Frontier, Cody, and Mesaverde Formations in the Wind River and Southern Bighorn Basins, Wyoming

GEOLOGICAL SURVEY PROFESSIONAL PAPER 495-E

Prepared in cooperation with the Geological Survey of Wyoming and the Department of Geology of the University of Wyoming as part of a program of the Department of the Interior for development of the Missouri River basin

Keefer—FRONTIER, CODY, AND MESAVERDE FORMATIONS, WIND RIVER AND BIGHORN BASINS, WYOMING—Geological Survey Professional Paper 495-E

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By WILLIAM R. KEEFER

GEOLOGY OF THE WIND RIVER BASIN, CENTRAL WYOMING

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By WILLIAM R. KEEFER

ABSTRACT

The Upper Cretaceous Frontier, Cody, and Mesaverde Formations compose a thick sequence of sedimentary rocks deposited during the final major transgression and regression of the epicontinental sea in central Wyoming. These rocks consist of a complexly intertongued succession of marine, brackish, deltaic, and fluviatile strata in which individual units show pronounced changes in thickness, lithology, and age across the Wind River and southern Bighorn Basins.

The Frontier Formation, of both marine and nonmarine origin, is an alternating sequence of sandstone and shale. The formation is of varied thickness, ranging from 470 to 1,045 feet, because it intertongues with adjacent strata of both the underlying Mowry Shale and the overlying Cody Shale. Three conspicuous zones of sandstone, referred to by petroleum geologists as the "First, Second, and Third Wall Creek sands," are present at most localities in the Wind River Basin. In the southern Bighorn Basin the Peay and Torchlight Sandstone Members are the base and top of the formation, respectively. Despite lateral changes in lithology, several other discrete stratigraphic intervals were also traced over wide areas, largely on the basis of electric-log correlations. In terms of the composite reference sequence of Upper Cretaceous rocks in the western interior region, the Frontier contains equivalents of the following formations in the areas indicated: (1) western Wind River Basin—Belle Fourche Shale, Greenhorn Limestone, Carlile Shale, and lower part of the Niobrara Formation, (2) eastern Wind River Basin—Belle Fourche Shale, Greenhorn Limestone, and Carlile Shale, and (3) southern Bighorn Basin—Belle Fourche Shale and lower part of the Greenhorn Limestone.

The marine Cody Shale consists predominantly of shale in its lower part and of interbedded shale and sandstone in its upper part; its thickness ranges from 3,150 to 4,700 feet. In two zones, one across the central part of the region of study and the other across the eastern part, extensive westward-projecting tongues of the Cody are intercalated with eastward-projecting tongues of the Mesaverde Formation. The zones of intertonguing trend nearly north and are as much as 40 miles wide. Intertonguing units in the eastern zone are the Fales Sandstone Member of the Mesaverde and the overlying Wallace Creek Tongue of the Cody Shale; in places, the Wallace Creek Tongue is included with the Mesaverde Formation for mapping convenience. The basal part of the Cody ranges in age from early Niobrara in approximately the western part of the Wind River Basin to probable late Carlile in the eastern part. In the southern Bighorn Basin the formation incorporates beds as old as early Greenhorn. Conversely, the uppermost Cody strata become progressively younger eastward across the region; it contains equivalents of late Niobrara age toward the west and early Pierre age toward the east.

The largely nonmarine Mesaverde Formation consists of 550 to at least 2,000 feet of interbedded sandstone, shale, and carbonaceous beds. A typical section in the eastern part of the Wind River Basin consists, in descending order, of: (1) the Teapot Sandstone Member, (2) an unnamed middle member, (3) the Parkman Sandstone Member, (4) the Wallace Creek Tongue (of the Cody Shale), and (5) the Fales Sandstone Member. Conspicuous sandstone units also occur at the top and base of the Mesaverde at most other localities, but the Teapot Sandstone Member is generally the only unit to be formally designated elsewhere in the region. A local, and perhaps regional, erosional unconformity separates the Teapot from the older strata. The bulk of the Mesaverde Formation is equivalent in age to some of the lower and middle members of the Pierre Shale in terms of the western interior reference sequence, but toward the west the lowermost beds are as old as strata in the upper part of the Niobrara Formation.

The Frontier Formation, deposited in a wide variety of onshore and offshore environments, records a limited eastward withdrawal of the sea across central Wyoming at the beginning of Late Cretaceous time. The Cody Shale represents a major westward transgression, and the Mesaverde Formation the ensuing eastward regression. Clastic debris was derived chiefly from the west and northwest. A minor readvance of the sea (represented by the Lewis Shale) took place following Mesaverde deposition but was limited to the eastern parts of the Wind River and Bighorn Basins.

Thickness maps of units indicate that an incipient downwarp formed along the present north and northeast margins of the Wind River Basin during deposition of the Frontier, Cody, and Mesaverde Formations. The position of this shallow trough coincides closely with the area in which the greatest amount of basin subsidence took place during the major phases of Laramide deformation in latest Cretaceous and early Tertiary times. Incipient upwarps formed contemporaneously along the south and northwest margins of the basin, perhaps reflecting early growth of segments of the Granite Mountains and Wind River Range, respectively, and of related Laramide anticlinal trends. The Owl Creek

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Mountains and Casper arch along the north and east margins, on the other hand, are not reflected by the isopachs. Rock units thin northward into the southern part of the Bighorn Basin, and that area apparently remained a fairly shallow shelf area throughout the depositional period.

INTRODUCTION

The Upper Cretaceous Frontier, Cody, and Mesaverde Formations compose a thick sequence of sedimentary strata that was deposited during the final major transgression and regression of the epicontinental sea in central and western Wyoming. Owing to both academic and economic interest, this complex group of rocks has been studied extensively for many years, resulting in the accumulation of abundant basic data concerning lithologies, invertebrate faunas, and depositional histories throughout the region. Many of these data were obtained by the U.S. Geological Survey during a systematic program of detailed geologic mapping and stratigraphic studies in the Wind River Basin (fig. 1) begun in the early 1940's. The synthesis of these data and other pertinent information, supplemented by the examination and interpretation of numerous well logs, forms the basis of this report.

Many individuals have contributed materially to this study; specific contributions are cited in the appropriate sections of the text. However, I wish to mention particularly the comprehensive work on the Upper Cretaceous rocks of Wyoming and adjacent States by W. A. Cobban, J. R. Gill, and the late J. B. Reeside, Jr. Their investigations have provided a fundamental understanding of the stratigraphic and paleontological relations of these strata throughout the Rocky Mountain region. Their basic data and

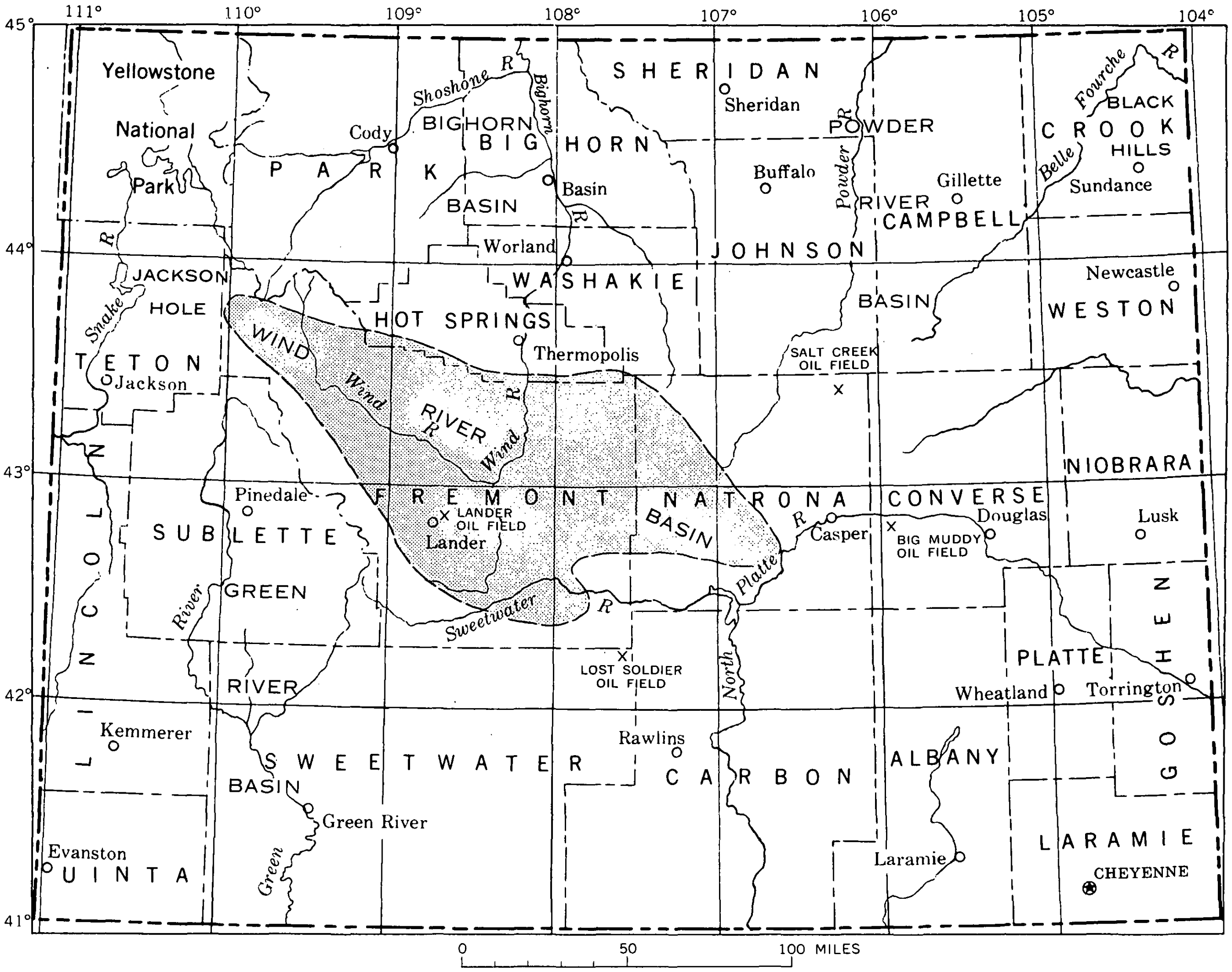


FIGURE 1.—Index map of Wyoming showing Wind River Basin (stippled) and other areas mentioned in text.

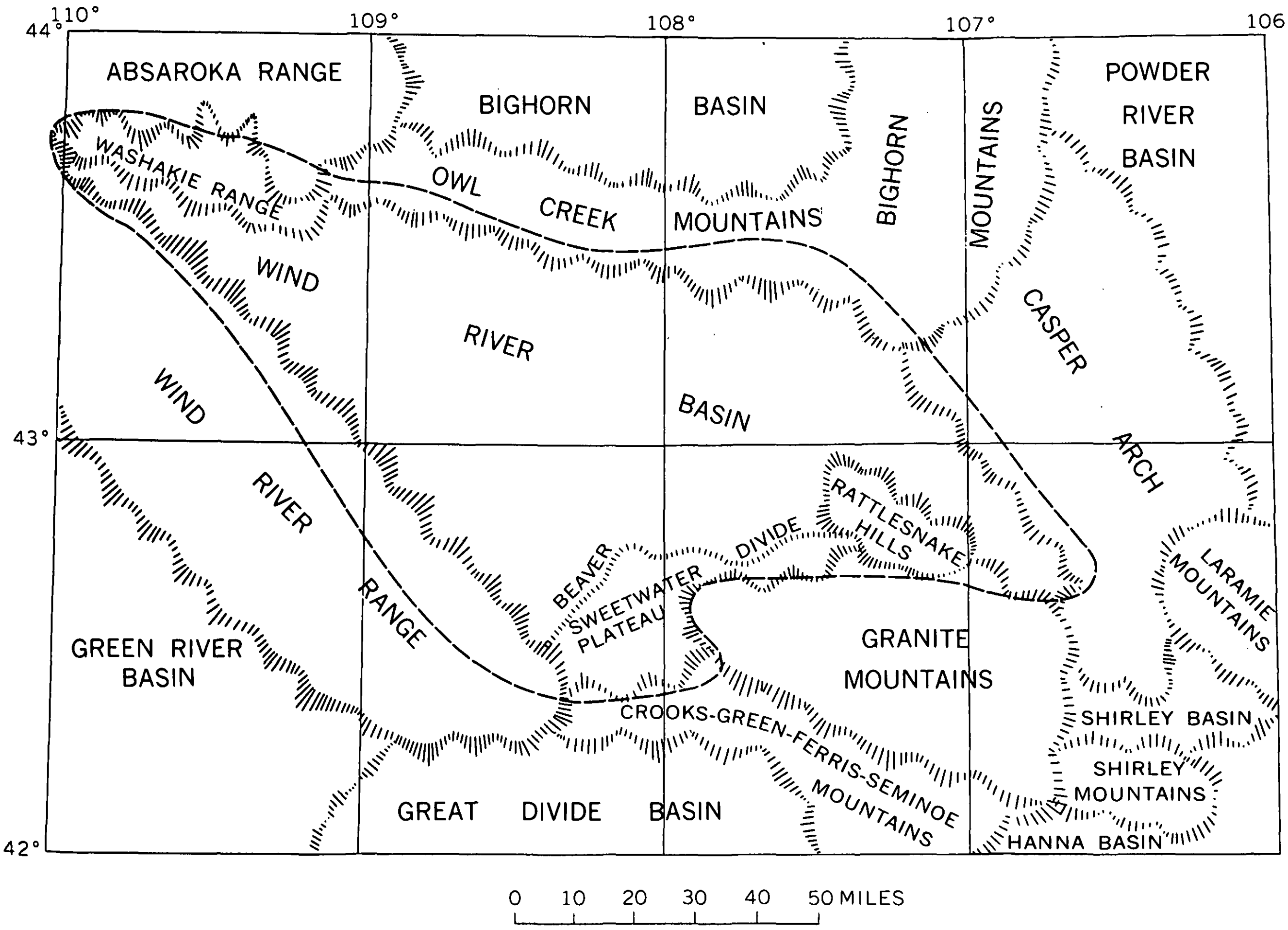


FIGURE 2.—Major physiographic and structural features in central Wyoming. Dashed line indicates approximate outline of Wind River structural basin.

interpretations have been especially valuable in this study of the Frontier, Cody, and Mesaverde Formations in the Wind River Basin.

