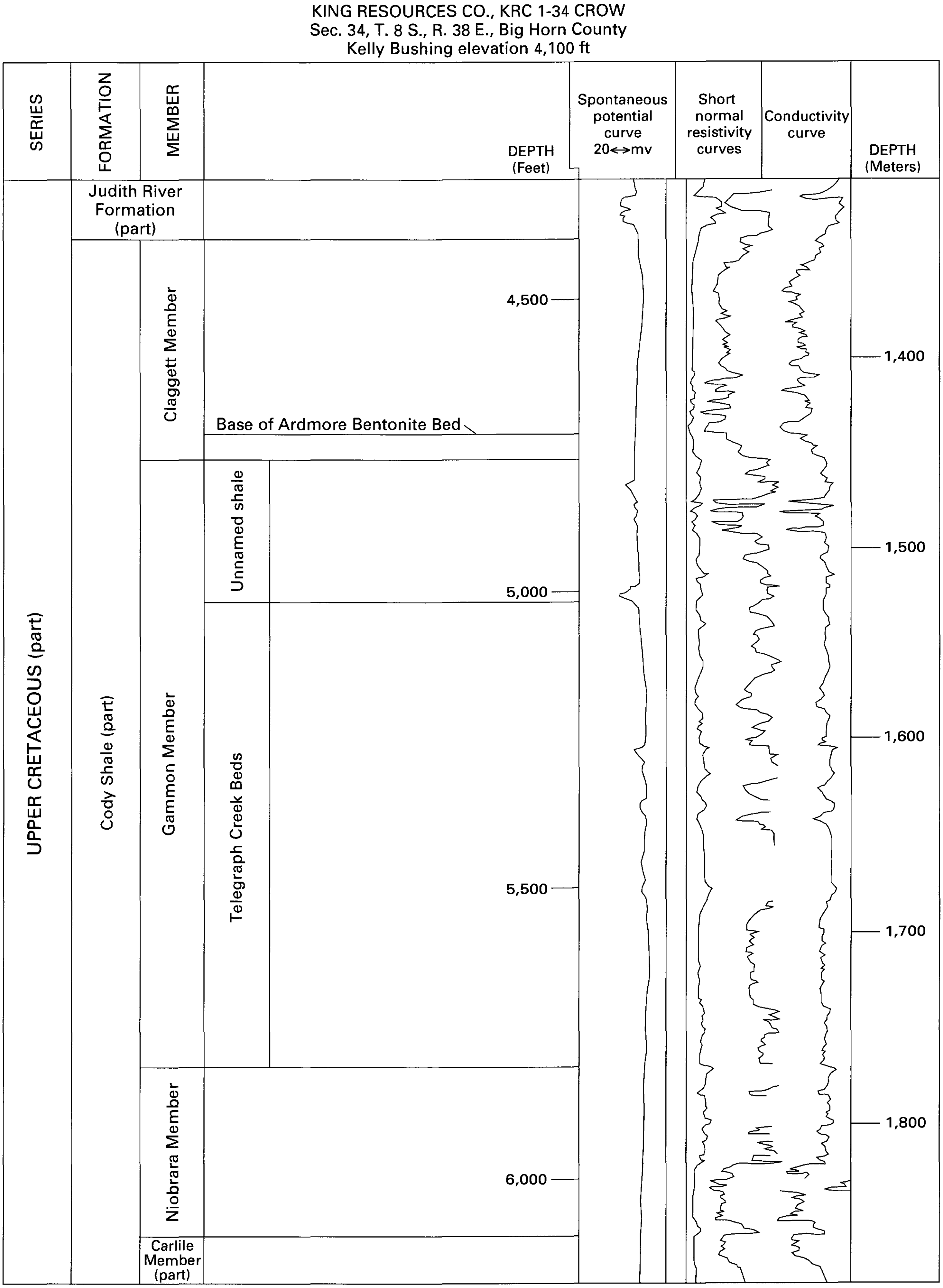


Figure 13. Geophysical logs of Upper Cretaceous Carlile, Niobrara, Gammon, and Claggett Members of Cody Shale, Big Horn County, Montana.

Horn County, the basal beds of the Niobrara enclose bivalves of middle Coniacian age (fig. 4, zone 30), and the upper part of the formation contains ammonites of middle Santonian age (fig. 4, zone 34).

Much of the Niobrara in the Powder River Basin resembles and is about the same age as the Smoky Hill Shale Member of the Niobrara Formation to the south and southeast in Colorado and Kansas (Merewether and Cobban, 1985; Weimer and Flexer, 1985). In the region of the Powder River Basin the Niobrara was deposited in open-marine environments, probably in a basin, apparently during a marine transgression and a subsequent marine regression. In sequence stratigraphy (Van Wagoner and others, 1990), a lower part of the formation could be a retrogradational parasequence set (part of a transgressive systems tract), a middle part an aggradational parasequence set, and an upper part a progradational parasequence set (part of a highstand systems tract).

In at least the southeastern part of the basin calcareous sediments of the basal Niobrara accumulated on an eroded surface of considerable relief (Weimer and Flexer, 1985). Asquith (1970) concluded that the formation in that area was deposited in a topographic basin in water depths of at least 366 m (1,200 ft). On the basis of microfossils in the upper part of the Carlile Shale and the basal part of the Niobrara in Weston County, Evetts (1976) suggested that the uppermost Carlile was deposited on an upper slope in water 200–600 m (656–1,968 ft) deep. He also proposed that the Niobrara accumulated in deeper water and that the associated pelagic microfauna indicated an oxygen-poor environment on the seafloor. Weimer and Flexer (1985) interpreted the formation on the eastern flank of the Powder River Basin as "a deep-water basin deposit" and proposed water depths of 183–488 m (600–1,600 ft) for those beds. The Niobrara of northeastern Wyoming and southeastern Montana, according to Shurr and Rice (1986), accumulated at depths of 100–300 m (328–984 ft).

NIOBRARA MEMBER OF THE CODY SHALE

The unit of mainly calcareous strata in the lower part of the Cody Shale on the western flank of the Powder River Basin in Wyoming was referred to as the Niobrara Member by Merewether and others (1977a, b). Outcrops of similar and partly equivalent beds near the northwestern edge of the basin, in northern Johnson, Sheridan, and Big Horn Counties, are also called the Niobrara Member of the Cody Shale. At the surface, rocks of the Niobrara Member are soft, and they form topographically lower areas. The sparse outcrops consist of dark-gray shale, which is partly calcareous and concretion bearing, and less yellowish gray to greenish-gray bentonite in many thin beds (figs. 12, 14). Concretions in the member are generally calcareous and are partly septarian and fossiliferous.

At outcrops near the southwestern margin of the basin the Niobrara Member appears conformable with the underlying Sage Breaks Member of the Cody, although Fox (1993d) depicts a disconformable contact in the subsurface. In that area the Niobrara is conformably overlain by strata herein assigned to the Steele Member (rank reduced) of the Cody. Thicknesses of the Niobrara from boreholes near the western edge of the basin (fig. 9C), as depicted by Fox and Higley (1987c), include 100 m (330 ft) in south-central Big Horn County, as much as 200 m (650 ft) in Johnson County, and 135–150 m (450–500 ft) in eastern Natrona County. Throughout much of the basin, the Niobrara Formation and Member thicken toward the southwest, although in Converse and southern Campbell Counties the thickness varies irregularly between 73 and 177 m (240–580 ft) (Fox and Higley, 1987c).

Macrofossils are sparse in the Niobrara but have been collected by W.A. Cobban at outcrops in Big Horn and Johnson Counties (Thom and others, 1935; Richards, 1955; Mapel, 1959). Cobban identified several species of bivalves and ammonites and reported the remains of gastropods, nautiloids, echinoids, and fish. Near the southwestern margin of the basin, molluscan fossils are in beds that underlie and overlie the member. These faunas indicate that the age of the Niobrara might be late Coniacian to early Campanian (fig. 7, zones 31–38) in the southwestern part of the basin and middle Coniacian to middle Santonian (fig. 7, zones 30–34) in the northwestern part of the basin.

The shale of the Niobrara Member grades eastward into shale and limestone of the Niobrara Formation near the Black Hills and westward into shale and glauconitic sandstone (Eldridge Creek Member) of the Cody Shale in southwestern Montana (Roberts, 1972). These rocks record a major marine transgression and a subsequent marine regression in the region of the middle Rocky Mountains. In terms of sequence stratigraphy (Van Wagoner and others, 1990) the Niobrara Member of the Cody as well as the Niobrara Formation consist of, from oldest to youngest, a retrogradational parasequence set (part of a transgressive systems tract), aggradational parasequence set, and progradational parasequence set (part of a highstand systems tract). The calcareous and noncalcareous strata of the Niobrara Member of the Cody Shale and of the Niobrara Formation probably accumulated in the open-marine environments of a topographic basin and adjoining slope, in water depths between 120 and 400 m (400–1,300 ft).

GAMMON MEMBER OF THE PIERRE SHALE AND GAMMON MEMBER OF THE CODY SHALE

The "Fort Pierre group" was named in central South Dakota by Meek and Hayden (1862) and was recognized on the flanks of the Black Hills by Whitfield (1877). The

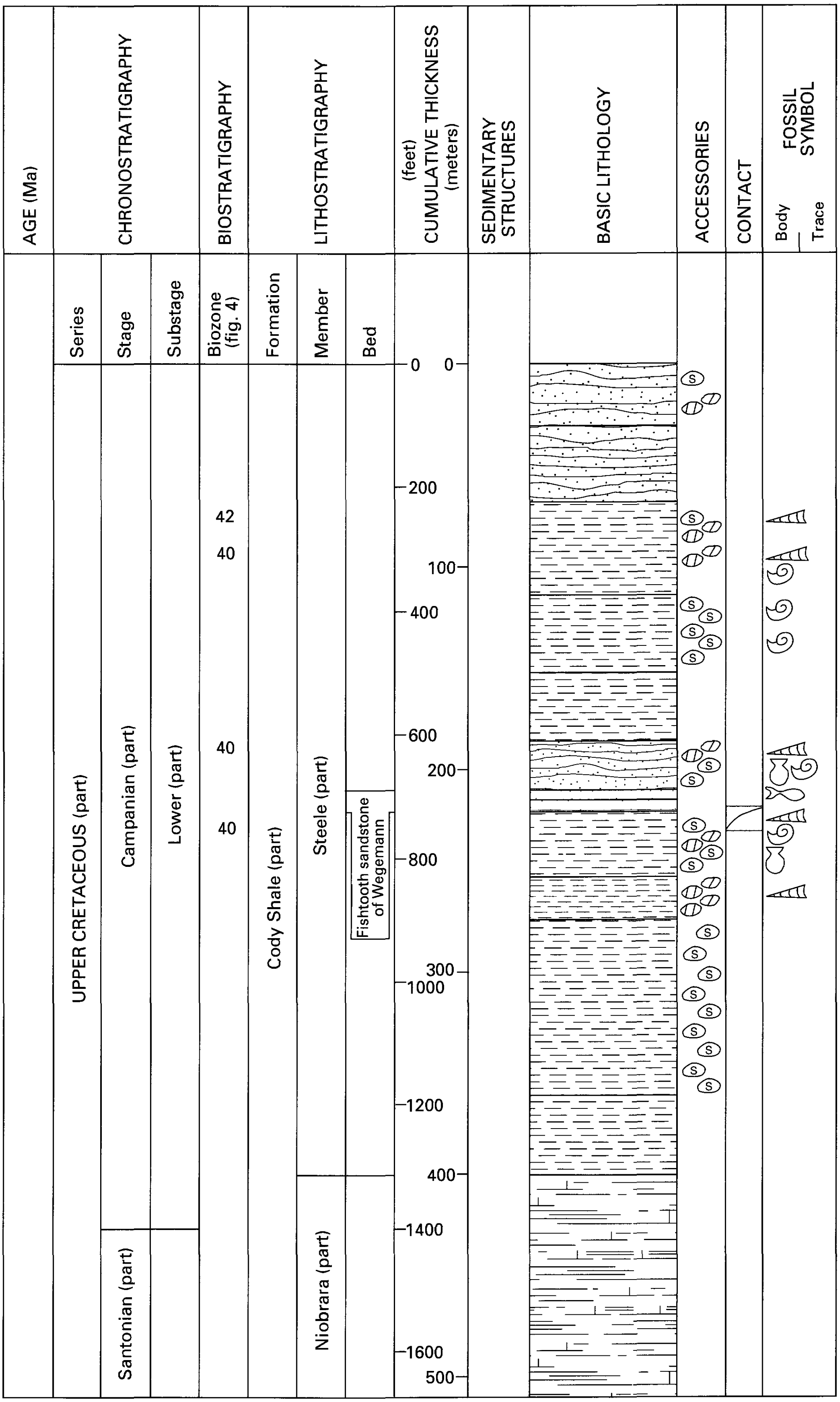


Figure 14. Outcrop sections of lower part of the Cody Shale, northeastern Natrona County, Wyoming (section 10, table 1). Explanation as in figure 8. Modified from Gill and Burkholder (1979).

name Pierre Shale was applied to Upper Cretaceous strata in southeastern Weston County and northeastern Niobrara County by Darton (1901). At scattered outcrops along the eastern edge of the Powder River Basin, the Pierre is composed of gray shale and less siltstone, sandstone, and bentonite, all of which were deposited in offshore-marine environments. Molluscan fossils in the formation are of Campanian and Maastrichtian age (figs. 4, 7). The Pierre conformably overlies the Niobrara Formation and is conformably overlain by the Fox Hills Sandstone. On the east side of the basin the Pierre thickens irregularly south-southeast from about 488 m (1,600 ft) on the northern flank of the Black Hills (Cobban, 1952), to about 625 m (2,050 ft) in northern Campbell County (Robinson and others, 1964), to about 945 m (3,100 ft) in northeastern Niobrara County (Gill and Cobban, 1966a). The Pierre in the basin consists of, in ascending order, the Gammon Member, which locally encloses the Groat Sandstone Bed at outcrops (generally called the Shannon Sandstone Member in the subsurface), the Sharon Springs Member, the Mitten Member, the Red Bird Silty Member, and the unnamed shale member, which locally encloses the Monument Hill Bentonitic Member and the younger Kara Bentonitic Member (fig. 4).

Outcrops of a concretion-bearing dark-gray mudstone that overlies the Niobrara in northwestern Crook County were named the "Gammon Ferruginous Member of the Pierre Shale" by Rubey (1930). The Gammon is now recognized along most of the eastern flank of the Powder River Basin. Where the member forms the topographic surface, it underlies gentle slopes and flats and rarely crops out. Robinson and others (1964) described the outcropping Gammon as mostly "dark-gray shale that weathers light gray and contains numerous red-weathering ferruginous concretions." The strata (fig. 10) are generally noncalcareous and rarely silty or sandy. The concretions are sideritic and are closely spaced in layers, although middle and upper parts of the member also contain a few layers of dark-gray, septarian, limestone concretions.

The upper part of the Gammon encloses the Groat Sandstone Bed in Powder River, Carter, northern Campbell, and northern Crook Counties. Ruby (1930) named the Groat Sandstone Bed from outcrops of sandstone, siltstone, and silty shale in southwestern Carter County. Cobban (1952) reported that the Groat on the northern flank of the Black Hills is about 15 m (50 ft) thick. The Groat also has been called the "Shannon Sandstone Member of the Gammon Shale" (Shurr, 1984). Robinson and others (1964) described the Groat as light- to light-yellowish-gray, fine- to medium-grained, "glauconitic and ferruginous sandstone interbedded with siltstone and gray shale." They also reported that the "sandstone is friable, calcareous, ripple marked, and crossbedded." This sandy and silty bed grades into the underlying shale of the Gammon; it is about 15–46 m (50–150 ft) thick (Gill and Cobban, 1966a), and its top is about 46 m (150 ft) below the top of the member. Shurr (1984) described the outcropping Groat (Shannon) in Carter County as a coarsening-upward sequence that includes interbedded claystone, siltstone, and bioturbated fine-grained sandstone and overlying burrowed and crossbedded, fine- to coarse-grained sandstone. The uppermost sandstone unit is either bioturbated or displays tabular or trough crossbedding, and it is overlain by the shale in the upper part of the Gammon. Fossils from outcrops of the Groat are early Campanian (fig. 7, zones 40, 41). The upper part of the Gammon in Carter and Crook Counties, above the Groat Sandstone Bed, contains a conspicuous bed of bentonite that is 30–60 cm (1–2 ft) thick (Robinson and others, 1964).

On the eastern flank of the Powder River Basin the basal part of the Gammon Member interfingers with the upper part of the underlying Niobrara Formation, and the Gammon is disconformably overlain by either the Sharon Springs Member or the Mitten Member of the Pierre Shale. In the subsurface of Weston County the Gammon is disconformably overlain by an unnamed member of the Pierre that, in turn, is disconformably overlain by the Sharon Springs (Asquith, 1970). The Gammon and laterally equivalent rocks in the eastern part of the basin thin generally eastward from more than 305 m (1,000 ft) in eastern Campbell and Converse Counties to less than 15 m (50 ft) in eastern Weston and Niobrara Counties.

In the northwestern part of the basin the Niobrara Member of the Cody Shale is conformably overlain by strata herein called the Gammon Member of the Cody Shale that are about 317–379 m (1,040–1,242 ft) thick (Richards, 1955; Knechtel and Patterson, 1956) (figs. 12, 13) and can be divided into the Telegraph Creek Beds (rank reduced) and an overlying unnamed shale (figs. 4, 12). This Gammon was previously called the "Telegraph Creek Member" and "unnamed shale member of the Cody Shale" (Richards, 1955; Knechtel and Patterson, 1956). The Telegraph Creek is 239–259 m (785–850 ft) thick and consists of sandy shale that encloses calcareous concretions and a few thin beds of sandstone (fig. 12). Overlying the Telegraph Creek is the unit called "shale member equivalent to the Eagle Sandstone" by Richards (1955) and "unnamed sandy shale member" by Knechtel and Patterson (1956). The unit is about 75–114 m (245–375 ft) thick and comprises silty and sandy shale, abundant ferruginous and calcareous concretions, and bentonite.

The Gammon on the eastern flank of the basin probably is of early Campanian age (figs. 4, 7), although the lower part of the member has not been dated. Molluscan fossils of Campanian age have been collected from middle and upper parts of the member. In the northwestern part of the basin ammonites of middle Santonian age were found by W.A. Cobban in the upper part of the underlying Niobrara Member (Richards, 1955). In outcrops of the Gammon on the west side of the Black Hills, bivalves, ammonites, and the bones and teeth of fish and mosasaurs were collected (Robinson and others, 1964). Arenaceous foraminifera were identified by Mello (1971) in samples of the Gammon from northeastern Niobrara County.

Regional chronostratigraphic data from Robinson and others (1964), Gill and Cobban (1966a, 1973), Gill and Burkholder (1979), and Rice and Shurr (1983) indicate that the Gammon along the eastern edge of the Powder River Basin grades westward into a lower part of the Steele Member of the Cody Shale near the western margin of the basin (figs. 5, 6). In sequence stratigraphy (Van Wagoner and others, 1990), the Gammon is a progradational parasequence set in a highstand systems tract. Van Wagoner and others (1990) suggested that the surface that extends eastward from the top of Asquith's (1970) unnamed member to the top of the Gammon is a ramp margin. Gill and Cobban (1961, 1973) proposed that sediments of the Gammon were transported into the region of the Powder River Basin during a marine regression and a subsequent brief marine transgression and that the sediments accumulated in the epeiric sea at depths greater than 60 m (200 ft). Asquith (1970) stated that, in Weston and northern Niobrara Counties, "Much of the sediment of the Gammon Ferruginous Member entered the area from the northwest" and was deposited on an outer shelf, on the contiguous slope, and in the associated basin; the marineward edge of that shelf would now trend mostly northeast.

Asquith (1970) also proposed that the slope sediments accumulated in water no shallower than about 150 m (500 ft). Weimer (1984) reported that estimates of the water depth for Cretaceous shelves generally range from 30 to 90 m (100–300 ft) and that the depths for the basins during sea-level highstands probably ranged from 180 to 300 m (600–1,000 ft). On the basis of studies of the Gammon near the northern end of the Black Hills, Rice and Shurr (1983) concluded that the member was "deposited in an outer shelf or basin environment" and that the Groat (Shannon) Sandstone Bed accumulated "on a broad, shallow shelf as much as 370 km (230 mi) from maximum eastward extent of equivalent nonmarine rocks."

LOWER PART OF THE STEELE MEMBER AND THE ENCLOSED SHANNON SANDSTONE AND SUSSEX SANDSTONE BEDS OF THE CODY SHALE

This part of the Cody Shale is delimited by the top of the underlying Niobrara Member and by the base of the overlying Ardmore Bentonite Bed; it can be recognized at outcrops (fig. 14) and in the subsurface (fig. 15) along the western flank of the Powder River Basin (Fox, 1993d). The sequence was deposited in marine environments and contains molluscan fossils of early Campanian age (figs. 4, 7). At outcrops in south-central Johnson County and in northeastern Natrona County, this part of the Steele Member consists of concretion-bearing shale and concretion-bearing silty or sandy shale and lesser siltstone, sandstone, and bentonite (fig. 14) (Gill and Burkholder, 1979). The most conspicuous and widespread units of sandstone in the sequence have been named, from oldest to youngest, the Fishtooth sandstone (informal name) (Wilmarth, 1938; Horn, 1954), Shannon Sandstone Member (Wegemann, 1911), and Sussex Sandstone Member (Wilson, 1951). In the present report, the Shannon and the Sussex are reduced in rank and considered beds of the Steele Member. Most of the shale in this part of the Steele is medium dark gray, noncalcareous, and silty and contains calcareous and ferruginous concretions. At outcrops, beds of comparatively unweathered bentonite are greenish gray and are as thick as 2.4 m (8 ft) (Gill and Burkholder, 1979).

The sandstone in the lower part of the Steele is mainly light gray to greenish gray and in units that coarsen upward from very fine grained to medium grained; it is commonly silty or clayey and encloses concretions. Crews and others (1976) indicated that their Shannon Member in an area in the central part of the basin is disconformable with the underlying rocks and that the coarsest grained beds can be in either the lower, middle, or upper parts of the member. Tillman and Martinsen (1984) reported that the Shannon Sandstone consists of many depositional lithofacies that are composed of sandstone and sparse interbedded siltstone and shale and that locally display trough and planar-tangential crossbedding, subhorizontal plane-parallel laminae, and current ripples. Trace fossils in those rocks include *Thalassinoides*, *Asterosoma*, *Teichichnus*, *Chondrites*, *Planolites*, a *Skolithos*-type, and plural curving tubes (Tillman and Martinsen, 1984). Burrows in the Shannon identified by Hansley and Whitney (1990) are *Terebellina*, *Zoophycos*, and *Chondrites*.

The Sussex Sandstone Bed is composed of sandstone and lesser siltstone and shale and exhibits trough crossbedding, planar-tangential crossbedding, planar-tabular crossbedding, ripple laminations, horizontal bedding, and bioturbation (Berg, 1975; Hobson and others, 1982; Higley, 1992). Van Wagoner and others (1990) designated sequence boundaries near the base and top of the Sussex. Trace fossils in outcrops and cores of the Sussex include *Arenicolites*, *Skolithos*, *Chondrites*, *Diplocraterion*, *Terebellina*, *Teichichnus*, and *Planolites* (Higley, 1992).

This lower part of the Steele Member is 616 m (2,021 ft) thick at outcrops in south-central Johnson County (Gill and Burkholder, 1979). In boreholes near the western edge of the Powder River Basin, the thickness of the sequence ranges from about 335 m (1,100 ft) in southeastern Big Horn County to more than 579 m (1,900 ft) in northeastern Natrona County. In the subsurface, these rocks and the approximately equivalent Gammon Member

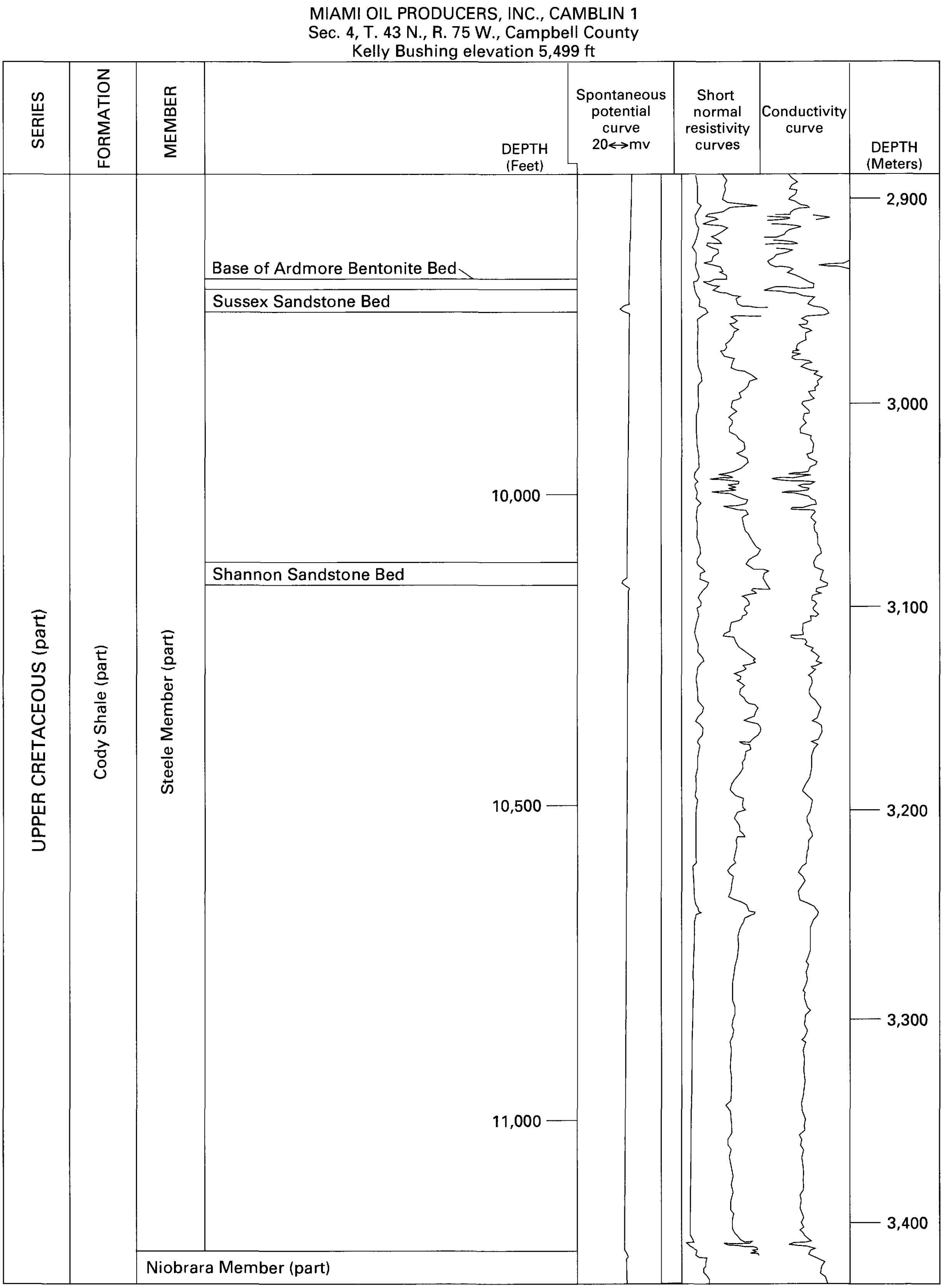


Figure 15. Geophysical logs of parts of the Niobrara and Steele Members of the Cody Shale, Campbell County, Wyoming.

and Asquith's (1970) unnamed member of the Pierre Shale thin generally eastward from about 610 m (2,000 ft) in south-central Johnson County on the western flank of the basin to less than 30 m (100 ft) in eastern Weston and Niobrara Counties near the eastern edge of the basin.

The Shannon Sandstone Bed at outcrops on the west side of the basin is 66 m (215 ft) thick in northern Johnson County (Hose, 1955; Mapel, 1959), 24 m (80 ft) thick in south-central Johnson County, and 44 m (145 ft) thick in northeastern Natrona County (Gill and Burkholder, 1979). The Shannon and the laterally equivalent Groat Sandstone Bed, as depicted by G.L. Dolton and J.E. Fox (written communication, 1989), are, however, more than 30 m (100 ft) thick along the western flank of the basin in western Converse County, eastern Natrona County, central and northern Johnson County, and southwestern Sheridan County and across the northern part of the basin in southern Big Horn and Powder River Counties.

An isopachous map by Fox and Higley (1987d) shows that the Sussex Sandstone Bed is more than 24 m (80 ft) thick at scattered boreholes in Converse County, southern Campbell County, and central Johnson County and less than 12 m (40 ft) thick at boreholes in central Campbell County, eastern Johnson County, and in Sheridan and Big Horn Counties.

Marine fossils of early Campanian age are common and locally abundant in the lower to middle part of the Steele along the western edge of the basin. These rocks enclose fossil bivalves, ammonites, gastropods, and bryozoa (Hose, 1955; Mapel, 1959; Gill and Burkholder, 1979). At outcrops in northeastern Natrona County, the Shannon Sandstone Bed contains mollusks (fig. 4, zone 41) as well as foraminifers and ostracods (Gill and Burkholder, 1979; Tillman and Martinsen, 1984). Parker (1958) reported that planktonic and benthonic foraminifera were found by N.M. Curtis and D.M. Curtis in cores of the Shannon in Powder River County. Arenaceous "shelf-type" foraminifera were identified by C.H. Ellis (written commun., 1975, in Spearing, 1976) in silty shale directly beneath the Shannon in northeastern Natrona County. In outcropping shale from 6 to 76 m (20–250 ft) below the Shannon in that area, D.H. Dailey (written commun., 1978, in Tillman and Martinsen, 1984) found foraminifers that are mainly agglutinated, of "low to medium-low diversity," and devoid of planktonic species.

Gill and Burkholder (1979) collected *Baculites* sp. (weak flank ribs) (fig. 7, zone 42) from outcrops of the Sussex Sandstone Bed in northeastern Natrona County. Arenaceous foraminifera were obtained by Berg (1975) from shale underlying the Sussex in a borehole in southern Campbell County.

The lower part of the Steele in the southwestern area of the Powder River Basin grades westward into the upper part of the Cody and the lower part of the overlying Mesaverde in northwestern Wyoming (Gill and Cobban, 1973). This part of the Steele is possibly equivalent in age to units on the southeastern flank of the basin that include, in ascending order, an upper part of the Niobrara Formation, the Gammon Member of the Pierre Shale, and Asquith's (1970) unnamed member of the Pierre Shale. Asquith (1970) concluded that the Sussex Sandstone Bed and an underlying unit of silty shale in the Steele grade eastward into his unnamed member of the Pierre. Moreover, the uppermost strata in the lower part of the Steele, including the Sussex Sandstone Bed, are probably represented by the hiatus at the top of the Gammon in Weston and Niobrara Counties (Asquith, 1970).

Van Wagoner and others (1990) reported a sequence boundary at the base of the Sussex and described a sequence boundary at the top of the Gammon and the Sussex. In terms of sequence stratigraphy, the part of the Steele between the Niobrara and the Sussex are progradational parasequence sets and overlying aggradational parasequence sets, whereas the Sussex is a progradational parasequence set. Van Wagoner and others (1990) also suggested that the horizon that extends eastward from the top of the Sussex to the top of Asquith's (1970) unnamed member of the Pierre to the top of the Gammon is a ramp margin.

Sediments of the lower part of the Steele on the western flank of the basin were transported southeastward and deposited mainly on a submarine topographic shelf and slope in water 18–183 m (60–600 ft) deep (Asquith, 1970; Berg, 1975; Rice and Shurr, 1980, 1983; Tillman and Martinsen, 1984). Litharenite in the Shannon and Sussex contains scattered fragments of sedimentary, igneous, and metamorphic rocks (Berg, 1975; Hansley and Whitney, 1990; Higley, 1992) that were transported probably southeastward from eroding areas in northwestern Wyoming and southwestern Montana.

