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Geological Characteristics of Low-permeability Upper Cretaceous and Lower Tertiary Rocks in the Pinedale Anticline Area, Sublette County, Wyoming

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GEOLOGICAL CHARACTERISTICS OF LOW-PERMEABILITY UPPER CRETACEOUS AND LOWER TERTIARY ROCKS IN THE PINEDALE ANTICLINE AREA, SUBLETTE COUNTY, WYOMING

By Ben E. Law

INTRODUCTION

In 1977 the Greater Green River Basin of Wyoming, Colorado, and Utah (fig. 1) was identified by the U.S. Department of Energy as one of four areas in the Rocky Mountain region to be included in their Western Tight Gas Sands Program. The basin encompasses an area of about 19,700 mi^2 (51,000 km^2) and contains large gas resources in Upper Cretaceous and lower Tertiary low-permeability reservoir sequences, that in places are more than 10,000 ft (>3,048 m) thick. The National Petroleum Council (1980) estimated the total gas resources in the basin at about 136 trillion cubic feet (tcf) and the recoverable gas resource at about 86.5 tcf.

Because of the large areal extent and great thickness of these low-permeability rocks, U.S. Geological Survey research efforts have focused on individual wells or small areas containing several wells in which there are relatively large amounts of data available. The research approach has been multidisciplinary. The reports of investigations include structure, stratigraphy, petrography, x-ray mineralogy, source-rock evaluation, abnormally high formation pressure, application of borehole geophysical logs to stratigraphy, thermal maturity mapping, fission-track age dating, fluid inclusions, and isotopic geochemistry. These investigations are in various stages of completion and are, therefore, reports of ongoing studies. The objectives of these focused investigations are to provide data and interpretations related to the geology of gas-bearing low-permeability reservoirs.

The Pinedale anticline, the subject of this report, is one of these intensely studied areas. This large anticline is located in the northern part of the Green River Basin (figs. 1 and 2). The first well drilled on the Pinedale anticline was completed in 1939 to a depth of 10,000 ft (3,048 m) by The California Company. Since that time, there have been 19 additional wells drilled in the area. Figure 2 shows the location of wells drilled on the Pinedale anticline. Specific locations and other pertinent data are shown in table 1. Most of the wells have been drilled to depths of 10,000 to 12,000 ft (3,048 to 3,658 m) in the Upper Cretaceous Lance Formation. The deepest well is the El Paso Natural Gas, Wagon Wheel No. 1 well, which was drilled to 19,000 ft (5,791 m) into the Upper Cretaceous Baxter Shale. All the wells have indicated the existence of large gas accumulations. In particular, data obtained from the Wagon Wheel well have conclusively demonstrated the occurrence of a thick gas-bearing interval below a depth of about 8,000 ft (2,438 m).

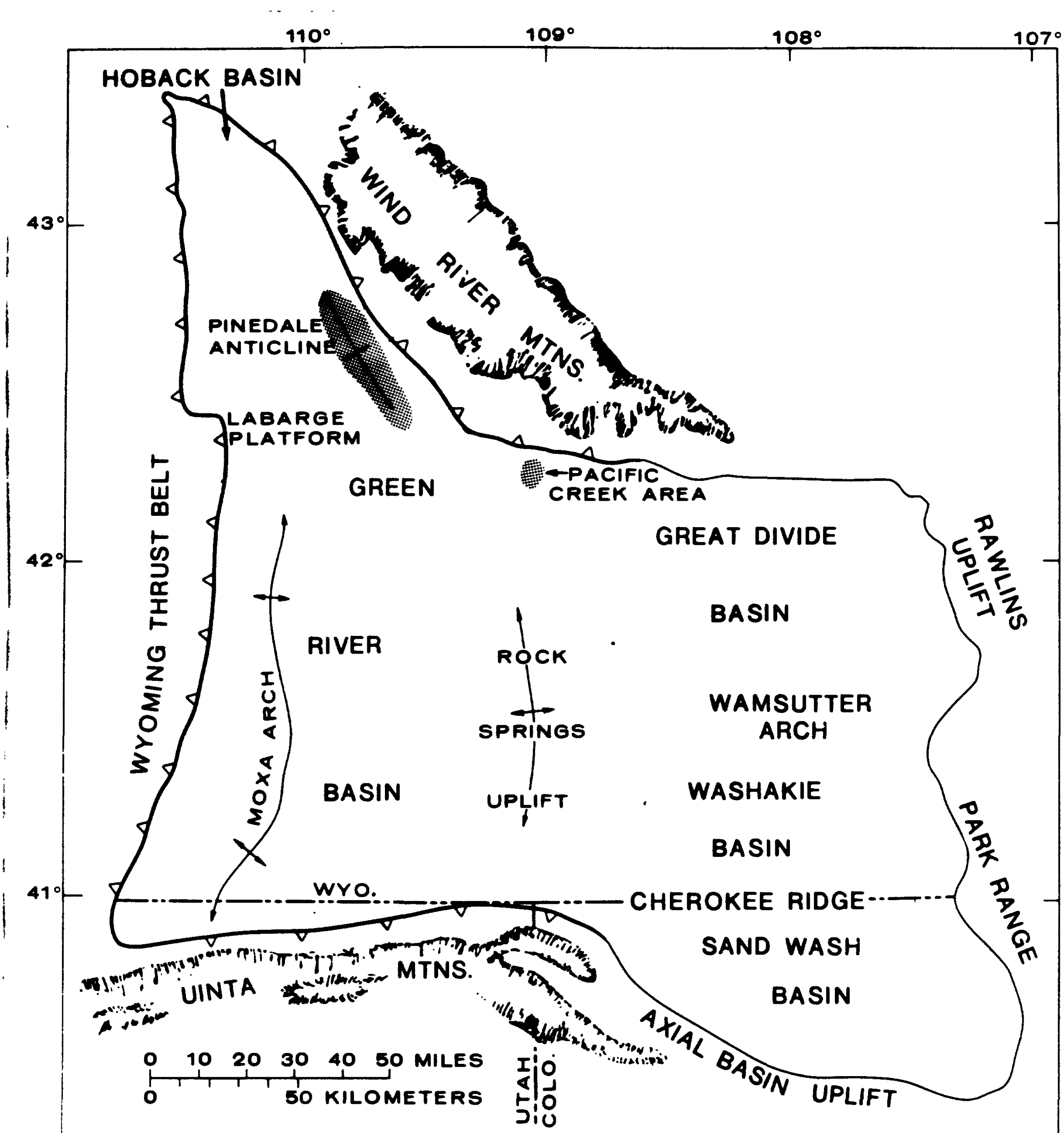

Figure 1.--Map of Greater Green River Basin showing major structural features, including the Pinedale anticline.

The Wagon Wheel well, completed in 1970, was proposed as part of a nuclear stimulation project. It was intended to be the fourth nuclear experiment following the Gasbuggy, Rulison, and Rio Blanco detonations in the San Juan Basin, New Mexico, and the Piceance Creek Basin, Colorado. However, due to environmental considerations and disappointing test results obtained in these wells, plans for detonation of a nuclear device in the Wagon Wheel well were abandoned. A report of the project, including the drilling and testing results, are discussed by Martin and Shaughnessy (1969) and Shaughnessy and Butcher (1973, 1974).

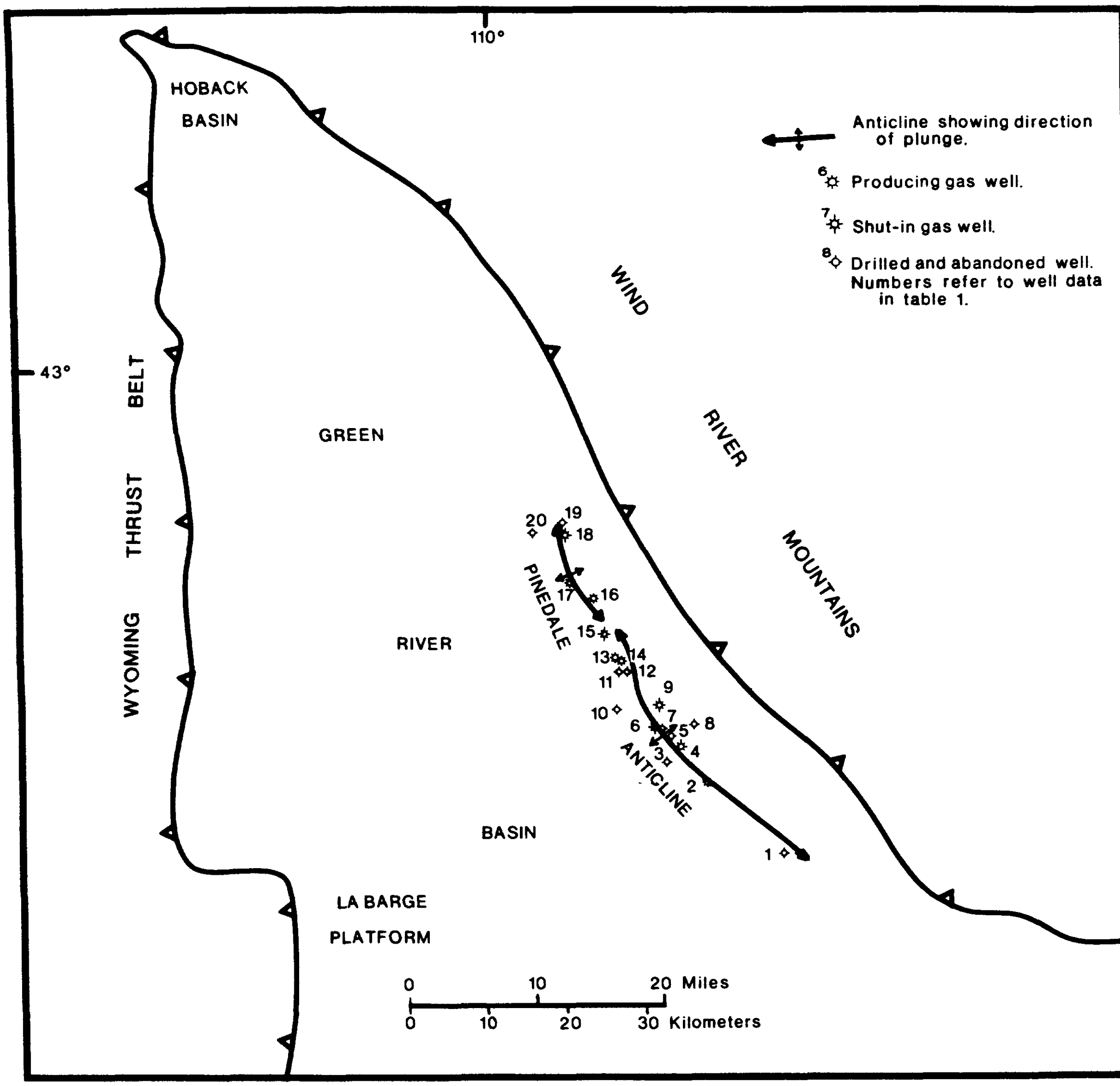

Figure 2.--Map of the northern part of the Green River Basin and the Pinedale anticline with location of wells. Specific locations of wells are shown in table 1.

As a consequence of the extensive testing and coring conducted in the Wagon Wheel well, most of the geological interpretations in the Pinedale area are derived from data obtained from this well. Within the depth interval of 5,000 and 18,000 ft (1,524-5,486 m), approximately 900 ft (274 m) of rock was cored. The cored intervals are shown on figure 4 of Law (p. 11, this volume). Data derived from cores in the Wexpro and American Hunter wells (table 1) have also been incorporated into these investigations.

Table 1.--Wells drilled in Pinedale anticline area, Sublette County, Wyoming

[Prod., Producing well; D & A, Drilled and Abandoned well; SI, Shut-In well; ---, no data]

Map no.	Well name	Operator	Location	KB (feet)	TD (feet)	Formation	Status
1	Unit 1	Texaco	NE 1/4 SW 1/4, sec. 25, T. 29 N., R. 107 W.	7,134	11,008	Lance	D & A
2	New Fork 1	American Hunter	SW 1/4 NE 1/4, sec. 25, T. 30 N., R. 108 W.	7,338	10,989	Lance	Prod.
3	Pinedale 6	El Paso Natural Gas	SE 1/4 NW 1/4, sec. 21, T. 30 N., R. 108 W.	7,294	11,057	do	D & A
4	Pinedale 7	do	SE 1/4 NE 1/4, sec. 15, T. 30 N., R. 108 W.	7,369	10,270	do	SI
5	Pinedale 1	do	NE 1/4 SE 1/4, sec. 9, T. 30 N., R. 108 W.	7,196	10,550	do	D & A
6	Wagon Wheel 1	do	SE 1/4 NW 1/4, sec. 5, T. 30 N., R. 108 W.	7,089	19,000	Baxter	SI
7	Pinedale 5	do	C SE 1/4, sec. 5, T. 30 N., R. 108 W.	7,056	15,018	Rock Springs	D & A
8	New Fork 2	American Hunter	SW 1/4 NE 1/4, sec. 2, T. 30 N., R. 108 W.	7,282	11,986	Lance	Do.
9	Pinedale 2	El Paso Natural Gas	SE 1/4, sec. 29, T. 31 N., R. 108 W.	7,034	10,694	do	SI
10	New Fork 4	American Hunter	NW 1/4 SE 1/4, sec. 35, T. 31 N., R. 109 W.	6,957	11,550	do	D & A
11	Gov't 1	California Co.	SW 1/4 NE 1/4, sec. 14 T. 31 N., R. 109 W.	---	10,000	do	Do.
12	Pinedale 3	El Paso Natural Gas	C NW 1/4, sec. 13, T. 31 N., R. 109 W.	6,982	11,009	do	Do.
13	Jensen 1	Leonard Hay	SW 1/4 NW 1/4, sec. 11, T. 31 N., R. 109 W.	6,932	10,320	do	Prod.
14	Jensen 2	do	SE 1/4 SE 1/4, sec. 11, T. 31 N., R. 109 W.	---	10,310	do	Do.
15	Pinedale 4	El Paso Natural Gas	C NW 1/4, sec. 34, T. 32 N., R. 109 W.	7,204	11,123	do	SI
16	Mesa 2	Wexpro	SE 1/4 NW 1/4, sec. 16, T. 32 N., R. 109 W.	7,474	12,190	do	Prod.
17	Mesa 1	do	NE 1/4 NE 1/4, sec. 7, T. 32 N., R. 109 W.	7,525	12,050	do	Do.
18	Pinedale 8	Mountain Fuel	NE 1/4 SW 1/4, sec. 20, T. 33 N., R. 109 W.	7,448	10,500	do	SI
19	Unit 1	Stanolind	NW 1/4 SE 1/4, sec. 17, T. 33 N., R. 109 W.	---	7,797	Unnamed Tert.	D & A
20	Baumgartner Fed. 21-24.	Black Hawk Resources	NE 1/4 NW 1/4, sec. 24, T. 33 N., R. 110 W.	7,344	11,238	Lance	Do.