The present report is one of a series designed to cover all major aspects of the stratigraphy, structure, and geologic history of the Wind River Basin. Previous publications (Keefer, 1965, 1966, 1970; Love, 1970) contain descriptions of the principal geographic and geologic features within and around the basin (fig. 2). Such data are not repeated here, except those that relate to discussions of the Frontier, Cody, and Mesaverde Formations. Petroleum occurrences in these rocks have also been discussed (Keefer, 1969).

GENERAL STRATIGRAPHIC FEATURES OF THE FRONTIER, CODY, AND MESAVERDE FORMATIONS

During Paleozoic and much of Mesozoic time, the present site of the Wind River Basin was part of the interior stable shelf region which lay east of the main Cordilleran geosyncline. Rocks representing all systems except possibly the Silurian were deposited during repeated transgressions of the epicontinental seas, but the stratigraphic sequence is thin and discontinuous as compared with the thick geosynclinal accumulations farther west in Idaho.

In latest Jurassic or earliest Cretaceous time, highlands formed in southeastern Idaho (Armstrong and Oriel, 1965, p. 1854), and the major sites of deposition shifted eastward. By Late Cretaceous time the main seaways had migrated into eastern Wyoming, and a thick fairly continuous sequence of alternating transgressive, regressive, and nonmarine sediments accumulated across central Wyoming. The Frontier and Mesaverde Formations and the intervening Cody Shale represent a major part of this complexly intertongued succession of marine, brackish, deltaic, and fluviatile strata. Eastward toward the Powder River Basin the sequence grades into predominantly marine shales (Gill and Cobban, 1966b); and westward into the Jackson Hole region the equivalent rocks are largely nonmarine coarse clastics (Love, 1956, p. 79–81). A westward readvance of the sea took place in post-Mesaverde time (represented by the Lewis Shale), but it covered only the eastern part of the Wind River Basin.

As the preceding paragraph implies, the Frontier, Cody, and Mesaverde all have pronounced facies changes from east to west across the region of study. Although superficially similar stratigraphic successions occur at most localities, the ages of individual rock units vary considerably from one place to another. It is therefore essential that correlations of rock-stratigraphic units be established on intervals as closely spaced (both laterally and vertically) as possible, and that the units' ages also be identified as precisely as the available paleontological data permit.

The Frontier, Cody, and Mesaverde Formations are exposed discontinuously along all sides of the Wind River Basin except the north (fig. 3). They also underlie the entire basin interior but have been penetrated by wells only in localities near the margins. Individual measured surface sections or drilled subsurface sections were selected at 64 key localities, including several along the south margin of the Bighorn Basin to the north; the localities and sources of data are listed in table 1, and the localities are shown in figure 3. The sections are plotted graphically on three correlation charts (pls. 1–3),[1] which show in detail the author's interpretation of the stratigraphic relationships throughout the region.

Because the thick, commonly poorly exposed Cody Shale has been measured in its entirety at very few localities, it was necessary to use data from subsurface sections to provide complete stratigraphic sequences of all three formations in most areas of the basin. The electric logs also serve as the most reliable means for determining the lateral continuity of stratigraphic horizons, owing to the distinctive and easily recognizable log characteristics of many individual units within the Frontier, Cody, and Mesaverde Formations. On the other hand, wide gaps in exposures along the basin margins prohibit continuous tracing of any given series of strata during the course of surface geologic mapping. The fairly precise identification of key "markers" or "kicks" on self-potential and resistivity curves is especially useful for interpreting the position of formation contacts with respect to time lines and for compiling thickness maps. As shown on the correlation charts (pls. 1–3), and mentioned specifically in later discussions, mappable formation boundaries in surface exposures vary in vertical position from one place to another, and therefore they may not coincide with regionally persistent stratigraphic horizons that can be identified more readily in subsurface sections.

[1] Plotted subsurface sections have not been corrected for dip. However, corrections have been made for all thicknesses mentioned in the text and shown on isopach maps (figs. 6 and 7), insofar as reliable information regarding dips was available.

FRONTIER FORMATION

DEFINITION

The Frontier Formation was named and described by Knight (1902, p. 721) from exposures along the west edge of the Green River Basin, near the small town of Frontier (2 miles north of Kemmerer) in southwestern Wyoming. A historical summary of the subsequent application and use of the name in other areas of Wyoming and adjacent States has been given by Cobban and Reeside (1952, p. 1916).

Hares (1916, p. 246) was apparently the first to employ the term Frontier in central Wyoming, and he gave the following generalized description of the formation in the southern part of the Wind River Basin:

> The Mowry shale is overlain by shale and sandstone that are referred to the Frontier formation of Upper Cretaceous age. The sandstones, of which there are three distinct divisions corresponding in ascending order to the Peay, an intermediate sand, and the Wall Creek * * * [are] from 20 to 200 feet thick. The formation attains a maximum thickness of 1,000 feet. The intervening shale, which makes up more than half of the formation, is dark and sandy.

Later investigations (for example, Thompson and others 1949; Masters, 1951; Towse, 1952; Cobban and Reeside, 1952; Goodell, 1962) have provided large amounts of data regarding the Frontier Formation in central Wyoming. As recognized by Hares (1916, p. 246), at least three major sandstone units are present in most places in the Wind River Basin; these are generally designated by petroleum geologists, in descending order, as the "First, Second, and Third Wall Creek sands." These names are adaptations of the name Wall Creek sandstone lentil of the Benton shale first used by Wegemann (1911, p. 45) in the Salt Creek oil field in the western Powder River Basin. One more or less persistent sandstones

TABLE 1.—*List of geologic sections used in correlation charts (pls. 1–3)*

Locality No. (pls. 1–3)	Name	Location			Source of information (blank space indicates well-log interpretation by W. R. Keefer)
		Section	Township	Range	
1	Horse Creek	1 36	42 N. 43 N.	107 W. 107 W.	Love and others, (1947, p. 3–6).
2	Davis Oil Co. Bermingham 1	SW¼NE¼ 2	41 N.	106 W.	
3	Carter Oil Co. Indian Meadows-State 1	NW¼NE¼ 17	41 N.	105 W.	
4	Red Creek	7, 8, 17	6 N.	3 W.	Thompson, Love, and Tourtelot (1949).
5	Skelly Oil Co. O. E. Seipt 2	SW¼SW¼ 26	6 N.	3 W.	
6	Carter Oil Co. Sheldon Tribal 1	SE¼NE¼ 16	5 N.	2 W.	
7	Maverick Springs	13, 18, 19, 22, 27, 28 18	6 N. 6 N.	1 W. 1 E.	Thompson, Love, and Tourtelot (1949); Keefer and Troyer (1964, p. 69–71, 80–86).
8	Cities Service Oil Co. Tribal 1	NE¼SW¼ 9	5 N.	1 E.	
9	British-American Oil Producing Co. Tribal C–6	SE¼ 19	4 N.	1 W.	
10	Superior Oil Co.–British-American Oil Producing Co. 3.	SE¼NW¼ 27	3 N.	1 W.	
11	Sage Creek	28	2 N.	1 W.	Thompson, Love, and Tourtelot (1949).
12	Mill Creek	26, 27	1 S.	1 W.	Love and others (1947, p. 26–29).
13	Carter Oil Co. Shoshone-Arapahoe 1	NE¼SW¼ 24	1 S.	1 E.	
14	Lander	2, 3	33 N. N½ 33N.	99 W. 98 W.	Thompson, Love, and Tourtelot (1949); Yenne and Pipiringos (1954).
15	Dallas Dome	5, 8	32 N.	98 W.	Thompson, Love, and Tourtelot (1949).
16	Derby Dome	27, 34, 35	32 N.	98 W.	Do.
17	Continental Oil Co. Govt. Draw 2	SE¼SE¼ 8	32 N.	97 W.	
18	Stanolind Oil and Gas Co. Johnson 1	SE¼SE¼ 3	33 N.	96 W.	Sample study by J. D. Love (written commun., 1969).
19	Alkali Butte Atlantic Refining Co. Tribal A–1	32, 33 4, 9 23 SE¼SE¼ 29	1 S. 2 S. 34 N. 1 S.	6 E. 6 E. 95 W. 6 E.	M. W. Reynolds (written commun., 1969); J. R. Gill (written commun., 1969); Yenne and Pipiringos (1954).
20	Conant Creek	7, 5 12, 13, 24 32	33 N. 33 N. 34 N.	93 W. 94 W. 93 W.	Love and others (1947, p. 45–47); Yenne and Pipiringos (1954).
21	Sun Oil Co. Wolf-Federal 1	NW¼SE¼ 31	35 N.	92 W.	
22	A. Edmiston Govt. 1	NW¼NW¼ 26	35 N.	91 W.	
23	Sinclair Oil and Gas Co. Castle Garden 1	NW¼NW¼ 13	34 N.	91 W.	
24	Castle Gardens	16	34 N.	90 W.	K. A. Yenne (written commun., 1950).
25	Dutton Basin	12	33 N.	90 W.	Love and others (1947, p. 55–56).
26	Davis Oil Co. Govt. 1	NW¼NW¼ 30	34 N.	89 W.	
27	Continental Oil Co. Raderville 1	SE¼SE¼ 36	35 N.	89 W.	
28	Coalbank Hills	5	34 N.	88 W.	J. R. Gill (written commun., 1969).
29	Polegate Creek	33	34 N.	88 W.	Masters (1951, p. 53–57).
30	Fales Rocks	4, 9	33 N.	87 W.	Barwin (1961a, p. 66–72); J. R. Gill (written commun., 1969).
31	Davis Oil Co. Govt.-Clare 1	NW¼NE¼ 3	33 N.	87 W.	
32	Stinking Creek	1 31	32 N. 33 N.	87 W. 86 W.	Masters (1951, p. 74–77).
33	Grieve Ranch	2	32 N.	86 W.	Barwin (1961a, p. 73–78).
34	Petroleum Inc.–Apache Oil Co. Grieve 46	NW¼SE¼ 13	32 N.	86 N.	
35	Cities Service Oil Co. Govt. C–1	SW¼ 12	32 N.	85 W.	
36	Tidewater Assoc. Oil Co. Poison Springs 73–31	SE¼NE¼ 31	32 N.	83 W.	
37	Shell Oil Co. Govt. 23–20	NE¼SW¼ 20	32 N.	82 W.	
38	Casper Canal	15, 16	31 N.	82 W.	Rich (1962, p. 465–466).
39	Batzer Oil Corp. Miles Land and Livestock 1	NW¼SW¼ 21	31 N.	82 W.	
40	East Sheep Creek	14, 23, 24, 25	6 N.	2 E.	Keefer and Troyer (1964, p. 86–95, 108–114).
41	Thermopolis	14	43 N.	95 W.	Thompson, Love, and Tourtelot (1949).
42	Continental Oil Co. Kiraly 28–1	NE¼SE¼ 28	44 N.	94 W.	
43	Lucerne	13, 23, 26	44 N.	94 W.	Gill and Cobban (1966a, fig. 1).
44	Greer and Davis Govt. 1	NW¼NE¼ 7	44 N.	93 W.	
45	Chicago Corp. Govt.-Atlantic 1	NW¼SE¼ 7	44 N.	92 W.	
46	Zimmerman Butte	15 25, 26	44 N. 44 N.	92 W. 93 W.	Gill and Cobban (1966a, fig. 1).
47	Sinclair Oil and Gas Co. Nowater 1	NE¼SE¼ 28	45 N.	91 W.	
48	Pan American Petroleum Corp. Honeycomb 1	SW¼NW¼ 15	44 N.	90 W.	
49	No Water Creek	35	44 N.	90 W.	Gill and Cobban (1966a, fig. 1).
50	Superior Oil Co. 24–5	SE¼SW¼ 5	42 N.	89 W.	
51	Buffalo Creek	14	42 N.	89 W.	Thompson, Love, and Tourtelot (1949).
52	Arminto	19 24	38 N. 38 N.	86 W. 87 W.	Do.
53	Cave Gulch	29, 31 13	37 N. 37 N.	86 W. 87 W.	J. R. Gill (written commun., 1969).
54	Pure Oil Co. Waltman 1	SW¼NW¼ 29	37 N.	86 W.	
55	Husky Oil Co. Lox 1	SW¼NW¼ 35	37 N.	86 W.	
56	Powder River	29, 30	36 N.	85 W.	J. R. Gill (written commun., 1969).
57	Farmers Union Central Exchange, Inc. Govt.-Ames 1.	SW¼SW¼ 28	36 N.	85 W.	
58	Richfield Oil Corp. Chicago Corp. 1	SE¼NW¼ 10	35 N.	85 W.	
59	R. L. Manning Co. Yandell 1	NE¼SW¼ 20	35 N.	85 W.	
60	Pine Mountain	15, 22	35 N.	84 W.	Towse (1952, fig. 16).
61	Pure Oil Co. West Poison Spider 3	NW¼SE¼ 10	33 N.	84 W.	
62	Northwest Poison Spider	5, 6	33 N.	83 W.	Workum (1959, p. 53–54).
63	Meadow Creek	30, 31	33 N.	82 W.	Rich (1962, p. 466–467).
64	Oil Mountain	35	33 N.	82 W.	Towse (1952, fig. 16).

are also commonly present, and where these become fairly conspicuous all sandstone units in a given area (particularly in certain oil and gas fields) are numbered by petroleum geologists as the First, Second, Third, and Fourth Frontier sands. Because several of the sandstones are important reservoirs of petroleum throughout the region, they have been the object of much interest and study.