Sandstone beds of the Shannon accumulated either on the shelf as north- to northwest-trending, shelf-ridge (bar) complexes at least 113 km (70 mi) from shore (Davis, 1976; Tillman and Martinsen, 1984) or near the shoreline mostly as shoreface deposits that were reworked by marine currents during and after a subsequent marine transgression (Hansley and Whitney, 1990). The average paleocurrent direction determined from 11 measurements in crossbedded sandstone of the Shannon in northeastern Natrona County is S. 12° E.

According to Berg (1975), Brenner (1978), and Hobson and others (1982), the Sussex Sandstone Bed was deposited and reworked on a shelf to form scattered, northwest-trending, low and narrow ridge (bar) complexes more than 161 km (100 mi) east of the contemporaneous shoreline. The several paleocurrent directions obtained from crossbedded sandstone of the Sussex in northeastern Natrona County have an average value of S. 28° W.

REGIONAL HIATUS FOR EARLY CAMPANIAN TIME

On the eastern flank of the Powder River Basin, where the outcropping Gammon Member is unusually thin and probably of early Campanian age, the Gammon Member is disconformably overlain by the Sharon Springs Member of the Pierre Shale in Niobrara County and by the Mitten Member of the Pierre in most of Weston County. Gill and Cobban (1966a) indicated that the Sharon Springs in Niobrara County is of early to middle Campanian age (fig. 7, zones 43, 44). In western Weston County in the subsurface, the Gammon and Sharon Springs are separated by Asquith's (1970) unnamed member of the Pierre, which is nearly equivalent to the Sussex Sandstone Bed and an underlying silty shale. The disconformity at the top of the Gammon extends from Weston County northward into Crook County (Gill and Cobban, 1966a); the magnitude of the associated hiatus apparently decreases to the north. Asquith (1970) indicated that the duration of the hiatus lessens toward the northwest and that the disconformity was caused by the nondeposition and slight erosion that accompanied two marine transgressions.

Van Wagoner and others (1990) proposed that the disconformity is a type-1 sequence boundary and formed by subaerial erosion during a lowstand of sea level and thereafter, following a sea-level rise, by deposition of marine siltstone, mudstone, and bentonite. They also determined that the disconformity represents a south-trending paleodrainage system. The disconformity is not evident at outcrops along the western edge of the basin.

ROCKS OF EARLY TO LATE CAMPANIAN AGE

SHARON SPRINGS MEMBER OF THE PIERRE SHALE

In the Pierre Shale in the southern part of the Black Hills, the distinctive, organic-rich shale that overlies the Gammon Member was assigned to the Sharon Springs Member by Moxon and others (1939). The Sharon Springs has been recognized in eastern Wyoming and adjoining areas, and it generally consists of interstratified dark-gray to grayish-black shale and very light gray to grayish-orange bentonite (fig. 10). Gill and Cobban (1966a) designated the associated Ardmore Bentonite Bed as the basal stratigraphic unit of the member. At outcrops, the Sharon Springs is commonly hard, buttress forming, and devoid of vegetation. The weathered shale is silvery gray and papery. Near the eastern margin of the Powder River Basin, the member contains sparse limestone concretions, phosphatic nodules, and marine macrofossils of early to middle Campanian age (fig. 7, zones 43, 44).

In Niobrara County and southern Weston County the Sharon Springs Member disconformably overlies the Gammon Member and is conformably overlain by the Mitten Member of the Pierre Shale. From east-central Weston County north to central Carter County, the Sharon Springs apparently grades laterally into the lower part of the Mitten, and the hiatus at the base of the Sharon Springs and Mitten decreases in magnitude. In eastern Niobrara County the Sharon Springs is 39 m (127 ft) thick at outcrops (Gill and Cobban, 1966a) and 49 m (160 ft) thick in boreholes (fig. 9A). The Sharon Springs in the Powder River Basin thickens to the south from less than 30 m (100 ft) on the western flank of the Black Hills to at least 122 m (400 ft) at the southern end of the basin (Crews and others, 1976).

Marine macrofossils in the Sharon Springs consist of ammonites, bivalves, the bones and scales of fish, and the bones of reptiles. Ammonites in the outcrops of northeastern Niobrara County include *Baculites obtusus* (figs. 4, 7, zone 43) in the lower part of the member and *Baculites mclearni* (figs. 4, 7, zone 44) near the top of the member (Gill and Cobban, 1966a). Arenaceous foraminifera, fewer calcareous benthonic foraminifera, and radiolaria have been found in samples of the member from Niobrara County (Mello, 1971).

Bituminous shale of the Sharon Springs in Niobrara and Weston Counties grades northward into shale of the lower part of the Mitten Member in Crook and Carter Counties and northwestward into shale of a basal part of the Claggett Member of the Cody Shale in Big Horn County (figs. 4, 14). Marine shale and minor sandstone of the same age along the southwestern edge of the Powder River Basin are within the upper part of the Steele Member of the Cody.

Gill and Cobban (1966a, 1973) proposed that the Sharon Springs accumulated at water depths of more than 60 m (200 ft) in the region of east-central Wyoming and adjoining South Dakota while the contemporary north-trending shoreline in north-central Wyoming was prograding eastward. Asquith (1970) concluded that sediments of the member were transported east-southeast on the Campanian shelf during a marine regression and were deposited on the shelf, slope, and basin. He also indicated that prior to deposition of the Sharon Springs seawater in the basin was more than 274 m (900 ft) deep; his estimate of water depth for the top of the Gammon Member in the southeastern part of the Powder River Basin is 372 m (1,220 ft). Van Wagoner and others (1990) indicated that the Sharon Springs onlaps, to the northwest, a sequence boundary and that marine mud and volcanic ash of transgressive and highstand system tracts in the member filled south-trending, incised valleys.

MITTEN MEMBER OF THE PIERRE SHALE AND CLAGGETT MEMBER OF THE CODY SHALE

Rubey (1930) named the Mitten Member of the Pierre Shale from outcrops of dark-gray shale along a tributary of the Little Missouri River in Crook County. This shale overlies either the Gammon or the Sharon Springs and is overlain by the Red Bird Silty Member of the Pierre (figs. 4, 16, 17). The Mitten crops out and locally forms low hills along the eastern edge of the Powder River Basin where it is composed mostly of two contrasting lithologic units of about equal thickness (Robinson and others, 1964). The lower unit consists of moderately hard, dark-gray shale that contains abundant organic matter; it includes several thin beds of bentonite near the base and large, light-gray-weathering, septarian limestone concretions in the upper half. The upper unit of the member consists of soft, grayish-black shale that contains many, dark-red-weathering sideritic concretions and a few layers of large, septarian limestone concretions that weather light gray or orange brown. Gill and Cobban (1966a) stated that at the type locality the lowermost Mitten is "a thin bed of polished black phosphate pebbles and rounded bone fragments" and that the basal stratum of the upper part of the member is "a thin bed of rounded phosphatized casts of baculites." Some of the concretions within the Mitten enclose marine macrofossils of mid-Campanian age (figs. 4, 7).

In the northwestern part of the basin, rocks similar in composition and age to those of the Mitten were assigned to the "Claggett Shale Member of the Cody Shale" (Richards, 1955; Knechtel and Patterson, 1956) but are herein called the Claggett Member of the Cody Shale (figs. 4, 18). An upper part of the Claggett, which corresponds in age to the Mitten, consists of dark-gray shale that encloses brown-weathering, calcareous concretions (fig. 18).

The Mitten in Niobrara County and in southern Weston County conformably overlies the Sharon Springs Member of the Pierre. In northern Weston County and Crook County the Mitten disconformably overlies the Gammon Member (Gill and Cobban, 1966a). On the northwestern flank of the Black Hills in Carter County the Mitten and the Gammon are apparently conformable. The thickness of the Mitten along the eastern edge of the basin increases southward (Asquith, 1970) from about 46 m (150 ft) in northwestern Crook County and in Carter County (Cobban, 1952; Robinson and others, 1964) to 286 m (938 ft) in northeastern Niobrara County (Gill and Cobban, 1966a). The Mitten and laterally equivalent rocks in the basin thicken mainly southward from less than 30 m (100 ft) in Powder River and Carter Counties to at least 274 m (900 ft) in Niobrara County (Crews and others, 1976).

Outcrops of the Mitten yield fossilized mollusks, the remains of fish, and the bones of mosasaurs (Robinson and others, 1964), all of which indicate marine environments of deposition. Ammonites of early late Campanian age (fig. 7, zones 44–48) were collected from lower and upper parts of the member in northeastern Niobrara County and from the upper part of the member in Weston, Crook, and Carter Counties (Robinson and others, 1964; Gill and Cbban, 1966a). Molluscan fossils have not been found in the lower part of the Mitten on the western flank of the Black Hills. Microfossils from the outcrops in northeastern Niobrara County include arenaceous foraminifera and minor numbers of calcareous benthonic foraminifera, planktonic foraminifera, and radiolaria (Mello, 1971).

The Mitten is the same age as a middle part of the Claggett Member, as well as the marine shale and sandstone in the upper part of the Cody Shale and in a lower part of the Mesaverde Formation along the western flank of the Powder River Basin (fig. 4). Gill and Cobban (1966a) suggested that the Mitten near the eastern edge of the Powder River Basin accumulated at water depths of less than 60 m (200 ft). Asquith (1970) concluded that sediments of the member in Weston County and adjoining areas were deposited on a shelf, slope, and basin and prograded eastward. Where the Mitten disconformably overlies the Gammon, it seemingly represents a thin transgressive systems tract and overlying progradational parasequence sets (Van Wagoner and others, 1990). While the member was accumulating, the shoreline in north-central Wyoming was moving eastward (Gill and Cobban, 1973).

UPPER PART OF THE STEELE MEMBER OF THE CODY SHALE

The upper unnamed part of the Steele Member includes those strata between the base of the Ardmore Bentonite Bed and the top of the Cody (figs. 19, 20); it can be recognized at several locations along the western flank of the Powder River Basin. Outcrops of the strata (fig. 19) are composed mainly of concretion-bearing, medium-gray, silty shale and minor yellowish-gray, very fine grained to medium-grained sandstone and greenish-gray bentonite (Gill and Burkholder, 1979). The concretions are mostly medium- to dark-gray limestone and enclose marine fossils mainly of middle Campanian age (fig. 7). Thin units of sandstone in southeastern Natrona County include clasts of claystone, straight-crested wave ripples, and tabular sets of planar and tangential crossbeds.

In west-central Natrona County a sandstone unit in the upper part of the Steele Member equivalent to the Fales Member of the Mesaverde Formation in the Wind River Basin (Barwin, 1959; Gill and others, 1970)

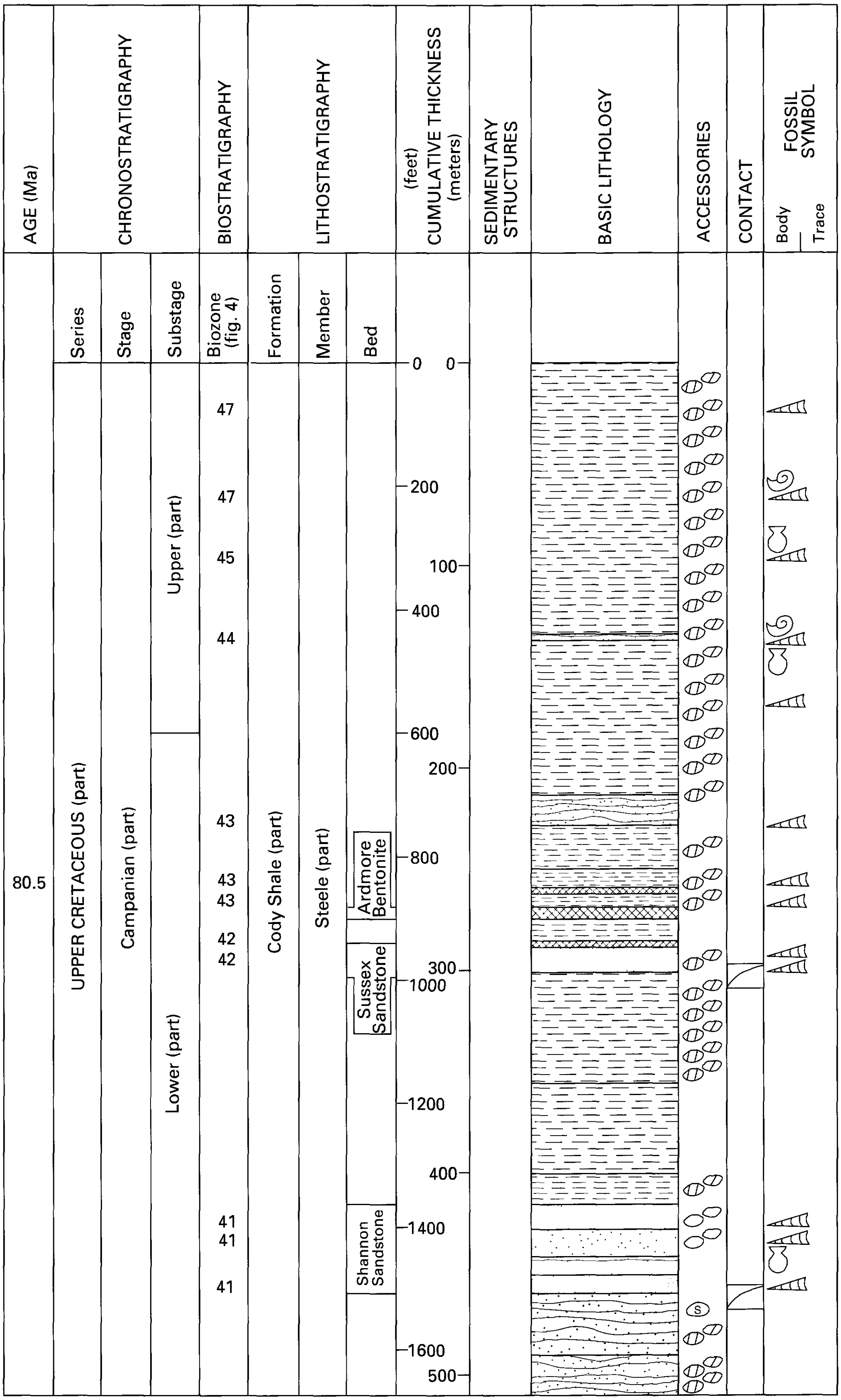


Figure 16. Outcrop sections of Mitten and Red Bird Silty Members of the Pierre Shale, northeastern Niobrara County, Wyoming (section 3, table 1). Explanation as in figure 8. Modified from Gill and Cobban (1966a) and U.S. Geological Survey (1974).

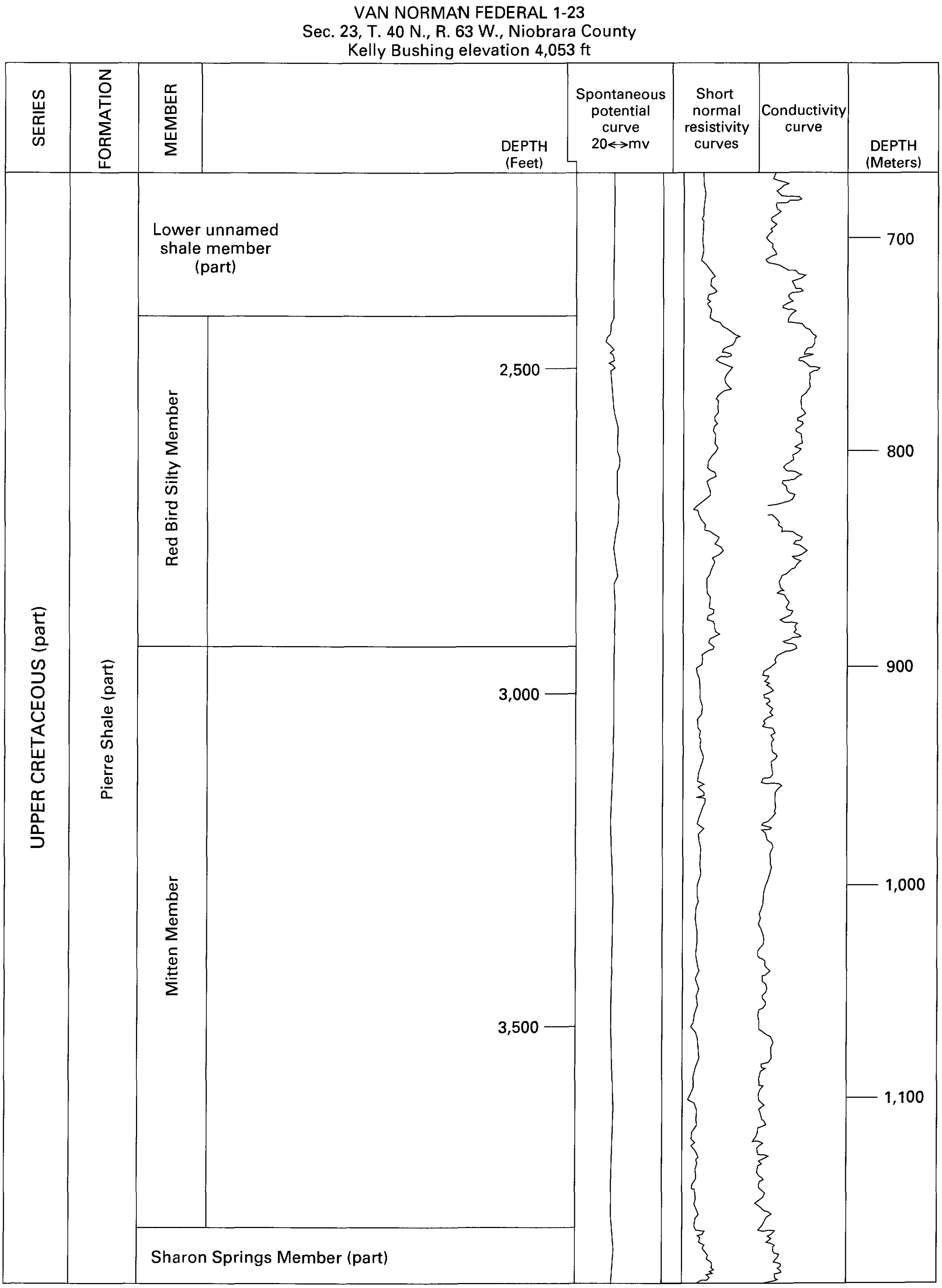


Figure 17. Geophysical logs of Mitten and Red Bird Silty Members of the Pierre Shale, Niobrara County, Wyoming.

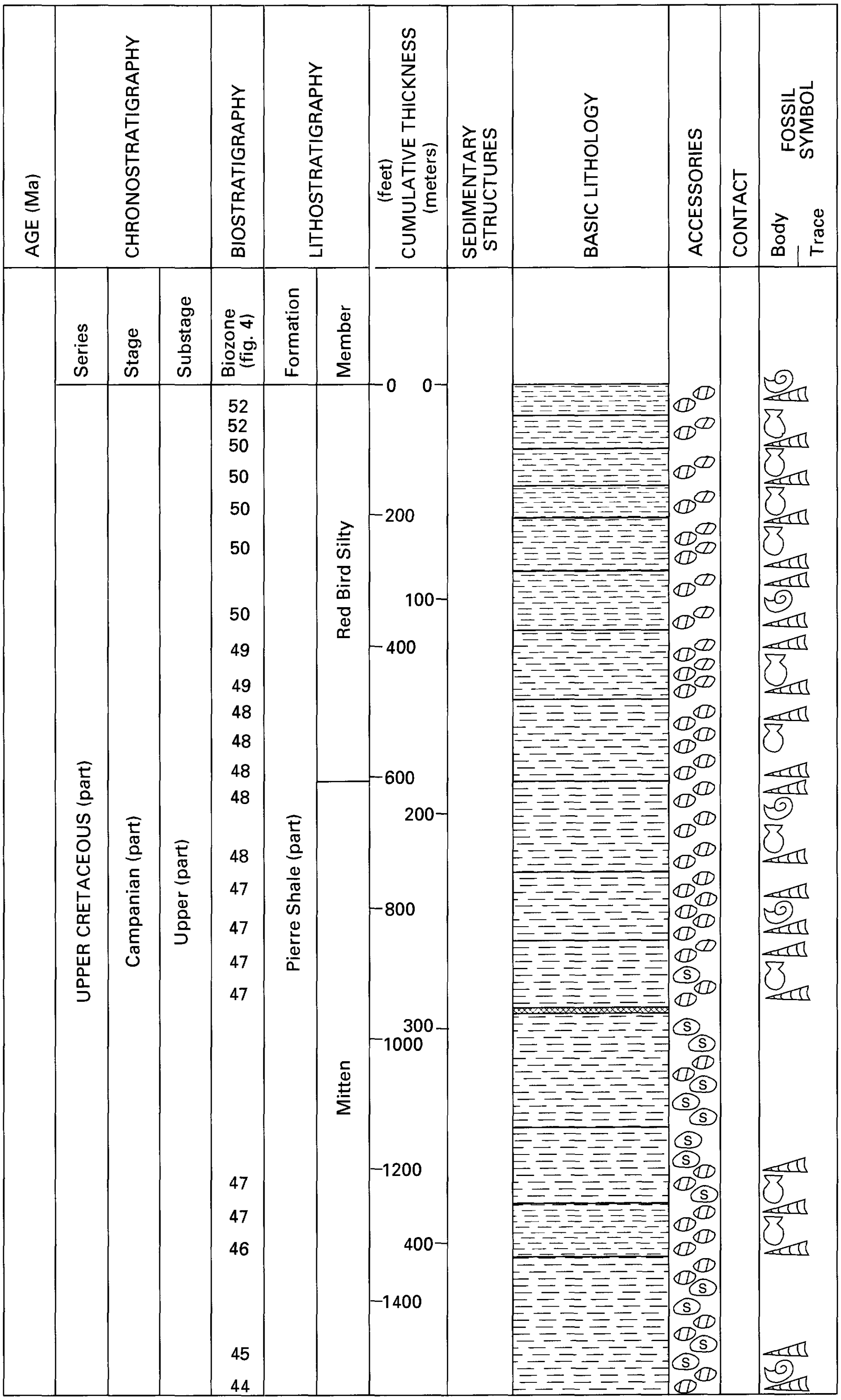


Figure 18. Outcrop sections of part of Cody Shale, and of Judith River Formation and Bearpaw Shale, northern Big Horn County, Montana (sections 7, 8, table 1). Explanation as in figure 8. Modified from Knechtel and Patterson (1956).

contains, in ascending order, hummocky crossbeds, trough crossbeds, horizontal laminae, and massive beds. The Fales Member of the Mesaverde is overlain by the Wallace Creek Tongue of the Cody Shale (Barwin, 1959).

This upper part of the Steele apparently is conformable with the lower part of the Steele, as well as with the overlying Mesaverde Formation, and it generally thickens to the south. Outcropping strata of the upper part of the Steele are about 110 m (360 ft) thick in northwestern Big Horn County, about 133 m (436 ft) thick in south-central Johnson County, and 287 m (940 ft) thick in northeastern Natrona County (Gill and Cobban, 1966b; Gill and Burkholder, 1979). In boreholes the upper part ranges in thickness from 134 m (440 ft) in west-central Sheridan County (Merewether and others, 1977c) to 239 m (785 ft) in south-central Natrona County (Merewether and others, 1977b).

Macrofossils from outcrops of this part of the Steele include bivalves, ammonites, bryozoa, brachiopods, and the remains of fish (Richards, 1955; Mapel, 1959; Gill and Burkholder, 1979). This fauna is marine, and the molluscan species are late early to early late Campanian in age (fig. 7, zones 43–48).

The upper part of the Steele Member grades eastward into the Sharon Springs and Mitten Members of the Pierre Shale on the eastern flank of the Powder River Basin and grades northward into the Claggett Member of the Cody Shale near the northwestern edge of the basin (fig. 4) (Gill and Cobban, 1973). West of the basin the upper part of the Steele is represented in northwestern Wyoming by nonmarine and nearshore-marine strata of the Mesaverde Formation.

In sequence stratigraphy (Van Wagoner and others, 1990), the upper part of the Steele consists of, from oldest to youngest, a retrogradational parasequence (transgressive systems tract) and aggradational and progradational parasequence sets (highstand systems tract). Shale and sandstone of the upper part of the Steele were probably derived from continental sediments in northwestern Wyoming and were deposited in offshore-marine environments of a Campanian shelf. At outcrops in southeastern Natrona County, the average paleocurrent direction determined from a few measurements in tabular crossbedded sandstone is S. 47° E. Asquith (1970) proposed that part of the seaward edge of the shelf was in Weston and Niobrara Counties. Gill and Cobban (1973) concluded that the nearest contemporary shorelines were in north-central Wyoming.

RED BIRD SILTY MEMBER OF THE PIERRE SHALE AND PARKMAN SANDSTONE MEMBER OF THE JUDITH RIVER FORMATION

Gill and Cobban (1962) named the Red Bird Silty Member from outcrops of concretion-bearing, "light- to medium-gray soft silty shale" (fig. 16) near the village of Red Bird in northeastern Niobrara County. They reported that the member is present in eastern Colorado, eastern Wyoming, eastern Montana, western South Dakota, and western North Dakota. The Red Bird along the western flank of the Black Hills is "gray to brownish-gray silty and sandy shale containing septarian limestone concretions that weather light gray and reddish gray" (Robinson and others (1964). The concretions commonly are silty, weather yellow, orange, or brown, and contain fossil mollusks of marine origin and of late Campanian age (Robinson and others, 1964; Gill and Cobban, 1966a).

The Red Bird Silty Member conformably overlies and grades into the Mitten Member and is conformably overlain by the lower unnamed shale member of the Pierre (fig. 4). At outcrops along the eastern margin of the Powder River Basin, the Red Bird Member thickens southward from 61 m (200 ft) in central Carter County at the north end of the Black Hills to 185 m (607 ft) in northeastern Niobrara County (Cobban, 1952; Robinson and others, 1964; Gill and Cobban, 1966a). From borehole logs (fig. 17), Fox and Higley (1987e) determined that the member thickens irregularly to the south-southeast from less than 46 m (150 ft) in southern Powder River County to about 183 m (600 ft) in Niobrara County.

Marine invertebrate fossils of late Campanian age (fig. 7, zones 48–52) are common in the concretions of the Red Bird Member (Robinson and others, 1964). Fossils from northeastern Niobrara County consist of bivalves, ammonites, bryozoa, and bored wood (Gill and Cobban, 1966a). Microfossils from that area are mainly arenaceous foraminifera but include calcareous benthonic and planktonic foraminifera, radiolaria, fragments of linguloid brachiopods, and seed or spore cases (Mello, 1971).

The Red Bird Silty Member is laterally continuous with the marine Parkman Sandstone Member of the Judith River Formation on the northwestern flank of the Powder River Basin and with marine and nonmarine beds in the Parkman Sandstone Member of the Mesaverde Formation on the western flank of the basin in southern Johnson and northern Natrona Counties (figs. 4, 5) (Gill and Cobban, 1966a). The Red Bird Member of northeastern Wyoming accumulated and prograded across a Campanian shelf (Asquith, 1970) during the latter part of a major marine regression. In the terminology of sequence stratigraphy (Van Wagoner and others, 1990), the member is a progradational parasequence in a highstand systems tract. Gill and Cobban (1966a) suggested that the Red Bird was deposited in water depths of less than 60 m (200 ft). Strandlines of middle to late Campanian age in northern Wyoming and southern Montana (Gill and Cobban, 1973) indicate a major regression as well as a possible source of sediments in northwestern Wyoming.

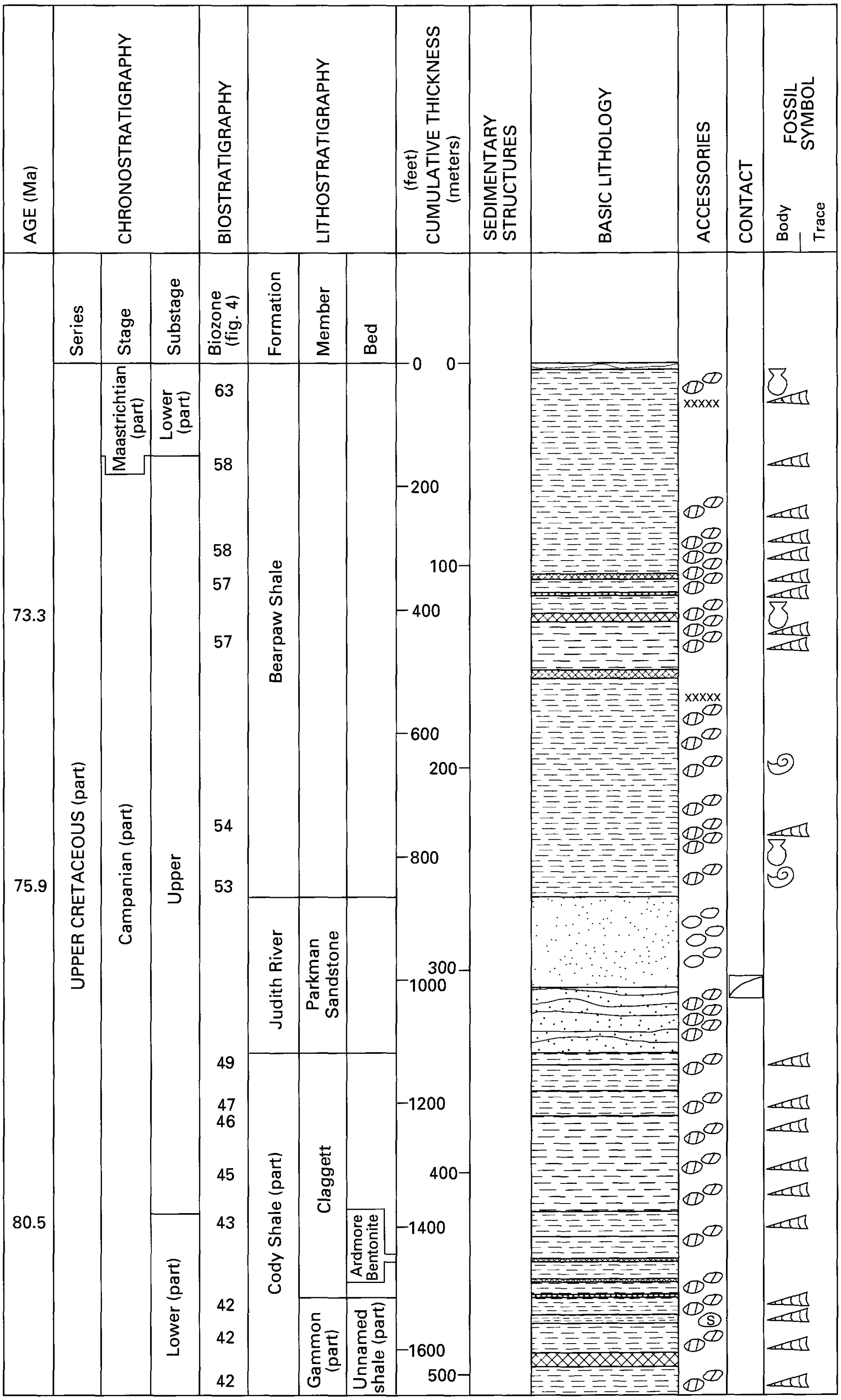


Figure 19. Outcrop sections of upper part of the Cody Shale, northeastern Natrona County, Wyoming (section 10, table 1). Explanation as in figure 8. Modified from Gill and Burkholder (1979).