There are currently five producing wells in the Pinedale anticline area and several other wells are shut-in (fig. 2 and table 1). Gas production, with minor amounts of condensate, is from low-permeability lenticular sandstones in the Lance Formation below a depth of about 8,000 ft (2,438 m). The reservoirs require stimulation for sustained economic production rates. Initial gas production rates are highly variable. Maximum rates of 1.5 million cubic feet per day (mmcfd) from single reservoirs and about 2.5 mmcfd from multiple reservoirs have been reported.

ACKNOWLEDGMENTS

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Structure and Stratigraphy of the Pinedale Anticline, Wyoming

By Ben E. Law

INTRODUCTION

Structural and stratigraphic data are essential components of many geological studies. The significance of highly specialized geological investigations may be lost or misleading if not placed in the correct structural and stratigraphic framework. To some degree, this has been the case in previous investigations of the Pinedale anticline, where structural and stratigraphic relationships are not well known. The main obstacles encountered in attempting to establish a more accurate framework in the Pinedale area are (1) the absence of Upper Cretaceous and lower Tertiary outcrops in the vicinity of the Pinedale anticline, (2) the insufficient number of stratigraphically deep wells, (3) the absence of reliable stratigraphic markers due to the discontinuous nature of the lithologic units, and (4) the paucity of biostratigraphic data.

The most significant previously published structural and stratigraphic studies in the Pinedale anticline are those related to Project Wagon Wheel by Martin and Shaughnessy (1969) and Shaughnessy and Butcher (1973, 1974). Other structural and stratigraphic studies that have been conducted in the Pinedale anticline area include subsurface correlations by Law (1979), a discussion of Upper Cretaceous and lower Tertiary rocks by Law and Nichols (1982), and an investigation of the origin and development of the northern Green River Basin by Shuster and Steidtmann (1983).

During the course of U.S. Geological Survey investigations in the Pinedale area, data have been obtained from well logs and cores that necessitates modification of the existing geological framework. Thus, the primary purpose of this report is to modify the structural and stratigraphic framework in the Pinedale anticline area.

STRUCTURE

The Pinedale anticline is located in the Rocky Mountains foreland in the northern part of the Green River Basin (fig. 1) between the Idaho-Wyoming thrust belt to the west and the Wind River Mountains to the east. The basin formed in response to loading by thrusting events in the Idaho-Wyoming thrust belt (Jordan, 1981) and by uplift of the Wind River Mountains. Structural deformation in these tectonically unstable areas has provided source terranes for some of the Upper Cretaceous and lower Tertiary rocks.

The axis of the Pinedale anticline trends southeastward, parallel to the southwest flank of the Wind River Mountains and associated Wind River thrust fault. The anticline is about 35 miles (56 km) long and about 6 miles (10 km) wide. Figure 2 is a structure contour map of the Pinedale anticline, constructed on the base of the Tertiary. A structural cross section extending from the Wyoming thrust belt, northeast across the Pinedale anticline to the Wind River Mountains is shown on figure 3. The fold is asymmetrical with the west flank steeper than the east flank. Total structural relief on the anticline is about 2,000 ft (610 m) with two areas of closure (fig. 2). According to Shaughnessy and Butcher (1973, 1974), the west flank of the anticline is bounded by a buried reverse fault (fig. 3), that at depth curves toward the Wind River Mountains. They indicate about 600 ft (182 m) of displacement across the fault and that the fault intersects the Wagon Wheel borehole at about 18,000 ft (5,486 m). Examination of the two deepest cores from the Wagon Wheel well (17,163 to 17,193 ft and 17,959 to 17,996 ft on figure 4) show increasingly steeper dips and increasing fracture frequency, indicating proximity to a fault.

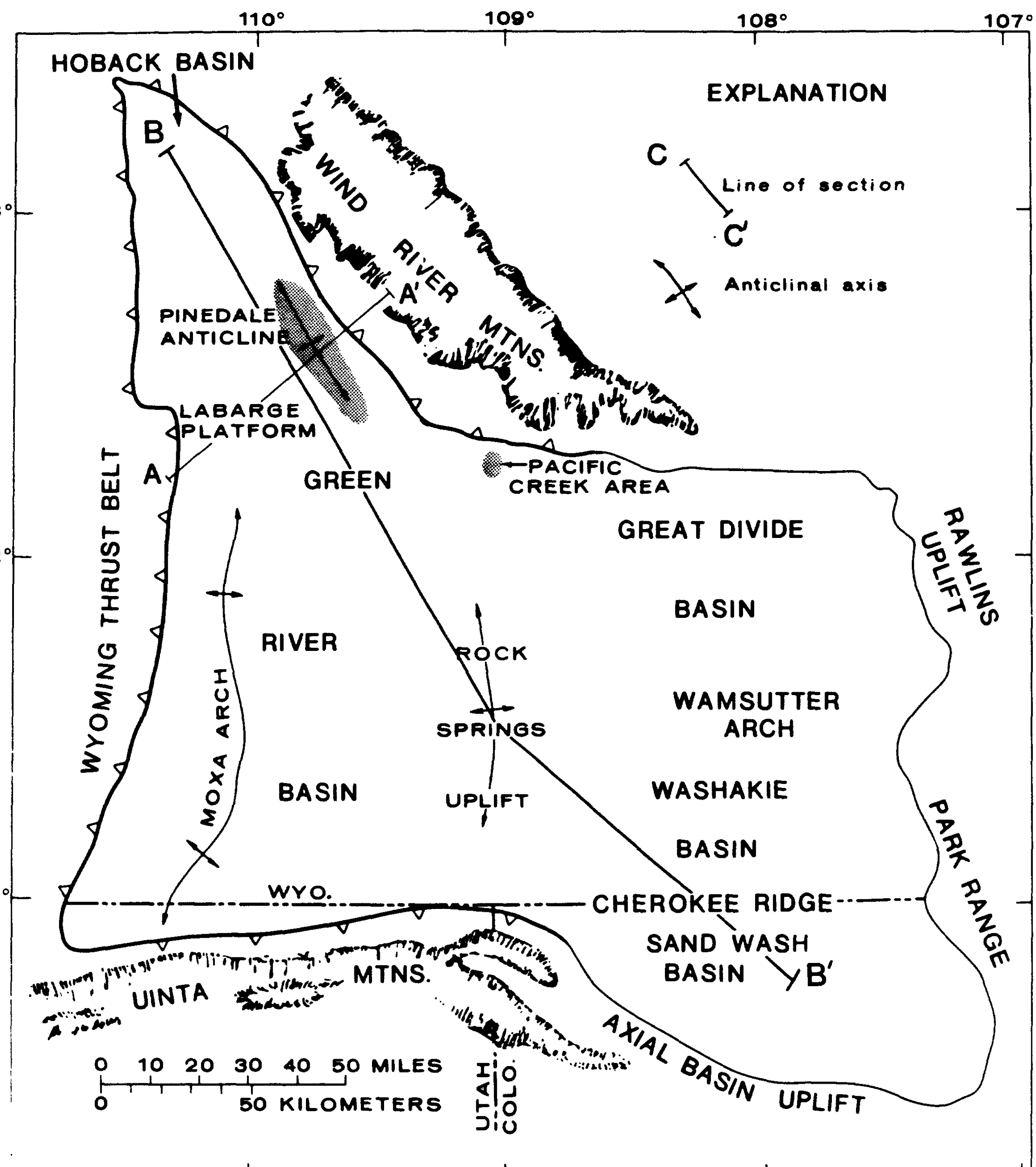

Figure 1.--Map of the Greater Green River Basin showing the location of the Pinedale anticline and cross sections A-A′ and B-B′

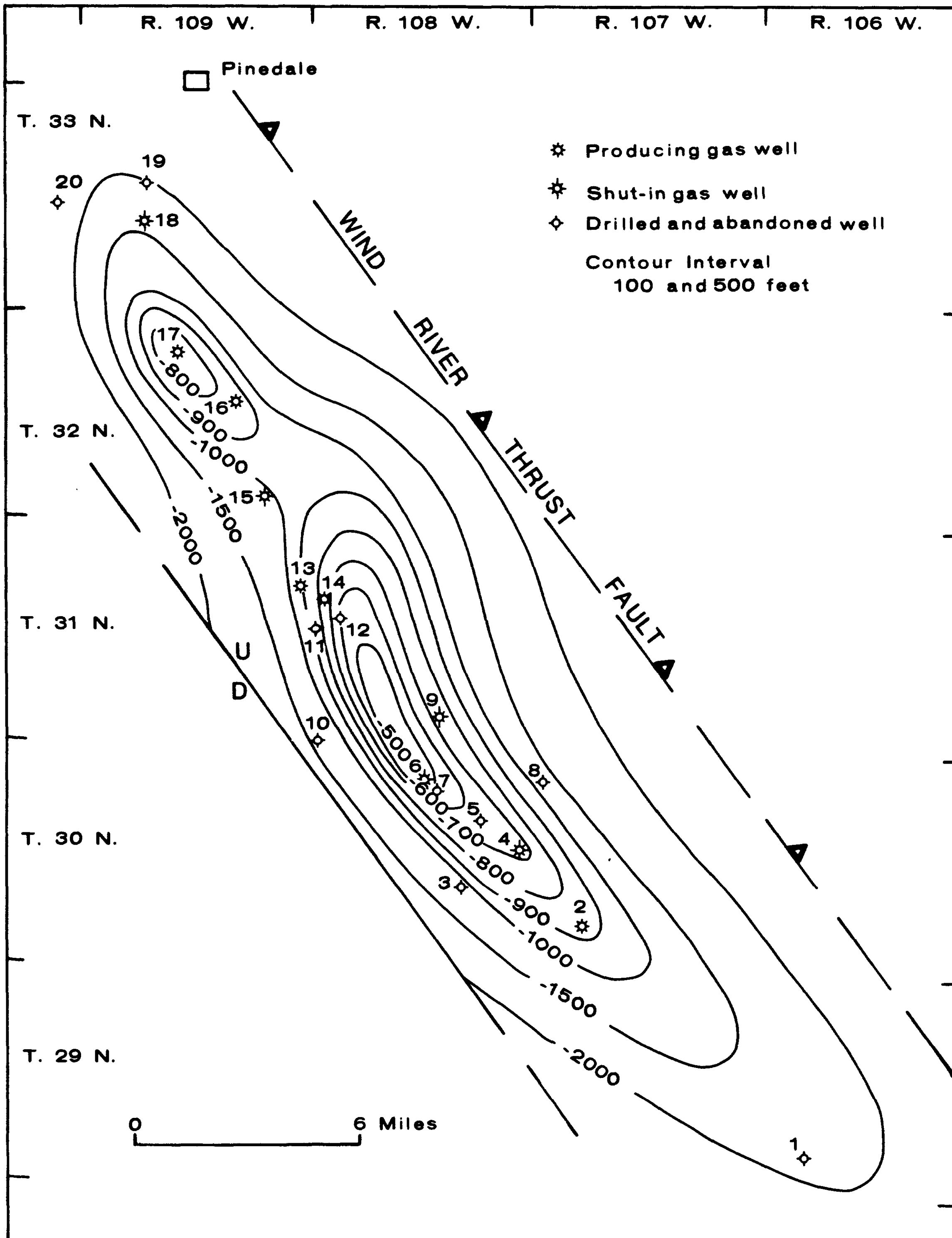

Figure 2.--Structure contour map of the Pinedale anticline. Structural datum is the Cretaceous-Tertiary boundary. Well names and other data are listed in table 1 of Law (p. 4, this volume).

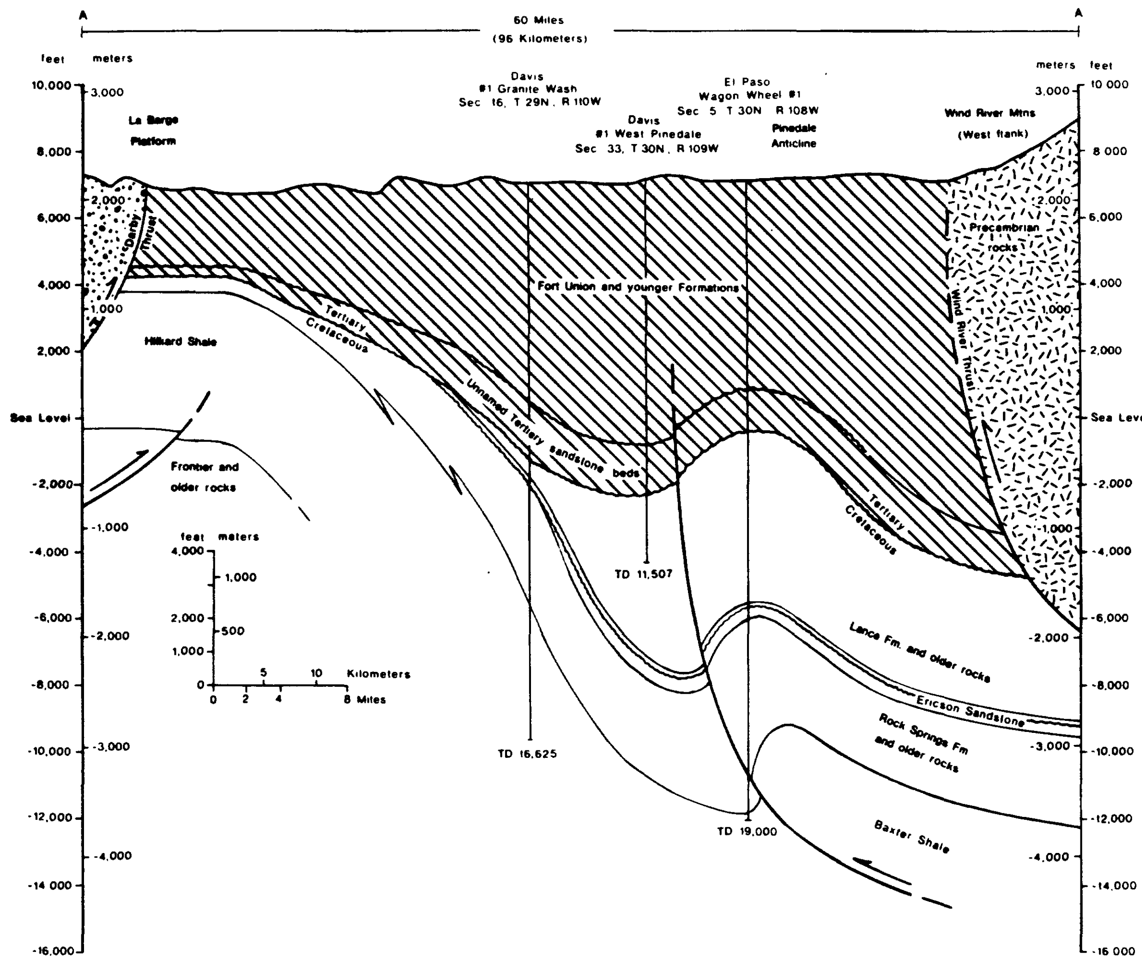

Figure 3.--Cross section A-A′ extending from the Wyoming thrust belt, northeast to the Wind River Mountains. High-angle reverse fault on west side of Pinedale anticline from Martin and Shaughnessy (1969) and Shaughnessy and Butcher (1973, 1974). Line of section shown on figure 1.