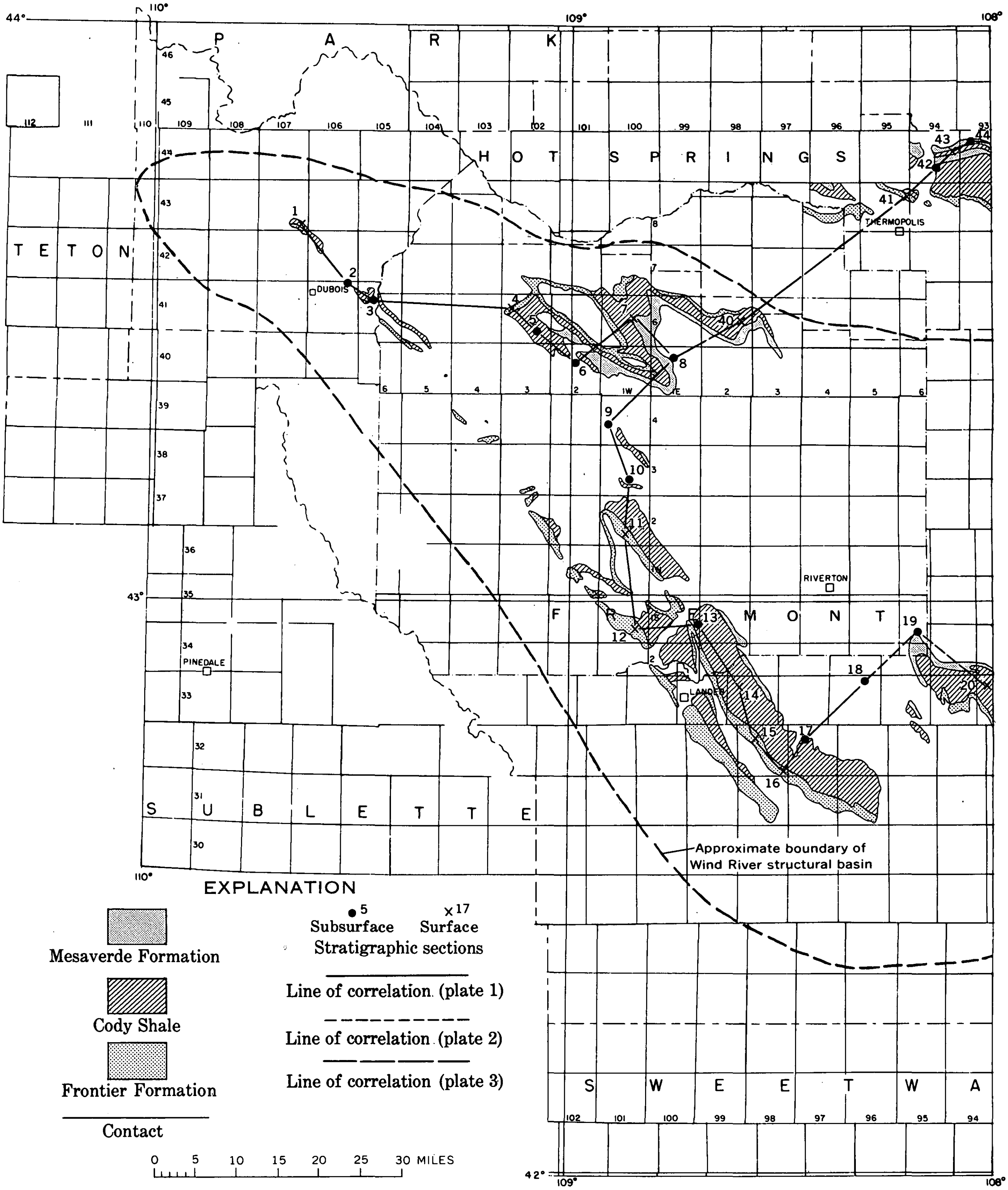
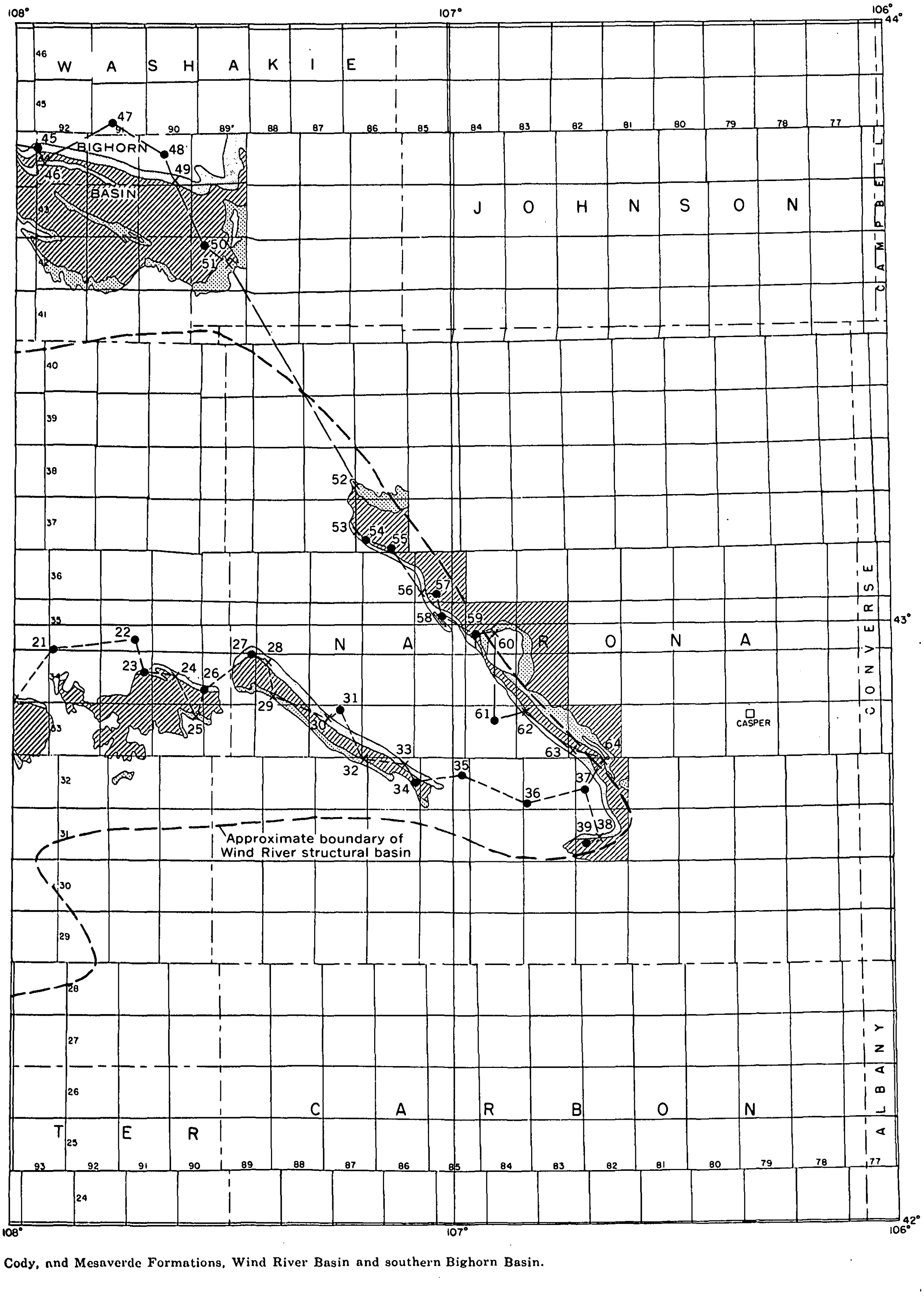


FIGURE 3.—Map showing major outcrops and locations of measured or drilled sections of the Frontier,



Cody, and Mesaverde Formations, Wind River Basin and southern Bighorn Basin.

FIGURE 4.— Frontier Formation (Kf) and Cody Shale (Kc) on north limb of Maverick Springs anticline (pl. 1, loc. 7). Frontier-Cody contact is along roadbed to left; Cody-Mesaverde contact is at top of bluffs to right. Note massive appearance of sandstones in upper part of Cody Shale. Outcrop of Cody Shale is 2 miles wide. View is to the northwest.

LITHOLOGY AND THICKNESS

The Frontier Formation is an alternating sequence of sandstone and shale; the sandstone generally predominates in the western part of the region and the shale in the eastern part, but over much of the area the two lithologies occur in about equal amounts (Goodell, 1962, fig. 10). The sandstone for the most part is gray, tan, and brown, fine to medium grained, thin bedded to massive, in part crossbedded, and lenticular. Most beds contain a moderate proportion of dark-colored mineral grains which impart a distinctive "salt and pepper" appearance to freshly exposed surfaces. Glauconite grains are also common constituents at many localities. Locally, some of the sandstone beds are coarse grained and conglomeratic; they contain rounded black and brown chert pebbles one-fourth to 3 inches in diameter. A petrographic analysis of the clastic rocks of the Frontier has been given by Goodell (1962, p. 192–203). The shales are gray to black, fissile, silty or sandy, and locally carbonaceous. Minor lithologies within the Frontier include bentonite, tuff and (or) porcellanite, lignite, and coal; many of these are widespread and provide valuable marker beds for detailed correlation. The formation erodes to a series of hogbacks and narrow strike valleys. Hogbacks formed by resistant sandstone beds in the upper part commonly contrast sharply with the subdued topography of the overlying Cody Shale (fig. 4).

The Frontier Formation, as generally mapped in most exposures around the east, south, and west margins of the Wind River Basin and along the south side of the Bighorn Basin, consists of those strata that lie between the base of the first sandstone above the hard siliceous shales of the Mowry Shale and the top of the first sandstone below the soft black shales of the Cody Shale (Thompson and others, 1949). However, owing to facies changes and the transitional nature of the rocks within the contact zones, the formation boundaries are not consistent over long distances. As a result, the thickness of the Frontier varies considerably from place to place; it ranges from a minimum of 470 feet at two localities (41 and 51)[2] in the southern Bighorn Basin to a maximum of 1,045 feet in the Arminto area (loc. 52) in the northeast corner of the Wind River Basin (pls. 1–3).

Despite facies changes and the lenticularity of many individual units, several discrete stratigraphic intervals, which seem to persist over wide areas in central Wyoming, can be identified, particularly on electric logs. (See also Towse, 1952; Goodell, 1962.) For the Frontier and closely related adjacent strata of the Mowry and Cody Shales, subdivisions arbitrarily chosen for purposes of the present report and designated as intervals A–H (in ascending order) are outlined in the following paragraphs. It should be emphasized that the description of each interval pertains to the dominant lithology (or lithologies) found in most of the sections studied and does not allude to all the variations that can be observed from one locality to another along the lines of correlation shown on plates 1–3.

Interval A.—Interval A consists chiefly of shale throughout much of the region, but it contains a large proportion of sandstone in the western part of the Wind River Basin. The lower boundary is marked by a sharply defined electric-log kick, probably a thin bentonite bed, which occurs within the upper siliceous shales of the Mowry Shale in most sections. The upper limit of interval A is defined by another easily identified marker that is used as the datum for the correlation charts (pls. 1–3). This

[2] Numbers refer to stratigraphic sections listed in table 1 and plotted on plates 1–3.

marker, which lies 20–100 feet above the base of the interval, is drawn at the base of a bentonite and (or) tuff bed that can also be recognized in many surface sections across the Wind River Basin. According to Goodell (1962, p. 177), the marker correlates with the "Clay Spur bentonite" of the Black Hills region in eastern Wyoming. It has been selected by many geologists as the lower boundary of the Frontier Formation in regional stratigraphic studies (chiefly subsurface) across central Wyoming. As discussed in the section "Contact with Mowry Shale," however, the bentonite and tuff do not everywhere occur at the most convenient horizon for mapping the lower limit of the formation in surface exposures.

Interval B.—Interval B incorporates 50–150 feet of strata which are predominantly shale over much of the region but which also contain interbedded sandstone at many localities as well as numerous thin beds of bentonite and (or) tuff. The shales are generally soft, gray, sandy, and silty, and are in sharp contrast to the hard black siliceous shales in the upper part of the Mowry Shale. The lower boundary of the interval is the base of the bentonite and (or) tuff described in the preceding paragraph. The upper boundary is marked by a rather sharp change from predominantly shaly strata below to sandy strata above that can be identified in both surface and subsurface sections over wide areas. This upper contact may coincide with a thin bentonite zone, although none was recognized at this horizon in most outcrops. Interval B was termed the lower shale member of the Frontier Formation in the eastern part of the Wind River Basin by Towse (1952), but Thompson, Love, and Tourtelot (1949) included it in the upper part of the Mowry Shale; the relationships are discussed in more detail in the section "Contact with Mowry Shale." The distinctive electric-log kick which marks the top of interval B in the southern Bighorn Basin was considered by Hunter (1952) and Masters (1952) to represent the "Clay Spur bentonite." However, according to the correlations established during the present study, the equivalent of the Clay Spur is at the base rather than the top of interval B in that area. (See also Goodell, 1962.)

Interval C.—Interval C contains the lowermost regionally persistent zone of sandstone within the Frontier Formation. Across most of the region of study, the interval consists of two fairly well defined sandstone units separated by a shale unit that contains various minor amounts of sandstone. Between localities 12 and 13, northwest of the town of Lander, however, the upper and lower sandstone units appear to merge, and from there northward and northwestward virtually the entire interval is sandstone (pl. 1). Anomolous sections of shale, on the other hand, occur in the upper part of interval C at localities 25, 26, and 27 in the south-central part of the Wind River Basin, and no continuous beds of sandstone can be traced along the top of the interval in that area. The thickness of interval C ranges from about 100 to 500 feet.