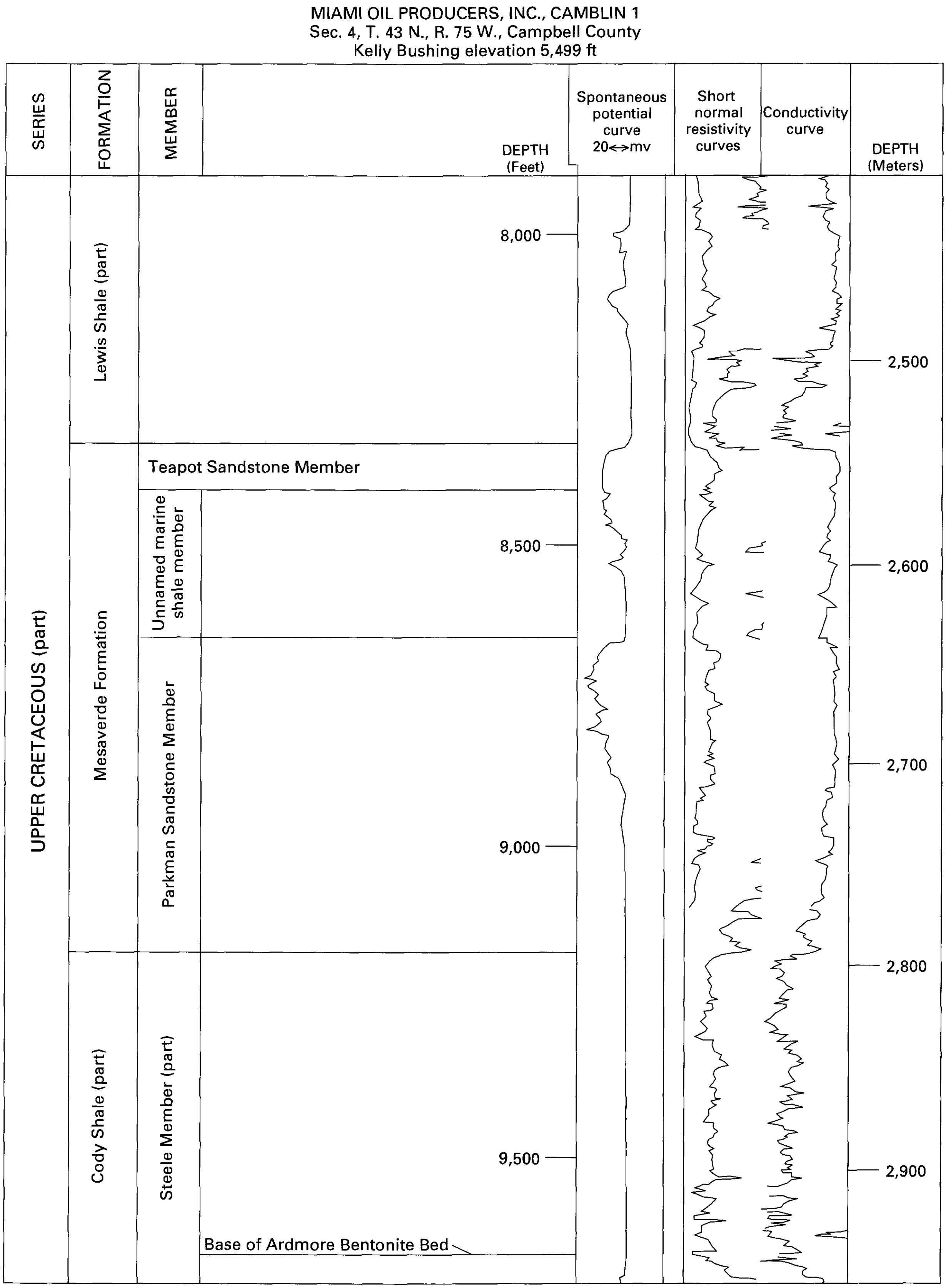


Figure 20. Geophysical logs of Upper Cretaceous strata including upper part of the Cody Shale, Mesaverde Formation, and lower part of the Lewis Shale, Campbell County, Wyoming.

PARKMAN SANDSTONE MEMBER OF THE MESAVERDE FORMATION

The name "Mesa Verde group" was first applied by Holmes (1877) to strata in southwestern Colorado and thereafter was modified to Mesaverde Formation and used in northeastern Natrona County, Wyoming, by Wegemann (1918). The Mesaverde of the Powder River Basin is composed of marine and nonmarine siliciclastic rocks (fig. 21), and it thickens generally toward the southwest, from perhaps 122 m (400 ft) in northern Campbell County to as much as 366 m (1,200 ft) in southern Converse County (fig. 22) (Purcell, 1961; Fox and Higley, 1987f). In northeastern Natrona County, Wegemann (1918) divided the Mesaverde into three members that he called, from oldest to youngest, the "Parkman sandstone," the "unnamed member," and the "Teapot sandstone."

Darton (1906) selected the name "Parkman sandstone" for rocks exposed in northwestern Sheridan County. The Parkman Sandstone Member crops out along the western margin of the Powder River Basin from Big Horn County, where it is the basal member of the Judith River Formation (fig. 23), to Converse County, where it is the basal member of the Mesaverde Formation (fig. 4).

Outcrops of the Parkman, most of which form ridges, ledges, and steep slopes, are composed mainly of thin-bedded, yellowish-gray, very fine grained and fine-grained sandstone and light-gray to dark-brown, partly carbonaceous and coaly, sandy shale (fig. 21) (Gill and Burkholder, 1979). The sandstone commonly contains pebbles of shale and concretions. Some of the shale encloses limestone and ironstone concretions.

The Parkman in northeastern Wyoming has been described as a complex of interstratified sandstone, siltstone, and shale and was divided into four lithogenetic units by Dogan (1984). Dogan (1984) found *Ophiomorpha* and "*Corophoides*-like U-shaped burrows" in the lower, marine part of the member. His basal unit (unit 1) is composed of silty shale that encloses irregular thin lenses of laminated and crosslaminated siltstone and ripple-laminated and crossbedded, fine-grained sandstone. His overlying unit 2 consists of fine-grained sandstone interstratified with lesser siltstone and shale. The sandstone is either horizontally laminated, ripple marked, contorted, or crossbedded (low to moderate angles or troughs). Overlying these rocks, unit 3 is made up almost entirely of fine-grained sandstone that coarsens upward and contains ripple marks and small-scale crossbedding but is mostly parallel laminated. The uppermost unit, unit 4, is mainly carbonaceous shale that locally grades into coal and encloses thin lenticular bodies of siltstone and fine-grained sandstone. Most of these sandstone lenses have sharp basal contacts, include basal shale-clast conglomerate, and are finer grained upward. Many of the sandstone bodies include trough crossbedding, ripple laminations, and horizontal laminations.

In west-central and south-central Natrona County the Parkman consists of a marine sandstone and an overlying sequence of nonmarine rocks (fig. 4) (U.S. Geological Survey, 1974). At outcrops in east-central Natrona County, sandstone in the lower part of the Parkman is trough crossbedded and in the upper part fills channels. In west-central Converse County, outcropping marine sandstone in the Parkman contains horizontal and hummocky laminae. Nearby nonmarine sandstone in the Parkman fills channels. Marine molluscan fossils collected from the lower part of the Parkman, from the underlying Cody, and from the overlying unnamed member indicate that the Parkman in west-central Converse County is of middle Campanian age (fig. 7, probably zones 48–51) (U.S. Geological Survey, 1974).

In the western part of the basin in Wyoming the Parkman Sandstone Member conformably overlies and grades into the Cody Shale and is either conformably overlain by an unnamed marine shale member of the Mesaverde (fig. 20) or is disconformably overlain by the nonmarine Teapot Sandstone Member of the Mesaverde (Merewether and others, 1977a, b, c). Near the northwestern edge of the basin in Big Horn County the Parkman Sandstone Member of the Judith River Formation conformably overlies the Claggett Member of the Cody Shale and is conformably overlain by an unnamed, mainly nonmarine member of the Judith River Formation (figs. 4, 22).

At outcrops the Parkman thickens southward from marine sandy shale and sandstone about 77 m (254 ft) thick (fig. 18) in northern Big Horn County (Knechtel and Patterson, 1956) to marine sandstone and overlying nonmarine beds 109 m (356 ft) thick in northwestern Sheridan County (Gill and Cobban, 1966a) and 169 m (553 ft) thick in south-central Natrona County (Rich, 1962). The Parkman in the subsurface of the Powder River Basin thickens generally to the southwest from less than 38 m (125 ft) in southeastern Big Horn and southern Powder River Counties to about 213 m (700 ft) in southwestern Converse County (Fox and Higley, 1987e).

Fossils in the lower marine part of the Parkman Member in the southwestern part of the basin include pelecypods, ammonites, brachiopods, and benthonic foraminifera (Cobban, 1958; Parker, 1958; Mapel, 1959; Rich, 1962; Gill and Burkholder, 1979; Dogan, 1984). In the upper nonmarine part of the member, fossils consist of pelecypods, gastropods, the bones of turtles, crocodiles, and dinosaurs, and plant remains (Wegemann, 1911; Thom and others, 1935; Heydenburg, 1966; Dogan, 1984). Marine mollusks from the Parkman and from the underlying and overlying strata indicate a middle Campanian age (fig. 7, zones 48–51) for the member.

Marine and nonmarine rocks of the Parkman in southern Johnson County and northern Natrona County are

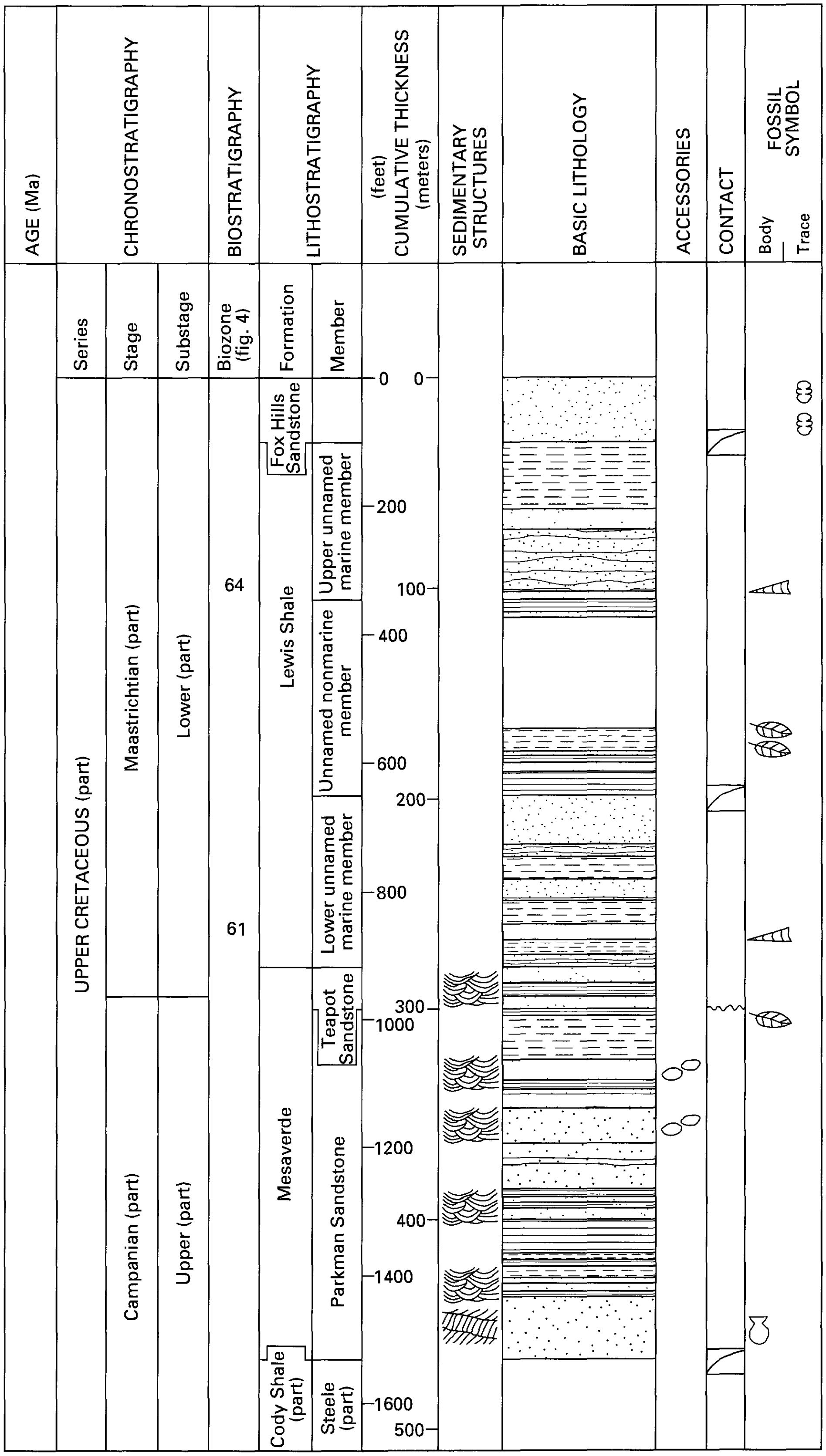


Figure 21. Outcrop sections of part of the Cody Shale, and of the Mesaverde Formation, Lewis Shale, and Fox Hills Sandstone, southern Natrona County, Wyoming (section 11, table 1). Explanation as in figure 8. Modified from Rich (1962) and J.R. Gill, (1972, written commun.).

about the same age as the marine Red Bird Silty Member of the Pierre Shale on the eastern flank of the Powder River Basin, the marine Parkman Sandstone Member of the Judith River Formation on the northwestern edge of the basin in Big Horn County, the lower parts of the marine and nonmarine Parkman in southern and western Natrona Counties and in northern Sheridan County, and probably the nonmarine beds and part of a hiatus in the Mesaverde Formation of northwestern Wyoming (Gill and Cobban, 1973). In the Powder River Basin the Parkman is a progradational stratigraphic sequence; it is represented by a series of north- and northwest-trending strandlines (Gill and Cobban, 1973) that indicate a marine regression toward the east and northeast during middle Campanian time. The source of the clastic sediments was probably in northwestern Wyoming.

Van Wagoner and others (1990) interpreted the Parkman of northeastern Wyoming as a progradational parasequence set. Sediments of the member in the southwestern part of the basin were deposited mostly in the marine and nonmarine environments of a delta that occupied areas in Converse, Natrona, Johnson, and Sheridan Counties. Hubert and others (1972) concluded that the delta was wave dominated and high destructive and that it prograded southeastward; however, Dogan (1984) proposed that the delta was river dominated, that marine sediments of the lower part of the sequence were transported northeasterly, and that nonmarine sediments of the upper part of the sequence were transported mostly eastward. The average paleocurrent direction from a few measurements in crossbedded marine sandstone in northwestern Sheridan County is S. 77° E. Several paleocurrent directions determined from crossbedded nonmarine beds in east-central Natrona County have an average value of N. 68° E., and the average direction from several measurements of crossbedded nonmarine rocks in west-central Converse County is N. 73° E.

LOWER UNNAMED SHALE MEMBER OF THE PIERRE SHALE AND LATERALLY EQUIVALENT BEDS IN THE JUDITH RIVER FORMATION AND BEARPAW SHALE

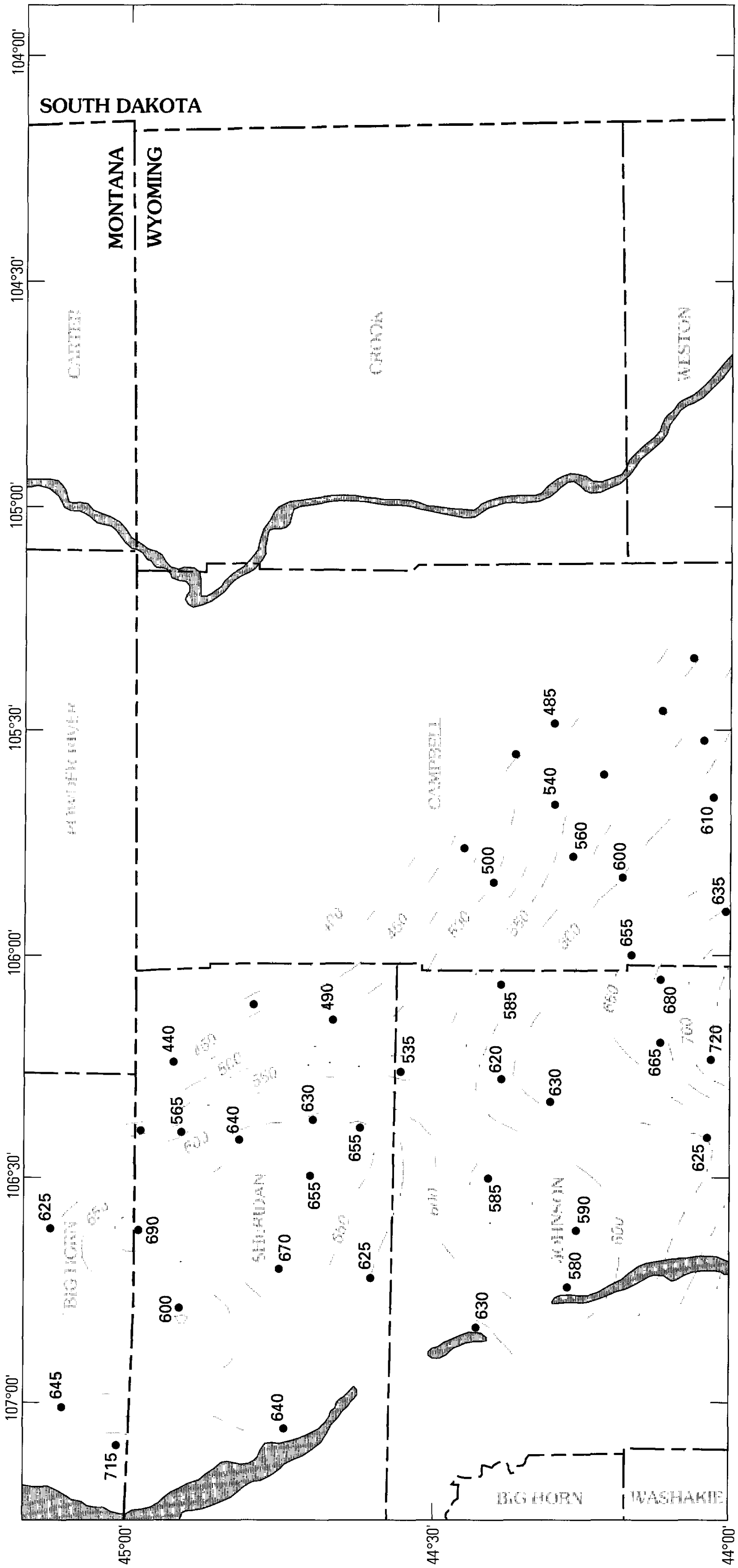
Gill and Cobban (1966a) applied the informal name "lower unnamed shale member" to strata in northeastern Niobrara County that overlie the Red Bird Silty Member of the Pierre Shale and are overlain by the Kara Bentonitic Member of the Pierre (figs. 4, 24). This unnamed member can be recognized at outcrops near the eastern margin of the basin in Carter, Crook, Weston, and Niobrara Counties (Robinson and others, 1964; Gill and Cobban, 1966a). In Carter County and in northern Crook County these rocks contain the Monument Hill Bentonitic Member of the Pierre, which was named by Rubey (1930). In Niobrara County the lower unnamed member may enclose a regional disconformity.

Gill and Cobban (1966a) described the lower unnamed shale member as a sequence of "thick alternating units of dark-, medium-, and light-gray-weathering shale" that includes, in the upper two-thirds of the member, beds of light-gray-weathering bentonite and bentonitic shale (fig. 25). These rocks enclose abundant fossiliferous limestone concretions and many ironstone concretions. Molluscan fossils within the lower unnamed member are of marine origin and of late Campanian to early Maastrichtian age (figs. 4, 7). The Monument Hill Bentonitic Member in Crook and Carter Counties is about 76 m (250 ft) above the base of the unnamed member and, according to Robinson and others (1964), is composed of "light-gray-weathering bentonitic and silty shale and impure bentonite."

The lower unnamed shale member of the Pierre is represented in the northwestern part of the basin by the unnamed member of the Judith River Formation and by an overlying lower part of the Bearpaw Shale (figs. 4, 23) (Richards, 1955; Knechtel and Patterson, 1956). This part of the Bearpaw (fig. 18) is composed of dark-gray shale that encloses brownish-gray calcareous concretions and greenish-gray bentonite.

The lower unnamed member of the Pierre is conformable with both the underlying Red Bird Silty Member and the overlying Kara Bentonitic Member. At outcrops near the eastern margin of the basin, the lower unnamed member thickens southward from as much as 175 m (575 ft) in Crook and Carter Counties (Knechtel and Patterson, 1962) to 219 m (720 ft) in northeastern Niobrara County (Gill and Cobban, 1966a). The enclosed Monument Hill Bentonitic Member in Crook and Carter Counties is 46–67 m (150–220 ft) thick (Cobban, 1952; Robinson and others, 1964).

The abundant marine macrofossils in the lower unnamed member are dominantly mollusks and bryozoans, but they also include, in one minor unit, brachiopods, echinoids, starfish, and the bones and scales of fish (Gill and Cobban, 1966a). Another unit of the member contains large ribs, probably from a mosasaur. Mollusks of late Campanian to early Maastrichtian age (fig. 7, zones 52–60) were collected from many horizons in these strata; however, species indicating three fossil zones of the latest Campanian (fig. 7, zones 56–58) were not found in the sequence in Niobrara County and, if present, would be confined to a unit of shale about 2 m (6 ft) thick. The missing fossils probably indicate a hiatus in the lower unnamed shale member. Microfossils from the member in Niobrara County are mostly arenaceous foraminifera but include calcareous benthonic foraminifera and radiolaria (Mello, 1971). Fossils in the Monument Hill Bentonitic Member and in contiguous beds in Carter and Crook Counties indicate that this bentonitic member is of late Campanian age (fig. 7, zones 55–56).


SOUTH DAKOTA
MONTANA
WYOMING
WESTON
CAMPBELL
JOHNSON
BIG HORN
WASHAKIE
104°00'
104°30'
105°00'
105°30'
106°00'
106°30'
107°00'
45°00'
44°30'
44°00'
485
540
560
600
610
635
655
500
680
720
665
585
620
630
625
535
490
440
565
640
630
655
655
585
590
580
630
625
670
690
625
600
645
640
715

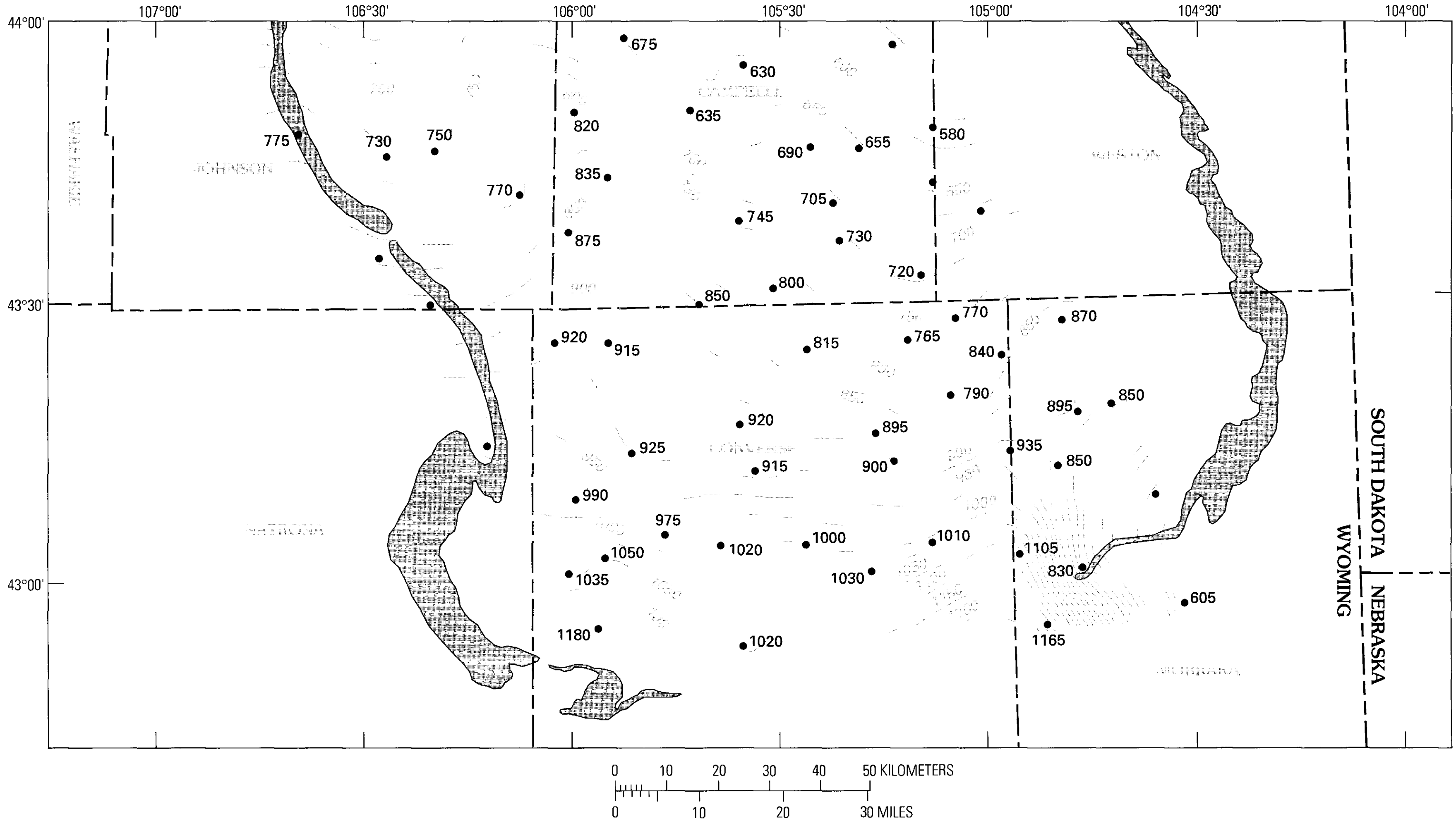


Figure 22. Preliminary isopachous map of Mesaverde Formation, Powder River Basin, Wyoming and Montana. Modified from Fox and Higley (1987f). Numbers are thicknesses in feet (100 ft=30.5 m) of formation; contour interval 25 ft; dots indicate locations of boreholes. Stipple pattern depicts locations of outcrops mainly of the Fox Hills Sandstone.

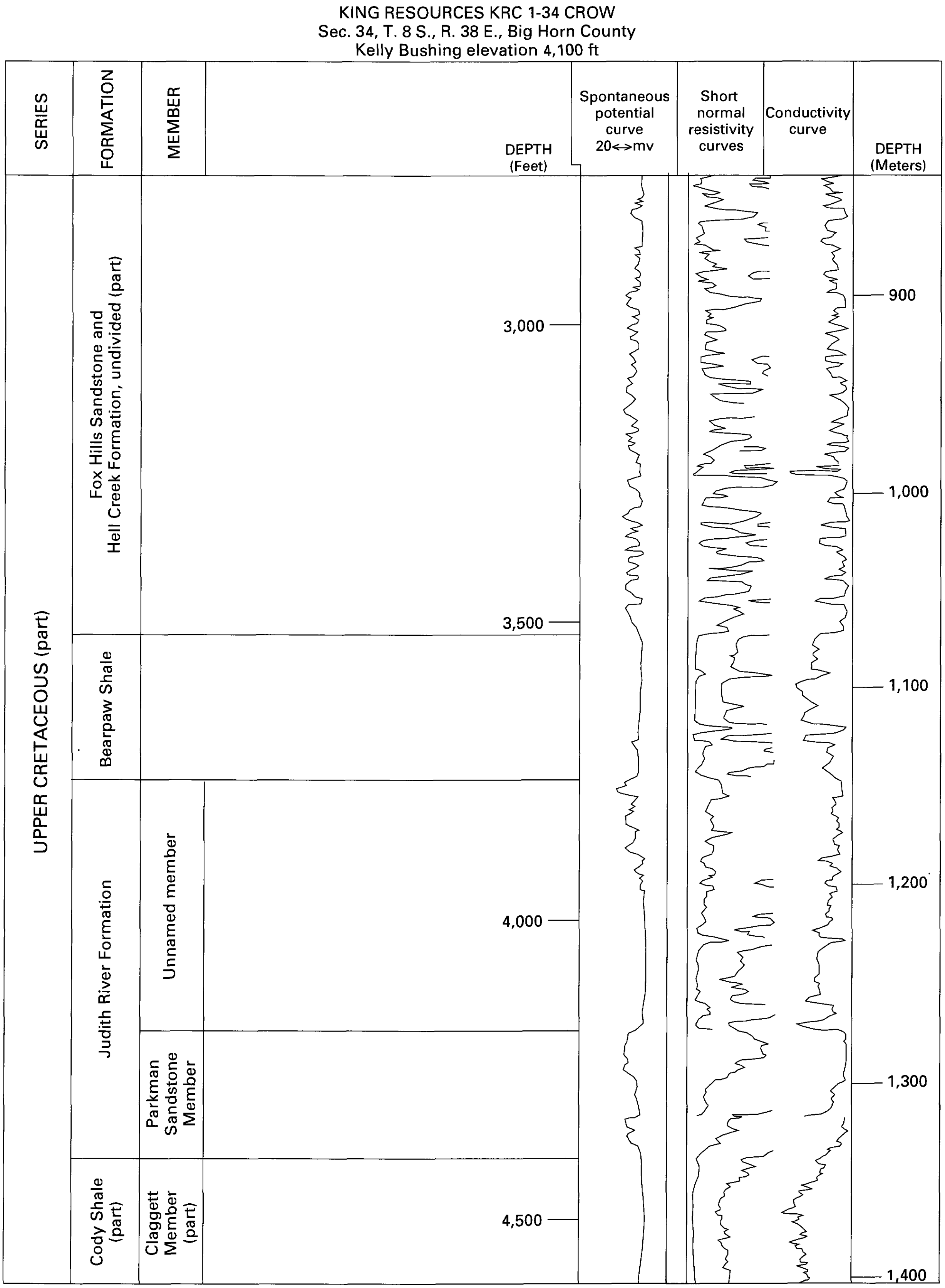


Figure 23. Geophysical logs of Upper Cretaceous strata including upper part of the Cody Shale and the Judith River Formation, Bearpaw Shale, and part of the Fox Hills Sandstone and Hell Creek Formation, undivided, Big Horn County, Montana.