The structural evolution of the Pinedale anticline appears to be related to movement on the Wind River thrust fault. The parallel trend of the fold axis, the asymmetry, the geometric similarity of the west bounding anticlinal fault, and proximity of the anticline to the Wind River thrust fault are consistent with this interpretation. The initiation of structural growth may have occurred during the Laramide Orogeny, although evidence such as thinning of Upper Cretaceous or lower Tertiary rocks over the structure is lacking. Ongoing thermal maturation and related studies (Naeser, this volume; Pollastro and Barker, this volume; Lickus and others, this volume; Law and Spencer, 1981; Law, 1984) indicate that the latest and most significant structural deformation was post-Eocene; possibly as recent as Pliocene.

STRATIGRAPHY

The focus of stratigraphic studies conducted in the Pinedale anticline area has been determined by the occurrence of gas-bearing reservoirs, the constraint of deep drilling, and the availability of cores. Consequently, the following discussion includes the upper part of the Upper Cretaceous and lower part of the lower Tertiary. Most of the stratigraphic data from the Pinedale anticline are from the El Paso Natural Gas, Wagon Wheel no. 1 well. Therefore, the Wagon Wheel well is presented here as the stratigraphic reference well for this area. Figure 4 shows the stratigraphic sequence penetrated in the Wagon Wheel well. The stratigraphic nomenclature used in the Pinedale anticline area is from the Rock Springs uplift area and is based on the stratigraphic correlations shown on figure 5.

Cretaceous Rocks

About 11,500 ft (3,505 m) of Upper Cretaceous rocks were penetrated in the Wagon Wheel well. With the exception of the lower 2,800 ft (853 m), the entire rock sequence was deposited in nonmarine environments. In response to thrusting events in the Wyoming thrust belt, these rocks were deposited as a prograding wedge of dominantly clastic debris derived from source terranes farther west and northwest. East and southeast of the Pinedale anticline, these rocks grade into and intertongue with marine, marginal marine, and nonmarine rocks. Figure 6 is a diagrammatic cross section extending from the northern part of the Green River Basin to the Sand Wash Basin showing these relationships. In ascending order, the Upper Cretaceous rocks include the Baxter Shale, Rock Springs Formation and older rocks, Ericson Sandstone, and Lance Formation and older rocks.

The Baxter Shale is composed chiefly of gray shale, grading upward to silty and sandy shale. Only about 1,300 ft (396 m) of the Baxter Shale was penetrated in the Wagon Wheel well. The total thickness of the Baxter Shale is estimated to be about 3,500 ft (1,067 m), as indicated by wells on the east flank of the LaBarge platform. The upper part of the Baxter Shale was deposited in a shallow water marine environment.

The Rock Springs Formation and older rocks are composed of tan to light-gray, fine- to medium-grained sandstone, siltstone, shale, carbonaceous mudstone, and coal. The lower contact is conformable with the underlying Baxter Shale. In well logs, the contact is placed at the base of predominantly sandstone-bearing rocks. The Rock Springs Formation and older rocks are about 4,200 ft (1,280 m) thick and can be subdivided into three parts. The lower part is about 1,500 ft (457 m) thick and consists of intertonguing sandstone and shales deposited in shallow-water marine and marginal marine environments. The middle part is about 1,200 ft (366 m) thick and consists of lower delta plain deposits that include a coal-bearing zone. The upper part is about 1,500 ft (457 m) thick and consists of interbedded sandstone, siltstone, and mudstone deposited in alluvial plain environments.

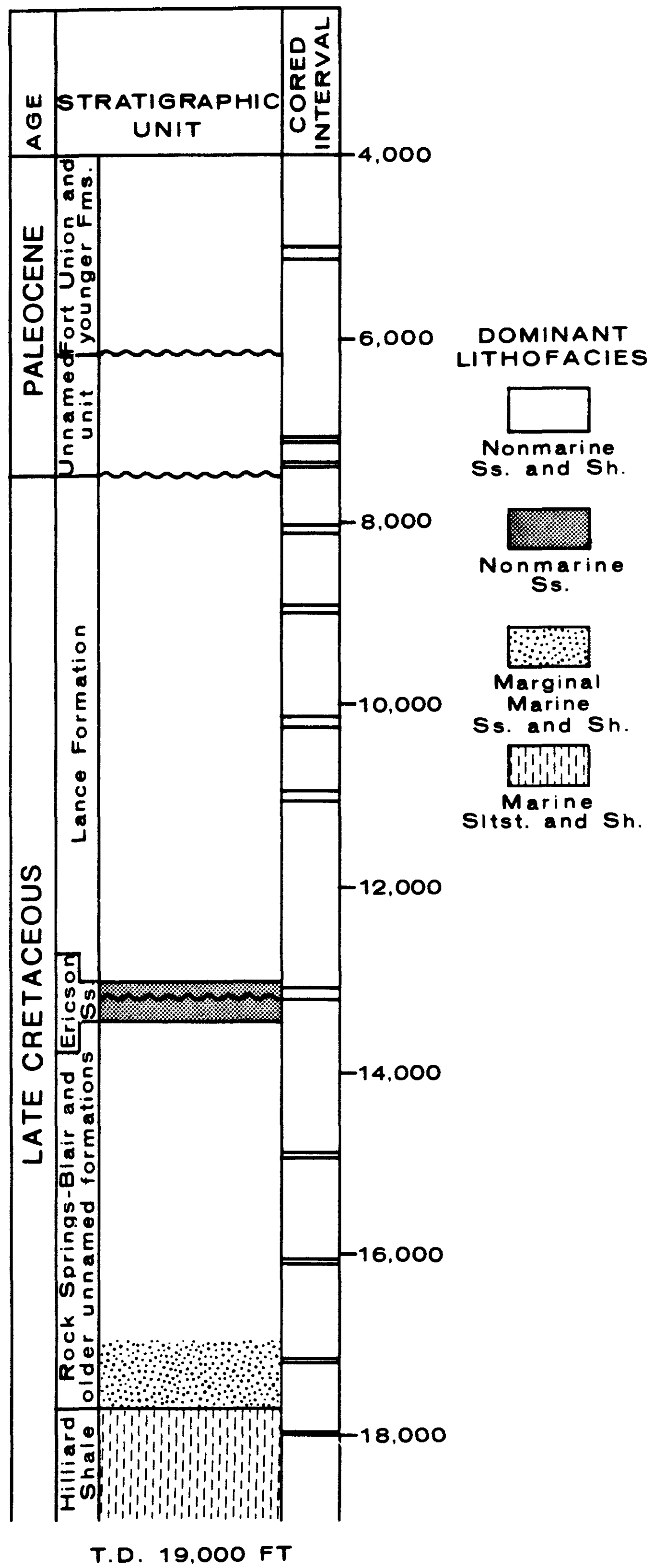

Figure 4.--Geologic column showing the stratigraphic sequence and cored intervals in the El Paso Natural Gas, Wagon Wheel no. 1 well.

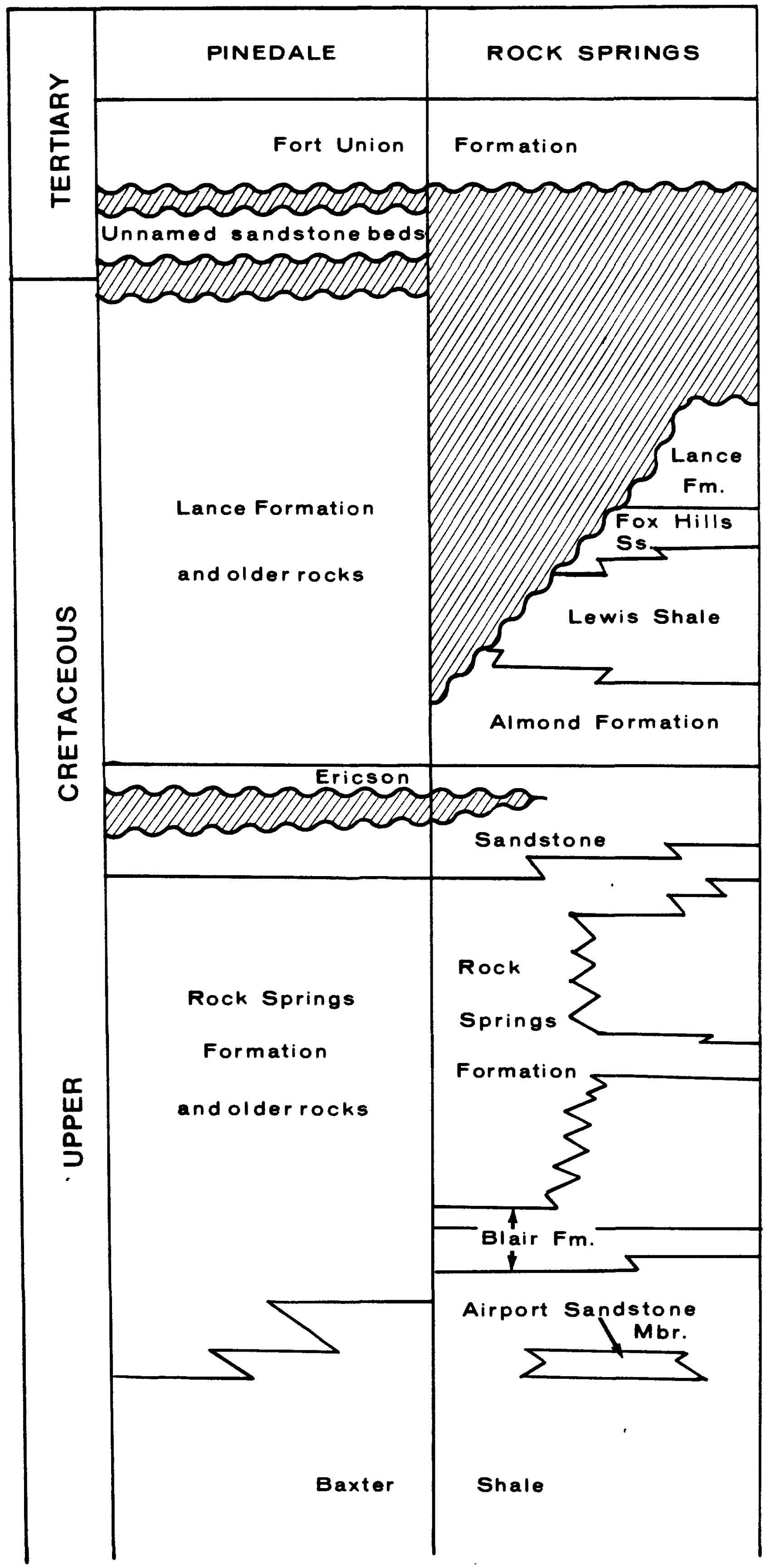

Figure 5.--Correlation of Upper Cretaceous and lower Tertiary rocks in the Pinedale anticline and Rock Springs uplift areas.

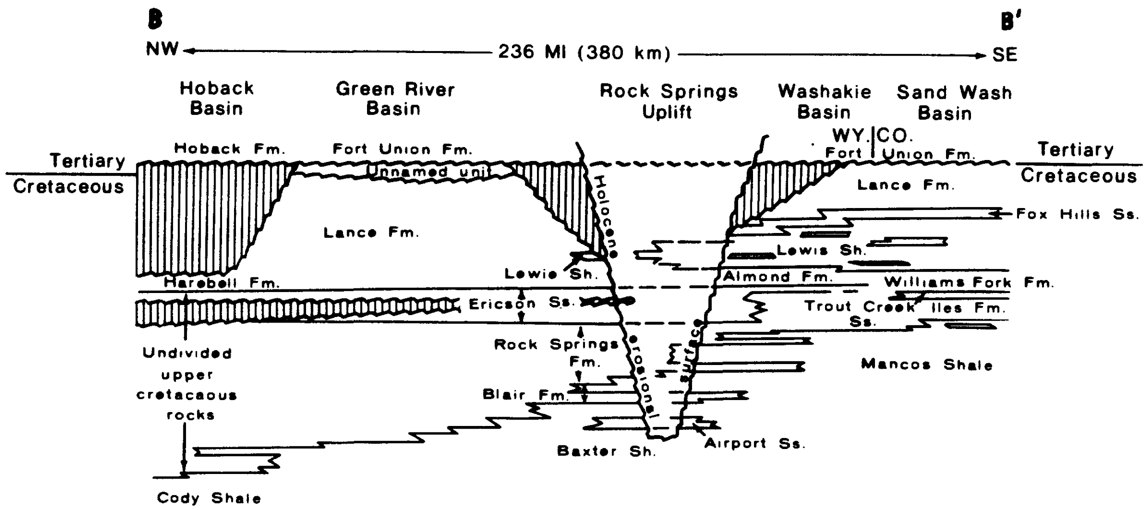

Figure 6.--Diagramatic cross section B-B′ showing stratigraphic relationships of Upper Cretaceous and lower Tertiary rocks between the northern Green River Basin, Wyoming, and the Sand Wash Basin, Colorado. Line of section shown on figure 1.