The name Third Wall Creek sand is used by many petroleum geologists to refer to all the sandstone units here included in interval C. Such usage is particularly common in oil and gas fields, although the terminology varies from place to place depending on the degree of development of the individual sandstones. In the Bighorn Basin the name Peay Sandstone Member is commonly applied to the basal strata of the Frontier Formation (Cobban and Reeside, 1952, p. 1956); the Peay corresponds generally to only the lower sandstone of interval C (pl. 3).

Interval D.—Interval D is a dual unit consisting of shale and shaly sandstone, 40–125 feet thick, and overlying sandstone, 25–130 feet thick. Thin beds of bentonite are present, particularly in the lower shale. The upper sandstone contains many thin beds of shale in sections across the Wind River Basin but, as correlated into the southern Bighorn Basin, this unit seems to be represented by a single sandstone bed 25 to 30 feet thick. Between localities 25 and 34, along the north and east sides of the Rattlesnake Hills (pl. 2), the sandstones of interval D locally grade into a predominantly shaly sequence. Correlations of individual units through this area are therefore uncertain. The persistent sandstone zone in the upper part of interval D has been identified in many oil and gas fields as the Second Wall Creek sand.

Interval E.—Interval E comprises interbedded sandstone and shale which intervene between the more persistent sandstone zones of intervals D and F. The unit ranges from 70 to about 250 feet in thickness. Locally it includes some well-defined sandstone beds, but these do not appear to be continuous for long distances. Delineation of interval E in the southern Bighorn Basin is problematic. However, the top of the interval in that area probably coincides closely with the top of the Torchlight Sandstone Member of the Frontier Formation (pl. 3; Hunter, 1952, p. 65); this relation is discussed more fully in the section "Age and Correlation." The Torchlight, which is fairly persistent across the south margin and elsewhere in the Bighorn Basin, is commonly conglomeratic, having black and brown chert and andesite pebbles as much as 3 inches in diameter (VanHouten, 1962, fig. 4; Horn, 1963).

Interval F.—Strata assigned to interval F represent the most conspicuous series of sandstones within the Frontier Formation. The unit is easily identified in nearly all surface and subsurface sections around the west, south, and east margins of the Wind River Basin. In the southern Bighorn Basin, on the other hand, shale and sandy shale predominate locally, and the interval becomes much less distinct. The thickness of the sandstone assigned to interval F in the Wind River Basin ranges from 80 to 140 feet. Interbedded shale is a minor constituent at most localities and, in sections extending northwest from the Beaver Creek field (loc. 18), the sequence also contains thin beds of carbonaceous shale, lignite, and coal. In most oil and gas fields the sandstones of interval F are referred to as the First Wall Creek sand by petroleum geologists (see Goodell, 1962).

Interval G.—Interval G is predominantly a shale and shaly sandstone sequence in the eastern part of the Wind River Basin which grades westward, in the vicinity of Conant Creek (locs. 20 and 21), into sandstone interbedded with minor amounts of shale. From Conant Creek west and northwest to the south end of Sage Creek anticline (loc. 11), the interval reaches a maximum thickness of 250–300 feet; elsewhere the thickness averages about 125 feet. There are equivalent strata in the southern Bighorn Basin, but the base of the unit cannot be located precisely in that area.

The top of interval G is marked in nearly all subsurface sections by a rather easily recognized change on electric logs from more expanded resistivity curves below to less expanded curves above. This difference in curve characteristics apparently reflects an upward decrease in sand content of the strata which span the contact.

Interval H.—Interval H, which is 100–240 feet thick, is almost entirely shale or slightly sandy shale and is assigned nearly everwhere to the Cody Shale. One exception is at locality 17, in the southwest corner of the Wind River Basin (pl. 1), where a fairly well defined sandstone seems to occupy part of the interval. Interval H is mentioned briefly in this discussion of the Frontier because the top of the interval is marked in all subsurface sections by one of the most easily recognized electric-log markers within the Upper Cretaceous sequence of this region. This marker has been referred to as the "chalk kick" (Thompson and others, 1949), and it forms an excellent reference horizon, along with the marker at the base of interval A, for bracketing all the rocks either assigned to the Frontier Formation in one place or another or otherwise included in the closely related stratigraphic units both above and below the Frontier.

CONTACT WITH MOWRY SHALE

The contact between the Frontier Formation and the underlying Mowry Shale, as drawn on the correlation charts (pls. 1–3), is selected on the basis of the best mappable boundary determinable in surface sections. For the intervening subsurface sections the position of the contact is interpretive, but it represents the author's opinion as to where the formation boundary would be placed if those sections were exposed and subject to surface geologic mapping. As stated earlier (p. E8), the contact generally coincides with the base of the first sandstone above the siliceous shales of the Mowry (fig. 5), but the strata commonly are gradational, and the boundary is not everywhere clearly defined.

The Frontier-Mowry contact, as determined by the preceding criteria, occurs near the middle of interval A along the west and part of the south margins of the Wind River Basin (pls. 1 and 2). This

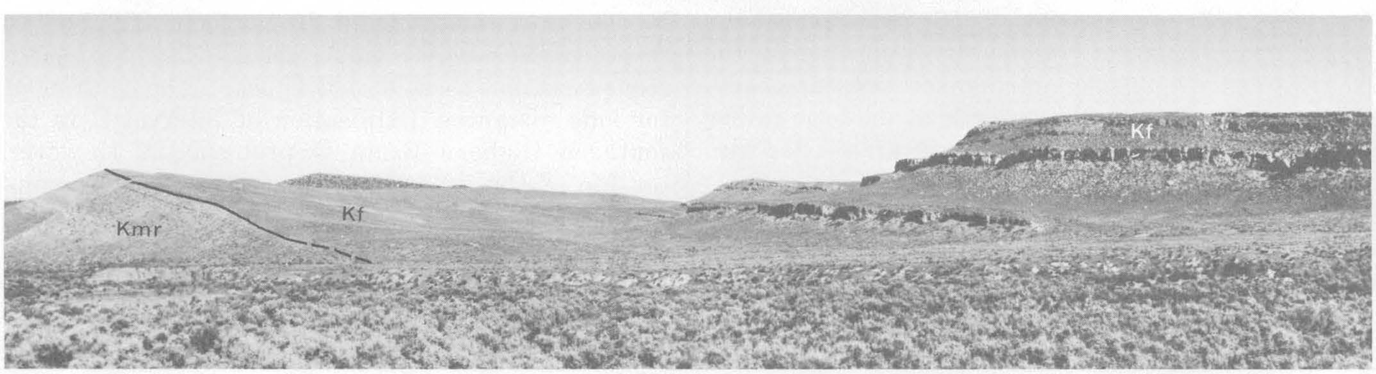


FIGURE 5.—Frontier Formation (Kf) and Mowry Shale (Kmr) on east limb of Derby Dome anticline (loc. 16, fig. 3). Note banded appearance of siliceous shales in Mowry and ledgy character of sandstones in Frontier. View is to the north.

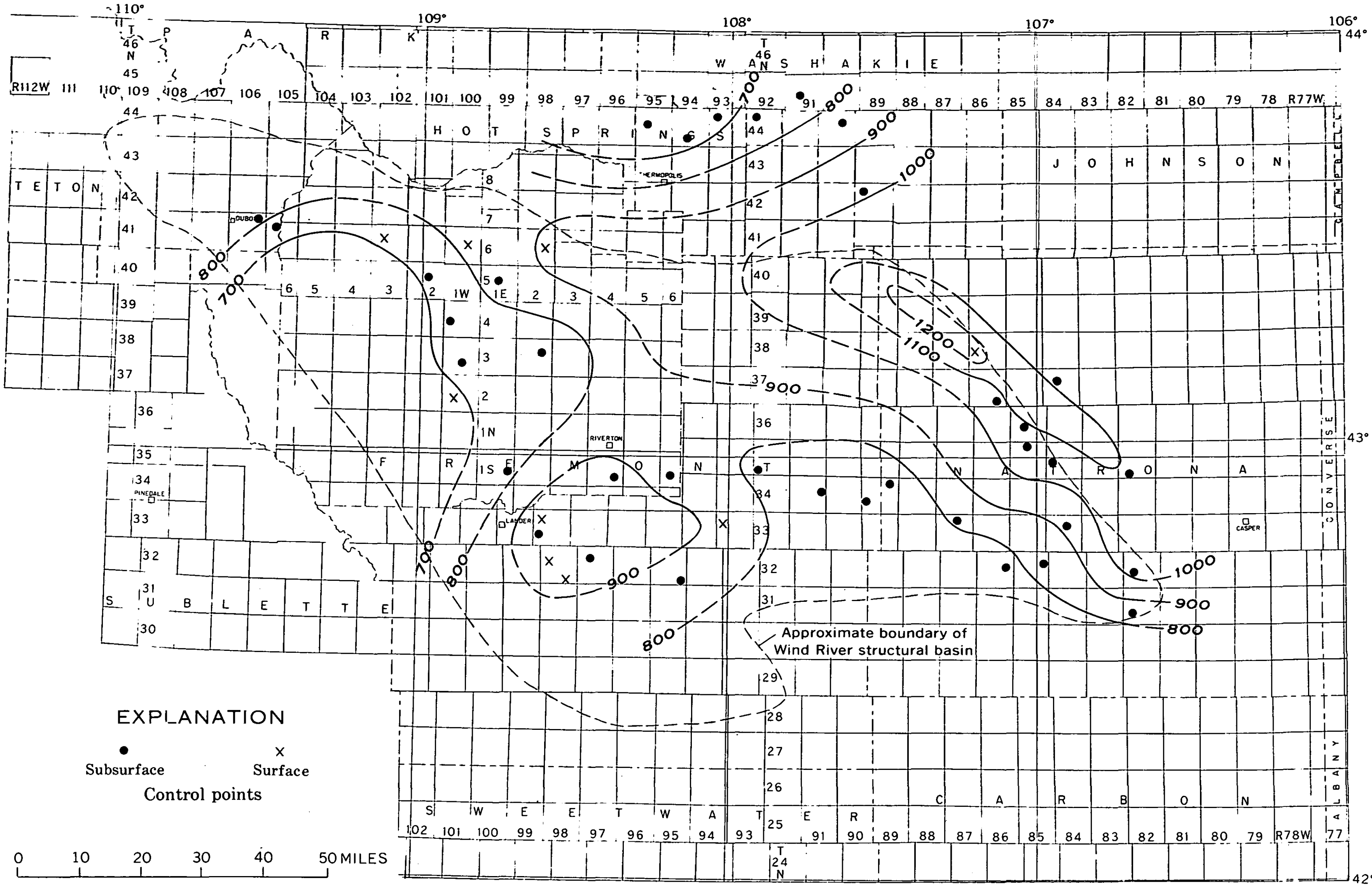


Figure 6.—Thickness map of intervals B through G of the Frontier Formation and associated strata. Interval is 100 feet; isopachs are restored across some mountain arches where rocks have been eroded; isopachs are dashed where control is inadequate.

horizon reflects the change from siliceous and (or) partly nonsiliceous shale below to sandstone interbedded with varying amounts of shale above; the Clay Spur Bentonite Bed equivalent occurs 30–50 feet above the base of the Frontier in most places. Eastward from locality 20 to locality 23, in the south-central part of the basin, the upper part of interval A, as well as interval B, becomes predominantly shaly, and the formation contact is gradually at higher levels until it is at the top of interval B (pl. 2). This horizon is then considered to form the best mappable Frontier-Mowry contact in all other sections around the southeast and east margins of the Wind River Basin, as well as along the south side of the Bighorn Basin (pl. 3). In these sections the Clay Spur equivalent is 50–150 feet below the top of strata generally included in the Mowry Shale for surface mapping, even though the shales in the upper part of interval B are not typical of the siliceous beds of the Mowry.

If the position of the Frontier-Mowry contact were to be determined solely for use in subsurface correlations, then the Clay Spur equivalent (base of interval B) would provide the most consistent horizon for separating the two formations in central Wyoming. This datum forms a valuable reference for isopaching rock units (fig. 6) and for studying the regional depositional history of the Frontier and associated strata.

CONTACT WITH CODY SHALE

Like the Frontier-Mowry contact, the contact between the Frontier Formation and the overlying Cody Shale is defined in terms of its mappability in surface exposures. Although transitional in many places, this upper boundary of the Frontier reflects a widespread lithologic change from predominantly sandy strata below to shaly strata above. In areas of good exposures the sandstones in the upper part of the Frontier commonly form conspicuous hogbacks, and in these areas the contact is generally easy to determine at least for local mapping (fig. 4).

In the eastern, southeastern, and south-central parts of the Wind River Basin, the Frontier-Cody contact is placed at the top of the conspicuous zone of sandstones that constitute interval F (First Wall Creek sand of petroleum geologists; pls. 2 and 3). Westward from Castle Gardens (loc. 24) to Conant Creek (loc. 20), successively younger sandstones occur in the section, and at Conant Creek the upper limit of the Frontier is at the top of interval G (pl. 2). The contact continues at that horizon throughout the remainder of the basin (pl. 1) except at locality 17 in the extreme southwest corner. At that locality another sandstone seems to be present above interval G and, if the upper boundary of the Frontier were exposed, it might even be mapped at the top of interval H.