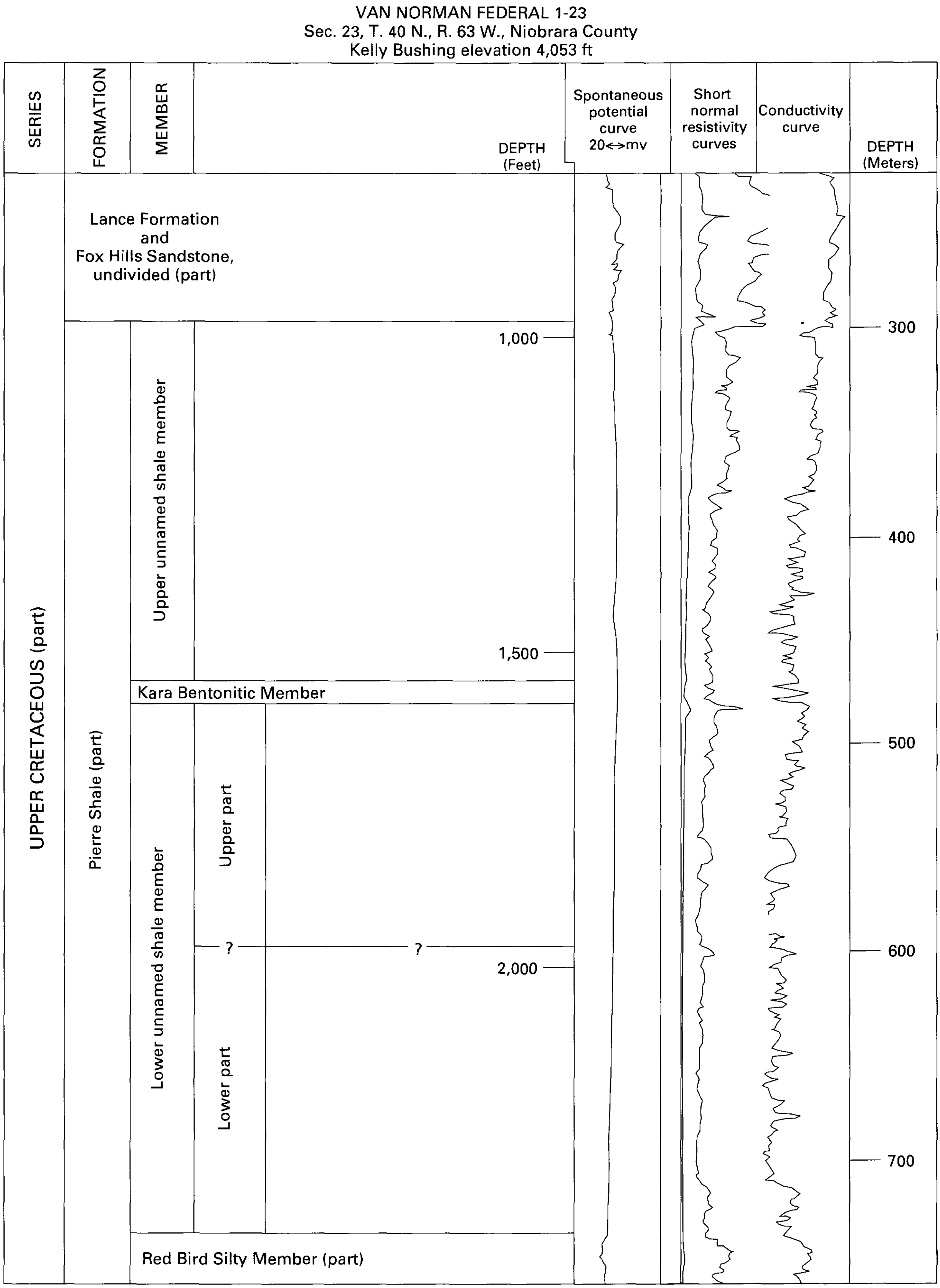


Figure 24. Geophysical logs of Upper Cretaceous strata including upper part of the Pierre Shale and lower part of the Fox Hills Sandstone and Lance Formation, undivided, Niobrara County, Wyoming.

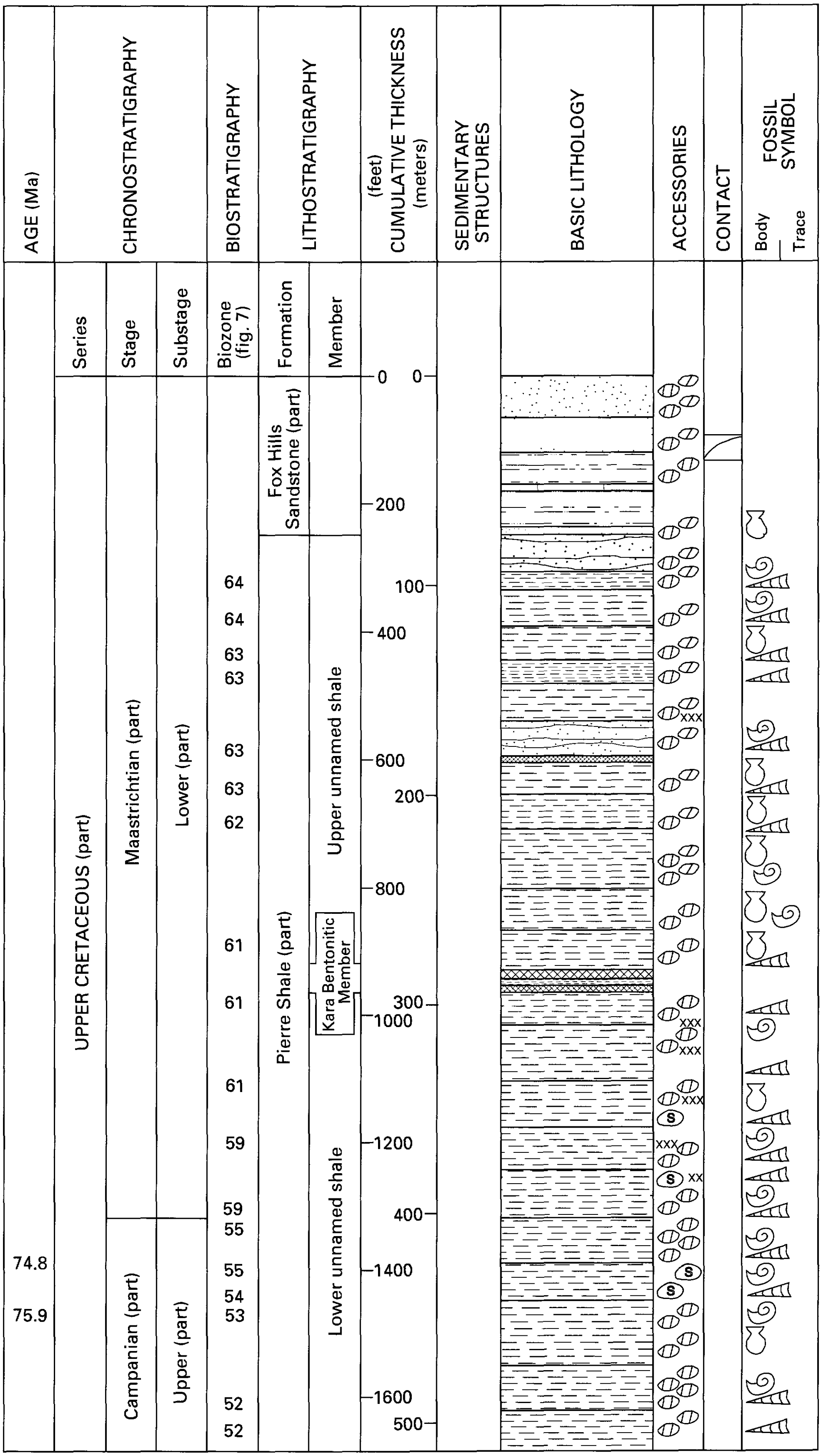


Figure 25. Outcrop section of upper part of the Pierre Shale and lower part of the Fox Hills Sandstone, northeastern Niobrara County, Wyoming (section 3, table 1). Explanation as in figure 8. Modified from Gill and Cobban (1966a) and U.S. Geological Survey (1974).

The lower unnamed shale member of the Pierre grades westward mostly into marine rocks of the Bearpaw Shale near the northwestern edge of the Powder River Basin and into marine and nonmarine rocks of the Mesaverde Formation and marine beds of the overlying Lewis Shale on the southwestern flank of the basin (figs. 4, 6) (Gill and Cobban, 1966a).

Paleostrandlines in northeastern Wyoming and southeastern Montana for the late Campanian and early Maastrichtian apparently reflect a time of marine regression and a following comparatively brief period of marine transgression (Gill and Cobban, 1973), as well as a contemporary source of sediments in western Wyoming. In the region of the Powder River Basin, sediments of the lower unnamed shale member probably accumulated on a depositional shelf. Gill and Cobban (1966a) suggested that the fossiliferous laminae in the lower unnamed member were deposited at moderately rapid rates in seawater less than 61 m (200 ft) deep.

Using nomenclature from sequence stratigraphy (Van Wagoner and others, 1990), the member includes, in ascending order, a retrogradational parasequence set (transgressive systems tract), progradational parasequence set (highstand systems tract), type-1 sequence boundary, progradational parasequence set (lowstand systems tract), and retrogradational parasequence set (transgressive systems tract).

UNNAMED MARINE SHALE MEMBER OF THE MESAVERDE FORMATION

These strata were described by Wegemann (1918) from outcrops in northeastern Natrona County and were recognized by Gill and Cobban (1973) at scattered outcrops in west-central Converse County, northeastern Natrona County, and south-central Johnson County (fig. 1). This member, excluding the uppermost beds, has been called the "Pumpkin Buttes Member"; a sandstone unit near the base of the member in west-central Campbell County has been called the "Ferguson sandstone lentil" (Purcell, 1961). The unnamed marine shale member is mostly soft, and at the surface it commonly underlies valleys; it is made up mostly of medium-gray, silty or sandy shale, medium-gray, clayey or sandy siltstone, yellowish-gray, clayey and silty, very fine grained sandstone, and greenish-gray, fine- to medium-grained sandstone (Gill and Burkholder, 1979). Units of sandstone in the member are as thick as 47 m (155 ft). These units commonly grade into underlying siltstone; some are crossbedded and some are massive, and many contain *Ophiomorpha*. At outcrops in west-central Converse County, the thick marine sandstone at the top of the member is horizontally bedded near the base and tabular tangentially crossbedded and hummocky crossbedded in the middle. Sandy concretions are sparse in the sandstone, and fossiliferous limestone concretions are abundant in the shale. From the few outcrops, Gill and Cobban (1973) collected marine fossils of middle and late Campanian age (fig. 7, zones 52–54).

The marine shale member conformably overlies nonmarine beds of the Parkman Sandstone Member and is disconformably overlain by the nonmarine Teapot Sandstone Member of the Mesaverde Formation (figs. 5, 6) in parts of Converse, Natrona, and Johnson Counties (Gill and Cobban, 1966a, b). It is replaced laterally by nonmarine and marine rocks of the Parkman in southern and western Natrona County, in northern Johnson County, and in Sheridan County. At outcrops, the shale member is about 55 m (180 ft) thick in south-central Johnson County and about 109 m (357 ft) thick in west-central Converse County. An isopach map by Headley (1958), derived from studies of borehole logs in northeastern Wyoming, shows that shale between the Parkman and Teapot Members thickens irregularly toward the southwest and south and ranges in thickness from less than 46 m (150 ft) in northern Campbell County to about 168 m (550 ft) in southeastern Converse County. Borehole logs indicate that the unnamed marine shale member in southwestern Campbell County is about 70 m (230 ft) thick (fig. 20).

Outcrops of the unnamed marine shale member in northeastern Natrona County and in west-central Converse County are composed of shale and fossiliferous concretions (J.R. Gill and W.A. Cobban, written commun., 1974; Gill and Burkholder, 1979). Bivalves and ammonites in the concretions are of late Campanian age (fig. 7, zones 52, 53). Some of these species were also collected from the member in Converse and Johnson Counties and from the lower part of the Bearpaw Shale in Big Horn County.

The marine shale member of the Mesaverde in Converse and Natrona Counties is laterally equivalent to the lower part of the lower unnamed shale member of the Pierre Shale in Niobrara County (fig. 24) (Gill and Cobban 1966a), to nonmarine and marine beds in the upper part of the Judith River and marine beds in the lower part of the Bearpaw Shale in Big Horn County (fig. 23) (Hose, 1955; Gill and Cobban, 1966a; Gill and Burkholder, 1979), and to a major hiatus in the stratigraphic record in northwestern Wyoming (fig. 4) (Gill and Cobban, 1973). Changes in the geographic locations of the strandlines during deposition of the marine shale member indicate a marine transgression followed by a marine regression (Gill and Cobban, 1973). Van Wagoner and others (1990) indicated that the member consists of a retrogradational parasequence set (transgressive systems tract) and overlying progradational parasequence set (highstand systems tract). The areal distribution of the strandlines, of lithofacies in the marine shale member, and of lithofacies and a hiatus in laterally equivalent strata are evidence of sources for late Campanian sediments in northwestern Wyoming. Siliciclastic sediments of the marine shale member probably accumulated on an inner shelf and in shoreface and delta-front environments. In west-central Converse County crossbedding in the upper part of the member indicates paleocurrent directions of S. 45°–60° W. Asquith's (1970) estimate of water depth for the marine shale member is 198 m (650 ft).

REGIONAL HIATUS FOR LATEST CAMPANIAN TIME

The disconformable contact of the marine shale member and the overlying Teapot Sandstone Member of the Mesaverde Formation was recognized by Gill and Cobban (1966b) at outcrops in the southwestern part of the Powder River Basin in Converse, Natrona, and Johnson Counties. Marine sandstone in the upper part of the shale member commonly is sharply overlain by nonmarine sandstone of the Teapot Member. This disconformity has been called a type-1 sequence boundary by Van Wagoner and others (1990). Molluscan fossils of late Campanian age in the shale member and of early Maastrichtian age in marine beds that overlie the Teapot provide sparse and local evidence of a period of erosion and nondeposition in the region during the latest Campanian (fig. 7, possibly zones 55–57). The almost complete sequence of Campanian and Maastrichtian index fossils in the lower unnamed shale member of the Pierre in Niobrara County is interrupted by a lack of fossils representing three consecutive late Campanian faunal zones (fig. 7, zones 56–58). If present in that area, fossils of the missing zones would be within a unit of shale about 2 m (6 ft) thick (Gill and Cobban, 1966a). Presumably, the hiatus at the base of the Teapot either extends throughout the southern part of the basin (Merewether and others, 1977c; Fox, 1993d) or is represented in the Pierre by a condensed section.

ROCKS OF LATEST CAMPANIAN AND MAASTRICHTIAN AGE

KARA BENTONITIC MEMBER AND UPPER UNNAMED SHALE MEMBER OF THE PIERRE SHALE AND AN UPPER PART OF THE BEARPAW SHALE

Robinson and others (1959) named the Kara Bentonitic Member (fig. 4) from an outcropping thin sequence of dark-gray shale, bentonitic shale, and yellowish-gray bentonite near the eastern margin of the Powder River Basin in northwestern Weston County. The Kara conformably overlies the lower unnamed shale member of the Pierre and is conformably overlain by the upper unnamed shale member of the Pierre. Outcrops of the Kara typically form a contrasting light-gray band of gumbo in the topography and are commonly devoid of vegetation. They can be recognized in Crook, Weston, and Niobrara Counties (fig. 25). The shale is noncalcareous but commonly encloses light-gray to dark-gray limestone concretions that contain marine molluscan fossils of earliest Maastrichtian age (fig. 7, zone 61). The member is about 30 m (100 ft) thick in west-central Crook County (Robinson and others, 1964) and northwestern Weston County and thins southward to about 11 m (36 ft) thick in northeastern Niobrara County (fig. 24) (Gill and Cobban, 1966a).

The upper unnamed shale member of the Pierre crops out at the eastern edge of the basin in southern Crook County and in Weston and Niobrara Counties, where it generally forms low hills and plains and is concealed by vegetation; concretions in the member locally form low ridges and buttes. This member is conformable with both the underlying Kara Bentonitic Member and the overlying Fox Hills Sandstone (fig. 4); it is composed of dark-gray, noncalcareous, silty or sandy shale enclosing dark-gray limestone concretions and includes several beds of yellowish-gray, bentonitic shale and bentonite (fig. 25) (Robinson and others, 1964; Gill and Cobban, 1966a). The upper unnamed member is about 43 m (140 ft) thick in southwestern Crook County (Robinson and others, 1964) and thickens southward to 171–207 m (562–680 ft) in eastern Niobrara County (fig. 24) (Gill and Cobban, 1966a). Molluscan fossils in the enclosed concretions are of marine origin and can be of early to middle Maastrichtian age (fig. 7, zones 61–64). Rocks of the same age at the northern end of the Black Hills in Carter County have been assigned to the uppermost Pierre and to the Fox Hills and are also conformable with the underlying and overlying beds.

Near the northwestern margin of the basin in Big Horn County beds of similar lithology and age in the upper part of the Bearpaw Shale are at least 14 m (46 ft) thick (figs. 4, 18, 23) according to W.A. Cobban (Richards, 1955; Knechtel and Patterson, 1956). These outcropping strata are composed mainly of dark-gray shale that contains brownish-gray, calcareous concretions. Some of the marine fossils in this sequence are of early Maastrichtian age (fig. 7, zone 63).

Marine bivalves and ammonites of early to middle Maastrichtian age (fig. 7, zones 61–64) have been collected from outcrops of the Kara Bentonitic Member and the upper unnamed member and from laterally equivalent strata near the eastern and northwestern margins of the basin (Richards, 1955; Robinson and others, 1964; Gill and Cobban, 1966a; W.A. Cobban, written commun., 1993). In northeastern Niobrara County, Gill and Cobban (1966a) found bryozoans encrusted on the living chambers of cephalopods in several parts of the upper member and a small solitary coral at one horizon. Mello (1971) recognized arenaceous foraminifera, smaller numbers of calcareous foraminifera, planktonic foraminifera, fragments of linguloid brachiopods, and seed or spore cases in samples of the upper unnamed shale member from Niobrara County.

Along the western flank of the Black Hills, shale and bentonite of the Kara Member and the upper unnamed member grade northward into the uppermost Pierre Shale and the Fox Hills Sandstone (Robinson and others, 1959). The Kara and the upper unnamed member, as well as shale in the upper part of the Bearpaw in Big Horn County, grade laterally into shale, siltstone, and sandstone of the Lewis Shale in the southwestern area of the Powder River Basin (fig. 4).

In sequence stratigraphy (Van Wagoner and others, 1990), the Kara Bentonitic Member and the upper unnamed shale member consist mainly of a progradational parasequence set (part of a highstand systems tract). Regional maps of strandlines in early Maastrichtian time (fig. 7, zones 61–64) reflect the progradation of a northeast-trending delta in the northern part of the basin (Gill and Cobban, 1973). Gill and Cobban (1966a) suggested that the Kara and the upper unnamed members of the Pierre were deposited near the delta and in water less than 61 m (200 ft) deep.

TEAPOT SANDSTONE MEMBER OF THE MESAVERDE FORMATION

Barnett (1915) named the Teapot Sandstone Member from the outcrops "of gray and buff sandstone, including some carbonaceous shale" near Teapot Rock in northeastern Natrona County. Wegemann (1918) assigned the Teapot Member of the type area to the Mesaverde Formation. The member is recognized at outcrops, which commonly form a conspicuous pine-covered, very light gray ridge, and in the subsurface in Campbell, Converse, Johnson, Natrona, and Sheridan Counties (Rich, 1962; Merewether and others, 1977a, b, c; Gill and Burkholder, 1979; Fox, 1993c, d).

At outcrops in Johnson and Natrona Counties (fig. 21), the Teapot is composed mostly of light-gray to light-brownish-gray, carbonaceous, very fine grained to medium-grained sandstone that locally contains shale pebbles, brownish-gray, carbonaceous, silty and sandy shale, and impure coal (Curry, 1976a; Gill and Burkholder, 1979). The sandstone can be even laminated, ripple laminated, crosslaminated, or flaser bedded; it commonly fills channels and comprises units as thick as 7 m (24 ft). Units of carbonaceous shale in the member are lenticular and are as thick as 2 m (7 ft). An underlying marine sandstone in the area, which is included in the Teapot by Curry (1976a, b), contains the trace fossil *Ophiomorpha*. Outcrops of the lower part of the member in west-central Converse County also contain *Ophiomorpha*. Isbell and others (1976) recognized *Ophiomorpha* in cores of the Teapot from eastern Converse County. These cores include "very feldspathic sandstone to litharenite (subgraywacke)" that is very fine grained to fine-grained, clayey, and slightly calcareous (Isbell and others, 1976). Part of the core has low-angle cross-stratification.

The nonmarine and marine beds that comprise the Teapot Sandstone Member disconformably overlie, according to Gill and Cobban (1966a, b), either the unnamed marine shale member or nonmarine beds of the Parkman Member of the Mesaverde and are conformably overlain by marine rocks of the Lewis Shale. At outcrops near the western margin of the basin the Teapot is commonly 19 to 50 m (62–165 ft) thick (Rich, 1962; Gill and Burkholder, 1979). In the subsurface, the sandstone in the lower part of the Teapot and the sandstone in the upper part of the underlying member are not easily distinguished; consequently, thicknesses of the Teapot from borehole logs and from outcrops might not be comparable. In the subsurface the Teapot thickens mostly southwestward, from less than 18 m (60 ft) in northeastern Campbell County to more than 61 m (200 ft) in a north-northwest-trending area in Converse, Campbell, Johnson, and Sheridan Counties (Fox and Higley, 1987g).

Outcropping nonmarine strata of the Teapot in Natrona and Johnson Counties enclose the fossilized remains of plants, including root casts, coalified wood, and leaf impressions (Curry, 1976a; Gill and Burkholder, 1979). Molluscan fossils of late Campanian age (fig. 7, zone 54) were collected from marine rocks that underlie the Teapot in Converse County, and younger fossils of late Campanian age (fig. 7, zone 59) were found in marine rocks that overlie the Teapot in Natrona and Johnson Counties (Gill and Burkholder, 1979). From this and other paleontological data (Gill and Cobban, 1973), the age of the member probably is late Campanian.

Nonmarine rocks of the Teapot Member on the western flank of the Powder River Basin apparently grade eastward into marine sandstone in the middle of the basin and into the marine, lower unnamed shale member of the Pierre near the eastern edge of the basin (figs. 5, 6). Beds of the same age near the northwestern margin of the basin are within the marine Bearpaw Shale (fig. 19) and consist mostly of dark-gray shale that contains fossiliferous, calcareous concretions (Richards, 1955; Knechtel and Patterson, 1956). The Teapot is also recognized in northwestern Wyoming (Gill and Cobban, 1973).

Gill and Cobban (1966b, 1973) proposed that the Teapot is a postorogenic deposit "derived from strongly uplifted areas in western Wyoming or eastern Idaho" and that it accumulated during a marine regression. Isbell and others (1976) concluded that the Teapot in the southern part of the basin accumulated as a high-destructive delta and associated strand plain "during an eastward progradation of the shoreline." In the context of sequence stratigraphy, Van Wagoner and others (1990) determined that the Teapot Member is a progradational parasequence set (lowstand systems tract). At outcrops in northeastern Natrona County, a few ripple marks indicate paleocurrent directions of about N. 15° E. The average paleocurrent direction determined from several sandstone-filled channels in east-central Natrona County is about S. 70° E. Ripple marks in nonmarine beds near the top of the Teapot in west-central Converse County indicate an average paleocurrent direction of N. 44° E. Curry (1976b) proposed that the member in the southern part of the basin was deposited in environments of a delta plain, delta front, delta bar, and delta slope. The disconformity at the base of the outcropping fluvial Teapot on the west side of the basin (Gill and Cobban, 1966b, 1973) possibly corresponds to the depositional break at the top of the marine sandstone assigned to the Teapot in the subsurface of Converse County (Isbell and others, 1976).

LEWIS SHALE

Cross (1899) named the Lewis Shale from outcrops in southwestern Colorado, and Wegemann (1918) applied the name to marine rocks overlying the Mesaverde Formation and underlying the Lance Formation in northeastern Natrona County, Wyoming. The Lewis crops out near the western margin of the Powder River Basin in Converse, Natrona, Johnson, and Sheridan Counties (Rich, 1962; Gill and Cobban, 1966a; Merewether and others, 1977c; Gill and Burkholder, 1979) and has been recognized in the subsurface of the basin (figs. 20, 26) (Fox, 1993c, d). In boreholes in southeastern Campbell County and adjoining areas, a middle part of the Lewis Shale is composed of two units of sandstone and an intervening unit of bentonitic shale that together were named the "Teckla Sand Member" by Runge and others (1973). Outcrops of the Lewis are composed mostly of medium-gray to dark-greenish-gray mudstone, sandy shale, and siltstone, which contain sparse limestone and sandstone concretions, and light-gray to brownish-gray, very fine grained to medium-grained sandstone that is thin- to medium-bedded or crossbedded and commonly contains sandstone concretions (Gill and Burkholder, 1979). Some of the thick units of sandstone contain *Ophiomorpha*. An outcropping thick sandstone in west-central Converse County contains tabular-planar crossbedding in the lower part, horizontal stratification in the middle, and bioturbation at the top. The formation in southeastern Natrona County (fig. 21) and south-central Johnson County also contains beds of carbonaceous shale, coal, and bentonite. Many beds in the Lewis contain marine macrofossils of early and middle Maastrichtian age.

The Lewis Shale conformably overlies the Mesaverde Formation and is conformably overlain by and grades into the Fox Hills Sandstone. At outcrops the Lewis ranges in thickness from about 45 m (147 ft) in northwestern Sheridan County to 400 m (1,311 ft) in northeastern Natrona County (Gill and Burkholder, 1979). An isopach map of the Lewis Shale by Fox and Higley (1987h) shows that the Lewis thickens southward from less than 61 m (200 ft) on the northwestern flank of the basin to more than 457 m (1,500 ft) at the southern end of the basin.

Isopach maps by Crews and others (1976) show a "lower Lewis" that thins mostly southwestward from more than 61 m (200 ft) to less than 30 m (100 ft) and a "Teckla" (upper part of the Lewis) that thickens southward from less than 30 m (100 ft) in the northern part of the basin to about 244 m (800 ft) at the southern end of the basin. The Teckla Sand Member of Runge and others (1973) apparently is an elongate body of mainly sandstone that is about 34 m (112 ft) thick in boreholes in southeastern Campbell County and that trends northwestward in the subsurface of Converse and Campbell Counties.

Molluscan fossils (mostly bivalves and ammonites) of marine origin are common in the Lewis. Ammonites from outcrops in southwestern Converse, northeastern Natrona, and southern Johnson Counties range in age from late Campanian to early Maastrichtian (fig. 7, zones 59–64) (Gill and Burkholder, 1979). Where the formation is thinner, in western Natrona, northern Johnson, and Sheridan Counties, the ammonites represent zones 60 and 61 (fig. 7) of the Maastrichtian. The Teckla Sandstone Member of the Lewis (Runge and others, 1973) probably is early Maastrichtian (fig. 7, zone 61 and possibly zone 62).

The Lewis Shale grades eastward into an upper part of the Pierre Shale near the eastern edge of the Powder River Basin, into the lower unnamed shale member, the Kara Bentonitic Member, and the upper unnamed shale member (figs. 4–6). To the west in the Wind River and Bighorn Basins the Lewis interval is represented mainly by nonmarine beds of the Meeteetse and Lance Formations (Gill and Cobban, 1973). Marine beds in the upper part of the Lewis in the southwestern part of the Powder River Basin grade northward into the overlying marine Fox Hills Sandstone and the overlying nonmarine Lance Formation of northern Johnson and Sheridan Counties.

Marine strata in the lower part of the Lewis, which conformably overlie nonmarine beds of the Teapot Sandstone Member, were deposited on a shelf during a marine transgression and subsequent marine regression. The overlying marine and nonmarine rocks in the Lewis, including the Teckla Sandstone Member and laterally equivalent strata to the west, accumulated in nearshore and deltaic environments during the regression. In western Converse, eastern Natrona, and southeastern Johnson Counties, where the outcropping Lewis is thickest, marine beds in the upper part of the formation probably reflect deposition on a shelf and indicate another marine transgression and following marine regression. The locations of early Maastrichtian

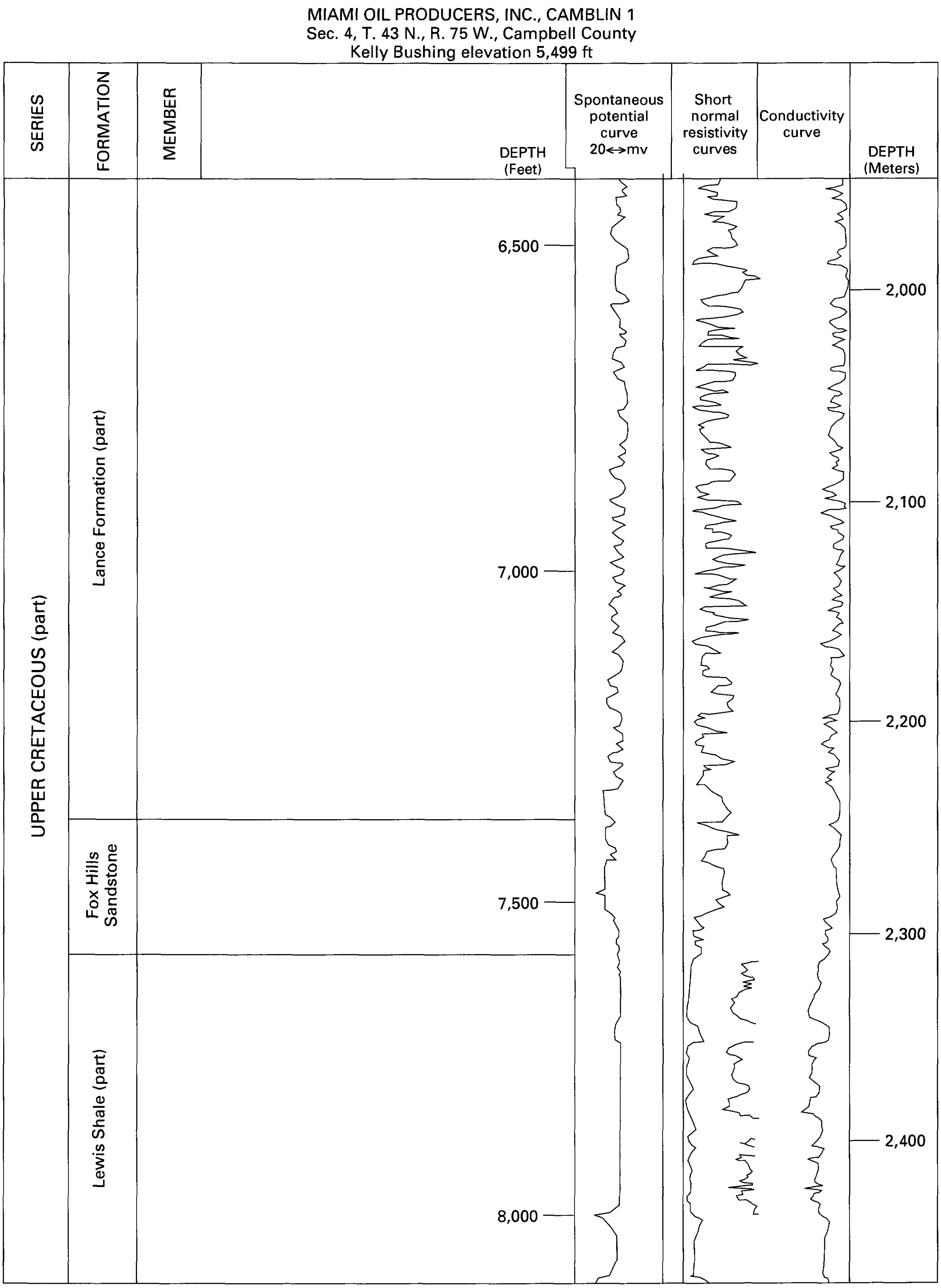


Figure 26. Geophysical logs of Upper Cretaceous strata including upper part of the Lewis Shale, the Fox Hills Sandstone, and lower part of the Lance Formation, Campbell County, Wyoming.

strandlines in the region of the Powder River Basin, as depicted by Gill and Cobban (1973), indicate only a transgression, a following regression, and the development of the northeast-trending, prograding Sheridan delta in the northern part of the basin.

In the sequence stratigraphy of Van Wagoner and others (1990), the Lewis is composed of, in ascending order, a retrogradational parasequence set (transgressive systems tract) and aggradational and progradational parasequence sets (part of the highstand systems tract). In the upper part of the Lewis in west-central Converse County, tabular-planar crossbeds in a thick marine sandstone indicate paleocurrent directions of from S. 10° E. to S. 70° W. and an average direction of S. 40° W. Runge and others (1973) concluded that their Teckla Member and associated rocks in the southern part of the basin represent northwest-trending strand plains and contiguous delta plains to the southwest.

FOX HILLS SANDSTONE

Meek and Hayden (1862) named an outcropping sequence of sandstone and siltstone in central South Dakota the "Fox Hills beds." Darton and O'Harra (1907) applied the name Fox Hills Sandstone to outcropping sandstone along the west side of the Black Hills. This formation presently is recognized throughout the Powder River Basin except for a northwestern part of the basin in Big Horn and Rosebud Counties. Outcrops of the Fox Hills either have no appreciable topographic expression or form low hills and ridges.