The Ericson Sandstone is chiefly composed of sandstone with lesser amounts of siltstone and mudstone. The lower contact is interpreted to be conformable with the underlying Rock Springs Formation. The Ericson can be subdivided into two parts. The lower part is about 260 ft (79 m) thick and consists of fine-grained sandstone deposited in braided-stream environments. The upper part is about 100 ft (30 m) thick and consists of conglomeratic sandstone, with lesser amounts of siltstone and mudstone deposited in braided-stream environments. Based on regional stratigraphic correlations (Law, 1979; Law and Nichols, 1982; Law and others, 1983; Bucurel-White, 1983), there is reason to suspect that the contact between the lower and upper parts of the Ericson Sandstone is unconformable.

The Lance Formation and older rocks are composed of tan to brown, fine- to medium-grained sandstone, siltstone, shale, and carbonaceous mudstone. The lower contact is conformable with the underlying Ericson Sandstone. In the Pinedale anticline area the lower part of the Lance Formation is a temporal equivalent of the Almond Formation, Lewis Shale, and Fox Hills Sandstone in the Rock Springs area (fig. 5). The Lance Formation is about 5,550 ft (1,692 m) thick in the Wagon Wheel well and was deposited in an alluvial plain environment.

Tertiary Rocks

Lower Tertiary rocks were deposited in fluvial-dominated environments. Depositional patterns in these rocks are more complex than the older Cretaceous rocks because of the emergence of adjacent highlands, multiple source terranes, and the trend to internal basin drainage during the Tertiary. The discussion of Tertiary rocks is restricted to the lower Tertiary inasmuch as younger Tertiary rocks are not deeply buried and generally have better reservoir characteristics than the older rocks.

Probably the most significant departure from previous stratigraphic studies in the Pinedale anticline area is the identification of the Cretaceous-Tertiary boundary. The base of the Tertiary in southwestern Wyoming is marked by a regional unconformity (Ritzma, 1965; Roehler, 1961, Dorr and others, 1977; Beaumont, 1979). Throughout most of the region the oldest Tertiary unit is the Paleocene Fort Union Formation or equivalent rocks. However, in the subsurface of the northern Green River and Great Divide Basins an older unnamed Tertiary interval has been identified on the basis of well-log correlations and palynology (Law, 1979; Law and Nichols, 1982; Bucurel-White, 1983). In the Pinedale anticline area, Martin and Shaughnessy (1969) and Shaughnessy and Butcher (1973, 1974) indicated that the Cretaceous-Tertiary boundary in the Wagon Wheel well is at a depth of about 10,000 ft (3,048 m). However, more recent work by Law (1979) and Law and Nichols (1982) has shown that the contact is at a depth of 7,520 ft (2,302 m).

The unnamed Tertiary sandstone beds consist of interbedded conglomerate, sandstone, siltstone, and mudstone. The unnamed Tertiary sandstone beds unconformably overlie the Cretaceous Lance Formation. In the Pinedale anticline area the unit ranges from 1,285 to 1,510 ft (391 to 460 m) thick. The unit is interpreted to have been deposited in alluvial plain environments.

The Fort Union Formation in the Pinedale anticline area consists of interbedded conglomerate, sandstone, siltstone, mudstone, and carbonaceous mudstone. Coal beds, which are commonly associated with the lower part of the Fort Union Formation in the Rock Springs area and elsewhere, are not present in the Pinedale area, presumably because of facies changes related to the proximity of source terranes in the nearby Wind River Mountains. The Fort Union unconformably overlies the unnamed Tertiary sandstone beds in the northern Green River Basin, but in the Rock Springs uplift, the Fort Union unconformably overlies Cretaceous rocks due to truncation of the unnamed Tertiary Sandstone beds (fig. 5). No attempt has been made to determine the upper contact of the Fort Union. The Fort Union Formation was deposited in fluvial-dominated environments.

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Petrographic and Selected Reservoir Characteristics of Some Tertiary and Cretaceous Sandstones, Pinedale Anticline, Sublette County, Wyoming

By C. William Keighin

INTRODUCTION

Petrographic and limited petrophysical studies of core samples of sandstones from the Mountain Fuel Supply Company (Wexpro) Mesa Unit No. 1 well, and the American Hunter Exploration Company wells New Fork Nos. 1, 2, and 4, indicate that the sandstones are similar in composition and behavior to other low-permeability sandstones of the Rocky Mountains. Locations of the wells are given in Law (this volume, fig. 2, p. 3, and table 1, p. 4). Studies of rocks from the Pinedale Anticline are reported on by Butcher (1971), Gas Research Institute (1981), Pollastro and Bader (1983), Quong and LaGuardia (1971), and Thomas (1978). General properties of low-permeability sandstones of the Rocky Mountains are discussed by Spencer (1983). The purpose of the studies was to relate observed petrographic and petrophysical properties to gas-free and gas-bearing zones.

PETROGRAPHY

Samples of sandstones from cores from the wells noted above were examined in thin section by scanning electron microscopy (SEM) and X-ray diffraction. Although samples were collected through a depth range below surface 8,711-11,956 ft (2,655-3,644 m) for the Mesa No. 1 well, and 8,260-10,570 ft (2,518-3,222 m) for the New Fork 1, 2, and 4 wells, the number of samples is limited, and the petrographic characteristics should be considered to be general rather than definitive. Only the Upper Cretaceous Lance Formation was sampled in the Mesa No. 1 well, whereas the unnamed lower Tertiary and Lance were sampled in the New Fork wells. The modal characteristics of the Wexpro samples are summarized on figure 1; those for the New Fork wells are shown on figure 2. Although the modal characteristics of many samples from the two areas are similar, there is significantly more mineralogical variation in the samples from the New Fork area. Feldspar is often markedly higher in the unnamed Tertiary from the New Fork samples; it was often not detected in the Lance Formation.

The sandstones examined in the Wexpro Unit No. 1 well are generally fine grained with moderate sorting. Porosity has been reduced moderately through compaction and deformation of labile rock fragments (fig. 3). Some intergranular pores remain, but many pores are partially to completely filled with authigenic clays (figs. 3 and 4). Much of the porosity in the low-permeability sands is due to partial leaching of rock fragments. Porosity is sometimes reduced by intergranular carbonate (more calcite than dolomite) cement, but the distribution of carbonate cement is highly variable. The distribution of this cement does not follow any recognized pattern.

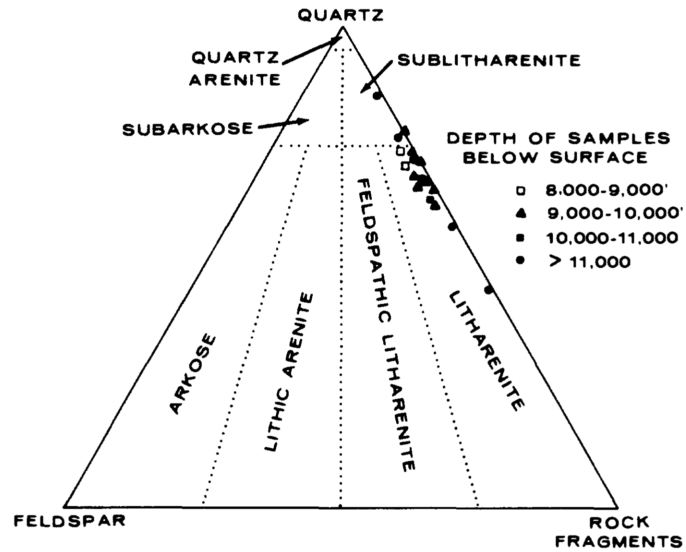

Figure 1.--Triangular diagram illustrating modal composition of selected samples of the Lance Formation from the Wexpro Mesa Unit No. 1 well (classification of Folk, 1980).

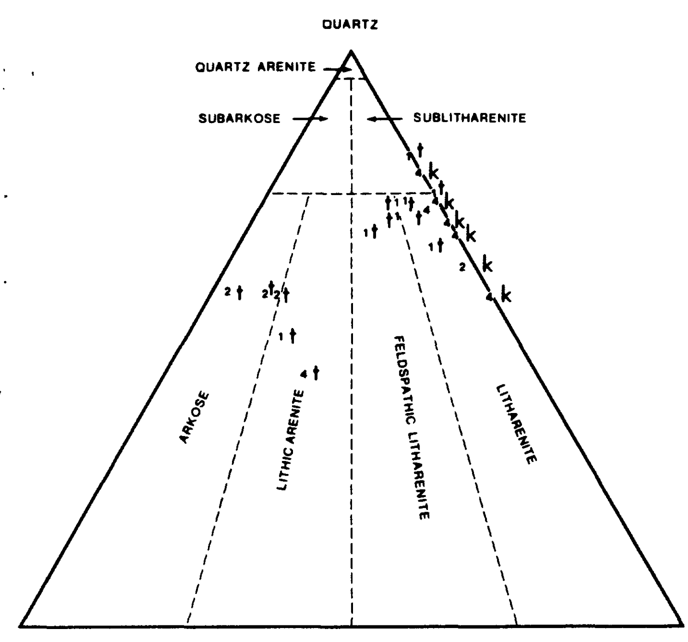

Figure 2.--Triangular diagram illustrating modal composition of selected samples from American Hunter wells, New Fork 1 (1), New Fork 2 (2), and New Fork 4 (4) (classification of Folk, 1980). (Age of strata sampled: t, Tertiary; k, Cretaceous).

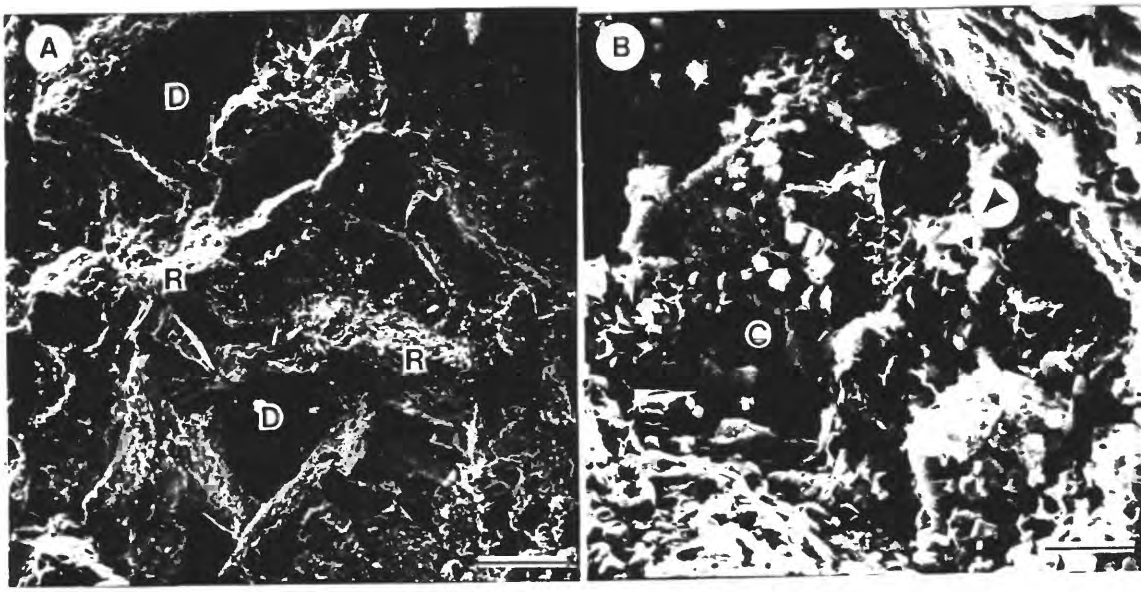

Figure 3.--Scanning electron micrograph of sample 8, Mesa Unit No. 1 well, depth 9,140.9 ft (2,786 m), porosity 3.9 percent, permeability 2 µd. A, Detrital quartz grains (D) enclosed by compacted and partially leached rock fragments (R). No large pores are seen. Scale bar 100 µm. B, Intergranular carbonate (C) reduced porosity. Authigenic clays (arrow) produce micropores and tortuous pore network. Scale bar 10 µm.

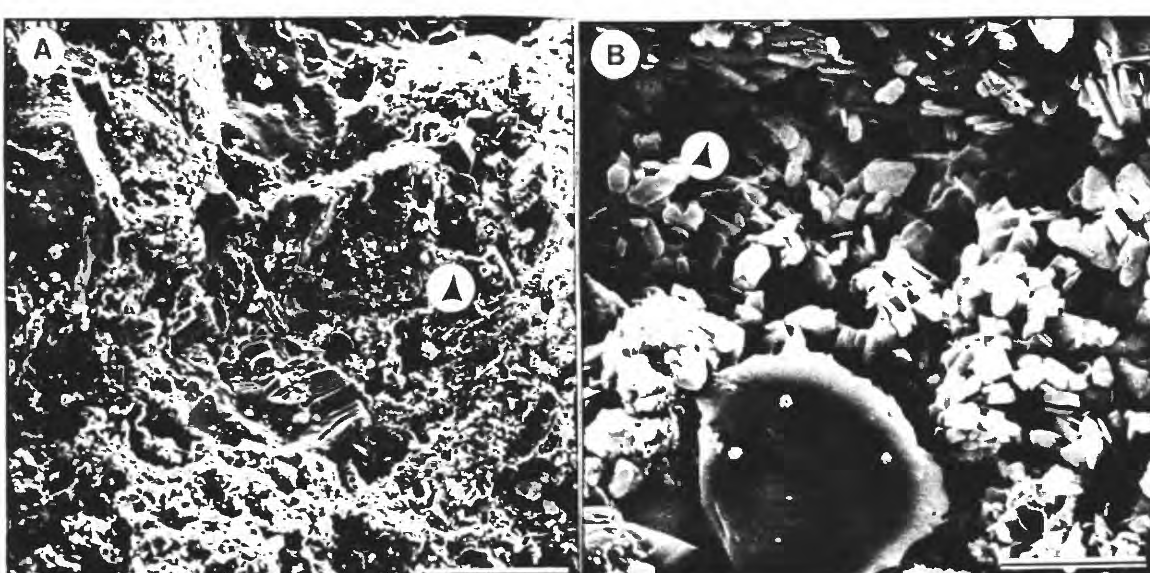

Figure 4.--Scanning electron micrograph of sample 9, Mesa Unit No. 1 well, depth 11,265 ft (3,434 m), porosity 10.8 percent, permeability 140 µd. A, Minor intergranular porosity (arrow); most pores are due to partial leaching of detrital grains, especially rock fragments. Scale bar 100 µm. B, Intergranular pores (arrow) and micropores between authigenic minerals. Scale bar 10 µm.