The top of the Torchlight Sandstone Member appears to form the best mappable contact between the Frontier Formation and the Cody Shale in most exposures along the south margin of the Bighorn Basin (pl. 3; also, see Goodell, 1962, p. 182 and fig. 4; Hunter, 1952, pls. 2 and 3). As noted previously, (p. E9), this horizon is considered to correlate approximately with the top of interval E. Some fairly well defined sandstone beds occur above the Torchlight in places, however, and VanHouten (1962, pl. 2), for example, locally included these in the Frontier also. In the surface section at Buffalo Creek (loc. 51), the uppermost bed of the Frontier may represent a sandstone that is older than the Torchlight, but correlations are uncertain. Solely on the basis of subsurface considerations, the most convenient reference horizon for defining the upper limit of the Frontier Formation in central Wyoming is believed to be at the top of interval G.

AGE AND CORRELATION

Diagnostic marine invertebrate fossils have been found in abundance only in the upper part of the Frontier Formation; they are sparse to absent at most other horizons. Numerous collections taken in the western and southwestern parts of the Wind River Basin indicate that the sandstones of interval G (and, locally, interval H), which form the upper unit of the formation in these areas, represent the oldest zone of the Niobrara. (See table 2 for faunal zones and age references.) This youngest Frontier fauna is characterized by the zone fossils *Inoceramus deformis* and *Scaphites preventricosus.* The species *Scaphites ventricosus,* representing the next to the oldest zone of the Niobrara, has been reported from the Derby Dome and East Sheep Creek sections (locs. 16 and 40). However, *I. deformis* also occurs in these faunas (Love and others, 1947, p. 18, 38), and W. A. Cobban (oral commun., 1969) suggested that *S. ventricosus* was perhaps misidentified from *S. preventricosus* at both localities.

Other diagnostic fossils collected from the Frontier Formation in the Wind River Basin include the following:

1. *Plesiacanthoceras wyomingense* (initially reported as *Acanthoceras?* sp. A by Cobban and Reeside, 1952, p. 1952), found in middle of interval E at Conant Creek (loc. 20) and in upper part of interval E at Dutton Basin

TABLE 2.—*Relations of the Upper Cretaceous Frontier, Cody, and Mesaverde Formations to the western interior reference sequence and faunal zones*

[No.: Refers to fossil collections plotted on correlation charts (pls. 1–3). Western interior faunal zones: From Gill and Cobban (1966b, p. A35), Cobban and Reeside (1952, fig. 4), and W. A. Cobban and J. R. Gill (oral commun., 1969)]

No.	Western interior faunal zones (part)	Series	European stages	Composite western interior reference sequence		This report: Wind River Basin, West	Wind River Basin, East	Southern Bighorn Basin, West	Southern Bighorn Basin, East
1	*Baculites eliasi*	Upper Cretaceous	Campanian	Pierre Shale (part)	Upper unnamed shale member	Meeteetse Formation (part)	Lewis Shale (part)	Meeteetse Formation (part)	Lewis Shale (part)
2	*Baculites jenseni*				Kara Bentonitic Member				
3	*Baculites reesidei*				Lower unnamed shale member (part)	Mesaverde Formation		Mesaverde Formation	
4	*Baculites cuneatus*								
5	*Baculites compressus*				Absent or very thin	Teapot Sandstone Member		Teapot Sandstone Member	
6	*Didymoceras cheyennense*								
7	*Exiteloceras jenneyi*				Lower unnamed shale member (part)	Unnamed middle member		? ?	
8	*Didymoceras stevensoni*								
9	*Didymoceras nebrascense*								
10	*Baculites scotti*					Parkman Sandstone Member		Lower part	
11	*Baculites gregoryensis*				Red Bird Silty Member				
12	*Baculites perplexus*				Mitten Black Shale Member			Wallace Creek Tongue	
13	*Baculites* sp. (smooth)					Fales Sandstone Member			
14	*Baculites asperiformis*								
15	*Baculites mclearni*				Sharon Springs Member				
16	*Baculites obtusus*								
17	*Baculites* sp. (weak flank ribs)				Gammon Ferruginous Member				
18	*Baculites* sp. (smooth)				?				
19	*Haresiceras natronense* *Scaphites hippocrepis* III			Niobrara Formation	Smoky Hill Chalk Member				
20	*Haresiceras placentiforme* *Scaphites hippocrepis* II								
21	*Haresiceras montanaense* *Scaphites hippocrepis* I					?		?	
22	*Desmoscaphites bassleri*		Santonian			Cody Shale			
23	*Desmoscaphites erdmanni*								
24	*Clioscaphites choteauensis*								
25	*Clioscaphites vermiformis*		?						
26	*Scaphites depressus*		Coniacian						
27	*Scaphites ventricosus*								
28	*Scaphites preventricosus* *Inoceramus deformis*		?		Fort Hays Limestone Mbr				
29	*Scaphites corvensis*		Turonian	Carlile Shale	Sage Breaks Member	Frontier Formation		Cody Shale	
30	*Scaphites nigricollensis* *Prionocyclus reesidei*				Turner Sandy Member				
31	*Prionocyclus wyomingensis*								
32	*Scaphites ferronensis*								
33	*Scaphites warreni*								
34	*Prionocyclus hyatti*				Blue Hill Shale Member				
35	*Collignoniceras woolgari*				Fairport Chalky Shale Member				
36	*Inoceramus labiatus*			Greenhorn Limestone	Pfiefer Limestone Member				
37	*Sciponoceras gracile*		Cenomanian		Jetmore Chalk Member				
38	*Dunveganoceras albertense*				Hartland Shale Member				
39	*Dunveganoceras conditum*							? ?	
40	*Dunveganoceras pondi*				Lincoln Limestone Member			Frontier Formation	
41	*Plesiacanthoceras wyomingense*			Belle Fourche Shale					
42	*Acanthoceras amphibolum*	Lower Cretaceous							
43	*Calycoceras* sp.					? ?		? ?	
44	*Neogastroplites* spp.		Albian	Mowry Shale (part)		Mowry Shale (part)		Mowry Shale (part)	

(loc. 25); rocks are equivalent to upper part of Belle Fourche Shale (table 2, No. 41).

2. *Prionocyclus hyatti* (initially reported as *Collignoniceras hyatti* by Cobban and Reeside, 1952, p. 1952), found near contact between intervals E and F in the Conant Creek area (loc. 20); rocks are early Carlile in age (table 2, No. 34).

The species *Dunveganoceras pondi,* of early Greenhorn age (table 2, No. 40), characterizes the contact zone between the Torchlight Sandstone Member of the Frontier Formation and the Cody Shale in the southeastern part of the Bighorn Basin (Horn, 1963; Cobban and Reeside, 1952, fig. 4). If sandy beds younger than the Torchlight are included in the Frontier in this region, as suggested by Van-Houten (1962, pl. 2), then the formation includes strata as young as early Carlile.

The available data thus show that the Frontier Formation, as delineated in this report, contains equivalents of the following formations in the areas indicated: (1) Western Wind River Basin—Belle Fourche Shale, Greenhorn Limestone, Carlile Shale, and Fort Hays Limestone Member of the Niobrara Formation, (2) eastern Wind River Basin—Belle Fourche Shale, Greenhorn Limestone, and Carlile Shale, (3) southern Bighorn Basin—Belle Fourche Shale and lower part of Greenhorn Limestone. (See the composite reference sequence of Cretaceous rocks in the western interior region, table 2.) Although no definite unconformities have been recognized in the region, there are indications that sedimentary breaks occur locally within the Frontier Formation. In the vicinity of Conant Creek (loc. 20), for example, the Greenhorn and earliest Carlile equivalents are very thin (Cobban and Reeside, 1952, p. 1952–1953) and certain parts may even be absent. Cobban and Reeside (1952, fig. 4) showed two periods of nondeposition during early and middle Carlile times in the Lost Soldier area, approximately 40 miles south of Dutton Basin (loc. 25). These hiatuses may also be reflected in places in the Wind River Basin, but many more fossil collections are necessary before the relationships can be worked out in detail.

Many petroleum geologists have used the names First, Second, and Third Wall Creek sands in central Wyoming to imply correlation of the rocks so named with a similar succession of conspicuous sandstone units in the Salt Creek oil field at the west edge of the Powder River Basin (50 miles east of loc. 52). The First Wall Creek sand (interval F of this report), as generally designated in the Wind River Basin, correlates temporally with the Wall Creek Sandstone Member at the top of the Frontier Formation at Salt Creek (Cobban and Reeside, 1952, fig. 4). The Second Wall Creek sand (upper part of interval D), however, is older than its counterpart in the western Powder River Basin and correlates more closely with the unit called Third Wall Creek sand in that area. The Third Wall Creek sand (interval C) of the Wind River Basin is therefore probably older than any of the commonly designated sandstone units at Salt Creek. The Torchlight Sandstone Member of the Frontier in the southern part of the Bighorn Basin is the temporal equivalent of the Second Wall Creek sand of the Salt Creek section (Cobban and Reeside, 1952, fig. 4) and thus appears to have no correlative in the sequence of regionally persistent sandstone units in the Wind River Basin.

CODY SHALE

DEFINITION

The name Cody Shale was given by Lupton (1916, p. 171) to the "* * * strata lying between the top of the Frontier formation and below the base of the Mesaverde formation * * * in the vicinity of Basin [Wyoming] * * *." This locality is along the east side of the Bighorn Basin, but the name was derived from the town of Cody at the west margin. The name Cody is now in general use in the Bighorn and Wind River Basins, in the Jackson Hole region of western Wyoming (Love, 1956, p. 79–80), and in south-central Montana (Roberts, 1965).

LITHOLOGY AND THICKNESS

The Cody Shale consists of marine shale and sandstone ranging in thickness from 3,150 to 4,700 feet. Shale predominates in the lower part of the formation, and interbedded sandstone and shale in the upper part. A general distinction can be made, in both surface and subsurface sections, between a shaly member and a sandy member in the western part of the Wind River Basin and in parts of the Bighorn Basin. However, the two major lithologies show all degrees of gradation, from silty and sandy shale below to siltstone and shaly sandstone above, so the contact can be selected only arbitrarily in most places. Farther east (east of locs. 21 and 47) the subdivision of the Cody into two lithologic sequences is even less distinct, although thick zones of sandstone in the upper part of the formation also extend into those areas. In contrast with the ledge- and ridge-forming formations that overlie and underlie it, the Cody Shale is easily weathered and eroded; hence it forms broad flat soil-covered valleys

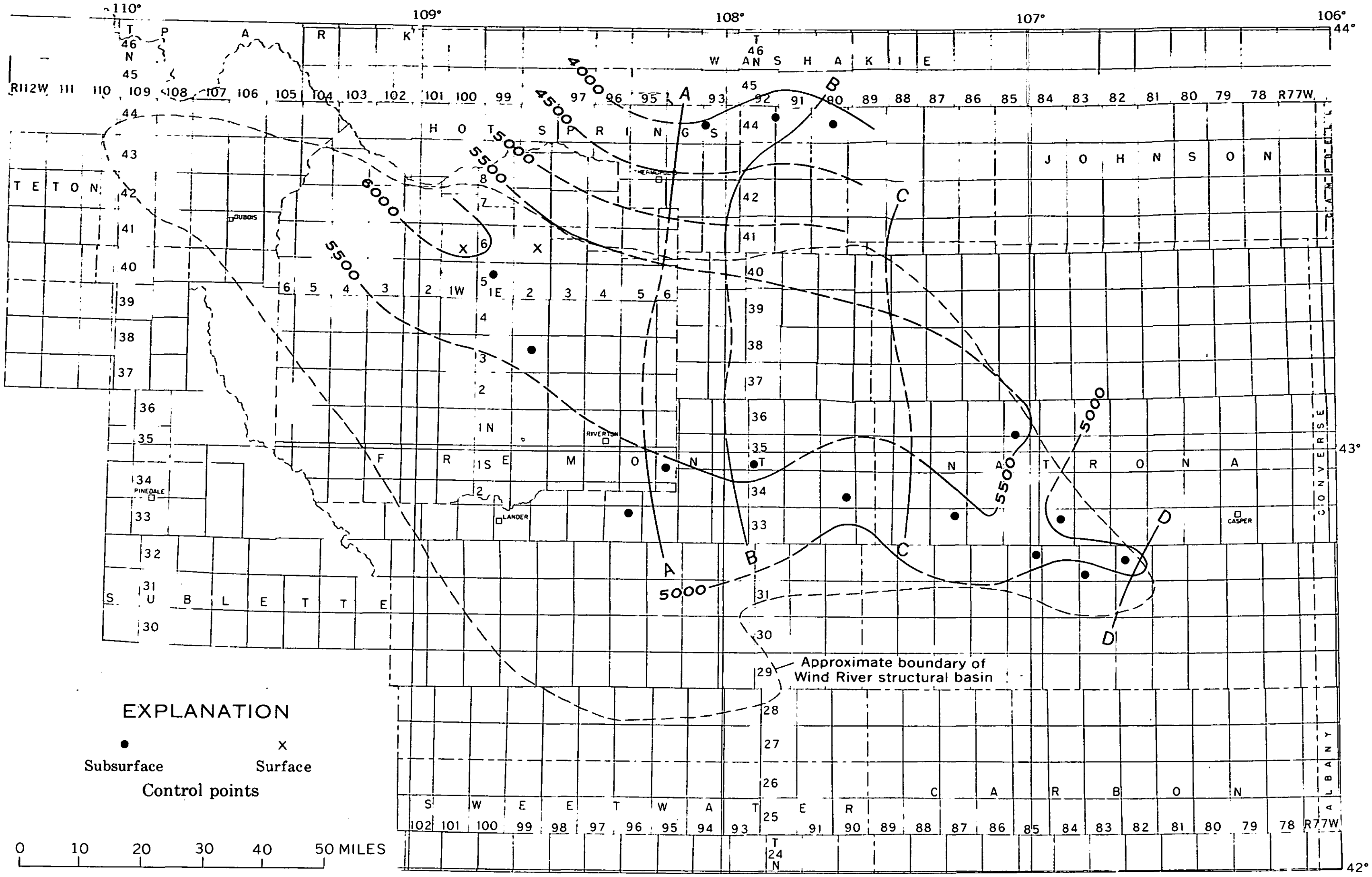


FIGURE 7.—Thickness map of interval H of the Frontier Formation, Cody Shale, and Mesaverde Formation. Interval is 500 feet; isopachs are restored across some mountain arches where rocks have been eroded; isopachs are dashed where control is inadequate. Labeled lines: A, western limit of tongue of Cody Shale at Alkali Butte; B, eastern limit of lower tongue of Mesaverde Formation at Conant Creek; C, western limit of Wallace Creek Tongue of Cody Shale; D, eastern limit of Fales Sandstone Member of Mesaverde Formation.