Near the Black Hills and the eastern edge of the basin, the lower part of the formation consists of interbedded, gray sandy shale and siltstone and gray to brownish-gray, fine-grained, thin-bedded and crossbedded sandstone (Robinson and others, 1964). The sandstone contains scattered ferruginous and calcareous sandstone concretions. In that area, the upper part of the Fox Hills is composed of very light gray, fine- to medium-grained sandstone that commonly is massive. In central Niobrara County the formation consists of, from oldest to youngest, a massive, yellowish-gray sandstone that contains brownish-gray sandstone concretions, a unit of sandy shale and thin-bedded sandstone, and an upper unit of very light gray to yellowish-gray, massive sandstone (Gill and Cobban, 1966a) (fig. 25).

On the western side of the basin in Natrona and Johnson Counties (fig. 21) the formation comprises very light gray to yellowish-gray to moderate-olive-brown, very fine grained to medium-grained sandstone, light- to medium-gray siltstone, and minor medium-gray shale and dark-gray-brown carbonaceous shale (Gill and Burkholder, 1979). Much of the sandstone encloses sandy or calcareous concretions. In most of the basin the Fox Hills is conformable and gradational with marine shale and siltstone of the underlying Pierre Shale or Lewis Shale and conformable with overlying nonmarine beds of the Lance or Hell Creek Formations. Molluscan fossils in the Fox Hills represent nearshore-marine environments of early and early late Maastrichtian age.

At outcrops in the Powder River Basin the thickness of the Fox Hills Sandstone increases irregularly southeastward from a feather edge in Big Horn County, to 12–20 m (38–67 ft) in Sheridan and Johnson Counties, to 91–122 m (300–400 ft) in Niobrara County (Stanton, 1910; Dobbin and Reeside, 1929; Dorf, 1942) and Converse County. Nevertheless, the Fox Hills in Natrona County is 10–64 m (32–210 ft) thick (Merewether and others, 1977a, b; Gill and Burkholder, 1979).

The sparse fossils in the Fox Hills Sandstone of the basin are marine and mainly mollusks (bivalves and ammonites) and the bones and scales of fish. Breithaupt (1985) reported, however, that the formation also contains reptilian remains, including crocodiles, at scattered locations in Wyoming. Mollusks from the Fox Hills and underlying formations indicate that the Fox Hills in the basin is of early to early late Maastrichtian age (fig. 4). Fossiliferous beds near the base of the Fox Hills become younger toward the south. Fossils in the west-central part of the basin in northern Johnson County represent zone 61 (fig. 7) (W.A. Cobban, oral commun., 1963), whereas those in the northeastern part of the basin in Carter and Crook Counties probably represent zone 62 (Robinson and others, 1964; Gill and Cobban,1966a) and those in southeastern and southern parts of the basin in Weston and Converse Counties represent zone 64. Age also decreases eastward from west-central Natrona County (zone 61) to west-central Converse County (zone 64) to northeastern Niobrara County (zone 65).

The Fox Hills Sandstone of the Powder River Basin was deposited in nearshore marine and deltaic environments that succeeded offshore-marine environments of the underlying Pierre and Lewis Shales and were followed by nonmarine environments of the overlying Lance and Hell Creek Formations. This widespread transitional sequence of mostly sandstone is the youngest marine unit in the basin, and it records the final withdrawal of the Cretaceous epeiric sea from the Western Interior. Strandlines in the region of Wyoming, Montana, and adjacent areas during early and late Maastrichtian time (Gill and Cobban, 1973) indicate that the Fox Hills in the basin was deposited in several shallow-water environments along the southeastern margin of the major, generally northeast prograding Sheridan delta. In sequence stratigraphy (Van Wagoner and others, 1990), the Fox Hills is a progradational parasequence set and part of a highstand systems tract. Sparse paleocurrent directions from outcropping crossbedded sandstone in west-central Converse County are N. 10°– 40° E.

LANCE AND HELL CREEK FORMATIONS

Hatcher (1903) proposed the name "Lance Creek beds" for outcropping siliciclastic strata of continental origin near Lance Creek in Converse County. Wegemann (1918) used the name Lance Formation in northeastern Natrona County. The Hell Creek Formation was originally named by Brown (1907) from outcrops of nonmarine beds in northeastern Montana. These two formations differ only in their geographic extent; the Lance is recognized in Wyoming, and the Hell Creek is recognized in Montana.

On the western flank of the Black Hills, the Lance rarely crops out, and it commonly forms lowlands that have little topographic relief. It consists mostly of interstratified light-gray to yellowish-gray sandstone, medium to dark-gray sandy shale and claystone, and brownish-gray carbonaceous shale (Robinson and others, 1964). Units of sandstone are fine- to medium-grained, friable, very thin bedded to very thick bedded, and crossbedded and contain large calcareous sandstone concretions. Along the western edge of the Powder River Basin in northeastern Natrona County and southern Johnson County scattered outcrops of the Lance are composed mainly of light-gray to dusky yellow, fine- or medium-grained sandstone that contains calcareous sandstone concretions, dark-brown carbonaceous shale, and grayish-black to black coaly shale and coal (Gill and Burkholder, 1979). Some of the outcropping sandstone forms massive units as thick as 24 m (80 ft), and some fills paleochannels and forms lenticular crossbedded bodies 3–5 m (10–15 ft) thick. The shale is generally in units less than 4 m (13 ft) thick.

From studies of the Lance at outcrops and in boreholes in the basin, Connor (1992) determined that the formation consists of about 30 percent sandstone, which forms lenticular channel-filling bodies at least 6 m (20 ft) thick, and about 70 percent thinner sandstone units and finer grained interfluve beds. Connor also found that these lenticular bodies are either isolated or stacked in sequences as thick as 90 m (300 ft). The channel-filling sandstone commonly becomes finer grained upward, from coarse- or medium-grained to very fine grained; laterally, the channel-filling sandstone is coarser grained at the western edge of the basin. Bedforms in the channel-filling sandstone commonly include, in ascending order, large-scale crossbeds, contorted strata or a structureless interval, parallel laminations, and current ripples (Connor, 1992).

In the Powder River Basin, the nonmarine Lance and Hell Creek Formations conformably overlie and intertongue with the marine Fox Hills Sandstone and are conformably overlain by the nonmarine Tertiary Fort Union Formation. Locating the contact of the Lance or Hell Creek and the overlying Fort Union at outcrops and on borehole logs is difficult; consequently, the thicknesses of the Lance or Hell Creek reported by different authors may not be comparable.

The thickness of the Lance and Hell Creek ranges from about 152 m (500 ft) in southern Powder River County (Robinson and others, 1964) and 183–198 m (600–650 ft) in Big Horn County (Thom and others, 1935), to about 488 m (1,600 ft) in northern Weston County, to about 1,829 m (6,000 ft) in northwestern Natrona County (Keefer, 1965), and to 535 m (1,755 ft) in southern Natrona County (Rich, 1962). Borehole logs of the Fox Hills and Lance indicate that the thickness of the two formations ranges from less than 213 m (700 ft) at the northern end of the basin to more than 1,006 m (3,300 ft) at the southern end of the basin (Connor, 1992).

Fossils collected from outcrops of the Lance and Hell Creek near the perimeter of the basin include the remains of plants and freshwater mollusks, and the bones of dinosaurs (*Trachodon* and *Triceratops*) and turtles (Wegemann, 1912; Thom and others, 1935; Robinson and others, 1964). The formations in the basin are of Maastrichtian age, although the basal strata apparently vary in age from early to late Maastrichtian. According to Breithaupt (1985), the Lance at scattered locations in Wyoming contains a variety of fossil fish, amphibians, reptiles, and birds.

The Lance and Hell Creek are coeval formations that were deposited mainly in fluvial environments during the final regression of the Cretaceous epeiric sea. Beds in the lowest parts of the formations vary in age, although the tops of the formations apparently are everywhere synchronous. In the region of the Powder River Basin the basal strata are progressively younger toward the east and south (McGookey and others, 1972; Gill and Cobban, 1973).

Paleocurrent directions determined from all parts of the formations are generally eastward and indicate a regional paleoslope (Connor, 1992). Seeland (1988) suggested that a Maastrichtian trunk stream in an area now in the northern part of the Black Hills flowed southeastward to the seaway. Sediments of the Fox Hills and Lance–Hell Creek in the northern part of the basin were derived from western Montana, those in the central part of the basin were transported eastward from southwestern Montana and northwestern Wyoming, and those in the southern part of the basin were derived from uplifts in western and central Wyoming (Connor, 1992). In terms of sequence stratigraphy (Van Wagoner and others, 1990), the Lance–Hell Creek consists of a progradational parasequence set and is part of a highstand systems tract. The combined Fox Hills and Lance increases in thickness southward in the basin.

SEDIMENTATION RATES AND EUSTATIC EVENTS DURING THE LATE CRETACEOUS

In the region of the Powder River Basin about 98.5–97.2 Ma, sediments of the Mowry Shale were deposited at rates ranging from 7.9 cm (3.1 in.)/1,000 years in Niobrara County to as much as 17.8 cm (7.0 in.)/1,000 years in Big Horn County (table 5) during a major transgression and subsequent intermittent regressions and transgressions (represented by retrogradational, aggradational, and progradational parasequences) (Byers and Larson, 1979; Davis and Byers, 1989; Van Wagoner and others, 1990). According to Haq and others (1987), sea level throughout the world was generally rising during the period 99–97 Ma, although it fell and rose abruptly about 98–97.5 (short-term eustatic events) (fig. 27). Haq and others showed a major, condensed section at about 98.4 Ma, an abrupt fall of sea level at about 98 Ma that corresponds to a major, type-1 sequence boundary, and a medium, condensed section at 97 Ma. According to Van Wagoner and others (1990), a condensed section suggests "depositional starvation" and "rapidly rising sea level."

About 97.2–93.7 Ma in Big Horn County in the northwestern part of the basin, sediments of the Belle Fourche Formation were deposited in marine environments at a rate of 7.7 cm (3.0 in.)/1,000 years. About 97.2–94.8 Ma in Niobrara County in the southeastern part of the basin, the Belle Fourche Shale was accumulating in open-marine environments at a rate of 8.7 cm (3.4 in.)/1,000 years. In Natrona County in the southwestern part of the basin, perhaps about 97.2–94.3 Ma, the Belle Fourche Member of the Frontier Formation was deposited mainly in marine environments of the inner shelf at a rate of 12.1 cm (4.8 in.)/1,000 years. Sandstone, siltstone, and shale in the southwestern part of the basin represent marine regressions and transgressions, some of which may correspond to the short-term eustatic events (third-order sequence cycles) proposed by Haq and others (1987). Haq and others depicted a medium, condensed section at 97.0 Ma, a minor, type-2 sequence boundary at 96.5 Ma, a medium, condensed section at 95.75 Ma, a medium, type-2 sequence boundary at 95.5 Ma, a major, condensed section at 94.7 Ma, and a major, type-1 sequence boundary at 94 Ma.

The Greenhorn Formation and coeval beds in the region were deposited about 94.4–92.3 Ma, and the calcareous facies accumulated possibly on the lower part of a submarine slope and in the adjoining basin (Weimer, 1984; Weimer and Flexer, 1985). Component sediments of the Greenhorn were deposited at rates of 3.2–6.5 cm (1.2–2.5 in.)/1,000 years (table 5) during the latter part of a major transgression and the early part of a following regression. The transgression and regression correspond generally to the major eustatic rise and subsequent major

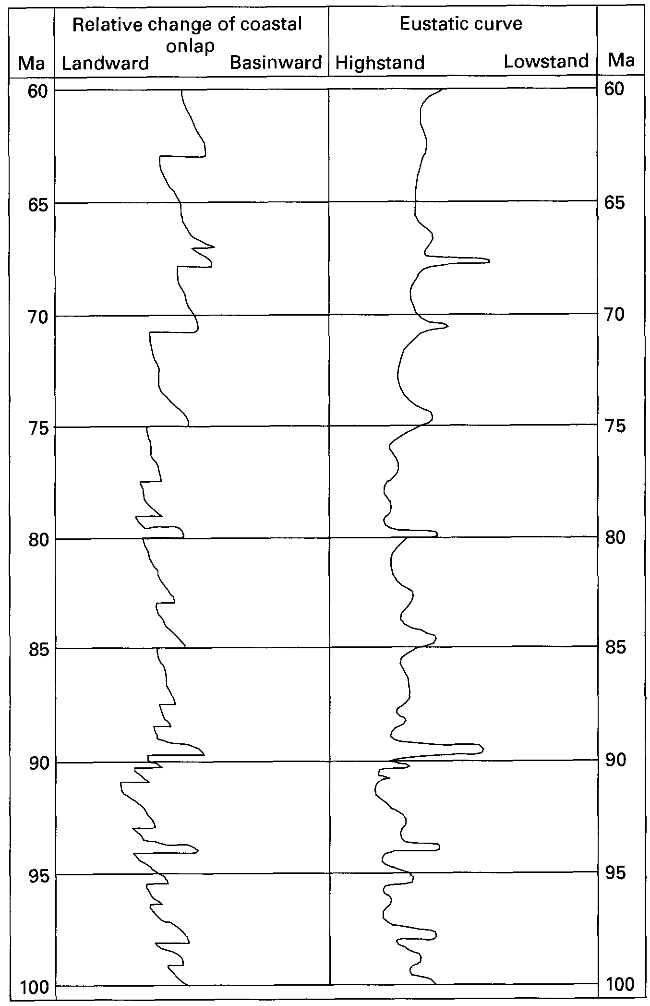


Figure 27. Graphic indices of global changes in sea level by B.U. Haq, J. Hardenbol, P.R. Vail, J.P. Colin, N. Ioannides, L.E. Stover, R. Jan Du Chene, R.C. Wright, J.F. Sarg, and B.E. Morgan (written commun., 1989).

eustatic fall (fig. 27) recognized by Hancock (1975), Hancock and Kauffman (1979), and Haq and others (1987). The interval from 94.8 to 92.3 Ma includes, according to Haq and others, about two third-order sequence cycles, as well as a major, condensed section at 94.7 Ma, a major, type-1 sequence boundary at 94 Ma, a medium, condensed section at 93.5 Ma, and a minor, type-2 sequence boundary at 93.0 Ma.

The upper part of the Belle Fourche Member of the Frontier Formation in southern Johnson County (Merewether and others, 1976) is the same age as lower and middle parts of the Greenhorn in northeastern Niobrara County: It consists of marine shale, siltstone, and sandstone that were deposited on a shelf and indicate a transgression interrupted by a regression. A body of sand now included in the member prograded seaward during a eustatic rise, perhaps as a consequence of tectonism and erosion west of

Table 5. Approximate rates of accumulation and erosion for stratigraphic units of Late Cretaceous age in areas of the Powder River Basin, Montana and Wyoming.
[Corrected depositional rate in centimeters (inches) per 1,000 years]

Formation (Member: Bed)	Area	Corrected depositional rate	Reference
Hell Creek	North Big Horn County	8.1 (3.2)	
Lance	Northwest Crook County	9.1 (3.6)	
Lance	South Johnson County	18.0 (7.1)	
Lance	Northeast Niobrara County	30.7 (12.1)	
Lance	Southeast Natrona County	21.4 (8.4)	
Lance and Fox Hills Sandstone	Northern Powder River Basin	4 (1.6)	Connor (1992)
Lance and Fox Hills Sandstone	Southern Powder River Basin	17 (6.7)	Connor (1992)
Fox Hills Sandstone	Northern Powder River Basin	<6.1 (<2.4)	Gill and Cobban (1973)
Fox Hills Sandstone	North Big Horn County	3.0 (1.2)	
Fox Hills Sandstone	Northwest Crook County	15.5 (6.1)	
Fox Hills Sandstone	South Johnson County	6.6 (2.6)	
Fox Hills Sandstone	Northeast Niobrara County	22.3 (8.8)	
Fox Hills Sandstone	Southeast Natrona County	7.3 (2.9)	
Lewis Shale	South Johnson County	21.0 (8.3)	
Lewis Shale	Southeast Natrona County	15.8 (6.2)	
Mesaverde (Teapot Sandstone)	South Johnson County	4.3 (1.7)	
Mesaverde (Teapot Sandstone)	Southeast Natrona County	2.5 (1.0)	
Pierre Shale (upper unnamed shale)	Northwest Crook County	6.5 (2.6)	
Pierre Shale (upper unnamed shale)	Northeast Niobrara County	12.0–21.4 (4.7–8.4)	
Mesaverde (unnamed marine shale)	South Johnson County	20.8 (8.2)	
Bearpaw Shale	North Big Horn County	7.6 (3.0)	
Pierre Shale (lower unnamed shale)	Northwest Crook County	6.3 (2.5)	
Pierre Shale (lower unnamed shale)	Northeast Niobrara County	10.2 (4.0)	
Judith River	North Big Horn County	7.8 (3.1)	
Mesaverde (Parkman Sandstone)	South Johnson County	11.7 (4.6)	
Mesaverde (Parkman Sandstone)	Southeast Natrona County	12.3 (4.9)	
Pierre Shale (Red Bird Silty)	Northwest Crook County	6.8 (2.7)	
Pierre Shale (Red Bird Silty)	Northeast Niobrara County	20.2 (7.9)	
Cody Shale (upper part of Steele)	South Johnson County	13.3 (5.3)	
Cody Shale (upper part of Steele)	Southeast Natrona County	17.0 (6.7)	
Pierre Shale (Mitten)	Northwest Crook County	3.9 (1.5)	
Pierre Shale (Mitten)	Northeast Niobrara County	26.8 (10.6)	
Cody Shale (Claggett)	North Big Horn County	7.8 (3.1)	
Pierre Shale (Sharon Springs)	Northeast Niobrara County	13.5 (5.3)	
Cody Shale (Steele: Shannon, Sussex, and intervening beds)	South Johnson County	50.2 (19.8)	
Cody Shale (Steele: Shannon, Sussex, and intervening beds)	Southeast Natrona County	148.4 (58.4)	
Pierre Shale (Gammon)	Northwest Crook County	13.3 (5.2)	
Pierre Shale (Gammon)	Northeast Niobrara County	1.7 (0.7)	
Cody Shale (lower part of Steele)	South Johnson County	44.2 (17.4)	
Cody Shale (lower part of Steele)	Southeast Natrona County	35.4 (13.9)	
Cody Shale (Gammon)	North Big Horn County	11.9 (4.7)	
Cody Shale (Niobrara)	North Big Horn County	8.1 (3.2)	
Cody Shale (Niobrara)	South Johnson County	5.0 (2.0)	
Cody Shale (Niobrara)	Southeast Natrona County	4.9 (1.9)	
Niobrara	Eastern Powder River Basin	1.7 (0.7)	Weimer and Flexer (1985)
Niobrara	Northwest Crook County	1.6 (0.6)	
Niobrara	Northeast Niobrara County	2.5 (1.0)	
Cody Shale (Sage Breaks)	South Johnson County	13.6 (5.4)	
Cody Shale (Sage Breaks)	Southeast Natrona County	26.4 (10.4)	
Carlile Shale (Sage Breaks)	Eastern Powder River Basin	4.5 (1.8)	Weimer and Flexer (1985)
Carlile Shale (Sage Breaks)	Northwest Crook County	4.9 (1.9)	
Carlile Shale (Sage Breaks)	Northeast Niobrara County	10.2 (4.0)	
Cody Shale (Carlile)	North Big Horn County	4.2 (1.6)	
Frontier (Wall Creek)	South Johnson County	8.1 (3.2)	
Frontier (Wall Creek)	Southeast Natrona County	16.0 (6.3)	

Table 5. Approximate rates of accumulation and erosion for stratigraphic units of Late Cretaceous age in areas of the Powder River Basin, Montana and Wyoming—Continued.
[Corrected depositional rate in centimeters (inches) per 1,000 years]

Formation (Member: Bed)	Area	Corrected depositional rate	Reference
Carlile Shale (Turner Sandy)	Eastern Powder River Basin	10 (3.9)	Weimer and Flexer (1985)
Carlile Shale (Turner Sandy)	Northwest Crook County	10.5 (4.1)	
Carlile Shale (Turner Sandy)	Northeast Niobrara County	22.8 (9.0)	
Frontier (Emigrant Gap)	Southeast Natrona County	4.0 (1.6)	
Carlile Shale (Pool Creek)	Eastern Powder River Basin	4.5 (1.8)	Weimer and Flexer (1985)
Carlile Shale (Pool Creek)	Northwest Crook County	2.1 (0.8)	
Carlile Shale (Pool Creek)	Northeast Niobrara County	3.7 (1.5)	
Frontier (Belle Fourche)	South Johnson County	8.1 (3.2)	
Frontier (Belle Fourche)	Southeast Natrona County	12.1 (4.8)	
Greenhorn	Eastern Powder River Basin	3.5 (1.4)	Weimer and Flexer (1985)
Greenhorn	North Big Horn County	4.8 (1.9)	
Greenhorn	Northwest Crook County	3.2 (1.2)	
Greenhorn	Northeast Niobrara County	6.5 (2.5)	
Belle Fourche	North Big Horn County	7.7 (3.0)	
Belle Fourche Shale	Eastern Powder River Basin	4.5 (1.8)	Weimer and Flexer (1985)
Belle Fourche Shale	Northwest Crook County	6.7 (2.6)	
Belle Fourche Shale	Northeast Niobrara County	8.7 (3.4)	
Mowry Shale	Southeastern Wyoming	1–1.5 (0.4–0.6)	Davis and others (1989)
Mowry Shale	North Big Horn County	17.8 (7.0)	
Mowry Shale	Northwest Crook County	9.8 (3.8)	
Mowry Shale	South Johnson County	13.6 (5.4)	
Mowry Shale	Northeast Niobrara County	7.9 (3.1)	
Mowry Shale	Southeast Natrona County	10.8 (4.2)	

the region. The hiatus at the disconformable contact of the Belle Fourche Member and the overlying Emigrant Gap Member in southern Natrona County represents an upper part of the Greenhorn, which was deposited during the culmination of a major transgression. This disconformity can be recognized throughout central Wyoming and apparently was caused by a widespread uplift in early to early middle Turonian time (Merewether and Cobban, 1986a).

The Pool Creek Member of the Carlile Shale was deposited about 92.3–90.5 Ma on the outer shelf and slope at depositional rates of 2.1–3.7 cm (0.8–1.5 in.)/1,000 years. This progradational sequence rests conformably on the Greenhorn. According to Haq and others (1987), there is a minor condensed section at 90.25 Ma.

The Pool Creek is almost coeval with the Emigrant Gap Member of the Frontier Formation, which accumulated in the southwestern part of the region at a rate of perhaps 4.0 cm (1.6 in.)/1,000 years. The disconformity at the top of the Belle Fourche Member, the marine sandstone and shale in the Emigrant Gap Member, and the disconformity at the top of the Emigrant Gap Member record a local marine regression, a subsequent marine transgression, and a following marine regression. The local transgression was simultaneous with the widespread regression represented by the uppermost Greenhorn and the lower part of the overlying Pool Creek, and it was caused probably by downfaulting in a west-trending area in central Wyoming (Merewether and Cobban, 1986b).

Overlying the Pool Creek, in ascending order, are the Turner Sandy Member and the Sage Breaks Member of the Carlile, which were deposited at some time between 90.5 and 88.5 Ma. Haq and others (1987) depicted third-order sequence cycles at 90.5–90 Ma and 90–88.5 Ma, a minor, type-2 sequence boundary at 90.5 Ma, a minor, condensed section at 90.25, a major, type-1 sequence boundary at 90 Ma, a minor, condensed section at 89 Ma, and a minor, type-2 sequence boundary at 88.5 Ma.

In the eastern part of the region the Turner Sandy Member accumulated on a shelf at rates of about 10.5–22.8 cm (4.1–9.0 in.)/1,000 years (table 5). Laterally equivalent strata in the Wall Creek Member of the Frontier Formation in Johnson and Natrona Counties were deposited at rates of 8.1–16.0 cm (3.2–6.3 in.)/1,000 years. The Sage Breaks in the eastern part of the region was deposited on a shelf and slope at rates of 4.9–10.2 cm (1.9–4.0 in.)/1,000 years. Laterally equivalent beds in the Sage Breaks Member of the Cody Shale in Johnson County accumulated at a rate of 13.6 cm (5.4 in.)/1,000 years. The Carlile Member of the Cody Shale in the northwestern part of the Powder River Basin, which is about the same age as the Carlile on the southeastern flank of the basin but apparently does not include a major disconformity, was deposited at a rate of 4.2 cm (1.6 in.)/1,000 years. The Turner and Sage Breaks Members of the Carlile, as well as the Wall Creek Member of the Frontier and the Sage

Breaks Member of the Cody, indicate an episodic marine transgression in northeastern and central Wyoming about 90.5–88.5 Ma that was caused partly by a eustatic rise (Haq and others, 1987).

The Niobrara is apparently conformable with the underlying Carlile in the northern part of the basin but is disconformable with the Carlile in the southern part of the basin. Truncation of the Carlile in an irregular northwest-trending area (fig. 28) in the southern part of the basin might have been caused by powerful submarine currents or by an uplift in middle to late Coniacian time (Weimer and Flexer, 1985). Slack (1981) concluded, however, that the location of oil-bearing tidal-channel filling sandstone in the Turner was controlled by small displacements along northeast-trending lineaments on the southeastern flank of the Sheridan–Belle Fourche arch (fig. 28).

The Niobrara Formation in the southeastern part of the region accumulated in a depositional basin about 87.8–82.3 Ma at a rate of 2.5 cm (1.0 in.)/1,000 years. Comparable strata in the northwestern part of the region were deposited about 88.4–85.6 Ma at a rate of 8.1 cm (3.2 in.)/1,000 years. The Niobrara Member of the Cody Shale in the southwestern part of the region was deposited about 88.3–82.8 Ma at a rate of 4.9 cm (1.9 in.)/1,000 years. These strata may represent the culmination of a major transgression and the beginning of a subsequent regression.

Haq and others (1987) depicted, however, a minor, type-2 sequence boundary at 87.5 Ma, a medium, condensed section at 86 Ma, a medium, type-1 sequence boundary at 85 Ma, a major, condensed section at 83.75 Ma, and a minor, type-2 sequence boundary at 83 Ma (fig. 27). Differences between these records may be the result partly of contrasting values on the two time scales and partly of contemporaneous tectonism in the Western Interior.

The Gammon Member of the Pierre Shale near the southeastern margin of the Powder River Basin was deposited about 82.3–81.3 Ma on an outer shelf, slope, and basin at a sedimentation rate possibly as low as 1.7 cm (0.7 in.)/1,000 years. The Gammon Member of the Cody Shale in the northwestern part of the basin accumulated about 85.7–80.7 Ma at a rate of 11.9 cm (4.7 in.)/1,000 years. On the southwestern flank of the basin, rocks correlative with the upper part of the Gammon Member of the Cody Shale are assigned to the lower part of the Steele Member of the Cody Shale and to overlying strata that include the Shannon Sandstone and Sussex Sandstone Beds. Strata of the basal Steele, between the Niobrara and the Shannon in southwestern and western parts of the basin, might have accumulated on a slope and outer shelf about 88.2–81.3 Ma at depositional rates of 35.4–44.2 cm (13.9–17.4 in.)/1,000 years. The Shannon, Sussex, and intervening rocks were deposited on a shelf about 81.3–80.7 Ma at rates possibly as high as 50.2–148.4 cm (19.8–58.4 in.)/1,000 years; however, if the sequence of basal Steele, Shannon, and Sussex includes disconformities, depositional rates could be significantly less than those noted above.

The unnamed lower part of the Steele and overlying beds assigned to, in ascending order, the Shannon Sandstone Bed, the unnamed middle part of the Steele, and the Sussex Sandstone Bed (about 82.8–80.7 Ma), which are similar in age to the upper part of the Gammon Member on the northwestern flank of the basin (fig. 4), seemingly represent a marine regression, following brief transgression, and later regression. Using sequence stratigraphy (Van Wagoner and others, 1990), the part of the Steele between the Niobrara and the Sussex can be interpreted as progradational parasequence sets and overlying aggradational parasequence sets (highstand systems tract), and the Sussex can be interpreted as a progradational parasequence set (lowstand systems tract). Haq and others (1987) depicted a long-term, eustatic rise from 85 to 79 Ma, a minor, condensed section at 82 Ma, and a major, type-1 sequence boundary at 80 Ma. The marine regression indicated by the uppermost Niobrara and the lower part of the Steele (about 84.0–81.3 Ma), partly during the eustatic rise of 82.5–81 Ma, suggests either differences in the time scales for the two records or penecontemporaneous uplift in the middle of the Western Interior. Reynolds (1976) proposed that the ancestral Granite Mountains in southwestern Natrona County were uplifted about 80.8 Ma. From isopach maps and cross sections of the eastern flank of the Powder River Basin, Asquith (1970, p. 1193) determined that "basin subsidence after deposition of the Niobrara Formation was accompanied by faulting or sharp flexing along parallel and slightly arcuate trends oriented approximately northeast-southwest."

The disconformity at the base of the Sharon Springs and at the base of correlative strata in the Mitten (a hiatus about 81.3–80.6 Ma) is, according to Van Wagoner and others (1990), a major, type-1 sequence boundary and formed at 80 Ma by subaerial erosion during a lowstand of sea level. Following a rapid sea-level rise, indicated by a medium, condensed section at 79.5 Ma, the Sharon Springs and laterally equivalent rocks were deposited mainly during a marine regression (Van Wagoner and others, 1990) indicated by the minor, type-2 sequence boundary at 79 Ma (Haq and others, 1987).

In the southeastern part of the Powder River Basin, the Sharon Springs is conformably overlain by the Mitten, which is conformably overlain by the Red Bird Silty Member of the Pierre. Sediments of the Sharon Springs and Mitten accumulated mainly in a basin and on a slope, whereas those of the Red Bird accumulated on a shelf. Estimated rates of sedimentation for the Sharon Springs, Mitten, and Red Bird Members (80.6–76.6 Ma) are 13.5 cm (5.3 in.)/1,000 years, about 3.9–26.8 cm (1.5–10.6 in.)/1,000 years, and 6.8–20.2 cm (2.7–7.9 in.)/1,000

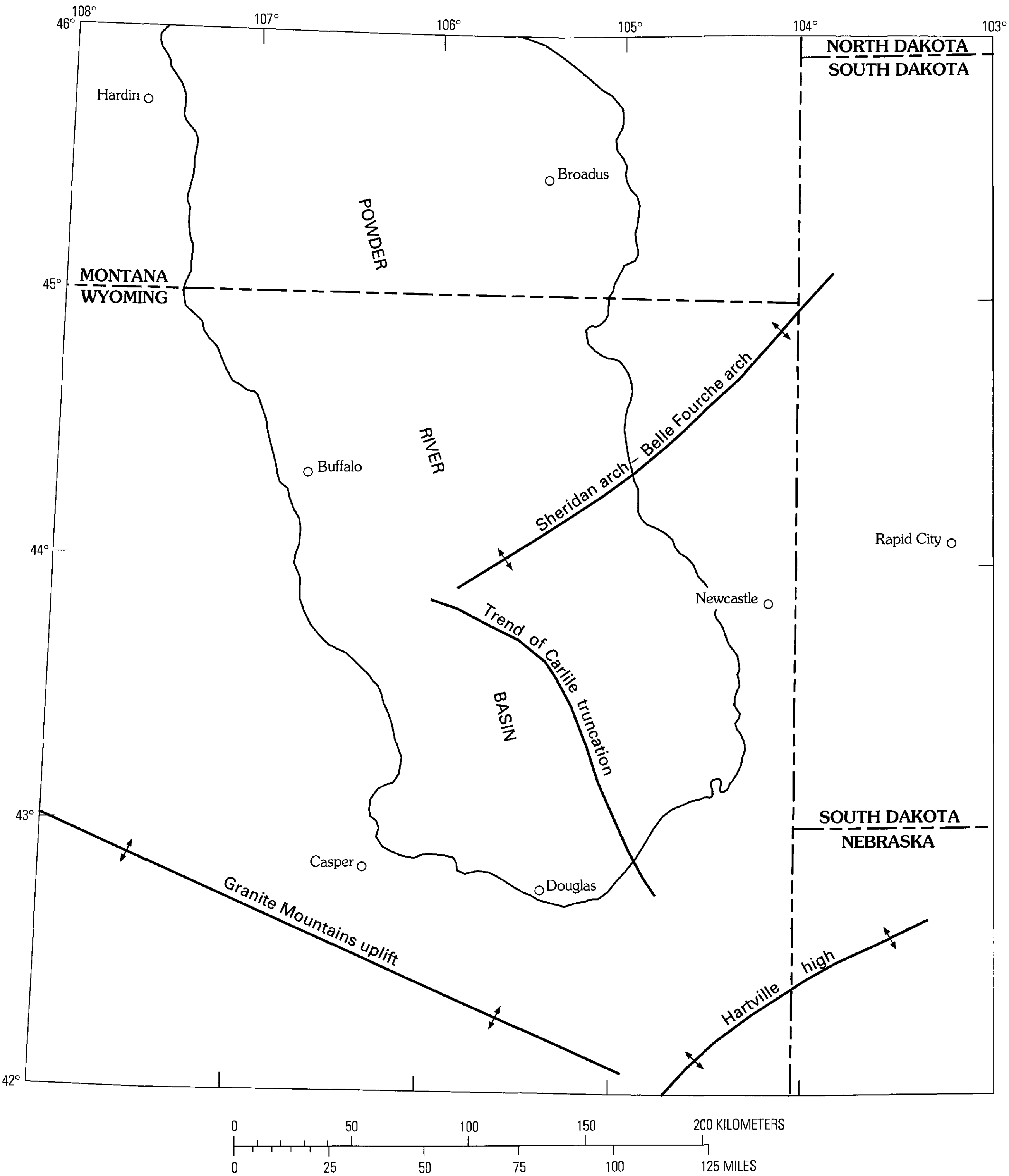


Figure 28. Map of southern part of Powder River Basin, Wyoming and Montana, showing crestlines of major Late Cretaceous uplifts and the trend of an area in which the Carlile Shale was truncated during Coniacian time. Compiled from Martinsen and Marrs (1985), Merewether and Cobban (1986a), Slack (1981), and Weimer (1984).

years, respectively. For the approximate time represented by these rocks, Haq and others (1987) proposed a major, type-1 sequence boundary at 80 Ma, a medium, condensed section at 79.5 Ma, a minor, type-2 sequence boundary at

79 Ma, a minor, condensed section at 78 Ma, a minor, type-2 sequence boundary at 77.5 Ma, and a minor, condensed section at 76 Ma.