Even though the composition of sandstones in the New Fork wells is more variable than in the Wexpro No. 1 well, many of the same comments apply. The most variable mineralogical difference noted between the two areas is the variation in feldspar content. Feldspar content varies not only between the two areas but also through the interval penetrated in the New Fork wells. Plagioclase and potassium feldspars, identified in thin section and by X-ray diffraction, are present in variable quantities in the lower Tertiary strata cored in the New Fork 1, 2, and 4 wells. Little or no feldspar was identified in samples from the zone between the unnamed Tertiary and the Lance Formation. Only trace amounts of plagioclase and no potassium feldspar were identified in the Lance Formation cored in New Fork wells 2 and 4.

PETROPHYSICAL PROPERTIES

Results of porosity and permeability determinations on four samples from the Wexpro Mesa Unit No. 1 well are listed in table 1.

Table 1.--Porosity and permeability for selected Wexpro Unit No. 1 well samples

[A and B, values determined by two laboratories; k^1, permeability determined under essentially ambient conditions; k^2, permeability determined under confining stress of 1,000 psia; k^3 permeability determined under confining stress of n psia.]

Sample no.	Depth below surface (feet)	Laboratory	Porosity (percent)	Permeability (μd) k^1	k^2	k^3	n (psia)
7	8,270.2	A	7.7	35			
	8,270.1	B	8.7		11.	3.5	3660
8	9,140.1	A	3.9	2			
	9,140.2	B	6.0		4.58	1.46	3840
9	11,265	A	10.8	140			
	11,265	B	11.4		88.3	58.4	4730
10	11,570	A	4.6	18			
	11,570	B	3.3		0.805	0.46	5000

Permeability was determined under essentially ambient conditions, as well as under confining stress similar to that expected at the depth from which the sample was taken. The results are similar to those of numerous investigators who have found that permeability in low-permeability sandstones typically is reduced significantly by increasing confining stress (for example, Walls and others, 1982). For the samples examined, which ranged in depth from 8,270 to 11,570 ft (2,520 to 3,527 m), porosity varied between 3.9 and 10.8 percent; permeability (under ambient conditions) varied between 2 and 140 microdarcies (μd). Studies reported by the Gas Research Institute (1981), based on data from drill stem tests, core tests, and well flowing, show that permeability of the low-permeability sandstones varied between 3 and 50 μd. There were not enough samples examined in this study to attempt to relate porosity variations to increasing depth; however, examination of porosity data for samples from the Mesa Unit No. 1 well, ranging in depth from 8,600 to 11,900 ft (2,621 to 3,627 m), gave a correlation coefficient of only 0.5 for porosity versus depth (W. W. Dickinson, oral commun., 1984).

Results of mercury injection tests on the same four samples (fig. 5) indicate that most pore throats are small. At 2,000 psia, the maximum pressure attained, pore throats, with a calculated size of 0.05 µm, permitted penetration of only 18 to 63 percent of the pores available. Typically, the small pore throats, in conjunction with numerous small pores, create a tortuous pathway for fluid flow, and low permeability is one result.

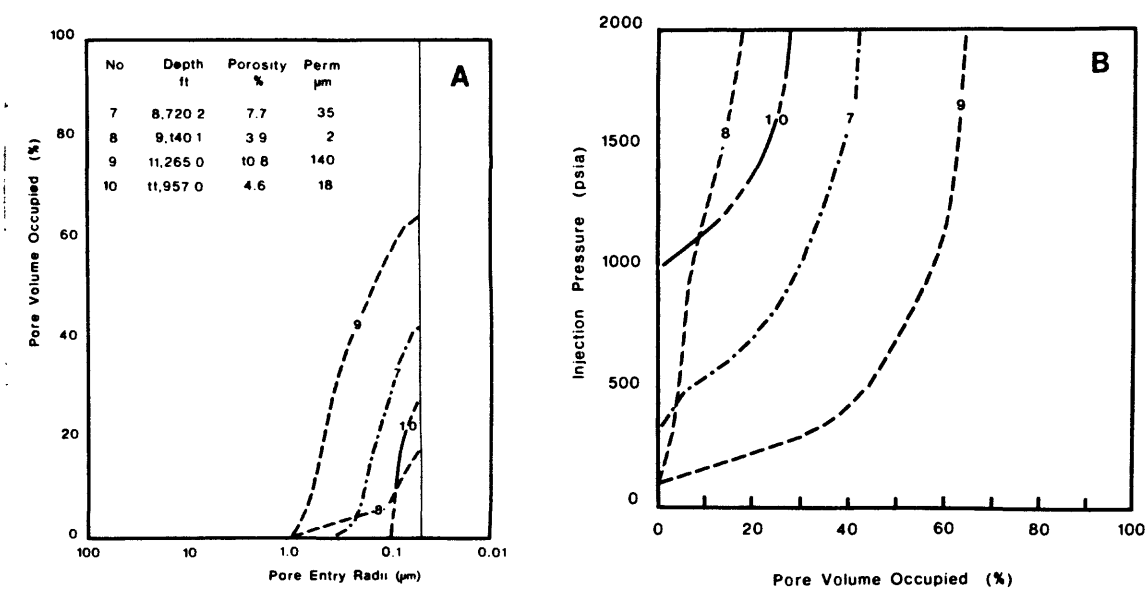

Figure 5.--Response of selected samples from Wexpro Unit No. 1 well to mercury injection at pressures up to a maximum of 2,000 psia. A, Calculated minimum size of pore throats penetrated at 2,000 psia is 0.05 µm. Pore volume occupied at 2,000 psia ranges from 18 percent (No. 8) to 63 percent (No. 9). B, Variations in pore volume occupied at various injection pressures of mercury.

SUMMARY

Samples examined in this study are similar to other samples of low-permeability sandstones from the Rocky Mountain region, although some samples from the unnamed Tertiary, cored in the New Fork wells, contain significant quantities of feldspar. Porosity is typically secondary, and often due to partial leaching of rock fragments. Micropores are formed by the growth of authigenic clays; pore throats connecting these pores are usually less than 1 µm across. Because of the small pore throats, the permeability of the sandstones--usually low--is very sensitive to changes in confining pressure, and may be reduced substantially by increased confining stress.

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A Gamma-ray Log Anomaly Associated With the Cretaceous-Tertiary Boundary in the Northern Green River Basin, Wyoming

By Stephen E. Prensky

INTRODUCTION

Identification and regional correlation of the Cretaceous-Tertiary (K/T) boundary in the subsurface of Rocky Mountain Basins is a long-standing stratigraphic problem (Robinson, 1970). This difficulty is due primarily to a lack of distinguishing physical characteristics between the Upper Cretaceous and lower Tertiary rocks, which are products of similar non-marine origins. Both vertebrate paleontological and palynological indicators have been used for defining and identifying the T/K boundary; however, many of these non-marine rocks do not contain fossils.

In the Wind River Basin of central Wyoming, where the K/T boundary is exposed around the periphery of the basin, vertebrate evidence has supported physical evidence for placement of the boundary (Keefer, 1965). In the northern Green River Basin the K/T boundary is not exposed, except possibly along the northwest margin.

Well log correlations of subsurface formation boundaries near the K/T boundary, particularly in the northern Green River Basin, are often imprecise due to: a) rapid changes in facies and thickness within short distances, b) an absence of consistent marker beds, and c) lithologic similarity and resultant similarity in well log response. Modern seismic processing and interpretation suggest that in the Wind River Basin, the K/T boundary is a mappable seismic reflector (Ray, 1982).

Recent work by Law (1979 and this volume) and Law and Nichols (1982) employs a combination of well logs and palynological evidence to define the K/T boundary.

GAMMA-RAY ANOMALY

Plots of gamma-ray log data at highly compressed depth scales for wells in the Pinedale area of the northern Green River Basin have revealed the presence of a strong anomaly in the lower Tertiary (Prensky and Dickinson, 1984). The depth plot of gamma-ray log data from the Mountain Fuel Supply Co. (Wexpro) no. 1 Mesa well shown on figure 1 represents a continuous open hole log run. The gamma-ray anomaly is indicated by offset of data at approximately 8,000 feet. Plots of gamma-ray log data from other wells in the area (fig. 2) of the Pinedale anticline generally show a similar shift (fig. 3). Petrographic examination of core from wells in the Pinedale area (Butcher, 1971; Greenfield, 1981; Keighin, this volume) have shown that the potassium feldspar content abruptly changes from as much as 25 percent in Tertiary rock samples to essentially zero in Cretaceous samples. Data from natural gamma-ray spectroscopy logs (fig. 4) indicate that the gamma anomaly present in wells in the Pinedale area is due primarily to a change in potassium content and secondarily to a change in thorium content. X-ray diffraction studies of data from the El Paso Natural Gas Wagon Wheel no. 1 well support the petrographic data (R. M. Pollastro, oral commun., 1983).

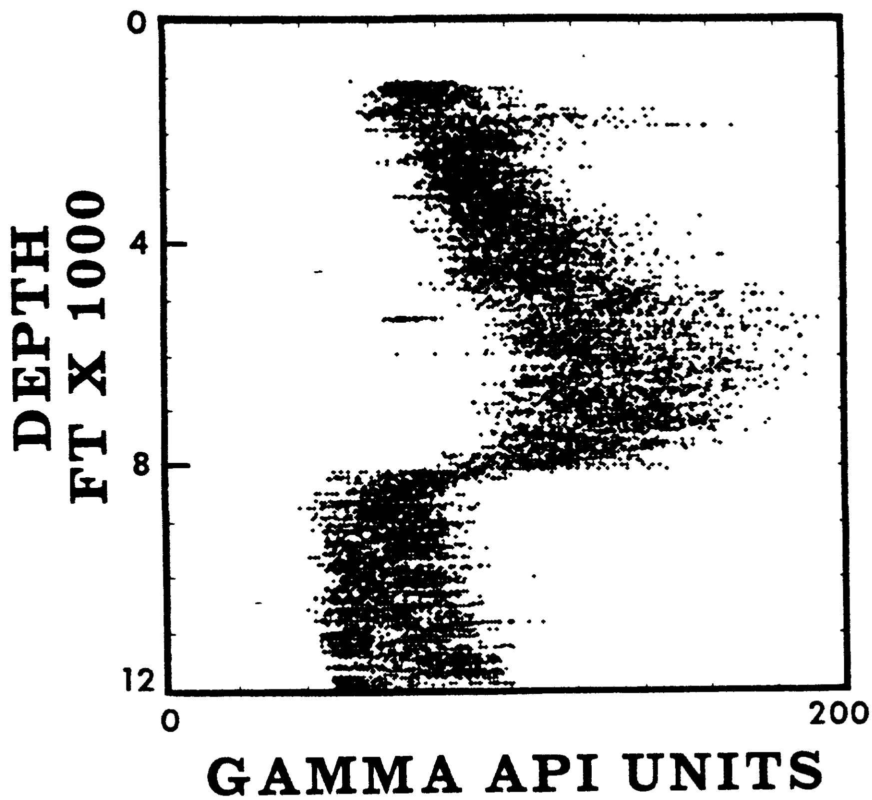

Figure 1.--Compressed-scale depth plot of the gamma-ray log from the Mountain Fuel Supply Co. (Wexpro) No. 1 Mesa well, sec 7, T. 32 N., R. 109 W., Sublette County, Wyoming. Gamma anomaly is indicated by the shift in API values at approximately 8,000 ft.

The gamma anomaly is most evident in wells on the Pinedale anticline (figs. 2 and 3). The magnitude of the anomaly (shift) diminishes in all directions from the Pinedale area (figs. 5A-C). The plotted gamma data of the Mesa well (fig. 1) form an arc-like pattern with the data shift at its base. This pattern, which is present in wells throughout the basin, can be used for locating the depth of the gamma anomaly in other parts of the basin, where the anomaly is subdued (figs. 5B and 5C).

The Wind River Mountains are surrounded by a lower Tertiary arkosic sandstone and conglomeratic facies. The proximity and areal distribution of this facies relative to these mountains indicate that the Precambrian core was the source of the arkose. By Eocene time, deposition of arkose in Rocky Mountain Basins was widespread (Love, 1960; Vine and Tourtelot, 1970). Arkosic sandstones are present throughout the northern Green River Basin and have been reported in wells in the Pinedale, La Barge and Big Sandy areas (Berg, 1961, 1962; Asquith, 1966; Martin and Shaughnessy, 1969). Regional variations in gamma-ray intensity may provide insight into lower Tertiary drainage patterns.