(fig. 4). In a few areas, however, the upper sandstones are sufficiently resistant to form bold cliffs (fig. 4).

The shale is gray to black, soft, finely fissile, and commonly bentonitic and calcareous. Numerous brown and gray claystone and limestone concretions occur within the thick shale units in many areas. Locally, small disk-shaped highly polished black chert pebbles are present in the lowermost beds. The sandstone is gray to buff and tan, very fine to fine grained, thin bedded to platy, calcareous, and commonly glauconitic. Some beds are soft and friable, but others are very hard and compact. Viewed from a distance many individual sandstone units appear to be thick and massive (fig. 4), whereas in detail they are actually thin bedded and platy. Locally, however, some of the beds near the top of the formation become thicker and more massive and resemble those in the lower part of the overlying Mesaverde Formation.

Electric logs of the Cody interval exhibit many distinctive resistivity peaks some of which can be used for correlation over extensive areas. Key markers in the lower part of the formation (for example, the chalk kick) may be caused in part by bentonitic and (or) calcareous shale beds, but such beds have not been specifically identified in either outcrops or well samples. Several conspicuous sandstone units in the upper part of the Cody in the south-central, southeastern, and eastern parts of the Wind River Basin are also recorded on electric logs, but, because of the common lateral changes in lithology, these beds cannot be correlated with certainty except for short distances. Tentative correlations with the Shannon and Sussex Sandstone Members of the Steele Shale in the western part of the Powder River Basin have been made by various investigators for sections penetrated by wells along the east side of the Wind River Basin; however, such correlations have not yet been definitely established.

Upper strata of the Cody Shale intertongue extensively with the basal part of the Mesaverde Formation across central Wyoming; for this reason the two formations are combined for isopaching (fig. 7). In general, two major zones of intertonguing occur in the Wind River Basin, one in the Alkali Butte–Conant Creek area (locs. 19 and 20) and the other east and southeast of the Rattlesnake Hills (loc. 28).

At the Alkali Butte locality approximately 900 feet of predominantly nonmarine strata of the basal Mesaverde Formation is overlain by a westward-projecting tongue of the Cody Shale 470 feet thick (pl. 2). Ten miles to the east, at the Conant Creek locality, only about 120 feet of the basal Mesaverde remains, and this is separated from the main mass of that formation by nearly 1,100 feet of marine sandstone and shale of the Cody. Conspicuous sandstone units project eastward from Conant Creek (for example, into the subsurface at loc. 22), but these are probably entirely marine and seem best assigned to the Cody Shale. A zone of intertonguing virtually the same age as that in the Alkali Butte–Conant Creek area exists between localities 43 and 48 in the southern Bighorn Basin (pl. 3). There, however, in its easternmost exposures (for example, at loc. 46, pl. 3), the basal Mesaverde tongue consists almost entirely of marine strata (Horn, 1963). The approximate locations of the wedge edges of the tongues described in this paragraph, as projected through the central part of the Wind River Basin, are shown in figure 7.

Southeast of the Coalbank Hills section (loc. 28), at the northeast corner of the Rattlesnake Hills, the basal half of the Mesaverde Formation is split by a westward-projecting tongue of marine shale and sandstone (pl. 2). This unit has been called the Wallace Creek Tongue of the Cody Shale by Barwin (1959, p. 141–142; 1961b, p. 172–174), and it can be traced eastward and southeastward for distances of more than 40 miles. The tongue is recognizable in the Cave Gulch section (loc. 53), at the northeast corner of the Wind River Basin, but apparently loses its identity farther north in the southern Bighorn Basin (for example, at loc. 49). The Wallace Creek, consisting of interbedded sandstone and shale, thickens from 120 feet at its type section near Fales Rock (loc. 30) to nearly 400 feet in the Shell Oil Co. Government 23–20 well (loc. 37). Farther south the underlying Fales Sandstone Member of the Mesaverde Formation wedges out, and the Wallace Creek Tongue merges with the main mass of the Cody Shale (for example, at loc. 38). Thickness of the Wallace Creek along the east margin of the Wind River Basin ranges from 200 to 400 feet (pl. 3). Minor intertonguing of the Cody Shale and Mesaverde Formation can be observed in a few places in the western part of the Wind River Basin, but the individual tongues are thin and can be traced for only short distances.

CONTACT WITH MESAVERDE FORMATION

Regionally the contact between the Cody Shale and the Mesaverde Formation is defined as the dividing line between strata that were deposited primarily in an offshore environment and those that were deposited in near-shore, brackish-water, swampy, or fluviatile environments. The contact is

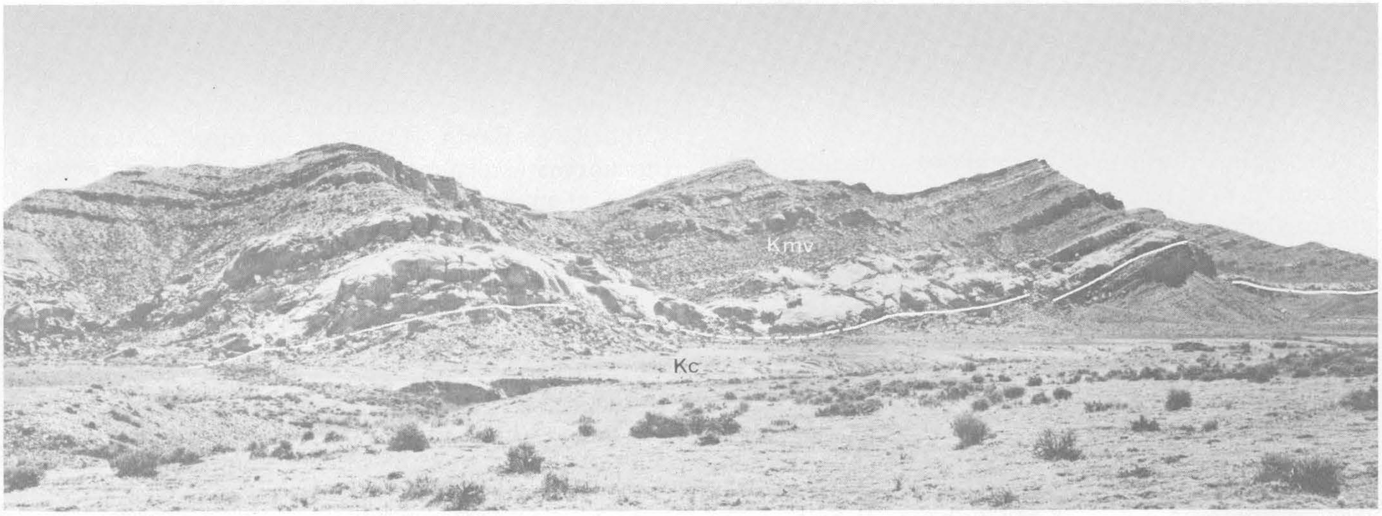


FIGURE 8.—Mesaverde Formation (Kmv) and Cody Shale (Kc) in northern Wind River Basin (approximately 1.5 miles north-northeast of loc. 7, fig. 3). Difference in altitude between base and top of ridge is 500 feet. View is to the east.

generally marked by a lithologic change from thin-bedded sandstone interbedded with shale below to massive sandstone closely associated with carbonaceous shale and coal above (fig. 8). Owing to the transitional nature of the rocks through the contact zone, however, the precise determination of a mappable boundary in surface exposures is difficult in many places, particularly where sandstones in the upper part of the Cody present a persistently massive appearance. On most electric logs there is a sharp increase in resistivity and self-potential in passing from the Cody into the Mesaverde.

In areas where extensive overlapping tongues of Cody Shale and Mesaverde Formation occur, the individual tongues have been mapped locally as separate units if they are sufficiently thick (for example, Horn, 1963). In many areas, though, strata of the Cody have been mapped with the Mesaverde, and vice versa, depending upon mapping convenience. Along the east flank of the Rattlesnake Hills, for example, the base of the lower member (Fales) of the Mesaverde, which is an easily recognizable unit, is commonly mapped as the Cody-Mesaverde boundary, thereby including the Wallace Creek Tongue with the Mesaverde Formation.

AGE AND CORRELATION

The Cody Shale is highly fossiliferous, as shown by the numerous collections of megafossils obtained from surface sections (pls. 1–3). Claystone and limestone concretions in the shale beds and friable irregular sandstone masses in the sandstone beds commonly yield well-preserved fossils in great numbers and variety; with close searching diagnostic fossils can be found in most areas of good exposures. Microfossils, chiefly Foraminifera, are also abundant, but efforts at precise zonation have yet proved largely unsuccessful (Prochaska, 1960; White, 1961).

The paleontological data show that, owing to facies changes, both the base and top of the formation vary in age across central Wyoming. The basal strata are early Niobrara in age (approximately equal to the *Scaphites ventricosus* zone) in approximately the western half of the Wind River Basin, but they include beds of probable late Carlile age in the eastern half (table 2). Basal Cody strata in the southern Bighorn Basin are even older, incorporating beds as old as early Greenhorn.

The upper part of the Cody Shale, west of a line drawn between locality 19 in the Wind River Basin and locality 43 in the Bighorn Basin, is approximately within the *Haresiceras montanaense–Scaphites hippocrepis* I zone (table 2). Thence eastward, the Cody-Mesaverde boundary crosses progressively younger time lines, and so in the eastern part of the region of study the upper strata of the main body of the Cody are represented by faunal zones as young as those of *Baculites mclearni* and possibly *Baculites asperiformis*. The Wallace Creek Tongue is in the still younger zone of *Baculites perplexus,* and this zone characterizes the uppermost Cody strata east of the wedge edge of the Fales Member of the Mesaverde Formation (for example, at loc. 38).

Interestingly, correlations of electric-log markers within the Cody interval appear to follow time lines closely enough for the markers to be used as guides in delineating rock units in the thick otherwise nondescript sequences of shale and sandstone.

MESAVERDE FORMATION

DEFINITION

The name Mesaverde Group was introduced by Holmes (1877, p. 245, 248) for the series of sandstone, shale, and coal that caps Mesa Verde, a large topographic feature in southwestern Colorado. The name (either as a group or as a formation) was used subsequently in reconnaissance studies of many of the coal fields of southern Colorado to designate generally the rocks lying between the Mancos Shale below and the Lewis Shale above. Woodruff (1911, p. 22–23) apparently was the first to apply the name Mesaverde Formation in the Wind River Basin; he used it during a study of the Lander oil field at the west margin of the basin. In virtually all later geologic studies in central Wyoming, the name has been used to identify the rocks lying between the Cody Shale and the Lewis and (or) Meeteetse Formations.

Hares (1916) and Hares and others (1946) referred the conspicuous sandstone units at the base and top of the Mesaverde in the southeastern part of the Wind River Basin to the Parkman and Teapot Sandstone Members, respectively; these names were used previously in the western and southern parts of the Powder River Basin.[3] The strata between the Parkman and Teapot, though not receiving formal designation, were referred to as the unnamed middle member of the Mesaverde Formation by Rich (1958, p. 2427).

Rich (1958, p. 2428) and Barwin (1959, p. 141) recognized that the Parkman Sandstone Member, as delineated by Hares and others (1946) along the east flank of the Rattlesnake Hills, was split by a westward-projecting tongue of the Cody Shale (Wallace Creek Tongue). Accordingly, Rich (1958, p. 2428) used the designations upper and lower tongues of the Parkman for the two units, but Barwin (1959, p. 141) restricted the name Parkman to the upper unit and introduced the name Phayles Reef Member for the lower unit. Barwin's terminology is used in the present report, except that the name of the lower unit is modified to Fales Sandstone Member,[4] following Gill, Merewether, and Cobban (1970, p. 11).

The Mesaverde Formation has not been formally subdivided in the central and western parts of the Wind River Basin. However, the upper sandstone in the northwestern part was called the white sandstone member by Troyer and Keefer (1955) and, according to the regional correlations established during the present study, this unit is equivalent to the Teapot Sandstone Member. The Teapot was also identified in the southern Bighorn Basin by Gill and Cobban (1966a, fig. 1). The thick basal unit of the Mesaverde in the Alkali Butte–Conant Creek area (locs. 19 and 20) and the lower tongue of the formation in the southern Bighorn Basin, which both occur well below the Fales Member stratigraphically, have not been given formal designation.

LITHOLOGY AND THICKNESS

The Mesaverde Formation is a highly variable sequence of sandstone, siltstone, shale, carbonaceous shale, and coal. The thickness ranges from 550 to 2,000 feet; much of the variation results from intertonguing at the base with the Cody Shale and, locally, from an intraformational unconformity at the base of the Teapot Sandstone Member. In many places a general tripartite division can be recognized, including a lower sandstone, a middle interbedded sandstone and shale unit, and an upper sandstone; most individual beds, however, are lenticular and can be traced laterally for only short distances.