The Sharon Springs, Mitten, and Red Bird Members are represented in northern Big Horn County in the northwestern part of the basin by most of the Claggett Member of the Cody Shale and by the overlying Judith River Formation (fig. 4). This sequence of marine rocks is composed of, from oldest to youngest, bentonitic shale, shale, sandy shale, and sandstone that presumably accumulated during a marine regression. Rates of deposition for the Claggett and Judith River are 7.8 cm (3.1 in.)/1,000 years and 7.8 cm (3.1 in.)/1,000 years, respectively.

Beds of almost the same age as the Sharon Springs, Mitten, and Red Bird, but on the southwestern flank of the basin, are assigned to the upper part of the Cody Shale and to the overlying Parkman Sandstone Member of the Mesaverde Formation. The upper part of the Cody was deposited on a shelf, and the Parkman accumulated on an inner shelf as a delta. Sedimentation rates for the upper part of the Cody and the Parkman could be 13.3–17.0 cm (5.3–6.7 in.)/1,000 years and 11.7–12.3 cm (4.6–4.9 in.)/1,000 years, respectively. These strata indicate a marine regression (Asquith, 1970) and a prograding delta (Hubert and others, 1972; Dogan, 1984) about 80.6–76.4 Ma. According to Haq and others (1987), that period is represented by a highstand, two third-order sequence cycles, and parts of two other third-order sequence cycles.

The upper part of the Pierre Shale (76.6–69.7 Ma), which conformably overlies the Red Bird Member and is conformably overlain by the Fox Hills Sandstone, consists of the lower unnamed shale member, the upper unnamed shale member, and the intervening Kara Bentonitic Member. This sequence was deposited mainly on a shelf and is composed of shale, siltstone, and bentonitic strata. The lower shale member may contain an extension of the disconformity that is present between the unnamed marine shale member and the Teapot Sandstone Member of the Mesaverde Formation on the western flank of the Powder River Basin. For the period 76.6–69.7 Ma, Haq and others (1987) depicted a long-term eustatic fall, a minor, condensed section at 76 Ma, a medium, type-2 sequence boundary at 75 Ma, a major, condensed section at 73.5 Ma, and a minor, type-1 sequence boundary at 71 Ma. Rates of sedimentation for the lower shale member of the upper part of the Pierre are 6.3–10.2 cm (2.5–4.0 in.)/1,000 years. Beds included in the overlying upper unnamed shale member accumulated at rates of 6.5–21.4 cm (2.6–8.4 in.)/1,000 years.

The argillaceous and bentonitic upper part of the Pierre, which overlies the Red Bird Silty Member, is represented in the northwestern part of the basin by marine shale and bentonite of the Bearpaw Shale. Molluscan fossils in the Bearpaw and the basinwide chronostratigraphy indicate that the formation may contain a sequence boundary (Van Wagoner and others, 1990), an extension of the disconformity at the base of the Teapot Sandstone Member. Presumably, the Bearpaw accumulated at a rate of 7.6 cm (3.0 in.)/1,000 years.

Comparable rocks in the southwestern part of the basin comprise, in ascending order, the unnamed marine shale member and the Teapot Sandstone Member of the Mesaverde Formation, and the Lewis Shale. The unnamed marine member, which conformably overlies the Parkman Member and is disconformably overlain by the Teapot Member, accumulated on a shelf at a rate of perhaps 20.8 cm (8.2 in.)/1,000 years. Beds of the Teapot were deposited as a delta at possible rates of 2.5–4.3 cm (1.0–1.7 in.)/1,000 years. The Lewis, which conformably overlies the Teapot and is conformably overlain by the Fox Hills, accumulated in nearshore and deltaic environments at rates of perhaps 15.8–21.0 cm (6.2–8.3 in.)/1,000 years.

The Fox Hills Sandstone and the conformably overlying Lance Formation vary little in composition throughout the Powder River Basin; however, the Fox Hills and the basal part of the Lance apparently are older in Crook County on the northwestern flank of the Black Hills than in the southern part of the basin. In the southeastern part of the basin the Fox Hills was deposited at a rate of 22.3 cm (8.8 in.)/1,000 years, whereas in the southwestern part of the basin the Fox Hills accumulated at rates of 6.6–7.3 cm (2.6–2.9 in.)/1,000 years.

Deposition of the Lance Formation in the southeastern part of the basin was at a rate of perhaps 30.7 cm (12.1 in.)/1,000 years. The Hell Creek Formation in the northwestern part of the basin accumulated at a rate of about 8.1 cm (3.2 in.)/1,000 years. In the southwestern part of the basin the Lance was deposited at rates of perhaps 18.0–21.4 cm (7.1–8.4 in.)/1,000 years. To the west, in part of the Wind River Basin, the Lance accumulated at a rate of more than 60 cm (24 in.)/1,000 years (W.R. Keefer, written commun., 1993).

The upper part of the Pierre Shale, the unnamed marine shale member and the Teapot Sandstone Member of the Mesaverde Formation, the Lewis Shale, the Fox Hills Sandstone, and the Lance Formation represent a marine transgression at about 76.6 Ma (basal strata of the lower unnamed shale member of the Pierre and laterally equivalent beds), a marine regression about 75.7–72.7 Ma (top of the unnamed marine shale member and base of the Teapot Sandstone Member of the Mesaverde), erosion at about 72.7 Ma (unconformity and sequence boundary at base of Teapot Sandstone Member), a second transgression at about 72.2 Ma (basal strata of the Lewis), and a final regression about 70–65.4 Ma (upper unnamed shale member of the Pierre, uppermost Lewis, Fox Hills, and Lance).

Haq and others (1987) indicated a long-term eustatic fall about 78.5–65 Ma, a minor, condensed section at 76 Ma, a medium, type-2 sequence boundary at 75 Ma, a major, condensed section at 73.5 Ma, a minor, type-1 sequence boundary at 71 Ma, a minor, condensed section at 69.5 Ma, a major, type-1 sequence boundary at 68 Ma, a minor, condensed section at 67.5 Ma, a minor, type-2 sequence boundary at 67 Ma, and a major, condensed section at 66 Ma. Shoreline movements represented by these strata could have been caused by eustatic events, although they also could have been influenced by uplifts of the ancestral Granite Mountains at about 73, 72, and 65.4 Ma (Reynolds, 1976).

LATE CRETACEOUS TECTONISM

Sedimentary rocks and the enclosed hiatuses of Late Cretaceous age in Wyoming and adjacent areas record regional and local structural deformation as well as eustatic events. A broad regional uplift that developed in west-central Wyoming during the late Campanian (about 73 Ma) was documented by Gill and Cobban (1966b). Tectonism and eustasy are indicated by changes in the locations of Late Cretaceous strandlines in Wyoming and adjoining areas (Gill and Cobban, 1973; Lillegraven and Ostresh, 1990). In central Wyoming, southwest of the Powder River Basin, the ancestral Granite Mountains (figs. 1, 23) were rising intermittently in the Campanian and Maastrichtian, at about 80.8, 73, 72, and 65.4 Ma, according to Reynolds (1976). Merewether and Cobban (1986a) concluded that a west-northwest-trending area centered in the Granite Mountains was rising during the early middle Turonian (about 92.4 Ma) and the late Turonian (about 90.4–90 Ma). Near the southern end of the Powder River Basin (fig. 28), at the border of Wyoming and Nebraska, the anticlinal northeast-trending Hartville high described by Weimer (1984) was rising probably in the late Turonian (about 90.3–90.0 Ma). A northeast-north-trending area in southeastern Wyoming, suggested by Merewether and Cobban (1986a), that extended into the southern part of the Powder River Basin might also have risen in the late Turonian (about 90.3 Ma).

Subsidence accompanied by faulting or sharp flexing in the southeastern part of the Powder River Basin in the early Campanian (about 83.5–80.6 Ma) was described by Asquith (1970). According to Slack (1981), episodic subtle displacements along lineaments in the region of the Powder River Basin during Cretaceous time, and the consequent development of the northeast-trending Sheridan–Belle Fourche arch in the middle of the basin (fig. 28), influenced the character of strata of Cenomanian through early Campanian age (about 98.5–80.5 Ma). Northeast-trending lineaments and less prominent northwest-trending lineaments in northeastern Wyoming and southeastern Montana (Peterson, 1958) indicate zones of structural deformation that define basement blocks and correspond to boundaries of lithofacies and changes in thickness of Upper Cretaceous strata (Marrs and others, 1984; Martinsen and Marrs, 1985). The northeast-trending zones in the basin region separate three basement blocks. According to Martinsen and Marrs (1985), displacements along lineaments affected deposition of the Belle Fourche Member of the Frontier Formation, Niobrara Formation, Gammon Member of the Pierre Shale, Claggett Member of the Cody Shale, and Fox Hills Sandstone. Displacements along west-trending faults in the southwestern part of the basin during the Turonian were suggested by Merewether and Cobban (1986b). The disconformity at the base of the Niobrara at outcrops near Douglas (Merewether and Cobban, 1873) and in the subsurface in the eastern part of the basin (Weimer and Flexer, 1985) could represent an uplift in the region during the middle to late Coniacian (about 88.5–86.3 Ma) (Merewether and Cobban, 1985).

An isopachous map (fig. 3) by W.D. Grundy and C.T. Pierson (written commun., 1991) shows that Upper Cretaceous strata in the Powder River Basin thicken south-southwestward from about 1,300 m (4,300 ft) in Powder River County to about 3,000 m (9,800 ft) in Converse County. The component stratigraphic units that clearly are thicker in the southern part of the basin include the Wall Creek Member (late Turonian age, about 89.5–89.2 Ma, southern Johnson County) of the Frontier Formation; the combined Sharon Springs, Mitten, and Red Bird Members (early and late Campanian age, about 80.6–76.6 Ma, Niobrara County) of the Pierre Shale and the age-equivalent upper part of the Cody Shale and the Parkman Member of the Mesaverde Formation (fig. 29); the Mesaverde Formation (fig. 22) (middle and late Campanian age, about 78.3–72.2 Ma); the Lewis Shale (late Campanian and early Maastrichtian age, about 72.2–69.6 Ma); and the combined Fox Hills Sandstone and Lance Formation (early and late Maastrichtian age, about 69.6–65.4 Ma).

Although the southwestern part of the basin region contained a succession of different marine and nonmarine depositional environments during the Late Cretaceous, Gill and Cobban (1973) concluded that it has the highest average rate of sedimentation for late Santonian to early Maastrichtian time (as recorded by the upper part of the Niobrara Member and the Steele Member of the Cody Shale, the Mesaverde Formation, and the Lewis Shale) in northeastern Wyoming. Rates of deposition determined recently for Upper Cretaceous stratigraphic units at five scattered locations near the margin of the basin (table 5) include 13 values that exceed 20 cm (7.9 in.)/1,000 years. All 13 values are from the three locations in the southern part of the basin. The southward thickening of several of the Upper Cretaceous units was caused probably by lateral changes in depositional environments and lithofacies; however, the conspicuous southward thickening of the Upper Cretaceous Series and of unlike siliciclastic units within the series suggests that the topographic and depositional paleosurfaces were subsiding more rapidly in the southern part of the region.

Positive rates of total subsidence (tectonic subsidence+local loading subsidence) determined for Upper Cretaceous stratigraphic units at five locations in the basin (table 6, figs. 30–32) include 27 values greater than 10 cm (3.9 in.)/1,000 years. Negative values for rates of subsidence at those locations correspond generally to unconformities in the sequences. Most of the higher positive values are for strata at the three locations in Johnson, Niobrara, and Natrona Counties in the southern part of the basin. At the three locations, total subsidence values of 10 cm (3.9 in.)/1,000 years or greater (table 6) are most common for rocks of late Turonian, early and middle Campanian, and Maastrichtian age. Total subidence exceeded 10 cm (3.9 in.)/1,000 years in Big Horn County only during deposition of the Mowry Shale. In Crook County the higher rates correspond to the Turner Sandy Member of the Carlile Shale, Gammon Member of the Pierre Shale, and Fox Hills Sandstone. The high rates in Niobrara County are associated with the Turner Sandy Member, Sharon Springs, Mitten, Red Bird, and upper unnamed shale members of the Pierre Shale, Fox Hills Sandstone, and Lance Formation. In Johnson County high rates of total subsidence are related to the Mowry Shale, Sage Breaks Member of the Cody Shale, lower part of the Steele Member of the Cody, part of the Steele that includes the Shannon and Sussex Sandstone Beds, unnamed marine shale member of the Mesaverde Formation, Lewis Shale, and Lance Formation. In Natrona County high rates are associated with the Belle Fourche and Wall Creek Members of the Frontier Formation, Sage Breaks Member of the Cody Shale, all parts of the Steele Member of the Cody Shale, Lewis Shale, and Lance Formation.

Positive rates of tectonic subsidence (total subsidence minus local loading subsidence) calculated for Upper Cretaceous stratigraphic units at the five locations (table 6, figs. 30–32) include five values greater than 10 cm (3.9 in.)/1,000 years as well as four negative values, which could indicate either near stability or uplift. The five positive values are from the southern part of the basin. In the southeastern area of the basin in northeastern Niobrara County tectonic subsidence exceeded 10 cm (3.9 in.)/1,000 years during deposition of the Turner Sandy Member of the Carlile Shale and Sharon Springs Member of the Pierre Shale. Tectonic subsidence was approximately 10 cm (3.9 in.)/1,000 years near the western margin of the basin in southern Johnson County during accumulation of the Sage Breaks Member of the Cody Shale and the Lewis Shale. On the southwestern flank of the basin in southeastern Natrona County tectonic subsidence was greater than 10 cm (3.9 in.)/1,000 years during deposition of the Wall Creek Member of the Frontier Formation, Sage Breaks Member of the Cody Shale, and middle part of the Steele Member of the Cody Shale, which consists of, from oldest to youngest, the Shannon Sandstone Bed, unnamed shale, and Sussex Sandstone Bed. Uplift might be indicated (table 6) by the larger negative rates of tectonic subsidence. Negative values of 1.3–8.5 cm (0.5–3.3 in.)/1,000 years were determined for the Gammon Member of the Pierre Shale in Niobrara County and for the Fox Hills Sandstone in Big Horn and Johnson Counties.

The amount of tectonic subsidence (total subsidence minus local loading subsidence) at the base of five sequences of Upper Cretaceous rocks in the region (table 7) is largest (as much as 762 m) at the end of the Cretaceous in the southern part of the basin, in southern Johnson and southeastern Natrona Counties. It is least in the northern part of the basin in Big Horn and Crook Counties. Negative values for tectonic subsidence (possible uplifts) are confined to the period 98.5–89.2 Ma (Cenomanian and most of Turonian time), and where possibly meaningful they range from –25.8 to –127.0 m (–84.6 to –416.7 ft). The high negative values associated with the oldest rocks (98.5 and 97.2 Ma) could be incorrect; they might reflect flaws in the program related to progradation and rapid filling of thick water columns. Negative values at 92.8–92.3 and 90.2–89.4 Ma in the Turonian for the sequences in Crook, Niobrara, Johnson, and Natrona Counties might be related to major unconformities.

During the several periods of time represented by widespread disconformities, the rate of basement subsidence either was exceeded by the rate of contemporaneous eustatic fall or was replaced by a rate of uplift that exceeded any rate of contemporaneous eustatic rise. Hiatuses in the stratigraphic record in the southern part of the basin indicate subaerial and submarine erosion sometime during the following periods: 94.3–92.3 Ma (probably in the late early Turonian, between the Belle Fourche Member and Emigrant Gap Member of the Frontier Formation in Natrona County); 90.5–89.2 Ma (probably in the early late Turonian, between the Emigrant Gap Member and Wall Creek Member of the Frontier in Natrona County); 88.6–87.8 Ma (in the middle Coniacian, between the Carlile Shale and Niobrara Formation in Niobrara County); 81.3–80.7 Ma (in the late early Campanian, between the Gammon Member and Sharon Springs Member of the Pierre Shale in Niobrara County); and perhaps 74.5–72.7 Ma (in the late Campanian, within the lower unnamed shale member of the Pierre in Niobrara County and between the unnamed marine shale member and Teapot Sandstone Member of the Mesaverde Formation in Johnson and Natrona Counties).

The two disconformities within the Frontier Formation in Natrona County were caused apparently by slight but extensive structural arching in central Wyoming

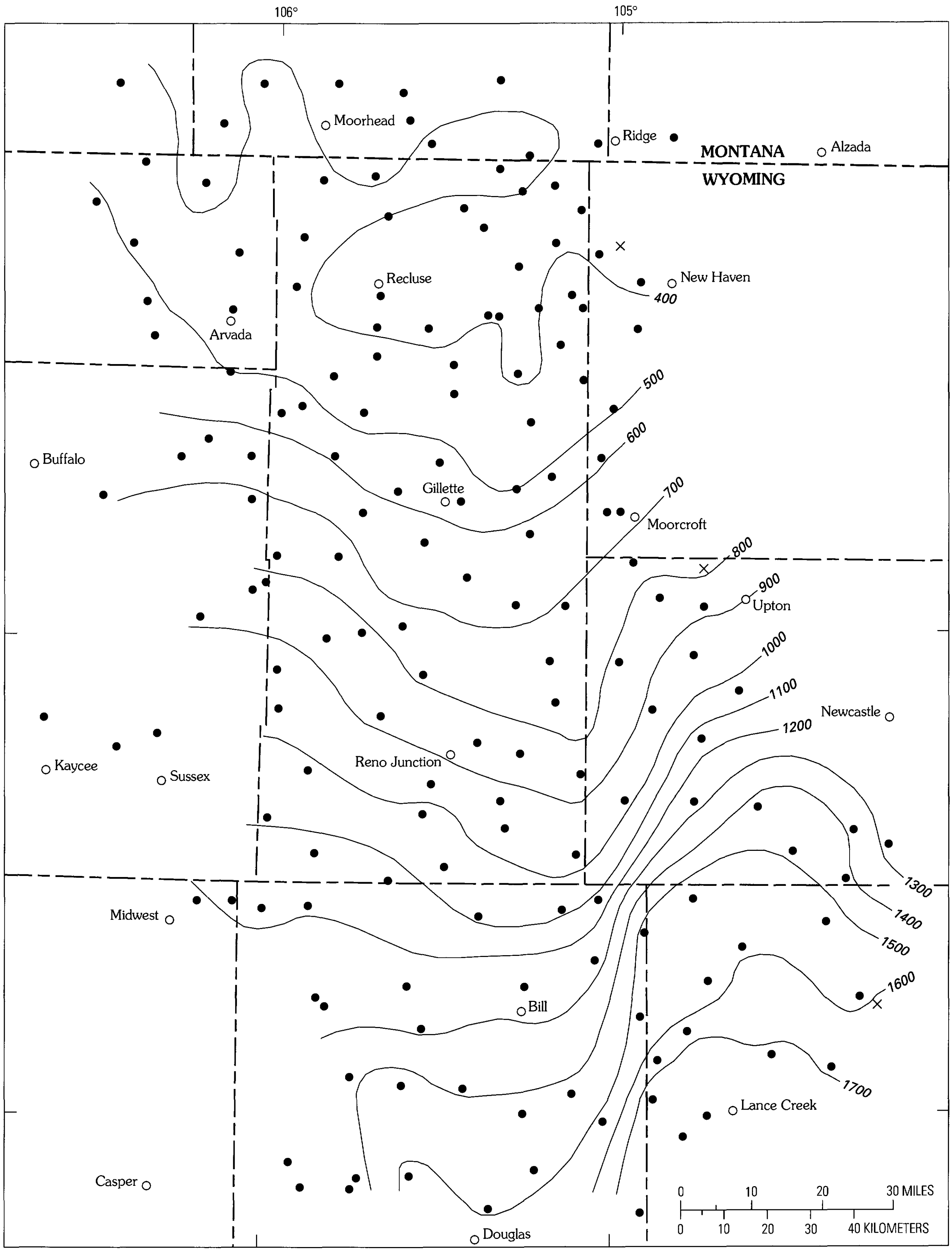


Figure 29. Isopachous map of combined Sharon Springs, Mitten, and Red Bird Members (middle Campanian, about 80.6–76.6 Ma) of the Pierre Shale and age-equivalent upper part of the Cody Shale and Parkman Member of the Mesaverde Formation, Montana and Wyoming. Numbers are thicknesses in feet (100 ft=30.5 m) of combined members; contour interval 100 ft; dots indicate locations of boreholes.

Table 6. Approximate rates of tectonic and total subsidence for stratigraphic units of Late Cretaceous age in areas of the Powder River Basin, Wyoming and Montana.
[Corrected rates in centimeters (inches) per 1,000 years]

Formation (Member: Bed)	Area	Corrected tectonic rate	Corrected total rate
Hell Creek	North Big Horn County	1.5 (0.6)	5.0 (2.0)
Lance	Northwest Crook County	1.2 (0.5)	5.7 (2.3)
Lance	South Johnson County	3.4 (1.3)	12.4 (4.9)
Lance	Northeast Niobrara County	4.9 (1.9)	20.6 (8.1)
Lance	Southeast Natrona County	3.3 (1.3)	13.6 (5.4)
Fox Hills Sandstone	North Big Horn County	Possible uplift=5.3 (2.1)	2.3 (0.9)
Fox Hills Sandstone	Northwest Crook County	4.5 (1.8)	11.6 (4.6)
Fox Hills Sandstone	South Johnson County	Possible uplift=8.5 (3.3)	3.8 (1.5)
Fox Hills Sandstone	Northeast Niobrara County	1.0 (0.4)	13.3 (5.2)
Fox Hills Sandstone	Southeast Natrona County	1.4 (0.6)	4.6 (1.8)
Lewis Shale	South Johnson County	10.6 (4.2)	17.4 (6.9)
Lewis Shale	Southeast Natrona County	4.3 (1.6)	10.7 (4.2)
Mesaverde (Teapot Sandstone)	South Johnson County	2.8 (1.1)	4.3 (1.7)
Mesaverde (Teapot Sandstone)	Southeast Natrona County	2.0 (0.8)	2.5 (1.0)
Pierre Shale (upper unnamed shale)	Northwest Crook County	5.5 (2.2)	6.5 (2.6)
Pierre Shale (upper unnamed shale)	Northeast Niobrara County	4.7 (1.9)	14.0 (5.5)
Mesaverde (unnamed marine shale)	South Johnson County	8.2 (3.2)	12.8 (5.0)
Bearpaw Shale	North Big Horn County	2.9 (1.2)	5.3 (2.1)
Pierre Shale (lower unnamed shale)	Northwest Crook County	2.6 (1.0)	4.1 (1.6)
Pierre Shale (lower unnamed shale)	Northeast Niobrara County	4.6–4.9 (1.8–1.9)	6.5–9.8 (2.6–3.9)
Judith River	North Big Horn County	Possible uplift=0.1 (0.03)	5.2 (2.0)
Mesaverde (Parkman Sandstone)	South Johnson County	1.1 (0.4)	7.0 (2.8)
Mesaverde (Parkman Sandstone)	Southeast Natrona County	1.5 (0.6)	7.6 (3.0)
Pierre Shale (Red Bird Silty)	Northwest Crook County	3.8 (1.5)	6.0 (2.4)
Pierre Shale (Red Bird Silty)	Northeast Niobrara County	4.7 (1.9)	14.9 (5.9)
Cody Shale (upper part of Steele)	South Johnson County	3.5 (1.4)	8.7 (3.4)
Cody Shale (upper part of Steele)	Southeast Natrona County	3.3 (1.3)	11.3 (4.4)
Pierre Shale (Mitten)	Northwest Crook County	1.7 (0.7)	3.9 (1.5)
Pierre Shale (Mitten)	Northeast Niobrara County	6.5 (2.6)	20.3 (8.0)
Cody Shale (Claggett)	North Big Horn County	0.8 (0.3)	5.5 (2.2)
Pierre Shale (Sharon Springs)	Northeast Niobrara County	11.7 (4.6)	12.7 (5.0)
Cody Shale (Steele: Shannon, Sussex, and intervening beds	South Johnson County	7.0 (2.8)	36.6 (14.4)
Cody Shale (Steele: Shannon, Sussex, and intervening beds	Southeast Natrona County	24.7 (9.7)	105.9 (41.7)
Pierre Shale (Gammon)	Northwest Crook County	6.2 (2.4)	10.3 (4.1)
Pierre Shale (Gammon)	Northeast Niobrara County	Possible uplift=1.3 (0.5)	1.3 (0.5)
Cody Shale (lower part of Steele)	South Johnson County	7.6 (3.0)	35.0 (13.8)
Cody Shale (lower part of Steele)	Southeast Natrona County	5.5 (2.2)	27.3 (10.7)
Cody Shale (Gammon)	North Big Horn County	2.4 (0.9)	9.3 (3.7)
Cody Shale (Niobrara)	North Big Horn County	3.7 (1.5)	6.2 (2.4)
Cody Shale (Niobrara)	South Johnson County	2.4 (0.9)	3.7 (1.5)
Cody Shale (Niobrara)	Southeast Natrona County	2.4 (0.9)	3.6 (1.4)
Niobrara	Northwest Crook County	1.0 (0.4)	1.2 (0.5)
Niobrara	Northeast Niobrara County	1.7 (0.7)	2.2 (0.9)
Cody Shale (Sage Breaks)	South Johnson County	9.7 (3.8)	10.4 (4.1)
Cody Shale (Sage Breaks)	Southeast Natrona County	16.8 (6.6)	24.1 (9.5)
Carlile Shale (Sage Breaks)	Northwest Crook County	1.8 (0.7)	3.5 (1.4)
Carlile Shale (Sage Breaks)	Northeast Niobrara County	5.8 (2.3)	7.2 (2.8)
Cody Shale (Carlile)	North Big Horn County	0.4 (0.2)	3.4 (1.3)
Frontier (Wall Creek)	South Johnson County	6.0 (2.4)	8.1 (3.2)
Frontier (Wall Creek)	Southeast Natrona County	14.1 (5.6)	16.0 (6.3)
Carlile Shale (Turner Sandy)	Northwest Crook County	9.0 (3.5)	10.1 (4.0)
Carlile Shale (Turner Sandy)	Northeast Niobrara County	19.2 (7.6)	19.6 (7.7)
Frontier (Emigrant Gap)	Southeast Natrona County	4.0 (1.6)	4.0 (1.6)
Carlile Shale (Pool Creek)	Northwest Crook County	1.1 (0.4)	1.7 (0.7)
Carlile Shale (Pool Creek)	Northeast Niobrara County	0.3 (0.1)	3.3 (1.3)

Table 6. Approximate rates of tectonic and total subsidence for stratigraphic units of Late Cretaceous age in areas of the Powder River Basin, Wyoming and Montana—Continued.
[Corrected rates in centimeters (inches) per 1,000 years]

Formation (Member: Bed)	Area	Corrected tectonic rate	Corrected total rate
Frontier (Belle Fourche)	South Johnson County	3.0 (1.2)	7.4 (2.9)
Frontier (Belle Fourche)	Southeast Natrona County	4.1 (1.6)	11.2 (4.4)
Greenhorn	North Big Horn County	2.1 (0.8)	3.8 (1.5)
Greenhorn	Northwest Crook County	1.1 (0.4)	3.1 (1.2)
Greenhorn	Northeast Niobrara County	4.8 (1.9)	5.8 (2.3)
Belle Fourche	North Big Horn County	4.3 (1.7)	6.9 (2.7)
Belle Fourche Shale	Northwest Crook County	4.1 (1.6)	6.3 (2.5)
Belle Fourche Shale	Northeast Niobrara County	4.3 (1.7)	8.3 (3.3)
Mowry Shale	North Big Horn County	7.6 (3.0)	17.8 (7.0)
Mowry Shale	Northwest Crook County	4.2 (1.7)	9.8 (3.8)
Mowry Shale	South Johnson County	5.9 (2.3)	13.6 (5.4)
Mowry Shale	Northeast Niobrara County	3.3 (1.3)	7.9 (3.1)
Mowry Shale	Southeast Natrona County	4.7 (1.8)	10.8 (4.2)

during the late early to early middle Turonian and during the earliest late Turonian (Merewether and Cobban, 1986a, b). A disconformable contact of the Carlile Shale or Sage Breaks Member of the Cody Shale with the overlying Niobrara Formation or Niobrara Member of the Cody in the southern part of the Powder River Basin (fig. 28) defines an elongate area that extends northwest from south-central Niobrara County through northeastern Converse County to southwestern Campbell County. Scouring in this area might have been caused either by locally strong submarine currents or by structural deformation in the middle to late Coniacian (Weimer and Flexer, 1985).

A hiatus (perhaps 81.3–80.7 Ma) at the contact of the Gammon Member and overlying Sharon Springs Member of the Pierre Shale in the southeastern part of the basin, and possibly correlative but lesser hiatus between the Sussex Sandstone Bed and the younger Ardmore Bentonite Bed of the Cody Shale in the southwestern part of the basin, indicates erosion followed by a rapid marine transgression and a time of little deposition in the eastern part of the region (Asquith, 1970). Gill and Cobban (1973) depicted a regressing shoreline from about 84.5 to 81.2 Ma, a transgressing shoreline about 80.9 Ma (fig. 7, fossil zone 42), and a regressing shoreline about 80.8–79.6 Ma in Wyoming; Haq and others (1987) showed a eustatic rise at 82–81 Ma, a eustatic fall at 81–80 Ma, and a eustatic rise at about 80–79.5 Ma.

A regional disconformity between the unnamed marine shale member and Teapot Sandstone Member of the Mesaverde Formation in Natrona County, as well as the absence of several fossil zones in the lower unnamed shale member of the Pierre Shale in Niobrara County, probably represents a significant hiatus. The hiatus could be during 74.5–72.7 Ma (late Campanian) in Niobrara County and might be longer in Natrona County. Haq and others (1987) depicted a major condensed section at 73.5 Ma and a medium, type-1 sequence boundary at 71 Ma. Gill and Cobban (1966b) concluded that the unconformity at the base of the Teapot and within laterally equivalent formations elsewhere in Wyoming was caused by regional uplift and erosion in central Wyoming during the late Campanian.