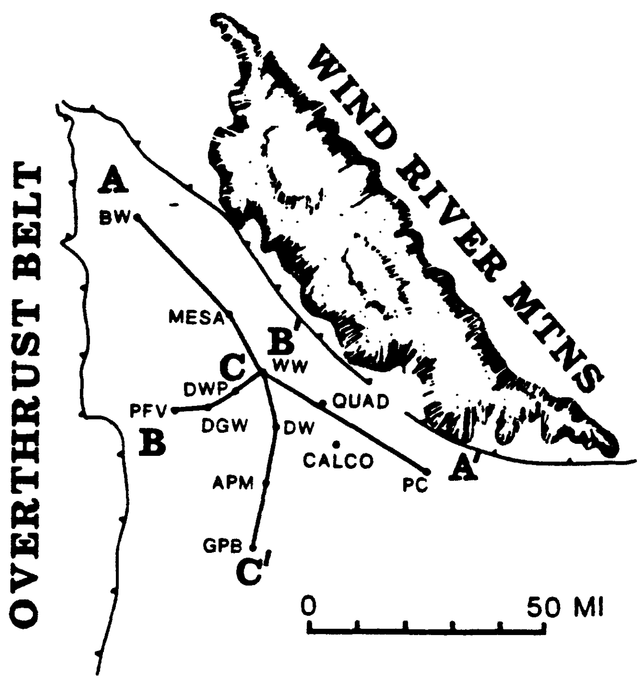

Figure 2.--Index map showing location of wells used in cross sections. Well abbreviations: (BW) Merged Inexco A-1 WASP (28-36N-112W) and Belco Oil 3-28 Merna; Mtn. Fuel Supply Co. (Wexpro) No. 1 Mesa (7-32N-109W); (WW) El Paso Natural Gas Co. 1 Wagon Wheel (5-30N-108W); (QUAD) Quadrant Oil Co. 14-16 State (16-29N-106W); (CALCO) California Co. 1 Government (34-28N-106W); (PC) Merged Rainbow Resources 1-34 Pacific Creek (34-27N-103W) and Rainbow Resources 1-3 Pacific Creek well (3-26N-103W); (DWP) Davis Oil 1 West Pinedale (33-30N-109w); (DGW) Davis Oil 1 Granite Wash (16-29W-110W); (PFV) Primary Fuels Van Buren 24-20 Federal (20-29N-111W); (DW) Davis Oil 1 Wardell Federal (9-28N-108W); (APM) Merged American Hunter 1 Aspirin (13-26N-109W) and Davis Oil 1 Parrish Mark (12-26N-109W); (GPB) General Petroleum Co. 62-A-9 Buckhorn (9-24N-109W).

On the Pinedale anticline, the gamma anomaly occurs at depths which are very close to the K/T boundary as correlated by Law (1979) (table 1). Since this gamma event appears to be present throughout the northern Green River Basin it may serve as a local stratigraphic marker for this boundary.

Table 1--List of wells used in this study.

[Completion date, from Petroleum Information completion records; TD, Total depth (ft); KB, Kelly bushing elevation (ft); GR Log Y, Log run and available; GR Log N, Log either not run or not available; Lithology Log Y, mudlog log available; Lithology log N, none available; Lithology Log A, Amstrat log available; Arkose Depth, lowest reported depth for arkose or feldspar (ft); Arkose Depth NR, Arkose not reported or recorded; GR Shift, Depth (ft) of gamma-ray anomaly taken off compressed-scale plot; Law, Log depth (ft) of K/T boundary from Law (1979); --, No data or not applicable; ?, Questionable depth; Palyn., palynological data available; OWDD, old well drilled deeper]

Well Name	Location	Compl. Date	TD	KB	GR log	Lith log	Arkose Depth	GR Shift	Law	Comments
General Petroleum 62-A-9 Buckhorn	9-24N-109W	10/30/55	9275	6635	Y	A	NR	6400	--	Palyn.
Davis Oil 1 Pirate Unit	30-25N-101W	02/26/81	15590	7339	Y	Y	NR*	3900	--	*Samples begin @ 4000
Pan American 1 State I	16-25N-105W	11/23/63	8441	6708	Y	A	7200	9700*	--	*Projected below TD
Davis 1 Sandy/Simson	25-25N-108W	08/17/79	17034	6811	Y	N	--	7450	--	
General Petroleum 67-28	28-25N-109W	11/04/54	8205	6789	N	A	4080	--	--	Palyn.
Davis Oil 1 Muskateer	08-26N-101W	03/17/82	19565	7543	Y	Y	NR*	6225	--	*Samples begin @ 5000
Davis 1 Buccaneer	23-26N-102W	11/14/81	17825	7346	Y	Y	NR*	4850	--	*Samples begin @ 5000
Rainbow Resources Pacific Creek 1-3	03-26N-103W	07/02/80	15500	7003	Y	Y	NR*	8275	8650	*Samples begin @ 7000
Rainbow Resources Pacific Creek 1-34	34-27N-103W	09/10/82	25764	7081	Y	Y	8660	--	--	
Forest Oil 1 Jonah Gulch	09-26N-107W	01/21/80	10570	6678	Y	Y	NR	7900	8750	
Davis Oil 1 Parrish Mark	12-26N-109W	01/27/79	15872	6907	Y	N	--	--	--	
American Hunter 1 Aspirin	13-26N-109W	01/21/81	10621	6921	Y	Y	NR	6230	--	
Mountain Fuel 1 Dickie Spings	24-27N-101W	10/03/70	12282	8035	Y	N	--	8670?	--	
Ferguson 1 Government	18-27n-102W	02/01/68	8421	7154	Y	N	--	--	--	
Woods Petroleum 18-1-A Government	18-27N-102W	06/26/69	12492	7157	Y	A*	8600	9800?	--	*Samples begin @ 8100; OWDD
Mountain Fuel 1 Sublette Flat	07-27N-107W	05/02/65	10525	6807	N	A	6600	--	--	
Davis Oil 1 Bright Trail	21-27N-108W	06/04/79	18000	6905	Y	N	--	7475	--	
American Hunter 1 Old Road	27-27N-108W	04/20/82	12413	6835	Y	Y	NR	7450	--	
Davis Oil 1 Yellow Point Ridge	07/27N-109W	10/15/78	15772	7085	Y	A	6570	6670	--	
California Oil 1 Government	34-28N-106W	08/30/62	8502	6991	Y	A	8600*	9275^	--	*Arkose reported @ TD ^Projected below TD

Table 1--Continued.

[Completion date, from Petroleum Information completion records; TD, Total depth (ft); KB, Kelly bushing elevation (ft); GR Log Y, Log run and available; GR Log N, Log either not run or not available; Lithology Log Y, mudlog log available; Lithology log N, none available; Lithology Log A, Amstrat log available; Arkose Depth, lowest reported depth for arkose or feldspar (ft); Arkose Depth NR, Arkose not reported or recorded; GR Shift, Depth (ft) of gamma-ray anomaly taken off compressed-scale plot; Law, Log depth (ft) of K/T boundary from Law (1979); --, No data or not applicable; ?, Questionable depth; Palyn., palynological data available; OWDD, old well drilled deeper]

Well Name	Location	Compl. Date	TD	KB	GR log	Lith log	Arkose Depth	GR Shift	Law	Comments
General Petroleum 63X-21 Bar Cross	21-30N-112W	08/20/54	8270	7008	Y	A	4200	4550		Palyn.
El Paso Natural Gas 2 Pinedale Unit	29-31N-108W	01/05/56	10694	7034	Y*	A	6790	7450	7750	*GR log 7000-10264 only
Hay Carollo 2 Jensen	11-31N-109W	1983	10300	6925	Y	--	7015	7025	--	
El Paso Natural Gas 3 Pinedale Unit	13-31N-109W	01/05/56	11009	6983	Y*	A	7290	7130	7520	*GR log 6500-10821 only
California Co. 1 Government	14-31N-109W	04/19/40	10000	7000	N	N	--	--	--	
American Hunter 4 New Fork	35-31N-109W	04/20/82	11553	6957	Y	Y	NR	8150	--	
Belco Petroleum 2-27 Mason	27-31N-113W	03/14/83	13340	7295	Y	Y	NR	5300	--	
Mountain Fuel 1 Mesa	07-32N-109W	07/15/81	12050	7524	Y	Y	8050	8070	--	
Wexpro 2 Mesa	16-32N-109W	06/22/81	12190	7474	Y	Y	7920	8100	--	
El Paso Natural Gas 4 Pinedale Unit	34-32N-109W	01/30/56	11124	7204	Y*	A	7650^	7500	8320	*GR log 6800-11103 only ^No samples 7820-8400
Mountain Fuel 1 Antelope Draw	22-32N-111W	10/30/57	8996	7108	N	A	3070	--	7200	
Phillips Petroleum 4 Marbleton	10-32N-112W	02/15/60	11565	7380	N	A	5600*	--	--	*Samples begin @ 4970
Davis Oil 1 Aspen Ridge	22-32N-113W	06/15/74 04/23/76	7854 14940	7891 7902	Y Y	No No	-- --	6100? --	-- --	 OWDD
Pan American 1 Unit Stanolind 1 Pinedale	17-33N-109W	03/29/49	7797	--	N	A	7470	--	--	
Mountain Fuel 8 Pinedale Unit	20-33N-109W	01/06/64	10500	7448	N	N	--	--	--	
Blackhawk Resources 21-24 Baumgartner	24-33N-110W	12/12/81	11238	7344	Y	Y	NR	9430	--	
Phillips Petroleum 1 Daniel	21-33N-111W	04/04/56	16531	7307	Y*	A	7710	*	7715	*GR log 10,000-16,000 only
Pacific Gas 14-28-2 Willow	28-36N-109W	11/01/64	6650	8526	Y	A	3270	--	--	
Skinner 1 Government	20-36N-109W	10/09/61	3003	7911	--	A	*	--	--	*To at least TD

Table 1--Continued.

[Completion date, from Petroleum Information completion records; TD, Total depth (ft); KB, Kelly bushing elevation (ft); GR Log Y, Log run and available; GR Log N, Log either not run or not available; Lithology Log Y, mudlog log available; Lithology log N, none available; Lithology Log A, Amstrat log available; Arkose Depth, lowest reported depth for arkose or feldspar (ft); Arkose Depth NR, Arkose not reported or recorded; GR Shift, Depth (ft) of gamma-ray anomaly taken off compressed-scale plot; Law, Log depth (ft) of K/T boundary from Law (1979); --, No data or not applicable; ?, Questionable depth; Palyn., palynological data available; OWDD, old well drilled deeper]

Well Name	Location	Compl. Date	TD	KB	GR log	Lith log	Arkose Depth	GR Shift	Law	Comments
Davis Oil 1 Wardell Federal	09-28N-108W	10/21/76	11324	7050	Y	N	--	7875	--	
Woods Petroleum 2 Cutlass	18-28N-109W	10/30/82	17700	7102	Y	--	--	7100	--	
Davis Oil 1 Ferry Island	29-28N-109W	07/09/79	16800	7089	--	Y	NR*	--	--	*Samples begin @ 7790
Energetics 10-8 Mohr Federal	08-28N-110W	1983	15832	7227	Y	--	--	6875	--	
Energetics 30-21 Chorney Federal	21-28N-111W	1983	12150	--	Y	--	--	4800	--	
Husky Oil 8-2 Federal	02-29N-106W	10/02/73	12944	7208	Y	A	4420*	4450	--	*Feldspar to pC thrust
Quadrant Oil 14-16 State	16-29N-106W	08/12/72	10050	7113	Y	A	8640	9300	--	
Texaco 1 Tabernacle Butte	25-29N-107W	03/04/63	11008	7134	N	A	8740	--	9080	
Davis Oil 1 Granite Wash	16-29N-110W	11/30/77	16625	7018	Y	Y	--	6600	--	
Primary Fuels 24-20 Van Buren Fed.	20-29N-111W	09/27/82	12394	6876	Y	--	--	4650	--	
American Hunter 2 New Fork	02-30N-108W	07/08/81	11986	7282	Y	Y	8550	8530	--	
El Paso Natural Gas 1 Wagon Wheel	05-30N-108W	08/01/71	19000	7089	Y	A	7660*	7225	7515	*Samples begin @ 7000; Palyn.
El Paso Natural Gas 5 Pinedale Unit	05-30N-108W	09/10/56	15018	7056	Y*	A	7370	7870	7560	*GR log 7000-14956 only
El Paso Natural Gas 1 Pinedale Unit	09-30N-108W	02/10/55	10550	7196	Y*	N	--	7430	7860	*GR log 6500-10495 only
El Paso Natural Gas 7 Pinedale Unit	15-30N-108W	12/12/60	10270	7373	Y*	N	--	*	8060	*GR log 7652-9557 only
El Paso Natural Gas 6 Pinedale Unit	21-30N-108W	06/06/57	11057	7294	Y*	A	7100	--	8400	*GR log 7700-8000 only
American Hunter 1 New Fork	25-30N-108W	07/10/81	10989	7338	Y	Y	7720	7875	--	
Davis Oil 1 West Pinedale	33-30N-109W	11/18/75	11507	7052	Y	N	--	7775	--	
Mountain Fuel 1 Three Bridges	07-30N-110W	10/14/65	10003	7022	N	A	NR	--	--	
Phillips Petroleum Marbleton 2-C	06-30N-111W	11/12/58	7395	7078	N	A	3100	--	--	

Table 1--Continued.