Sandstones in the lower and middle parts of the Mesaverde are characteristically tan, gray, and yellowish gray; very fine to medium grained; irregularly bedded to massive and crossbedded; and friable to well cemented. Individual beds at the base range from a few feet to as much as 250 feet in thickness, and the thicker units generally form conspicuous ledges and cliffs (fig. 8). In many weathered outcrops the basal massive sandstones also present an extremely pitted appearance which results primarily from wind abrasion. Most beds are highly ferruginous and contain much limonite staining. Conspicuous in many exposures are concretionlike masses of brown-weathering irregularly bedded sandstone as much as 30 feet in diameter. These masses contain a higher percentage of calcareous and ferruginous cement than the host rock and hence are more resis-

[3] The 1946 publication by Hares and others is based on mapping and stratigraphic studies conducted during the summers of 1913 and 1914. The Parkman was originally named by Darton (1906, p. 58–59) as a formation along the east flank of the Bighorn Mountains; it was later made a member of the Pierre Shale at the Salt Creek oil field by Wegemann (1911, p. 47), and still later was made a member of the Mesaverde Formation at the same locality (Wegemann, 1918, p. 21). The Teapot was named as a member of the Pierre Shale at the Big Muddy oil field by Barnett (1915, p. 113), east of Casper, Wyo., and was made the upper member of the Mesaverde Formation at Salt Creek by Wegemann (1918, p. 21).

[4] The U.S. Geological Survey topographic map of the Garfield Peak 7½-minute quadrangle, Wyoming, shows that the geographic feature from which this name was taken is Fales Rocks rather than Phayles Reef. It is in the SW¼ sec. 4, T. 33 N., R. 87 W., near locality 30, figure 3 and plate 2.

tant than the surrounding strata. The sandstones everywhere contain slight to moderate amounts of dark-colored mineral grains; these sandstones, however, do not have the same pronounced "salt and pepper" appearance as do the sandstones of the Frontier Formation. Very locally, the basal Mesaverde sandstone beds incorporate lenses of "black sand" in which heavy dark-colored and opaque mineral grains, chiefly oxides of iron and titanium, make up as much as 80 percent of the rock (Houston and Murphy, 1962).

Shales and siltstones in the Mesaverde Formation are gray to brown and commonly carbonaceous. Coal beds occur both in the lower and middle parts of the formation but most abundantly in the lower. The basal sandstone sequences at localities 7, 14, 19, 40, and 43, for example, are all overlain by thin-bedded strata which include one or more coal beds ranging in thickness from a few inches to 13 feet. (See Woodruff and Winchester, 1912; Thompson and White, 1952; Horn, 1963; Keefer and Troyer, 1964.) The coal beds, which have been mined at several localities, are lenticular for the most part, and their thicknesses vary considerably in short distances.

As described earlier (p. E16), the basal part of the Mesaverde Formation in sections east of the Coalbank Hills (loc. 28) is split by the westward-projecting Wallace Creek Tongue of the Cody Shale (pls. 2 and 3). The basal unit of the formation in this region, the Fales Member, thins to a wedge edge between localities 37 and 38 in the extreme southeastern corner of the Wind River Basin. The Parkman Sandstone Member, which overlies the Wallace Creek Tongue, then forms the basal unit of the Mesaverde beyond the point of disappearance of the Fales (for example, at loc. 38).

Sandstones constituting the Teapot Sandstone Member at the top of the Mesaverde Formation are white to light gray, very fine to coarse grained, massive to crossbedded, moderately porous and friable, and ledge forming (fig. 9). One of the most characteristic features in many outcrops is the crisscross pattern of veinlets that stand out on weathered surfaces. These veinlets, which are $\frac{1}{16}$ to $\frac{1}{2}$ inch thick and stand in relief by as much as 2 inches, are composed of sandstone that is harder and more

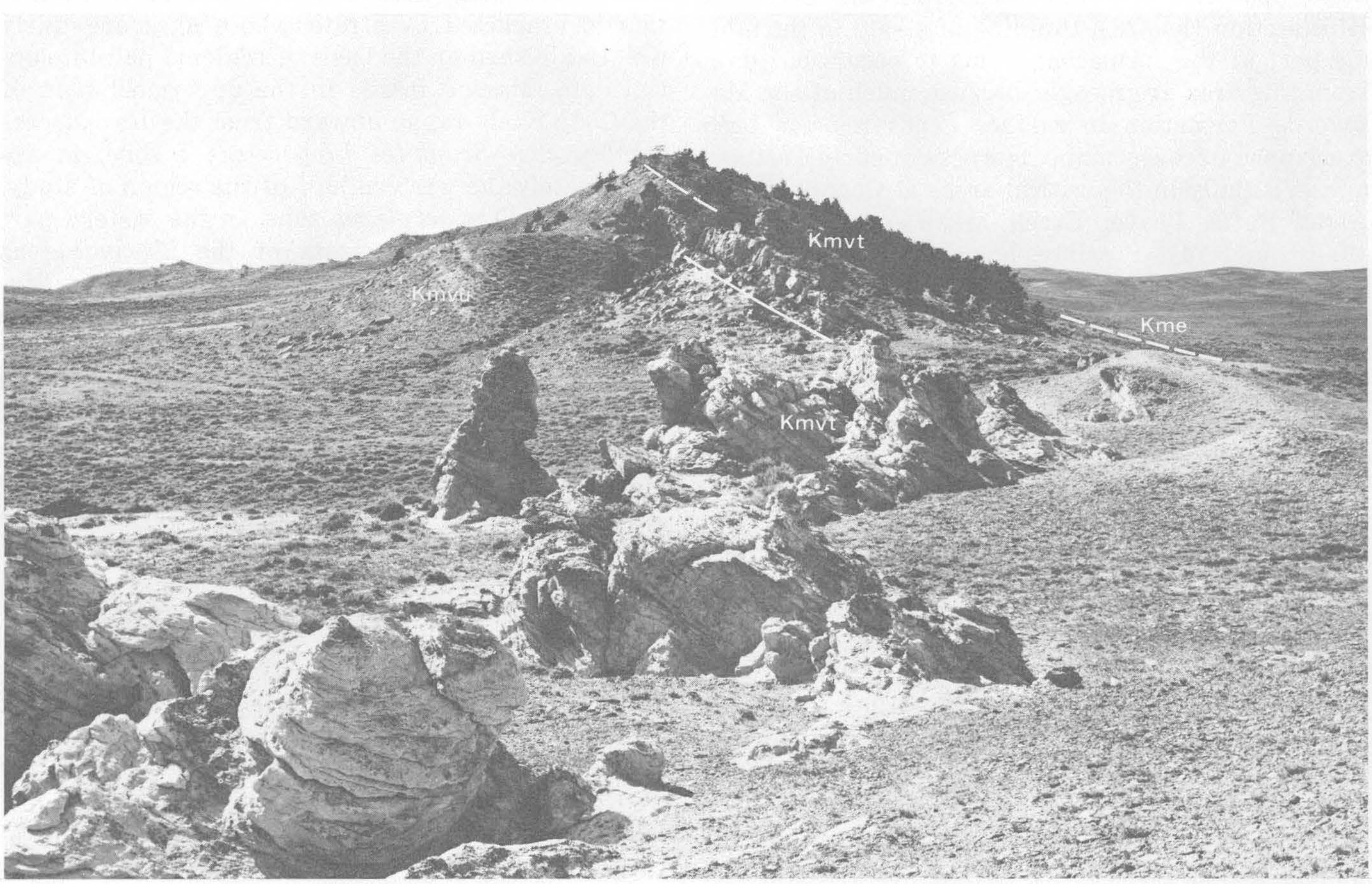


FIGURE 9.—Teapot Sandstone Member (Kmvt) of Mesaverde Formation at Coalbank Hills, northern Rattlesnake Hills (fig. 3, loc. 28). Kmvu, unnamed middle member of the Mesaverde Formation; Kme, Meeteetse Formation. View is to the north.

quartzitic than the surrounding rock. Minor lithologies within the Teapot include gray shale and claystone, brown carbonaceous shale, dark-brown to black ironstone, and, locally, coal. The member thickens from a minimum of about 50 feet in the eastern part of the Wind River Basin to a maximum of nearly 450 feet in the western part; in the southern Bighorn Basin it is 65–200 feet thick. The Teapot is generally the most easily recognized unit within the Mesaverde; it forms conspicuous dip slopes covered by profuse growths of pine trees in many areas (fig. 9).

An erosional unconformity at the base of the Teapot Sandstone Member has been described by Gill and Cobban (1966a) in the southern Bighorn Basin (shown on pl. 3) and by Reynolds (1966) in the Lost Soldier area of south-central Wyoming. Relationships in the intervening Wind River Basin, however, are not so well defined. Variations in the thickness of the unnamed middle member of the Mesaverde occur in the eastern and southeastern parts of the basin, but these may be due as much to local variations in the original distribution of sediments as to pre-Teapot erosion. Westward from the Coalbank Hills section (loc. 28), thinning of strata in the middle part of the formation seems to occur, but data from this area are meager because much of the Mesaverde Formation in surface exposures has been overlapped unconformably by rocks of early Tertiary age, especially in the critical areas at Conant Creek, Alkali Butte, Beaver Creek, and Lander (locs. 20, 19, 18, and 14). Possibly, however, the uppermost sandstone beds assigned to the formation at Alkali Butte (loc. 19) are equivalent to the Teapot Sandstone Member; if so, an unconformity is indicated within the Mesaverde at that locality. These beds were considered in earlier studies to be part of the Lance Formation of latest Cretaceous age (Yenne and Pipiringos, 1954; Keefer, 1965, p. A19), but more recent mapping by M. W. Reynolds (oral commun., 1969) indicates that they are best placed in the Mesaverde Formation, possibly in the Teapot Sandstone Member. If there is an unconformity at the base of the Teapot in exposures in the northwestern part of the Wind River Basin (locs. 7, 8, and 40) it does not appear to be reflected by any sharp or irregular contact with the underlying strata.

CONTACT WITH OVERLYING ROCKS

The Mesaverde Formation is overlain by nonmarine sandstone, shale, carbonaceous shale, and coal of the Meeteetse Formation in the central and western parts of the region of study, and by marine shale and sandstone of the Lewis Shale in the eastern part (Keefer, 1965, p. A8–A17). Strata of both the Meeteetse and Lewis are relatively nonresistant and thus are in sharp contrast with the conspicuously ledge-forming Teapot Sandstone Member of the Mesaverde (fig. 9). Where the Teapot is thin and poorly developed, on the other hand, the contact, particularly between the Mesaverde and Meeteetse Formations, is not so easily recognized because of the similarities in rock types both above and below it. The Teapot Sandstone Member, and hence the upper boundary of the Mesaverde, is readily distinguished on most electric logs.

The Mesaverde Formation is only partly present in most exposures in the southwestern Wind River Basin, because the upper part is overlapped unconformably by lower Tertiary rocks. The magnitude of the unconformity dimishes rapidly basinward, however, and the Mesaverde is fully represented in wells drilled a few miles downdip toward the basin interior.

AGE AND CORRELATION

Nonmarine rocks of the Mesaverde Formation contain few diagnostic fossils; however, the formation is bracketed by strata whose ages are fairly well established on the basis of regional paleontological data. Marine fossils in the uppermost part of the Cody Shale range upward from the *Haresiceras montanaense–Scaphites hippocrepis* I zone, in approximately the western half of the region of study, to the *Baculites perplexus* zone, in the eastern part (table 2). The basal strata of the Mesaverde as mapped in both the Wind River and southern Bighorn Basins therefore represent approximately the same age range.

The *Baculites jenseni* zone occurs from 50 to 100 feet above the base of the Lewis Shale in several sections. Thus, the upper beds of the Teapot Sandstone Member of the Mesaverde Formation in the eastern parts of the Wind River and Bighorn Basins are probably at least as young as the lower interval of the *Baculites reesidei* zone (table 2). The relationships in those areas seem to indicate that the top of the Teapot approximates a time line. (See, for example, Gill and Cobban, 1966a, fig. 1.) If so, then the upper boundary of the Mesaverde, where in direct contact with the unfossiliferous Meeteetse Formation, can also be interpreted to represent nearly the same temporal horizon.

In terms of the Cretaceous reference sequence of the western interior region, the Mesaverde Formation is equivalent to the upper part of the Niobrara Formation and lower and middle parts of the Pierre

Shale in the western half of the region of study; but it is equivalent to only the middle part of the Pierre in the eastern half (table 2).

SUMMARY OF DEPOSITIONAL HISTORY OF THE FRONTIER, CODY, AND MESAVERDE FORMATIONS

Widespread marine conditions prevailed in central Wyoming during deposition of the dark-colored shales of the Mowry Shale in Early Cretaceous time. The source of clastic sediments lay chiefly to the west, the material being eroded presumably from areas of uplift in the former miogeosynclinal region of eastern and (or) central Idaho. The bentonite beds of the Mowry, according to regional studies by Slaughter and Earley (1965, p. 89), may be "the natural prelude or the initial phase of an intense orogeny [and] * * * seem to mark the oncoming general [eastward] withdrawal of the Cretaceous seas."

Large quantities of sand, which now make up the lower beds of the Frontier Formation, began to accumulate in the western part of the Wind River Basin approximately at the beginning of Late Cretaceous time. The clastic debris was spread gradually eastward, and ensuing Frontier deposition took place primarily in shallow seas. Frontier strata record several cycles of transgression and regression, but the only major interruption in marine sedimentation apparently occurred during the deposition of interval F (First Wall Creek sand) in the western part of the basin, where thin beds of carbonaceous shale, lignite, and coal accumulated largely under fluviatile and swampy conditions at that time. Such conditions also prevailed in the extreme northwest corner of the basin (loc. 1) during parts of the period represented by the deposition of the lower beds of the formation.

Frontier sandstones have characteristics of a wide variety of onshore and offshore depositional environments because of varying sediment supply, constantly shifting strandlines, and changing water depths. Goodell (1962, p. 205) has pointed out that regressive sandstone units are commonly capped by 1–3 feet of transgressive sandstone; such relationships occur repeatedly through the formation. The shales are largely, if not wholly, marine, although they contain few fossils in most places. The meager faunal data from the Frontier suggest that some areas locally were raised above the level of the sea (or at least above wave base), resulting in short periods of nondeposition and (or) erosion.