Structural deformation in the region of the Powder River Basin was recurrent and generally minor during the Late Cretaceous. Rates of subsidence were greatest in the southern part of the region, at least during the late Turonian, early and middle Campanian, and early and late Maastrichtian. Slight episodic displacements along mostly northeast trending structural lineaments and arches within the basin (fig. 28) affected the facies and thicknesses of many Upper Cretaceous formations, according to Slack (1981) and Martinsen and Marrs (1985). Arching in central and western Wyoming during the middle and late Turonian (Merewether and Cobban, 1986a), during the late Campanian (Gill and Cobban, 1966b), and intermittently during the Campanian and Maastrichtian (Reynolds, 1976), as well as in southeastern Wyoming during the late Turonian and middle to late Coniacian (Weimer, 1984; Merewether and Cobban, 1985), caused thinning and disconformities in the Upper Cretaceous sequence near the southern end of the basin.

SUMMARY AND CONCLUSIONS

Formations of Late Cretaceous age (98.5–65.4 Ma) in the region of the Powder River Basin are mainly siliciclastic and carbonate rocks that thicken south-southwestward from about 1,300 m (4,300 ft) in Powder River County to about 3,000 m (9,800 ft) in Converse County. These strata accumulated in various marine and nonmarine environments on

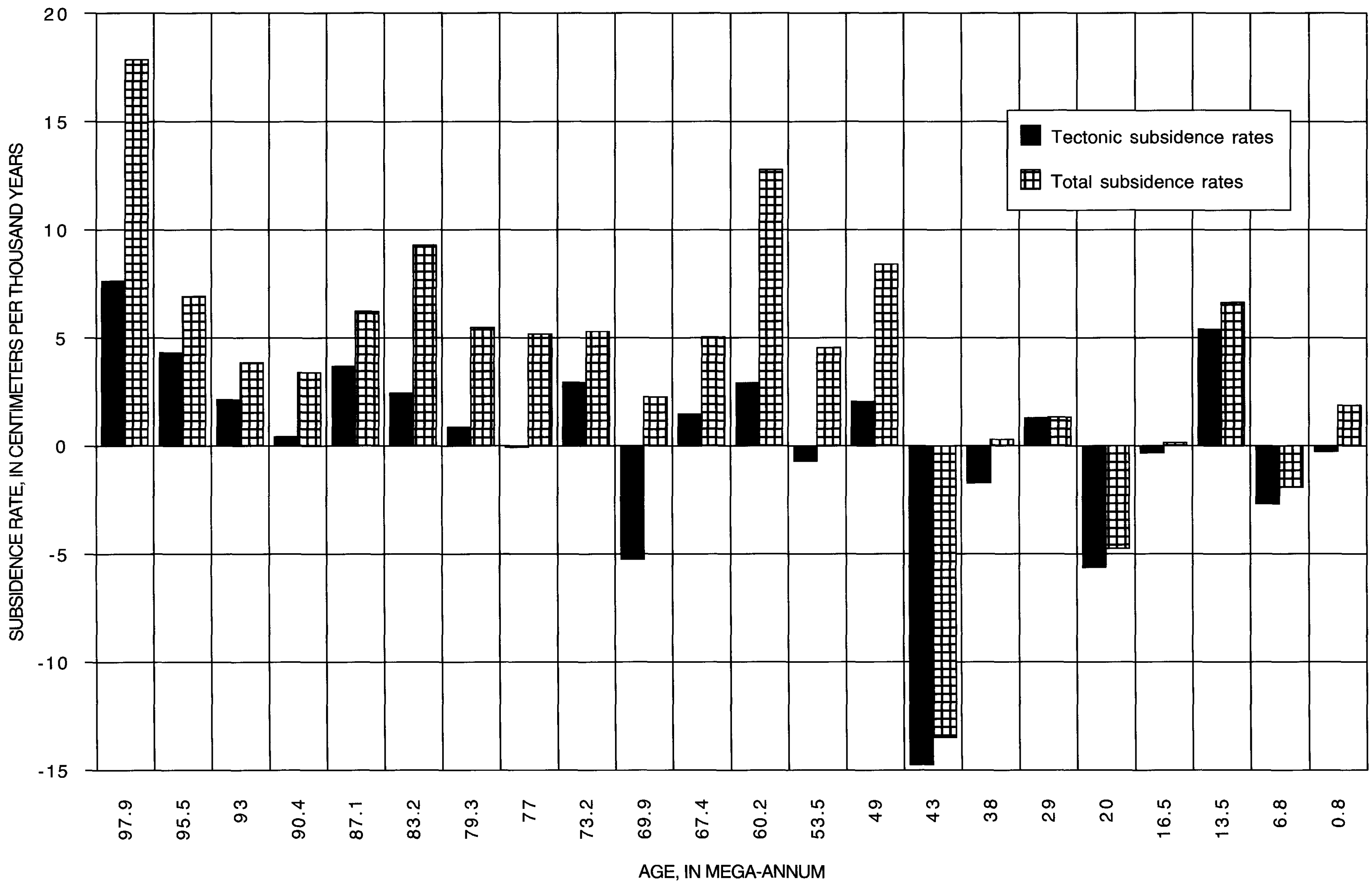


Figure 30. Approximate subsidence rates for Upper Cretaceous and Cenozoic strata, northern Big Horn County, Montana.

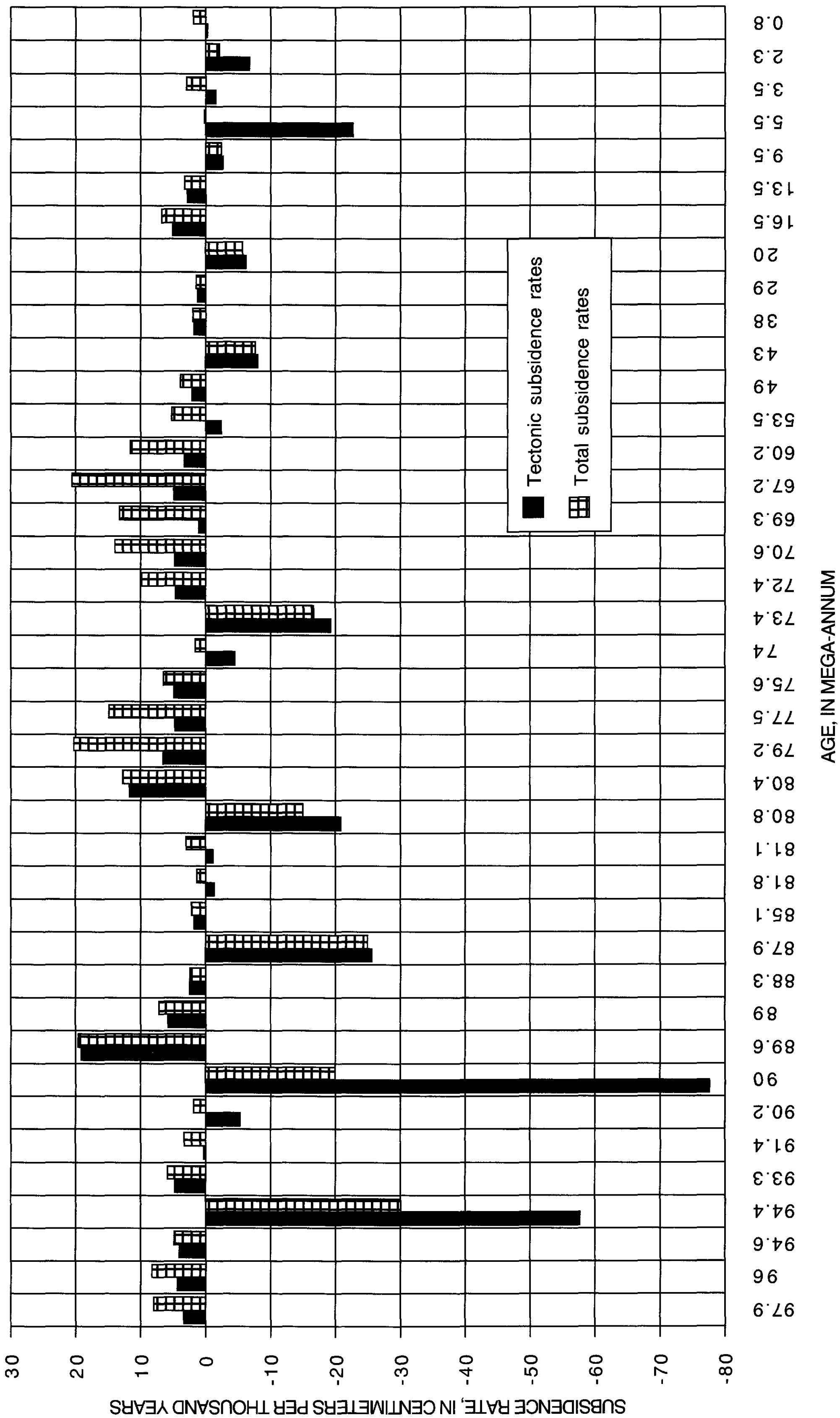


Figure 31. Approximate subsidence rates for Upper Cretaceous and Cenozoic strata, northeastern Niobrara County, Wyoming.

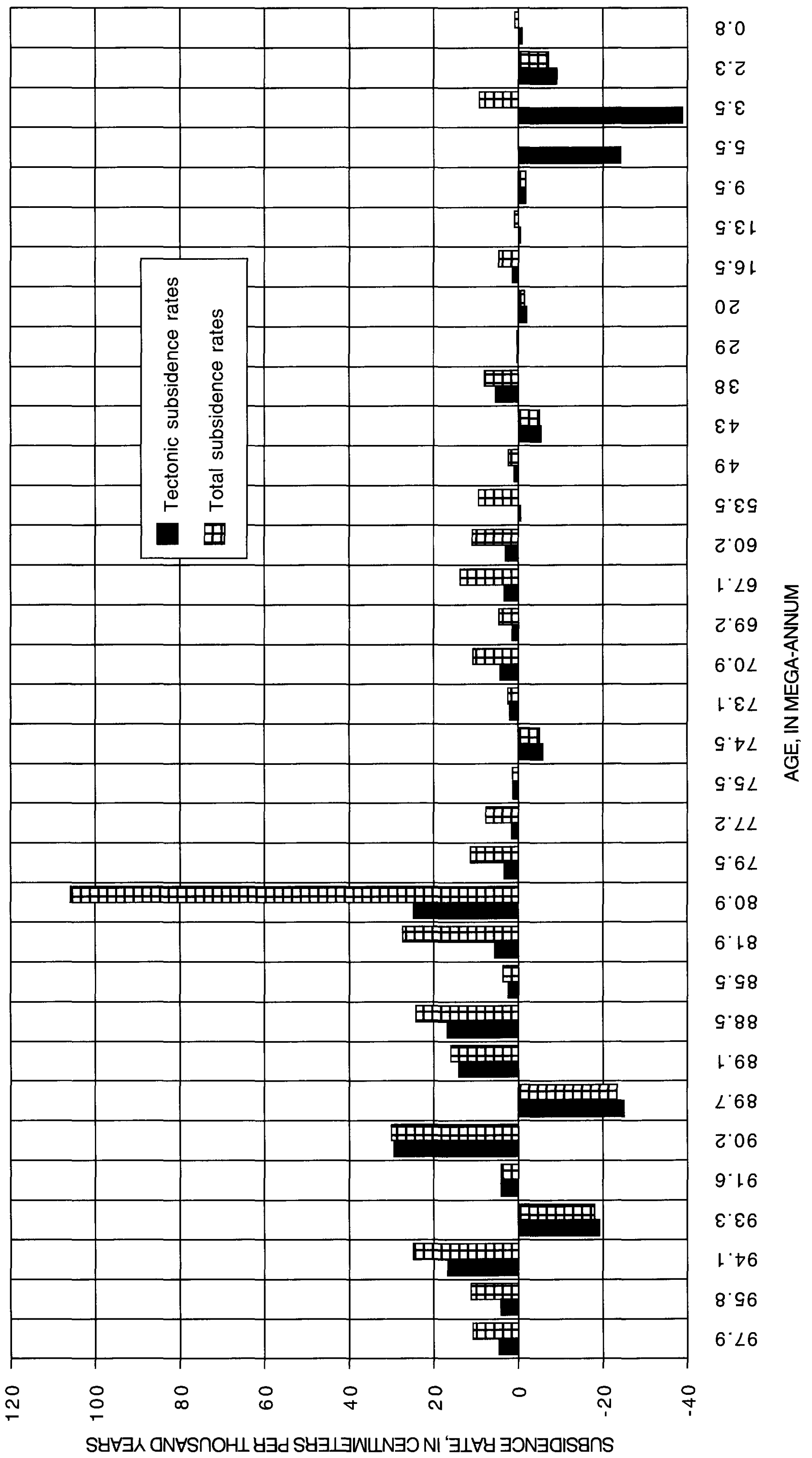


Figure 32. Approximate subsidence rates for Upper Cretaceous and Cenozoic strata, southeastern Natrona County, Wyoming.

Table 7. Tectonic subsidence of the base of Upper Cretaceous sequences in the Powder River Basin, northeastern Wyoming and southeastern Montana.

Northern Big Horn County		Northwestern Crook County		Southern Johnson County		Northeastern Niobrara County		Southeastern Natrona County	
Age (ma)	Subsidence of basement	Age (ma)	Subsidence of basement	Age (ma)	Subsidence of basement	Age (ma)	Subsidence of basement	Age (ma)	Subsidence of basement
65.4	523	65.4	306.3	65.4	761.8	65.4	681.3	65.4	760.7
--	--	--	--	--	--	--	--	68.8	648.3
--	--	--	--	--	--	68.9	510.1	--	
69.4	464.8	--	--	--	--	--	--	--	
--	--	--	--	--	--	--	--	69.6	637
--	--	--	--	--	--	69.7	502.1	--	
--	--	--	--	70	606.9	--	--	--	
70.3	512.2	--	--	70.3	632.5	--	--	--	
--	--	70.5	244.5	--	--	--	--	--	
--	--	71.2	212.8	--	--	--	--	--	
--	--	--	--	--	--	71.5	416.6	--	
--	--	72.2	157.7	--	--	--	--	72.2	524.5
--	--	--	--	72.3	421.1	--	--	--	
--	--	73	209.8	--	--	--	--	--	
--	--	--	--	--	--	73.2	338.2	--	
--	--	--	--	--	--	73.5	396.1	--	
--	--	73.7	220	--	--	--	--	--	
--	--	--	--	74	373	--	--	74	488.1
--	--	--	--	--	--	74.5	441.3	--	
--	--	--	--	75	562.1	--	--	75	546.4
--	--	--	--	75.9	533	--	--	--	
--	--	--	--	--	--	--	--	76	534.8
76.1	342.8	--	--	--	--	--	--	--	
--	--	76.2	154.7	--	--	--	--	--	
--	--	--	--	76.4	492	--	--	--	
--	--	--	--	--	--	76.6	339.1	--	
77.8	344	77.8	94.6	--	--	--	--	--	
--	--	--	--	--	--	78.3	258.7	78.3	500.4
--	--	--	--	78.7	465.9	--	--	--	
--	--	79	73.9	--	--	--	--	--	
--	--	80	154.3	--	--	--	--	--	
--	--	--	--	--	--	80.1	141.7	--	
--	--	80.6	140	80.6	398.7	--	--	--	
80.7	319.4	--	--	--	--	80.7	71.3	80.7	421.7
--	--	--	--	--	--	80.9	113	--	
--	--	--	--	--	--	--	--	81	347.5
--	--	--	--	81.1	363.9	--	--	--	
--	--	--	--	--	--	81.3	117.5	--	
--	--	--	--	--	--	82.3	131	--	
--	--	82.5	22.9	--	--	--	--	--	
--	--	--	--	82.8	234.6	--	--	82.8	248.1
--	--	85	-3.3	--	--	--	--	--	
85.7	197.1	--	--	--	--	--	--	--	
--	--	86.5	11	--	--	--	--	--	
--	--	87.5	16.6	--	--	--	--	--	
--	--	--	--	--	--	87.8	35.6	--	
--	--	--	--	--	--	88	86.8	--	
--	--	--	--	--	--	--	--	88.2	121.2
--	--	--	--	88.3	102.7	--	--	--	
88.4	97.9	--	--	--	--	--	--	--	

Table 7. Tectonic subsidence of the base of Upper Cretaceous sequences in the Powder River Basin, northeastern Wyoming and southeastern Montana--Continued.

Northern Big Horn County		Northwestern Crook County		Southern Johnson County		Northeastern Niobrara County		Southeastern Natrona County	
Age (ma)	Subsidence of basement	Age (ma)	Subsidence of basement	Age (ma)	Subsidence of basement	Age (ma)	Subsidence of basement	Age (ma)	Subsidence of basement
--	--	--	--	--	--	88.6	72.3	--	
--	--	--	--	--	--	--	--	88.8	20.5
--	--	89.2	-13.8	--	--	--	--	--	
--	--	--	--	89.3	5.4	89.3	31.8	--	
--	--	--	--	--	--	--	--	89.4	-63.8
--	--	89.9	-76.9	--	--	89.9	-83.2	--	
--	--	--	--	--	--	90	-5.5	90	86.3
--	--	90.2	-39.2	90.2	-48.7	--	--	--	
--	--	--	--	90.3	-0.8	--	--	--	
--	--	--	--	--	--	90.4	15.9	90.4	-31.4
--	--	90.5	-25.8	--	--	--	--	--	
92.3	81.6	92.3	-45.4	92.3	-32.1	92.3	9.8	--	
--	--	--	--	92.4	20.5	--	--	--	
--	--	--	--	92.6	18	--	--	--	
--	--	--	--	--	--	--	--	92.8	-127
--	--	93.3	-56.5	--	--	--	--	--	
93.7	51.7	93.7	-6.6	--	--	--	--	--	
--	--	--	--	--	--	--	--	93.8	64.7
--	--	94	-6.7	--	--	--	--	--	
--	--	--	--	--	--	94.3	-85.5	94.3	-18.6
--	--	--	--	--	--	94.4	-27.8	--	
--	--	--	--	--	--	94.8	-44	--	
97.2	-99	97.2	-137.3	97.2	-121.4	97.2	-147.8	97.2	-137.4
98.5	-198.1	98.5	-191.3	98.5	-198.1	98.5	-191.3	98.5	-198.1
--	--	--	--	--	--	--	--	--	

the west side of a north-trending epeiric sea at sedimentation rates ranging from about 2 cm (0.8 in.)/1,000 years to more than 30 cm (11.8 in.)/1,000 years. At two locations in the northern part of the basin, the average rates of sedimentation during the Late Cretaceous were 5.8 and 8.1 cm (2.3 and 3.2 in.)/1,000 years; at three locations in the southern part of the basin, the average rates of sedimentation ranged from 12.1 to 13.6 cm (4.8–5.4 in.)/1,000 years. This body of strata contains at least five important disconformities, and it records at least six major cycles of marine transgression and regression. According to the sequence stratigraphy of Haq and others (1987) and Van Wagoner and others (1990), these rocks include type-1 sequence boundaries within the Belle Fourche Member of the Frontier Formation, between the Belle Fourche and Emigrant Gap Members of the Frontier or the Emigrant Gap and Wall Creek Members of the Frontier, between the Gammon and Sharon Springs Members of the Pierre Shale, between the unnamed marine member and Teapot Member of the Mesaverde Formation, and within the Lance Formation.

During the Late Cretaceous, the basin region was affected by varying amounts of subsidence and by intermittent local and regional uplift. Total amounts of tectonic subsidence for the Series are 306 m (1,004 ft) in Crook County and 523 m (1,716 ft) in Big Horn County in the northern part of the basin and 681 m (2,234 ft) in Niobrara County and 761–762 m (2,497–2,500 ft) in Johnson and Natrona Counties in the southern part of the basin. Rates of tectonic subsidence are generally less than 9 cm (3.5 in.)/1,000 years, but they exceed 9 cm (3.5 in.)/1,000 years for upper Turonian beds in Niobrara, Johnson, and Natrona Counties, for lower and middle Campanian rocks in Niobrara and Natrona Counties, and for early Maastrichtian beds in Johnson County. Several of the tectonic subsidence rates are negative values and may reflect minor and local uplifts during the Campanian and Maastrichtian. Rates of total subsidence (tectonic subsidence+local loading subsidence) determined for Upper Cretaceous stratigraphic units at the five locations in the basin (table 6) include 27 values greater than 10 cm (3.9 in.)/1,000 years, 23 of which are from the three locations in the southern part of the basin.

Chronostratigraphic investigations of outcrops and extensive studies of geophysical borehole logs in eastern Wyoming indicate regional and local structural deformation during the Late Cretaceous. Large areas in central and southeastern Wyoming evidently were uplifted (Gill and Cobban, 1966b; Reynolds, 1976; Merewether and Cobban, 1985) at times during the early to middle Turonian (about 92.4 Ma), late Turonian (about 90.4–90 Ma), early Campanian (about 80.8 Ma), late Campanian (about 73 and 72 Ma), and latest Maastrichtian (65.4 Ma).

Structural deformation within the basin region apparently included small displacements along lineaments (Slack, 1981; Marrs and others, 1984; Martinsen and Marrs, 1985) in Cenomanian through early Campanian time (about 98.5–80.6 Ma), the related development of the northeast-trending Sheridan–Belle Fourche arch in the middle of the basin (fig. 28), possible arching in the southern part of the basin during the middle Coniacian (at about 88.5–87.8 Ma) (Weimer, 1984; Merewether and Cobban, 1985), and faulting or sharp flexing in the southeastern part of the basin during the early Campanian (about 83.5–80.6 Ma) (Asquith, 1970).

For the Upper Cretaceous Series in the Powder River Basin, the greatest thicknesses and highest rates of sedimentation and subsidence are in the southern part of the basin near areas of uplift and erosion. The most evident times of widespread subsidence in the southern part of the basin include the late Turonian, late early to early middle Campanian, early Maastrichtian, and late Maastrichtian. Periods of structural uplift in nearby areas to the south, mainly in southeastern Wyoming, were in the middle and late Turonian, early and late Campanian, early Maastrichtian, and latest Maastrichtian. Generally smaller uplifts probably developed intermittently within the basin region, at least during the late early to early middle Turonian (about 92.5 Ma), early late Turonian (about 90.3 Ma), early Campanian (about 80.7 Ma), late Campanian (about 73.2 Ma), and late early to early late Maastrichtian (about 69.5 Ma).

Periods of greater subsidence in the southern part of the basin seemingly correspond to periods of uplift in nearby areas of central and southeastern Wyoming. The greater thicknesses, sedimentation rates, and subsidence rates of the Upper Cretaceous Series in the southern part of the basin are apparently consequences of structural location; they indicate the recurrent subsidence of downwarps that adjoined uplifts to the south and perhaps minor northeast-trending uplifts to the north in the middle of the basin.

REFERENCES CITED

Asquith, D.O., 1970, Depositional topography and major marine environments, Late Cretaceous, Wyoming: American Association of Petroleum Geologists Bulletin, v. 54, no. 7, p. 1184–1224.

Barlow, J.A., Jr., and Haun, J.D., 1966, Regional stratigraphy of Frontier Formation and relation to Salt Creek field, Wyoming: American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2185–2196.

Barnett, V.H., 1915, Possibilities of oil in the Big Muddy Dome, Converse and Natrona Counties, Wyoming: U.S. Geological Survey Bulletin 581, p. 105–117.

Barron, E.J., 1989, Severe storms during Earth history: Geological Society of America Bulletin, v. 101, p. 601–612.

Barwin, J.R., 1959, Facies of the Mesaverde formation, east-central Wyoming: American Association of Petroleum Geologists, Rocky Mountain Section Geologic Record, February 1959, p. 139–142.

Berg, R.L., 1975, Depositional environment of Upper Cretaceous Sussex Sandstone, House Creek field, Wyoming: American Association of Petroleum Geologists Bulletin, v. 59, no. 11, p. 2099–2110.

Bitter, M.R., 1986, Origin of phosphatic nodules and cements in the Upper Cretaceous Frontier Formation, Natrona County, Wyoming: The Mountain Geologist, v. 23, no. 2, p. 45–50.

Breithaupt, B.H., 1985, Nonmammalian vertebrate faunas from the Late Cretaceous of Wyoming, *in* Nelson, G.E., ed., The Cretaceous geology of Wyoming: Wyoming Geological Association Annual Field Conference, 36th, 1985, Guidebook, p. 159–175.

Brenner, R.L., 1978, Sussex Sandstone of Wyoming—Example of Cretaceous offshore sedimentation: American Association of Petroleum Geologists Bulletin, v. 62, no. 2, p. 181–200.

Brown, Barnum, 1907, The Hell Creek beds of the upper Cretaceous of Montana; their relation to contiguous deposits, with faunal and floral lists, and a discussion of their correlation: American Museum of Natural History Bulletin, v. 23, art. 33, p. 823–845.

Burgess, J.D., 1971, Palynological interpretation of Frontier environments in central Wyoming: Geoscience and Man, v. 3, p. 69–82.

Burtner, R.L., and Warner, M.A., 1984, Hydrocarbon generation in Lower Cretaceous Mowry and Skull Creek shales of the northern Rocky Mountain area, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Denver, Rocky Mountain Association of Geologists, p. 449–467.

Byers, C.W., and Larson, D.W., 1979, Paleoenvironments of Mowry Shale (Lower Cretaceous), western and central Wyoming: American Association of Petroleum Geologists Bulletin, v. 63, no. 3, p. 354–375.

Cavanaugh, E.T., 1976, Stratigraphy of the Frontier Formation, Emigrant Gap anticline, Natrona County, Wyoming: Golden, Colorado School of Mines, M.S. thesis, 173 p.

Christie-Blick, Nicholas, 1990, Sequence stratigraphy and sea-level changes in Cretaceous time, *in* Ginsburg, R.N., and Beaudoin, B., eds., Cretaceous resources, events and rhythms: Netherlands, Kluwer Academic Publishers, p. 1–21.

Cobban, W.A., 1951a, Colorado shale of central and northwestern Montana and equivalent rocks of Black Hills: American Association of Petroleum Geologists Bulletin, v. 35, no. 10, p. 2170–2198.

———1951b, Scaphitoid cephalopods of the Colorado Group: U.S. Geological Survey Professional Paper 239, 42 p.

———1952, Cretaceous rocks on the north flank of the Black Hills uplift, *in* Sonnenberg, F.P., ed., Black Hills–Williston basin: Billings Geological Society Annual Field Conference, 3rd, September 4–7, 1952, Guidebook, p. 86–88.

———1958, Late Cretaceous fossil zones of the Powder River Basin, Wyoming and Montana, *in* Strickland, John, Byrne, Frank, and Barlow, James, eds., Powder River Basin: Wyoming Geological Association Annual Field Conference, 13th, Guidebook, p. 114–119.

———1984, Molluscan record from a mid-Cretaceous borehole in Weston County, Wyoming: U.S. Geological Survey Professional Paper 1271, 24 p.

———1987, Some middle Cenomanian (Upper Cretaceous) Acanthoceratid ammonites from the Western Interior of the United States: U.S. Geological Survey Professional Paper 1445, 28 p.

———1988a, Some acanthoceratid ammonites from Upper Cenomanian (Upper Cretaceous) rocks of Wyoming: U.S. Geological Survey Professional Paper 1353, 17 p.

———1988b, Tarrantoceras Stephenson and related ammonoid genera from Cenomanian (Upper Cretaceous) rocks in Texas and the Western Interior of the United States: U.S. Geological Survey Professional Paper 1473, 30 p.

———1990, Ammonites and some characteristic bivalves from the Upper Cretaceous Frontier Formation, Natrona County, Wyoming: U.S. Geological Survey Professional Paper 1917–B, 13 p.

Cobban, W.A., and Kennedy, W.J., 1989a, *Acompsoceras inconstans* zone, a lower Cenomanian marker horizon in Trans-Pecos Texas, U.S.A.: Neues Jahrbuch für Geologie und Palaontologie Abhandlungen, v. 178, p. 133–145.

———1989b, A note on the occurrence of *Allocrioceras billinghursti* Klinger, 1976 (Cretaceous Ammonoidea) in the middle Turonian of the Western Interior of the United States: Cretaceous Research, v. 10, p. 173–175.

Cobban, W.A., and Reeside, J.B., Jr., 1952, Correlation of the Cretaceous formations of the Western Interior of the United States: Geological Society of America Bulletin, v. 63, p. 1011–1044.

Collier, A.J., 1922, The Osage oil field, Weston County, Wyoming: U.S. Geological Survey Bulletin 736–D, p. 71–110.

Connor, C.W., 1992, The Lance Formation—Petrography and stratigraphy, Powder River Basin and nearby basins, Wyoming and Montana: U.S. Geological Survey Bulletin 1917–I, 17 p.

Couillard, R., and Irving, E., 1975, Palaeolatitude and reversals—Evidence from the Cretaceous period, *in* Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper 13, p. 21–29.

Crews, G.C., Barlow, J.A., Jr., and Haun, J.D., 1976, Upper Cretaceous Gammon, Shannon, and Sussex Sandstones, central Powder River Basin, Wyoming, *in* Laudon, R.B., Curry, W.H., III, and Runge, J.S., eds., Geology and energy resources of the Powder River: Wyoming Geological Association Annual Field Conference, 28th, 1976, Guidebook, p. 33–44.

Cross, Whitman, 1899, La Plata Folio: U.S. Geological Survey Geologic Atlas, Folio 60.

Curry, W.H., III, 1976a, Type section of the Teapot Sandstone, *in* Laudon, R.B., Curry, W.H., III, and Runge, J.S., eds., Geology and energy resources of the Powder River: Wyoming Geological Association Annual Field Conference, 28th, 1976, Guidebook, p. 29–32.

———1976b, Late Cretaceous Teapot delta of southern Powder River Basin, Wyoming, *in* Laudon, R.B., Curry, W.H., III, and Runge, J.S., eds., Geology and energy resources of the Powder River: Wyoming Geological Association Annual Field Conference, 28th, 1976, Guidebook, p. 21–28.

Darton, N.H., 1901, Geology and water resources of the southern half of the Black Hills and adjoining regions in South Dakota and Wyoming: U.S. Geological Survey Twenty-first Annual Report, 1899–1900, pt. 4–Hydrography, 599 p.

———1904a, Comparison of the stratigraphy of the Black Hills, Bighorn Mountains, and Rocky Mountain Front Range: Geological Society of America Bulletin, v. 15, p. 379–448.

———1904b, Description of the Newcastle quadrangle, Wyoming–South Dakota: U.S. Geological Survey Geologic Atlas, Folio 107, 9 p.

———1906, Geology of the Bighorn Mountains: U.S. Geological Survey Professional Paper 51, 129 p.

———1909, Geology and water resources of the northern portion of the Black Hills and adjoining regions in South Dakota and Wyoming: U.S. Geological Survey Professional Paper 65, 105 p.

Darton, N.H., and O'Harra, C.C., 1907, Description of the Devils Tower quadrangle, Wyoming: U.S. Geological Survey Geologic Atlas, Folio 150, 9 p.

Davis, H.R., and Byers, C.W., 1989, Shelf sandstones in the Mowry Shale—Evidence for deposition during Cretaceous sea level falls: Journal of Sedimentary Petrology, v. 59, no. 4, p. 548–560.

Davis, H.R., Byers, C.W., and Dean, W.E., 1988, Pyrite formation in the Lower Cretaceous Mowry Shale—Effect of organic matter type and reactive iron content: American Journal of Science, v. 288, p. 873–890.

Davis, H.R., Byers, C.W., and Pratt, L.M., 1989, Depositional mechanisms and organic matter in Mowry Shale (Cretaceous), Wyoming: American Association of Petroleum Geologists Bulletin, v. 73, no. 9, p. 1103–1116.

Davis, J.C., 1970, Petrology of Cretaceous Mowry Shale of Wyoming: American Association of Petroleum Geologists Bulletin, v. 54, no. 3, p. 487–502.