[Completion date, from Petroleum Information completion records; TD, Total depth (ft); KB, Kelly bushing elevation (ft); GR Log Y, Log run and available; GR Log N, Log either not run or not available; Lithology Log Y, mudlog log available; Lithology log N, none available; Lithology Log A, Amstrat log available; Arkose Depth, lowest reported depth for arkose or feldspar (ft); Arkose Depth NR, Arkose not reported or recorded; GR Shift, Depth (ft) of gamma-ray anomaly taken off compressed-scale plot; Law, Log depth (ft) of K/T boundary from Law (1979); --, No data or not applicable; ?, Questionable depth; Palyn., palynological data available; OWDD, old well drilled deeper]

Well Name	Location	Compl. Date	TD	KB	GR log	Lith log	Arkose Depth	GR Shift	Law	Comments
Skinner 5 Government	29-36N-109W	10/11/65	4740	8621	--	A	2600	--	--	
Gulf 1 New Fork Unit	05-36N-110W	10/11/59	6775	7865	N	A	1350*	--	--	*Weathered Feld to 4300
Pacific Transmission 33-13 Federal	13-36N-111W	02/12/74	11153	7743	Y	A	NR	6200?	--	
Inexco A-1 WASP	28-36N-112W	11/14/70	14363	7812	Y	N	--	6650?	5610	
Belco Petroleum 3-28 Merna	28-36N-112W	02/24/77	18124	7815	Y	N	--	--	--	OWDD
Belco Petroleum 1 Merna Unit	33-36N-112W	9/17/60	13695	7630	N	A	NR	--	5460	
Apache Corporation 36-1 Robbins	36-36N-112W	1983-84	16442	7625	Y	Y	NR	8800?	--	
Depco 1 Bondourant Unit	09-38N-113W	03/12/71	13300	7127	Y	A	NR	--	7560	

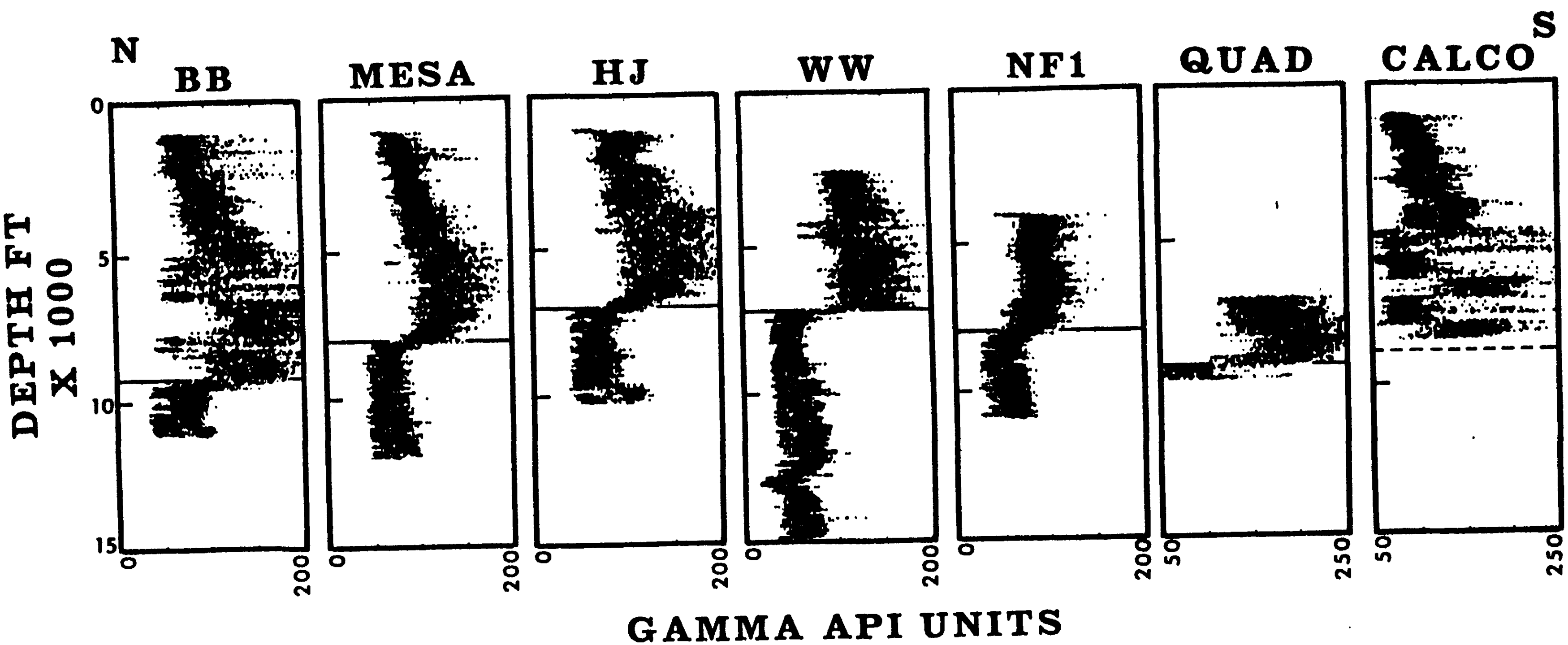

Figure 3.--Compressed-scale depth plots of gamma-ray log data for wells along the northwest-southeast trend of the Pinedale anticline. The horizontal line marks the depth of the gamma anomaly. Datum is kelly bushing elevation for each well. See figures 3 and 4 for index for well locations. Well abbreviations: (BB) Blackhawk Resources 21-24 Baumgartner (21-33N-110W); (MESA) Mtn. Fuel Supply Co. No. 1 Mesa (7-32N-109W); (HJ) Hay Carollo 2 Jensen (11-31N-109W); (WW) El Paso Natural Gas Co. Wagon Wheel 1 (5-30N-108W)(NF1) American Hunter 1 New Fork (25-30N-108W); (QUAD) Quadrant Oil Co. 14-16 State (16-29N-106W); (CALCO) California Co. Government 1 (34-28N-106W).

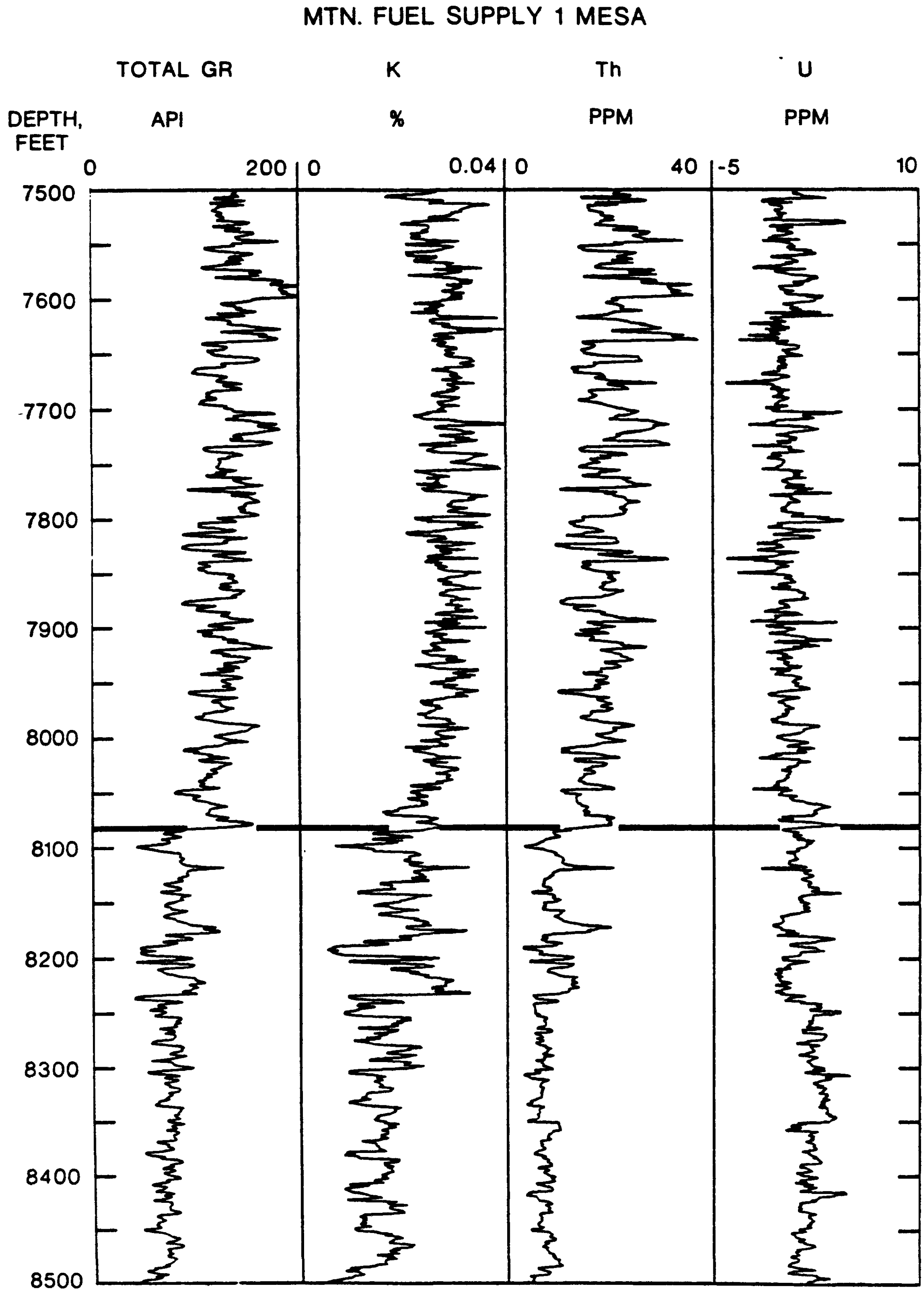

Figure 4.--Natural gamma-ray spectral log for the Mountain Fuel Supply Co. (Wexpro) 1 Mesa (7-32N-109W). The depth of the gamma anomaly is marked by the horizontal line. Note the abrupt increase in total gamma intensity above this line as well as the increase in potassium and thorium content.

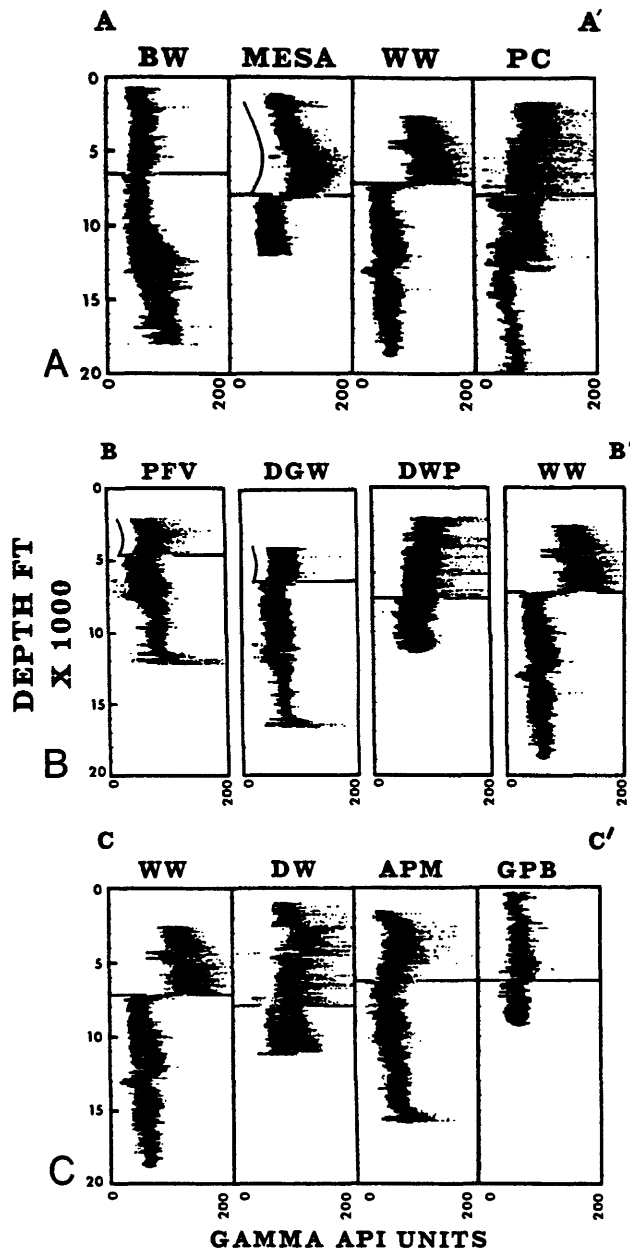

Figure 5.--Sections of compressed-scale gamma depth plots. Datum is kelly bushing elevation for each well. See figure 2 for location of corresponding line of section. The horizontal line marks the depth of the gamma anomaly and the curved line highlights the arcuate pattern discussed in the text. Well abbreviations A: (BW) Merged Inexco A-1 WASP (28-36N-112W) and the Belco Oil 3-28 Merna; (MESA) Mtn. Fuel Supply Co. (Wexpro) 1 Mesa (7-32N-109W); (WW) El Paso Natural Gas Co. 1 Wagon Wheel (5-30N-108W); (PC) Merged Rainbow Resources 1-34 Pacific Creek (34-27N-103W) and R.R 1-3 well (3-26N-103W). B: (DWP) Davis Oil 1 West Pinedale (33-30N-109w); (DGW) Davis Oil 1 Granite Wash (16-29W-110W); (PFV) Primary Fuels Van Buren 24-20 Federal (20-29N-111W). C: (DW) Davis Oil 1 Wardell Federal (9-28N-108W); (APM) Merged American Hunter 1 Aspirin (13-26N-109W) and Davis Oil 1 Parrish Mark (12-26N-109W); (GPB) General Petroleum Co. 62-A-9 Buckhorn (9-24N-109W).

TIME OF ONSET OF ARKOSE DEPOSITION

As discussed above, gamma-ray log data reflect the presence of arkosic rocks in the Tertiary. The magnitude of the gamma value appears to be proportional to the percentage of arkose present. The volume of arkose at a locality is a function of proximity to source terrane and stream gradient. Gamma intensity (percentage of arkose) may be an indication of relative stream gradients, which in turn reflect tectonic uplift or subsidence. In the arcuate pattern, seen on several of the plots (figs. 3 and 5), gamma intensity rises rapidly to a maximum value and then gradually decreases. This pattern parallels the major Laramide activity which began in latest Cretaceous time (Love, 1960). This coincides with uplift of the Wind River Mountains. By middle to late Paleocene, breaching of the crystalline core of the Wind River Mountains had occurred (Berg, 1961; Keefer, 1965). The period of most intense deformation, continued to increase through the early Eocene (Love, 1960) and began to diminish by middle and late Eocene (Love, 1960; Dorr and others, 1977).

In central and western Wyoming the Cretaceous-Tertiary boundary, seen both in outcrop and in the shallow subsurface at basin margins, is generally marked by an unconformity. However, there is disagreement as to whether deposition across the K/T boundary in the central portions of the various basins has been continuous (Berg, 1961; Keefer, 1965) or is also marked by an unconformity or disconformity (McDonald, 1972; Law, 1979; Law and Nichols, 1982; Law, this volume).

The arkosic facies in the northern Green River Basin is generally assigned to the Eocene Wasatch Formation or equivalents (Martin and Shaughnessy, 1969; West, 1969; Dorr and others, 1977). However, there is evidence for an earlier onset of arkose deposition. The oldest Tertiary rocks exposed in the vicinity of the northern Green River Basin are the lower part of the Hoback Formation in the Hoback Basin. These middle Paleocene rocks (Dorr, 1952, 1958; Guennel and others, 1973; Dorr and others, 1977) are composed of recycled Mesozoic rocks derived from the Hoback Range and are non-arkosic (Spearing, 1969). The Fort Union Formation, which is present in most of this area, is also assigned a middle Paleocene age based on vertebrate fossils in the vicinity of the Rock Springs uplift. Berg (1961) described Fort Union sandstones as having minor coarse-grained feldspars and an unnamed pre-Fort Union Tertiary sequence correlated by Law (1979 and this volume) northward from the Rock Springs area to the Merna area as arkosic (B. E. Law, oral commun., 1984). It is possible that in many parts of the northern Green River Basin, the earliest preserved Tertiary rocks are arkosic. If so, the gamma anomaly may mark the K/T boundary.