Although the main sources of clastic debris were toward the west and northwest (Goodell, 1962, p. 204), closer sources apparently furnished some debris during Frontier deposition (Towse, 1952, p. 1987–2000). The size and distribution of the chert and andesite pebbles in the Torchlight Sandstone Member in the southern Bighorn Basin led Hunter (1952, p. 65), VanHouten (1962, p. 229, fig. 4), and other workers to the conclusion that the coarse material was derived in part from ancestral uplift in the northern Bighorn Mountains.

During late Carlile and early Niobrara times, much of central and western Wyoming was again inundated by a westward-transgressing sea, and the Cody Shale was deposited chiefly in an offshore marine environment. Clastic debris continued to be furnished by a western source, as indicated by the progressive increase in the proportion of sandstone westward across the region. Approximately in middle Niobrara time the cycle was reversed, and a widespread regression commenced in the Jackson Hole region of western Wyoming (Love, 1956, p. 80). The eastward-retreating shoreline apparently reached a virtual stillstand on a line connecting localities 19 and 43 in the Wind River and Bighorn Basins, respectively, by the end of Niobrara time (*Scaphites hippocrepis* interval). The shoreline oscillated within a north-trending strip, 10 to 15 miles wide, for a long period (fig. 7). Appreciable eastward regression began again approximately at the beginning of the time interval represented by the *Baculites obtusus* faunal zone, and the strandline retreated to a position near the present east margin of the Wind River Basin. Then followed another westward transgression of approximately 40 miles, represented by the Wallace Creek Tongue, thence a final eastward regression beyond the Wind River Basin area at the close of Cody deposition. The various movements of the strandline are well documented by paleontological data; the regional cycles of transgression and regression have been studied and discussed in detail by Gill and Cobban (1966b, p. A43–A48).

The environment during the time of Mesaverde deposition was characterized by flood plains, lagoons, coastal swamps, and deltas. The surface of deposition must have been very broad and flat and must have had little gradient, as evidenced by the fine-grained clastic material and the abundance of carbonaceous beds. The basal sandstone unit originated everywhere as a regressive deposit laid down during the eastward withdrawal of the Cody Sea. The origin of the upper sandstone (Teapot Member), however, is not so readily apparent. The unit is enclosed by rocks that are (1) totally marine in the western Powder River Basin (Gill and Cobban, 1966a, fig. 1), (2) both marine and nonmarine in the eastern Wind River and Bighorn Basins, and (3) totally nonmarine in the western Wind River and Bighorn Basins. Sedimentary features suggest that the Teapot itself is entirely nonmarine throughout the areas listed above. Present opinion regarding the problem is best summarized by Gill and Cobban (1966a, p. B25–B26):

> The Teapot and its lateral equivalents * * * are considered to be postorogenic deposits derived from strongly uplifted areas in western Wyoming or eastern Idaho. These rocks differ in appearance and lithology from regressive deposits of the Mesaverde and other Cretaceous formations in Wyoming because of their somewhat different environments of deposition. The Mesaverde and similar rocks accumulated slowly in and along the margins of the regressing sea. The Teapot and its equivalents appear to have been deposited rapidly as a broad sheetlike body of nonmarine sand on the uplifted and eroded surface of nonmarine rocks of the [lower part of the] Mesaverde.

Deposition of the Teapot Sandstone Member of the Mesaverde Formation was followed by another westward transgression of the Cretaceous sea, but one that was limited to only the eastern part of the region of study (east of a line drawn between loc. 31 in the Wind River Basin and loc. 47 in the southern Bighorn Basin, fig. 3). This event, however, does not seem to be represented by noticeable transgressive sand deposits at the top of the Teapot in areas where it is overlain directly by the marine Lewis Shale.

Thickness maps of rock units (figs. 6 and 7) indicate the presence of certain structural features in central Wyoming during the depositional period of the Frontier, Cody, and Mesaverde Formations. Of particular significance was the development of an incipient west-northwest-trending downwarp along the north and northeast margins of the Wind River Basin. The position of this shallow trough coincides closely with the area in which the greatest amount of basin subsidence took place during the major phases of Laramide deformation in latest Cretaceous and early Tertiary times (Keefer, 1970). Incipient upwarps formed contemporaneously along the south and northwest margins of the basin, perhaps reflecting early growth of segments of the Granite Mountains and the Wind River Range, respectively, and of related Laramide anticlinal trends. The tectonic unrest is best evidenced by the relationships at the base of the Teapot Sandstone Member of the Mesaverde Formation. The contact of this member with older Mesaverde strata is an unconformity at least locally and perhaps regionally and thus is indicative of a period of folding and erosion in central Wyoming and perhaps also of accelerated uplift in the source area to the west at that time.

The Owl Creek Mountains and Casper arch, on the other hand, are not reflected by the isopachs (figs. 6 and 7). Rock units thin progressively northward into the southern part of the Bighorn Basin, and that area apparently remained a fairly shallow shelf during all Frontier, Cody, and Mesaverde deposition.

REFERENCES CITED

Armstrong, F. C., and Oriel, S. S. 1965, Tectonic development of Idaho-Wyoming thrust belt: Am. Assoc. Petroleum Geologists Bull., v. 49, no. 11, p. 1847–1866.

Barnett, V. H., 1915, The Moorcroft oil field, Crook County, Wyoming, *and* Possibilities of oil in the Big Muddy dome, Converse and Natrona Counties, Wyoming: U.S. Geol. Survey Bull. 581–C, p. 83–117.

Barwin, J. R., 1959, Facies of the Mesaverde formation, east-central Wyoming: Am. Assoc. Petroleum Geologists Rocky Mtn. Sec. Geol. Rec., Feb. 1959, p. 139–142.

——— 1961a, Stratigraphy of the (Cretaceous) Mesaverde Formation in the southeastern part of the Wind River Basin, Fremont and Natrona Counties, Wyoming: Laramie, Wyo., Wyoming Univ. unpub. M.S. thesis, 78 p.

——— 1961b, Stratigraphy of the Mesaverde Formation in the southern part of the Wind River Basin, Wyoming, *in* Symposium on Late Cretaceous rocks, Wyoming and adjacent areas, Wyoming Geol. Assoc., 16th Ann. Field Conf., Green River, Washakie, Wind River and Powder River Basins, 1961: Casper, Wyo., Petroleum Inf., p. 171–179.

Cobban, W. A., and Reeside, J. B., Jr., 1952, Frontier formation, Wyoming and adjacent areas: Am. Assoc. Petroleum Geologists Bull., v. 36, no. 10, p. 1913–1961.

Darton, N. H., 1906, Geology of the Bighorn Mountains: U.S. Geol. Survey Prof. Paper 51, 129 p.

Gill, J. R., and Cobban, W. A., 1966a, Regional unconformity in Late Cretaceous, Wyoming, *in* Geological Survey research 1966: U.S. Geol. Survey Prof. Paper 550–B, p. B20–B27.

——— 1966b, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming: U.S. Geol. Survey Prof. Paper 393–A, 73 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. Geol. Survey Prof. 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 Geol. Assoc. 17th Ann. Field Conf., Casper arch, western Powder River and northern Big Horn basins, 1962: Casper, Wyo., Petroleum Inf., p. 173–210.

Hares, C. J., 1916, Anticlines in central Wyoming: U.S. Geol. Survey Bull. 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. Geol. Survey Oil and Gas Inv. Map 51. (Repr. 1955.)

Holmes, W. H., 1877, Report [on the San Juan district, Colorado]: U.S. Geol. and Geog. Survey Terr. (Hayden), 9th Ann. Rept., p. 237–276.

Horn, G. H., 1963, Geology of the east Thermopolis area, Hot Springs and Washakie Counties, Wyoming: U.S. Geol. Survey Oil and Gas Inv. Map OM–213.

Houston, R. S., and Murphy, J. F., 1962, Titaniferous black sandstone deposits of Wyoming: Wyoming Geol. Survey Bull. 49, 120 p.

Hunter, L. D., 1952, Frontier formation along the eastern margin of the Big Horn Basin, Wyoming, *in* Wyoming Geol. Assoc. Guidebook 7th Ann. Field Conf., Southern Big Horn Basin, Wyoming, 1952: p. 63–66.

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. Geol. Survey Prof. Paper 495–A, 77 p.

——— 1966, Paleozoic formations in the Wind River Basin, Wyoming: U.S. Geol. Survey Prof. Paper 495–B, 60 p.

——— 1969, Geology of petroleum in Wind River Basin, central Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 53, no. 9, p. 1839–1865.

——— 1970, Structural geology of the Wind River Basin, Wyoming: U.S. Geol. Survey Prof. Paper 495–D, 35 p.

Keefer, W. R., and Troyer, M. L., 1964, Geology of the Shotgun Butte area, Fremont County, Wyoming: U.S. Geol. Survey Bull. 1157, 123 p.

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

Love, J. D., 1956, Cretaceous and Tertiary stratigraphy of the Jackson Hole area, northwestern Wyoming, *in* Wyoming Geol. Assoc. Guidebook, 11th Ann. Field Conf., Jackson Hole area, Wyoming, 1956: p. 75–94.

——— 1970, Cenozoic geology of the Granite Mountains area, central Wyoming: U.S. Geol. Survey Prof. Paper 495–C, 154 p.

Love, J. D., Tourtelot, H. A., Johnson, C. O., Thompson, R. M., Sharkey, H. H. R., and Zapp, A. D., 1947, Stratigraphic sections of Mesozoic rocks in central Wyoming: Wyoming Geol. Survey Bull. 38, 59 p.

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

Masters, J. A., 1951, Frontier Formation (Wyoming): Boulder, Colo., Colorado Univ. unpub. M.A. thesis, 93 p.

——— 1952, The Frontier formation of Wyoming, *in* Wyoming Geol. Assoc. Guidebook, 7th Ann. Field Conf., Southern Big Horn Basin, Wyoming, 1952: p. 58–62.

Prochaska, Eugene, 1960, Foraminifera from two sections of the (Upper Cretaceous) Cody Shale in Fremont and Teton Counties, Wyoming: Laramie, Wyo., Wyoming Univ. unpub. M.S. thesis, 79 p.

Reynolds, M. W., 1966, Stratigraphic relations of Upper Cretaceous rocks, Lamont-Bairoil area, south-central Wyoming, *in* Geological Survey research 1966: U.S. Geol. Survey Prof. Paper 550–B, p. B69–B76.

Rich, E. I., 1958, Stratigraphic relation of latest Cretaceous rocks in parts of Powder River, Wind River, and Big Horn basins, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 42, no. 10, p. 2424–2443.

——— 1962, Reconnaissance geology of Hiland-Clarkson Hill area, Natrona County, Wyoming: U.S. Geol. Survey Bull. 1107–G, p. 447–540.

Roberts, A. E., 1965, Correlation of Cretaceous and lower Tertiary rocks near Livingston, Montana, with those in other areas of Montana and Wyoming, *in* Geological Survey research 1965: U.S. Geol. Survey Prof. Paper 525–B, p. B54–B63.

Slaughter, M., and Earley, J. W., 1965, Mineralogy and geological significance of the Mowry bentonites, Wyoming: Geol. Soc. America Spec. Paper 83, 116 p.

Thompson, R. M., Love, J. D., and Tourtelot, H. A., 1949, Stratigraphic sections of pre-Cody Upper Cretaceous rocks in central Wyoming: U.S. Geol. Survey Oil and Gas Inv. Prelim. Chart 36.

Thompson, R. M., and White, V. L., 1952, The coal deposits of the Alkali Butte, the Big Sand Draw, and the Beaver Creek fields, Fremont County, Wyoming: U.S. Geol. Survey Circ. 152, 24 p.

Towse, D. F., 1952, Frontier formation, southwest Powder River Basin, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 36, no. 10, p. 1962–2010.

Troyer, M. L., and Keefer, W. R., 1955, Geology of the Shotgun Butte area, Fremont County, Wyoming: U.S. Geol. Survey Oil and Gas Inv. Map OM–172.

VanHouten, F. B., 1962, Frontier Formation, Bighorn Basin, Wyoming, *in* Symposium on Early Cretaceous rocks of Wyoming and adjacent areas, Wyoming Geol. Assoc. 17th Ann. Field Conf., Casper arch, western Powder River and northern Big Horn basins, 1962: Casper, Wyo., Petroleum Inf., p. 221–231.

Wegemann, C. H., 1911, The Salt Creek oil field, Wyoming, *in* The Lander and Salt Creek oil fields, Wyoming: U.S. Geol. Survey Bull. 452, p. 37–83.

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

White, R. K., 1961, Foraminifera from two sections of the (Upper Cretaceous) Cody Shale, central Wyoming: Laramie, Wyo., Wyoming Univ. unpub. M.S. thesis, 84 p.

Woodruff, E. G., 1911, The Lander oil field, Fremont County, *in* The Lander and Salt Creek oil fields, Wyoming: U.S. Geol. Survey Bull. 452, p. 7–36.

Woodruff, E. G., and Winchester, D. E., 1912, Coal fields of the Wind River region, Fremont and Natrona Counties, Wyoming: U.S. Geol. Survey Bull. 471–G, p. 516–564.

Workum, R. H., 1959, The stratigraphy of the Mesaverde Formation (Cretaceous) of the west flank of the Casper arch, Natrona County, Wyoming: Laramie, Wyo., Wyoming Univ. unpub. M.S. thesis, 68 p.

Yenne, K. A., and Pipiringos, G. N., 1954, Stratigraphic sections of Cody Shale and younger Cretaceous and Paleocene rocks in the Wind River Basin, Fremont County, Wyoming: U.S. Geol. Survey Oil and Gas Inv. Chart OC–49.

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