Davis, M.J.T., 1976, An environmental interpretation of the Upper Cretaceous Shannon Sandstone, Heldt Draw field, Wyoming, *in* Laudon, R.B., Curry, W.H., III, and Runge, J.S., eds., Geology and energy resources of the Powder River: Wyoming Geological Association Annual Field Conference, 28th, 1976, Guidebook, p. 125–138.

Dean, W.E., and Arthur, M.A., 1989, Iron-sulfur-carbon relationships in organic-carbon-rich sequences—I, Cretaceous

Western Interior seaway: American Journal of Science, v. 289, p. 708–743.

Dobbin, C.E., and Reeside, J.B., Jr., 1929, The contact of the Fox Hills and Lance formations: U.S. Geological Survey Professional Paper 158–B, p. 9–25.

Dogan, U.D., 1984, Stratigraphy, petrology, depositional and post-depositional histories and their effects upon reservoir properties of the Parkman Formation of the Mesaverde Group, Powder River Basin, Wyoming: Iowa City, University of Iowa, Ph.D. thesis, 265 p.

Dorf, Erling, 1942, Flora of the Lance formation at its type locality, Niobrara County, Wyoming, pt. 2 of Upper Cretaceous floras of the Rocky Mountain region: Carnegie Institute Washington Publication 508, p. 70–159.

Eicher, D.L., 1967, Foraminifera from Belle Fourche Shale and equivalents, Wyoming and Montana: Journal of Paleontology, v. 41, no. 1, p. 167–188.

Eicher, D.L., and Diner, Richard, 1985, Foraminifera as indicators of water mass in the Cretaceous Greenhorn sea, Western Interior, *in* Pratt, L.M., Kauffman, E.G., and Zelt, F.B., eds., Fine-grained deposits and biofacies of the Cretaceous Western Interior Seaway—Evidence of cyclic sedimentary processes: Society of Economic Paleontologists and Mineralogists Midyear Meeting, Golden, Colorado, Field Trip Guidebook 4, p. 60–71.

Ellis, C.H., 1963, Micropaleontology of the Mowry Shale, Newcastle Formation, and equivalent stratigraphic units, *in* Geology of the northern Denver Basin and adjacent uplifts: Rocky Mountain Association of Geologists Field Conference, 14th, Denver, p. 149–155.

Ericksen, M.C., and Slingerland, Rudy, 1990, Numerical simulations of tidal and wind-driven circulation in the Cretaceous interior seaway of North America: Geological Society of America Bulletin, v. 102, p. 1499–1516.

Evetts, M.J., 1976, Microfossil biostratigraphy of the Sage Breaks Shale (Upper Cretaceous) in northeastern Wyoming: The Mountain Geologist, v. 13, no. 4, p. 115–134.

Fouch, T.D., Lawton, T.F., Nichols, D.J., Cashion, W.B., and Cobban, W.A., 1983, Patterns and timing of synorogenic sedimentation in Upper Cretaceous rocks of central and northeast Utah, *in* Reynolds, M.W., and Dolly, E.D., eds., Mesozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Rocky Mountain Paleogeography Symposium 2, p. 305–336.

Fox, J.E., 1993a, Stratigraphic cross sections *A–A′* through *F–F′*, showing electric logs of Upper Cretaceous and older rocks, Powder River Basin, Montana and Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC–135.

———1993b, Stratigraphic cross sections *G–G′* through *L–L′*, showing electric logs of Upper Cretaceous and older rocks, Powder River Basin, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC–136.

———1993c, Stratigraphic cross sections *M–M′* through *R–R′*, showing electric logs of Upper Cretaceous and older rocks, Powder River Basin, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC–137.

———1993d, Stratigraphic cross sections *S–S′* through *V–V′*, showing electric logs of Upper Cretaceous and older rocks, Powder River Basin, Montana and Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC–138.

Fox, J.E., and Higley, D.K., 1987a, Thickness of Lower Cretaceous Mowry Shale, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 87–340–O.

———1987b, Thickness of Upper Cretaceous Greenhorn Formation, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 87–340–M.

———1987c, Thickness of the Upper Cretaceous Niobrara Formation, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 87–340–J.

———1987d, Thickness of Sussex Sandstone Member of the Upper Cretaceous Steele Shale, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 87–340–G.

———1987e, Thickness of Parkman Sandstone Member of the Upper Cretaceous Mesaverde Formation and the Redbird Silty Member of the Upper Cretaceous Pierre Shale, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 87–340–E.

———1987f, Thickness of Upper Cretaceous Mesaverde Formation, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 87–340–D.

———1987g, Thickness of the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 87–340–I.

———1987h, Thickness of Upper Cretaceous Lewis Shale, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 87–340–B.

Gill, J.R., and Burkholder, R.E., 1979, Measured sections of the Montana Group and equivalent rocks from Montana and Wyoming: U.S. Geological Survey Open-File Report 79–1143, 202 p.

Gill, J.R., and Cobban, W.A., 1961, Stratigraphy of lower and middle parts of the Pierre Shale, northern Great Plains: U.S. Geological Survey Professional Paper 424–D, p. D185–D191.

———1962, Red Bird Silty Member of the Pierre Shale, a new stratigraphic unit, *in* Short papers in geology, hydrology, and topography: U.S. Geological Survey Professional Paper 450–B, p. B21–B24.

———1966a, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming, *with a section on* A new Echinoid from the Cretaceous Pierre Shale of eastern Wyoming, by P.M. Kier: U.S. Geological Survey Professional Paper 393–A, p. A1–A73.

———1966b, Regional unconformity in Late Cretaceous, Wyoming: U.S. Geological Survey Professional Paper 550–B, p. B20–B27.

———1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U.S. Geological Survey Professional Paper 776, 37 p.

Gill, J.R., Merewether, E.A., and Cobban, W.A., 1970, Stratigraphy and nomenclature of some Upper Cretaceous and lower Tertiary rocks in south-central Wyoming: U.S. Geological Survey Professional Paper 667, 53 p.

Goodell, H.G., 1962, The stratigraphy and petrology of the Frontier formation of Wyoming, *in* Symposium on Early Cretaceous

Rocks of Wyoming and Adjacent Areas: Wyoming Geological Association Annual Field Conference, 17th, Guidebook, p. 173–210.

Hancock, J.M., 1975, The sequence of facies in the Upper Cretaceous of northern Europe compared with that in the Western Interior, *in* Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper 13, p. 83–118.

Hancock, J.M., and Kauffman, E.G., 1979, The great transgressions of the Late Cretaceous: Journal of the Geological Society (London), v. 136, p. 175–186.

Hansley, P.L., and Whitney, C.G., 1990, Petrology, diagenesis, and sedimentology of oil reservoirs in Upper Cretaceous Shannon Sandstone beds, Powder River Basin, Wyoming: U.S. Geological Survey Bulletin 1917–C, 33 p.

Haq, B.U., Hardenbol, Jan, and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.

Hares, C.J., 1916, Anticlines in central Wyoming: U.S. Geological Survey Bulletin 641–I, p. 233–279.

Hares, C.J., and others, 1946, Geologic map of the southeastern part of the Wind River Basin and adjacent areas in central Wyoming: U.S. Geological Survey Oil and Gas Investigations Preliminary Map 51, scale 1:126,720.

Hatcher, J.B., 1903, Relative age of the Lance (Ceratops) beds of Converse County, Wyoming, the Judith River beds of Montana, and the Belly River beds of Canada: American Geologist, v. 31, p. 369–375.

Haun, J.D., 1953, Stratigraphy of Frontier Formation, Powder River Basin, Wyoming: Laramie, University of Wyoming, Ph.D. thesis, 67 p.

———1958, Early Upper Cretaceous stratigraphy, Powder River Basin, Wyoming, *in* Strickland, John, Byrne, Frank, and Barlow, James, eds., Powder River Basin: Wyoming Geological Association Annual Field Conference, 13th, Guidebook, p. 84–89.

Headley, J.B., Jr., 1958, Oil in Mesaverde, Powder River Basin, Wyoming, *in* Strickland, John, Byrne, Frank, and Barlow, James, eds., Powder River Basin: Wyoming Geological Association Annual Field Conference, 13th, Guidebook, p. 103–108.

Heydenburg, R.J., 1966, Stratigraphy and depositional environment of the Parkman Sandstone member, Mesaverde Formation (Cretaceous), near Midwest, Natrona County, Wyoming: Laramie, University of Wyoming, M.S. thesis.

Higley, D.K., 1992, Petrology and reservoir paragenesis in the Sussex "B" Sandstone of the Upper Cretaceous Cody Shale, House Creek and Porcupine fields, Powder River Basin, Wyoming: U.S. Geological Survey Bulletin 1917–G, 16 p.

Hobson, J.P., Jr., Fowler, M.L., and Beaumont, E.A., 1982, Depositional and statistical exploration models, Upper Cretaceous offshore sandstone complex, Sussex Member, House Creek field, Wyoming: American Association of Petroleum Geologists Bulletin, v. 66, no. 6, p. 689–707.

Holmes, W.H., 1877, Report [on the San Juan district, Colorado]: U.S. Geological and Geographical Survey of the Territories, 9th Annual Report for 1875, p. 245, 248.

Horn, G.H., 1954, Geologic and structure contour map of the West Salt Creek oil field, Natrona County, Wyoming: U.S. Geological Survey, Conservation Division, unpublished administrative report (unnumbered map, scale 1:24,000).

Horton, M.D., 1953, Stratigraphy and structure of the Old Woman anticline, Niobrara County, Wyo.: Lincoln, University of Nebraska, M.S. thesis.

Hose, R.K., 1955, Geology of the Crazy Woman Creek area, Johnson County, Wyoming: U.S. Geological Survey Bulletin 1027–B, p. 33–118.

Hubert, J.F., Butera, J.G., and Rice, R.F., 1972, Sedimentology of Upper Cretaceous Cody-Parkman delta, southwestern Powder River Basin, Wyoming: Geological Society of America Bulletin, v. 83, no. 6, p. 1649–1670.

Huff, M.C., 1989, Transgressive parasequences in Cretaceous upper Frontier (Wall Creek) sandstone [abs.]: American Association of Petroleum Geologists Bulletin, v. 73, no. 9, p. 1161.

Huff, M.C., and Nummedal, Dag, 1990, Parasequence architecture in the Wall Creek Member of the Frontier Formation (Upper Cretaceous), Powder River Basin, Wyoming [abs.]: American Association of Petroleum Geologists Bulletin, v. 74, no. 8, p. 1328.

Isbell, E.B., Spencer, C.W., and Seitz, Tommie, 1976, Petroleum geology of the Well Draw field, Converse County, Wyoming, *in* Laudon, R.B., Curry, W.H., III, and Runge, J.S., eds., Geology and energy resources of the Powder River: Wyoming Geological Association Annual Field Conference, 28th, Guidebook, p. 165–174.

Keefer, W.R., 1965, Stratigraphy and geologic history of the uppermost Cretaceous, Paleocene, and lower Eocene rocks in the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495–A, 77 p.

Knechtel, M.M., and Patterson, S.H., 1956, Bentonite deposits in marine Cretaceous formations, Hardin district, Montana and Wyoming: U.S. Geological Survey Bulletin 1023, 116 p.

———1962, Bentonite deposits of the northern Black Hills district, Wyoming, Montana, and South Dakota: U.S. Geological Survey Bulletin 1082–M, p. 893–1030.

Knight, W.C., 1902, The petroleum fields of Wyoming III: The Engineering and Mining Journal, v. 73, p. 720–723.

Lanphere, M.A., and Jones, D.L., 1978, Cretaceous time scale from North America, *in* Cohee, G.V., Glaessner, M.F., and Hedberg, H.D., eds., Contributions to the geologic time scale: American Association of Petroleum Geologists Studies in Geology 6, p. 259–268.

Lillegraven, J.A., and Ostresh, L.M., Jr., 1990, Late Cretaceous (earliest Campanian/Maastrichtian) evolution of western shorelines of the North American Western Interior Seaway in relation to known mammalian faunas: Geological Society of America Special Paper 243, 30 p.

Lupton, C.T., 1916, Oil and gas near Basin, Big Horn County, Wyoming: U.S. Geological Survey Bulletin 621–L, pt. 2, p. 157–190.

Macdonald, R.H., and Byers, C.W., 1988, Depositional history of the Greenhorn Formation (Upper Cretaceous), northwestern Black Hills: The Mountain Geologist, v. 25, no. 3, p. 71–85.

Mapel, W.J., 1959, Geology and coal resources of the Buffalo–Lake DeSmet area, Johnson and Sheridan

Counties, Wyoming: U.S. Geological Survey Bulletin 1078, 148 p.

Marrs, R.W., Martinsen, R.S., and Raines, G.L., 1984, Regional structure and facies control in the Powder River Basin, Wyoming and Montana, interpreted from satellite imagery: International Symposium on Remote Sensing of Environment, Third Thematic Conference, Remote Sensing for Exploration Geology, Colorado Springs, Colorado, April 16–19, 1984, Proceedings; Environmental Research Institute of Michigan, p. 25–34.

Martinsen, R.S., and Marrs, R.W., 1985, Comparison of major lineament trends to sedimentary rock thicknesses and facies distribution, Powder River Basin, Wyoming: International Symposium on Remote Sensing of Environment, Fourth Thematic Conference, Remote Sensing for Exploration Geology, San Francisco, California, April 1–4, 1985, Proceedings, p. 9–19.

Massare, J.A., and Dain, L.E., 1989, The marine reptiles of the Mowry Shale (Albian) of northeastern Wyoming [abs.]: Journal of Vertebrate Paleontology, v. 9, supplement to no. 3, p. 32A.

McGookey, D.P., Haun, J.D., Hale, L.A., Goodell, H.G., McCubbin, D.G., Weimer, R.J., and Wulf, G.R., 1972, Cretaceous System, *in* Mallory, W.W., ed., Geologic atlas of the Rocky Mountain region, United States of America: Denver, Rocky Mountain Association of Geologist, p. 190–228.

Meek, F.B., and Hayden, F.V., 1862, Description of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska Territory * * *, with some remarks on the rocks from which they were obtained: Philadelphia Academy of Natural Sciences Proceedings 1861, v. 13, p. 415–447.

Mello, J.F., 1971, Foraminifera from the Pierre Shale (Upper Cretaceous) at Red Bird, Wyoming: U.S. Geological Survey Professional Paper 393–C, 54 p.

Merewether, E.A., 1980, Stratigraphy of mid-Cretaceous formations at drilling sites in Weston and Johnson Counties, northeastern Wyoming: U.S. Geological Survey Professional Paper 1186–A, 25 p.

———1983, The Frontier Formation and mid-Cretaceous orogeny in the foreland of southwestern Wyoming: The Mountain Geologist, v. 20, no. 4, p. 121–138.

Merewether, E.A., and Claypool, G.E., 1980, Organic composition of some Upper Cretaceous shale, Powder River Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 64, no. 4, p. 488–500.

Merewether, E.A., and Cobban, W.A., 1973, Stratigraphic sections of the Upper Cretaceous Frontier Formation near Casper and Douglas, Wyoming: Wyoming Geological Association Earth Science Bulletin (Guidebook Issue), v. 6, no. 4, p. 38–39.

———1985, Tectonism in the mid-Cretaceous foreland, southeastern Wyoming and adjoining areas, *in* Nelson, G.E., ed., The Cretaceous geology of Wyoming: Wyoming Geological Association Annual Field Conference, 36th, 1985, Guidebook, p. 67–73.

———1986a, Biostratigraphic units and tectonism in the mid-Cretaceous foreland of Wyoming, Colorado, and adjoining areas, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 443–468.

———1986b, Evidence of mid-Cretaceous tectonism in the Frontier Formation, Natrona County, Wyoming: Wyoming Geological Association Earth Science Bulletin, v. 19, pt. 2, p. 142–152.

Merewether, E.A., Cobban, W.A., and Cavanaugh, E.T., 1979, Frontier Formation and equivalent rocks in eastern Wyoming: The Mountain Geologist, v. 6, no. 3, p. 67–102.

Merewether, E.A., Cobban, W.A., Matson, R.M., and Magathan, W.J., 1977a, Stratigraphic diagrams with electric logs of Upper Cretaceous rocks, Powder River Basin, Natrona, Campbell, and Weston Counties, Wyoming, section *B–B'*: U.S. Geological Survey Oil and Gas Investigations Map OC–74.

———1977b, Stratigraphic diagrams with electric logs of Upper Cretaceous rocks, Powder River Basin, Natrona, Converse, and Niobrara Counties, Wyoming, section *C–C'*: U.S. Geological Survey Oil and Gas Investigations Map OC–75.

———1977c, Stratigraphic diagrams with electric logs of Upper Cretaceous rocks, Powder River Basin, Sheridan, Johnson, Campbell, and Converse Counties, Wyoming, section *D–D'*: U.S. Geological Survey Oil and Gas Investigations Map OC–76.

Merewether, E.A., Cobban, W.A., and Spencer, C.W., 1976, The Upper Cretaceous Frontier Formation in the Kaycee-Tisdale Mountain area, Johnson County, Wyoming, *in* Laudon, R.B., Curry, W.H., III, and Runge, J.S., eds., Geology and energy resources of the Powder River: Wyoming Geological Association Annual Field Conference, 28th, 1976, Guidebook, p. 33–44.

Moore, R.C., 1949, Meaning of facies, in Longwell, C.R., ed., Sedimentary facies in geologic history: Geological Society of America Memoir 39, p. 1–39.

Moxon, A.L., Olson, O.E., and Searight, W.V., 1939, Selenium in rocks, soils, and plants: South Dakota Agricultural Experimental Station Technical Bulletin 2, 94 p.

Nace, R.L., 1941, A new ichthyosaur from the Late Cretaceous, northeast Wyoming: American Journal of Science, v. 239, p. 908–914.

Newton, Henry, and Jenney, W.P., 1880, Geology and resources of the Black Hills of Dakota: U.S. Geographical and Geological Survey of the Rocky Mountain Region, 566 p.

Nixon, R.P., 1973, Oil source beds in Cretaceous Mowry Shale of northwestern interior United States: American Association of Petroleum Geologists Bulletin, v. 57, no. 1, p. 136–161.

Obradovich, J.D., 1988, A different perspective on glauconite as a chronometer for geologic time scale studies: Paleoceanography, v. 3, no. 6, p. 757–770.

———1993, A Cretaceous time-scale, *in* Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geological Association of Canada Special Paper 39, p. 379–396.

Obradovich, J.D., and Cobban, W.A., 1975, A time-scale for the Late Cretaceous of the Western Interior of North America, *in* Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper 13, p. 31–54.

Okumura, T.A., 1994, Palynostratigraphy and paleoecology of mid-Cretaceous formations at drilling sites in Weston and Johnson Counties, Powder River Basin, Wyoming: Boulder, University of Colorado, Ph.D. thesis, 289 p.

Parker, J.M., 1958, Stratigraphy of the Shannon Member of the Eagle Formation and its relationship to other units in the Montana Group in the Powder River Basin, Wyoming and Montana, *in* Strickland, John, Byrne, Frank, and Barlow, James, eds., Powder River Basin: Wyoming Geological Association Annual Field Conference, 13th, Guidebook, p. 90–102.

Parrish, J.T., and Barron, E.J., 1986, Paleoclimates and economic geology: Society of Economic Paleontologists and Mineralogists Lecture Notes for Short Course 18, 162 p.

Peterson, J.A., 1958, Paleotectonic control of marine Jurassic sedimentation in the Powder River Basin, *in* Strickland, John, Byrne, Frank, and Barlow, James, eds., Powder River Basin: Wyoming Geological Association Annual Field Conference, 13th, Guidebook, p. 56–63.

Pryor, W.A., 1961, Petrography of Mesaverde sandstones in Wyoming, *in* Wiloth, G.J., Hale, L.A., Randall, A.G., and Garrison, Lewis, eds., Symposium on Late Cretaceous Rocks, Wyoming and Adjacent Areas: Wyoming Geological Association Annual Field Conference, 16th, Guidebook, p. 34–46.

Purcell, T.E., 1961, The Mesaverde Formation of the northern and central Powder River Basin, Wyoming, *in* Wiloth, G.J., Hale, L.A., Randall, A.G., and Garrison, Lewis, eds., Symposium on Late Cretaceous Rocks, Wyoming and Adjacent Areas: Wyoming Geological Association Annual Field Conference, 16th, Guidebook, p. 219–228.

Reeside, J.B., Jr., and Cobban, W.A., 1960, Studies of the Mowry Shale (Cretaceous) and contemporary formations in the United States and Canada: U.S. Geological Survey Professional Paper 355, 126 p.

Reynolds, M.W., 1976, Influence of recurrent Laramide structural growth on sedimentation and petroleum accumulation, Lost Soldier area, Wyoming: American Association of Petroleum Geologists Bulletin, v. 60, no. 1, p. 12–33.

Rice, D.D., and Keighin, C.W., 1989, Configuration of shelf sandstone oil reservoirs, Upper Cretaceous (Turonian) Turner Sandy Member of Carlile Shale, Powder River Basin, Wyoming [abs.]: American Association of Petroleum Geologists Bulletin, v. 73, no. 3, p. 405.

Rice, D.D., and Shurr, G.W., 1980, Shallow, low-permeability reservoirs of northern Great Plains—Assessment of their natural gas resources: American Association of Petroleum Geologists Bulletin, v. 64, no. 7, p. 969–987.

———1983, Patterns of sedimentation and paleogeography across the Western Interior seaway during time of deposition of Upper Cretaceous Eagle Sandstone and equivalent rocks, northern Great Plains, *in* Reynolds, M.W., and Dolly, E.D., eds., Mesozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Rocky Mountain Paleogeography Symposium, 2nd, p. 337–358.

Rich, E.I., 1962, Reconnaissance geology of Hiland–Clarkson Hill area, Natrona County, Wyoming: U.S. Geological Survey Bulletin 1107–G, p. 447–540.

Richards, P.W., 1955, Geology of the Bighorn Canyon–Hardin area, Montana and Wyoming: U.S. Geological Survey Bulletin 1026, 93 p.

Roberts, A.E., 1972, Cretaceous and early Tertiary depositional and tectonic history of the Livingston area, southwestern Montana: U.S. Geological Survey Professional Paper 526–C, 120 p.

Robinson, C.S., Mapel, W.J., and Bergendahl, M.H., 1964, Stratigraphy and structure of the northern and western flanks of the Black Hills uplift, Wyoming, Montana, and South Dakota: U.S. Geological Survey Professional Paper 404, 134 p.

Robinson, C.S., Mapel, W.J., and Cobban, W.A., 1959, Pierre Shale along western and northern flanks of Black Hills, Wyoming and Montana: American Association of Petroleum Geologists Bulletin, v. 43, no. 1, p. 101–123.

Rubey, W.W., 1929, Origin of the siliceous Mowry shale of the Black Hills region: U.S. Geological Survey Professional Paper 154–D, p. 153–170.

———1930, Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region: U.S. Geological Survey Professional Paper 165–A, p. 1–54.

Runge, J.S., Wicker, W.L., and Eckelberg, D.J., 1973, A subsurface type section of the Teckla Sand Member of the Lewis Shale Formation: Wyoming Geological Association Earth Science Bulletin, v. 6, no. 3, p. 3–18.

Schultz, L.G., Tourtelot, H.A., Gill, J.R., and Boerngen, J.G., 1980, Composition and properties of the Pierre Shale and equivalent rocks, northern Great Plains region: U.S. Geological Survey Professional Paper 1064–B, 114 p.

Seeland, D.A., 1988, Laramide paleogeographic evolution of the eastern Powder River Basin, Wyoming and Montana, *in* Diedrich, R.P., and others, eds., Eastern Powder River Basin–Black Hills: Wyoming Geological Association Field Conference, 39th, Guidebook, p. 29–34.

Shurr, G.W., 1984, Geometry of shelf sandstone bodies in the Shannon Sandstone of southeastern Montana, *in* Tillman, R.W., and Siemers, C.T., eds., Siliciclastic shelf sediments: Society of Economic Paleontologists and Mineralogists Special Publication 34, p. 63–83.

Shurr, G.W., and Rice, D.D., 1986, Paleotectonic controls on deposition of the Niobrara Formation, Eagle Sandstone, and equivalent rocks (Upper Cretaceous), Montana and South Dakota, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 193–211.

Skolnick, Herbert, 1958, Lower Cretaceous Foraminifera of the Black Hills area: Journal of Paleontology, v. 32, no. 2, p. 275–285.

Slack, P.B., 1981, Paleotectonics and hydrocarbon accumulation, Powder River Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 65, no. 4, p. 730–743.

Spearing, D.R., 1976, Upper Cretaceous Shannon Sandstone—An offshore, shallow-marine sand body, *in* Laudon, R.B., Curry, W.H., III, and Runge, J.S., eds., Geology and energy resources of the Powder River: Wyoming Geological Association Annual Field Conference, 28th, Guidebook, p. 65–72.

Stanton, T.W., 1910, Fox Hills sandstone and Lance formation ("Ceratops beds") in South Dakota, North Dakota, and eastern Wyoming: American Journal of Science, 4th series, v. 30, no. 177, p. 172–188.

Thom, W.T., Jr., Hall, G.M., Wegemann, C.H., and Moulton, G.F., 1935, Geology of Big Horn County and the Crow Indian Reservation, Montana: U.S. Geological Survey Bulletin 856, 200 p.

Tillman, R.W., and Almon, W.R., 1979, Diagenesis of Frontier Formation offshore bar sandstones, Spearhead Ranch Field, Wyoming, *in* Scholle, P.A., and Schluger, P.R., eds., Aspects of diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication 26, p. 337–378.

Tillman, R.W., and Martinsen, R.S., 1984, The Shannon shelf-ridge sandstone complex, Salt Creek anticline area, Powder River Basin, Wyoming, *in* Tillman, R.W., and Siemers, C.T., eds., Siliciclastic shelf sediments: Society of Economic Paleontologists and Mineralogists Special Publication 34, p. 85–142.

Tourtelot, H.A., and Cobban, W.A., 1968, Stratigraphic significance and petrology of phosphate nodules at base of Niobrara Formation, east flank of Black Hills, South Dakota: U.S. Geological Survey Professional Paper 594–L, 22 p.

Towse, Donald, 1952, Frontier Formation, southwest Powder River Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 36, no. 10, p. 1962–2010.

Upchurch, G.R., Jr., and Wolfe, J.A., 1987, Mid-Cretaceous to early Tertiary vegetation and climate—Evidence from fossil leaves and woods, *in* Friis, E.M., Chaloner, W.G., and Crane, P.R., eds., The origin of angiosperms and their biological consequences: Cambridge, Cambridge University Press, p. 75–105.

U.S. Geological Survey, 1974, Selected stratigraphic sections and electric logs of Upper Cretaceous rocks in the Powder River Basin, Wyoming: U.S. Geological Survey Open-File Report, 11 sheets.

Van Houten, F.B., 1962, Frontier Formation, Bighorn Basin, Wyoming, *in* Symposium on Early Cretaceous Rocks of Wyoming and Adjacent Areas: Wyoming Geological Association Annual Field Conference, 17th, Guidebook, p. 221–231.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops—Concepts for high-resolution correlation of time and facies: American Association of Petroleum Geologists Methods in Exploration Series, no. 7, 55 p.

Wegemann, C.H., 1911, The Salt Creek oil field, Wyoming: U.S. Geological Survey Bulletin 452, p. 37–38.

———1912, The Sussex coal field, Johnson, Natrona, and Converse Counties, Wyoming: U.S. Geological Survey Bulletin 471–F, pt. II, p. 441–471.

———1918, The Salt Creek oil field, Wyoming: U.S. Geological Survey Bulletin 670, 52 p.

Weimer, R.J., 1984, Relation of unconformities, tectonics, and sea-level changes, Cretaceous of Western Interior, U.S.A., *in* Schlee, J.S., ed., Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Memoir 36, p. 7–35.

Weimer, R.J., and Flexer, Akiva, 1985, Depositional patterns and unconformities, Upper Cretaceous, eastern Powder River Basin, Wyoming, *in* Nelson, G.E., ed., The Cretaceous geology of Wyoming: Wyoming Geological Association Annual Field Conference, 36th, Casper, Wyoming, Guidebook, p. 131–147.

Whitfield, R.P., 1877, Preliminary report on the paleontology of the Black Hills, containing descriptions of new species of fossils from the Potsdam, Jurassic, and Cretaceous formations of the Black Hills of Dakota: U.S. Geographical and Geological Survey Rocky Mountain Region (Powell), 49 p.

Williams, G.D., and Stelck, C.R., 1975, Speculations on the Cretaceous palaeogeography of North America, *in* Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper 13, p. 1–20.

Wilmarth, M.G., 1938, Lexicon of geologic names of the United States: U.S. Geological Survey Bulletin 896, 2,396 p.

Wilson, J.B., 1951, Stratigraphy of the Sussex sandstone, Powder River Basin, Wyo.: Wyoming Geological Survey Report of Investigations 3, p. 3–11.

Winn, R.D., Jr., 1986, Marine deposition of the Frontier Formation at Emigrant Gap and Coal Creek areas, Powder River Basin: Wyoming Geological Association Earth Science Bulletin, v. 19, pt. 2, p. 157–164.

———1991, Storm deposition in marine sand sheets: Wall Creek Member, Frontier Formation, Powder River Basin, Wyoming: Journal of Sedimentary Petrology, v. 61, p. 86–101.

Wolfe, J.A., and Upchurch, G.R., Jr., 1986, Vegetation, climatic and floral changes at the Cretaceous-Tertiary boundary: Nature, v. 324, no. 6093, p. 148–152.

Published in the Central Region, Denver, Colorado
Manuscript approved for publication July 25, 1995
Edited by Judith Stoeser
Graphics by Gayle M. Dumonceaux
Photocomposition by Gayle M. Dumonceaux

☆ U.S. GOVERNMENT PRINTING OFFICE: 1996 - 774-045 / 20032 REGION NO. 8

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

'eriodicals

Earthquakes & Volcanoes (issued bimonthly).

Preliminary Determination of Epicenters (issued monthly).

'echnical Books and Reports

Professional Papers are mainly comprehensive scientific reports f wide and lasting interest and importance to professional scientists and ngineers. Included are reports on the results of resource studies and of pographic, hydrologic, and geologic investigations. They also include llections of related papers addressing different aspects of a single sci- ntific topic.

Bulletins contain significant data and interpretations that are of isting scientific interest but are generally more limited in scope or geo- raphic coverage than Professional Papers. They include the results of re- ource studies and of geologic and topographic investigations; as well as ollections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present sig- ificant interpretive results of hydrologic investigations of wide interest professional geologists, hydrologists, and engineers. The series covers vestigations in all phases of hydrology, including hydrology, availabil- y of water, quality of water, and use of water.

Circulars present administrative information or important scientif- c information of wide popular interest in a format designed for distribu- on at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an inter- retive nature made available to the public outside the formal USGS pub- cations series. Copies are reproduced on request unlike formal USGS ublications, and they are also available for public inspection at deposi- ories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, nd other material that are made available for public consultation at de- ositories. They are a nonpermanent form of publication that may be cit- d in other publications as sources of information.

laps

Geologic Quadrangle Maps are multicolor geologic maps on to- ographic bases in 7 1/2- or 15-minute quadrangle formats (scales main- y 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering eology. Maps generally include brief texts; some maps include structure nd columnar sections only.

Geophysical Investigations Maps are on topographic or planimet- ic bases at various scales, they show results of surveys using geophysical echniques, such as gravity, magnetic, seismic, or radioactivity, which re- lect subsurface structures that are of economic or geologic significance. lany maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or opographic bases of regular and irregular areas at various scales; they resent a wide variety of format and subject matter. The series also in- ludes 7 1/2-minute quadrangle photogeologic maps on planimetric ases which show geology as interpreted from aerial photographs. The eries also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; the principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from USGS Map Distribution, Box 25286, Building 810, Denver Federal Center, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879-1961" may be purchased by mail and over the counter in paperback book form and as a set microfiche.

"Publications of the Geological Survey, 1962-1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971-1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" is available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.–Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849