GAMMA ANOMALY AND THE CRETACEOUS-TERTIARY BOUNDARY

Biostratigraphic evidence for timing the gamma event is provided by unpublished palynological studies of core and sample cuttings from six wells located around the periphery of the northern Green River Basin (B. E. Law, oral commun., 1984). While sampling for palynological analysis was not sufficient to permit an accurate placement of the K/T boundary in most wells, the depth of the gamma anomaly is below the last sample assigned a definite Tertiary age. In the General Petroleum 62-A-9 Buckhorn well (sec. 9, T. 24

N., R. 109 W.) the gamma anomaly falls within a relatively narrow (400 ft thick) biostratigraphic bracket for the K/T boundary.

Depths for the gamma anomaly as well as the well log picks for the K/T boundary by Law (1979) are provided in table 1. In all wells (except the Inexco WASP) where both data are available, the gamma anomaly is shallower. This discrepancy may be due to: a) inaccuracies in biostratigraphic determination of the K/T boundary resulting from large gaps in sampling, or b) the gamma anomaly may represent an event above the K/T boundary. If the latter situation is the case, this anomaly may still be useful for approximating the depth of the K/T boundary as the difference is relatively small.

The lowest reported depth of arkose or feldspar obtained from sample logs (mud logs or Amstrat logs) are also provided (table 1) to assist in identifying the depth of the gamma anomaly either in combination with, or in place of, gamma-ray log data. However, since the lithologic descriptions on these logs are generally not uniform nor sufficiently detailed to report the presence of arkose or feldspar, caution is advised. In cases where this information is available and a gamma-ray log is not available, the lowest reported depth of arkose or feldspar can be used as an approximation for the gamma anomaly (K/T boundary).

SUMMARY

A strong anomaly seen in gamma-ray logs from wells in the Pinedale area of the northern Green River Basin is present throughout most of this area. This anomaly is in response to the abrupt appearance of arkosic material in lower Tertiary rocks and marks the onset of arkose deposition subsequent to breaching of the Precambrian core of the Wind River Mountains. The gamma anomaly occurs very close to the Cretaceous-Tertiary boundary as presently defined by palynology and well log correlations. Additional biostratigraphic data are needed to accurately assess the stratigraphic implications of these gamma-ray log data.

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Source-Rock Evaluation of Upper Cretaceous and Lower Tertiary Rocks in the Pinedale Anticline Area, Sublette County, Wyoming

By Ben E. Law

INTRODUCTION

Exploration geologists working in the Greater Green River Basin of Wyoming, Colorado, and Utah commonly assume that the gas contained in Upper Cretaceous and lower Tertiary low-permeability reservoirs is derived from the interbedded coal and carbonaceous lithologies. Studies by Law and others (1979, 1980) and Law (1984) have provided source-rock data of these interbedded lithologies. Law (1984) has shown that the quantitative and thermal maturity aspects of source rocks, in conjunction with pressure relationships, provide insight into the nature of gas generation and occurrence. Spencer (this volume) has discussed the relationship of overpressuring in this context.

The purpose of this report is to present the results of a source-rock study of Upper Cretaceous and lower Tertiary core samples from two wells in the Pinedale anticline area of southwestern Wyoming.

SOURCE-ROCK EVALUATION

A complete source-rock evaluation requires an analyses of the quantity, quality, and thermal maturity of organic matter. Assessment of these factors necessitates the use of several analytical methods. During the past few years several source-rock evaluation methods have been developed. Detailed explanations of these methods are given in comprehensive references by Tissot and Welte (1978), Hunt (1979), and Waples (1981).

Most samples collected for this investigation were analyzed for total organic carbon (weight percent), vitrinite reflectance (R_o), reflected light microscopy, and elemental composition (table 1); a few samples were analyzed using Rock-Eval pyrolysis (table 2).

Gas Source Rocks

Gas production from low-permeability reservoirs in the Pinedale anticline is from non-associated accumulations. In the absence of any evidence linking these gas accumulations to thermal cracking of heavy hydrocarbons, I suggest that the gas is a primary catagenetic product of the source-rock organic matter.

During coring operations in the Pacific Creek and Pinedale areas (Law, fig. 1, p. 2, this volume), an attempt was made to determine the origin of gas in low-permeability reservoirs. Core samples of the more organic-rich shales and mudstones from the Upper Cretaceous Mesaverde Group and Lance Formation were collected and placed in sealed cannisters for gas desorption tests. Periodically, during degassing of these samples, gas samples were collected and analyzed for chemical and isotopic composition. During subsequent testing of these wells, attempts were made to collect and analyze the recovered gas.

Table 1.--Source-rock analytical data from the El Paso Natural Gas, Wagon Wheel no. 1 and Wexpro, no. 1 Mesa, wells, Pinedale anticline, Sublette County, Wyoming

[PF - Plant fragments, F - Fossils, TF - Trace fossils, DOM - Dissemintaed organic matter, SS - Sandstone, Sltst - Siltstone, MS - Mudstone, Sdy - Sandy, Sh - Shale, Carb - Carbonaceous, Calc - Calcareous, Gn - Green, Gy - Gray, Var - Varigated, Ol - Olive, Brn - brown, Cl - Coal laminae; M - marine, MM - marginal marine, NM - Nonmarine]

Sample No.	Well No.	Strati-graphic unit	Depth (ft)	Sample type	Lithology	Environ-ment	Organic carbon (wt.%)	Vitrinite reflectance (R_o)	Atomic H/C	Organic Matter Type Percent			
										Exinite	Vitrinite	Inertinite	Amorphous
WW3*	6	Fort Union	5,028.2	Core	Gy MS	NM	0.34	0.51	0.67	5	55	25	15
WW5	6	Fort Union	5,072.5	Core	Gy MS/ Sdy/Coaly	NM	0.98	0.46	0.86	10	50	30	10
WW7	6	Unnamed Tertiary	7,048.5	Core	Gy SH/ Coaly	NM	0.84	0.68	0.78	5	60	30	5
WW12*	6	Unnamed Tertiary	7,038.2	Core	Gn SH/ Sdy	NM	0.27	--	0.79	T	70	20	10
WW21	6	Unnamed Tertiary	7,116.1	Core	Gy SH	NM	0.38	--	0.60	5	55	30	10
WW26	6	Unnamed Tertiary	7,130.2	Core	Blk SH/ Calc/Coaly	NM	2.00	0.74	0.76	20	10	35	20
WW28*	6	Unnamed Tertiary	7,137.2	Core	Blk SH/ Coaly	NM	13.28	0.70	0.76	10	45	25	20
WW39	6	Unnamed Tertiary	7,388.0	Core	Blk MS/PF	NM	1.68	0.72	0.72	10	30	40	20
WW41	6	Unnamed Tertiary	7,395.0	Core	Gy MS	NM	0.96	0.76	0.74	10	30	40	20
WW43*	6	Lance	8,037.0	Core	Gy MS/Calc	NM	0.37	--	0.87	5	60	25	10
WW50	6	Lance	8,073.4	Core	Gy SH/ Calc	NM	0.88	0.78	0.65	10	35	35	20
WW63	6	Lance	8,135.8	Core	Gy Sltst/ Calc/Coaly	NM	1.71	0.77	0.73	5	40	40	15
WW65	6	Lance	8,920.5	Core	Gy MS	NM	0.12	--	1.85	T	--	--	T
WW75*	6	Lance	8,984.4	Core	Blk SH/ Sdy/Calc	NM	1.24	0.85	0.77	5	45	30	20

Table 1.--Continued

Sample No.	Well No.	Strati-graphic unit	Depth (ft)	Sample type	Lithology	Environ-ment	Organic carbon (wt.%)	Vitrinite reflectance (R_o)	Atomic H/C	Organic Matter Type Percent: Exinite	Vitrinite	Inertinite	Amorphous
WW79	6	Lance	10,145.3	Core	Gy MS/ Calc	NM	0.33	0.95	0.88	T	70	20	10
WW83*	6	Lance	10,173.3	Core	Gy SH/ Coaly	NM	0.68	0.91	1.01	5	65	20	10
WW85	6	Lance	10,193.8	Core	Gy SH/ Coaly	NM	1.52	--	0.86	5	70	10	15
WW87	6	Lance	10,204.0	Core	Blk MS/ Coaly/F	NM	4.70	--	0.80	5	65	10	20
WW93*	6	Lance	10,252.3	Core	Gy MS Coaly	NM	0.82	--	0.78	5	55	20	20
WW98	6	Lance	10,995.3	Core	Blk SH/ Coaly	NM	1.03	--	0.82	5	60	15	20
WW103	6	Lance	11,024.8	Core	Gy MS	NM	0.80	0.96	0.68	5	50	20	25
WW105*	6	Lance	11,032.6	Core	Gy MS Calc/Coaly	NM	2.00	0.98	0.61	T	55	20	25
WW109	6	Lance	11,051.3	Core	Gy SH	NM	1.07	1.03	0.99	5	50	20	25
WW113*	6	Ericson	13,097.2	Core	Blk MS/ Coaly	NM	2.81	1.22	0.70	T	60	15	25
WW123	6	Ericson	13,141.8	Core	Blk SH	NM	3.32	1.15	0.63	5	55	20	20
WW134	6	Ericson	13,198.0	Core	Blk MS/ Sdy/Coaly	NM	8.40	1.13	0.65	T	65	15	20
WW135	6	Mesaverde	14,897.8	Core	Blk MS/ Calc/Coaly	NM	1.24	--	0.68	T	60	20	20
WW136	6	Mesaverde	14,902.3	Core	Coaly SH	NM	6.81	1.47	0.60	T	60	10	30
WW138	6	Mesaverde	14,914.1	Core	Blk MS/ Coaly/TF	NM	1.72	1.48	0.62	T	70	5	25
WW139	6	Mesaverde	14,918.4	Core	Blk SH/ Calc/Coaly	NM	5.84	1.53	0.63	T	70	10	20
WW141*	6	Mesaverde	14,923.8	Core	Gy SH, Calc/PF	NM	0.60	1.48	0.72	T	30	40	20
WW143	6	Mesaverde	14,930.3	Core	SH/Blk/Carb	NM	4.77	1.55	0.60	T	65	10	25
WW146	6	Mesaverde	14,942.5	Core	Gy MS/ Calc/PF	NM	0.91	1.49	0.69	T	50	20	30

Table 1.--Continued

Sample No.	Well No.	Strati- graphic unit	Depth (ft)	Sample type	Lithology	Environ- ment	Organic carbon (wt.%)	Vitrinite reflectance (R_o)	Atomic H/C	Organic Matter Type Percent: Exinite	Vitrinite	Inertinite	Amorphous
WW149	6	Mesaverde	16,062.1	Core	SS/Calc/PF	NM	0.24	--	0.49	0	70	20	10
WW151*	6	Mesaverde	16,068.5	Core	Blk MS/Coaly	NM	0.80	1.61	0.74	5	50	25	20
WW154	6	Mesaverde	16,078.8	Core	Blk MS/Coaly	NM	0.68	1.61	0.64	5	45	30	20
WW159	6	Mesaverde	16,101.9	Core	Blk MS/Calc/Coaly	NM	1.79	1.65	0.57	5	40	30	25
WW170*	6	Mesaverde	17,173.3	Core	Gy SS/Calc	M	0.41	1.77	0.64	T	30	40	30
WW176	6	Hilliard	17,960.0	Core	Blk MS/Calc	M	0.75	1.98	0.54	5	35	30	30
WW177*	6	Hilliard	17,965.0	Core	Sltst/Gy/TF	M	1.39	1.85	0.62	5	40	30	25
MF1	17	Lance	--	Core	Slty SH/Gy	NM	0.16	0.70	0.56	T	90	5	5
MF2	17	Lance	9,156.3	Core	SH/Gy/Calc	NM	0.24	0.70	0.75	T	90	T	5
MF3	17	Lance	9,201.7	Core	Slty SH/Gy/Calc	NM	0.11	0.70	0.75	T	90	5	5
MF4	17	Lance	9,209.5	Core	SH/Gy	NM	0.30	--	0.48	T	70	10	20
MF5	17	Lance	9,663.8	Core	Slty SH/Gy/Calc	NM	0.30	--	0.51	T	50	50	T
MF6	17	Lance	9,697.0	Core	SS/Gy/Calc	NM	0.60	0.72	0.71	5	70	10	15
MF7	17	Lance	9,792	Core	Sltst/Gy	NM	0.45	--	0.52	T	45	40	15
MF8	17	Lance	10,513.0	Core	Slty SH/Gy/Calc	NM	0.74	--	0.52	5	50	40	5
MF9	17	Lance	10,572.0	Core	Slty SH/Gy/Calc	NM	0.48	0.83	0.71	5	60	30	5
MF10	17	Lance	11,243.5	Core	SH/Gy	NM	0.20	1.14	0.59	T	85	10	5
MF11	17	Lance	11,245.0	Core	Sltst/Gy/Sh	NM	0.43	1.08	0.54	0	80	10	10

*Samples for which there are two total organic carbon analyses.

Table 2.--Continued

Sample No.	Well No.	Strati- graphic unit	Depth (ft)	Organic Carbon (wt. %)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	$T(S_2)$ (°C)	Genetic Potential (ppm)	H_2 Index (mg HC/gC)	O_2 Index (mg CO_2/gC)	Transformation Ratio (S_1/S_1+S_2)
WW-49	6	Lance	8070.0	0.13	0.121	0.01	0.16	428	130	10	125	0.91
WW-58	6	Lance	8117.0	.22	.099	.04	.12	435	140	18	52	.72
WW-64	6	Lance	8136.0	.12	.046	--	.18	--	50	--	146	1.00
WW-71	6	Lance	8959.0	.98	.131	.55	.12	443	680	56	12	.19
WW-75*	6	Lance	8984.4	.17	.117	.11	.13	445	220	62	77	.52
WW-77	6	Lance	9001.0	.14	.047	--	.15	--	50	--	107	1.00
WW-83*	6	Lance	10,173.3	.38	.177	.25	.12	450	420	65	32	.42
WW-88	6	Lance	10,212.0	1.00	.182	1.18	.11	446	1360	118	11	.14
WW-93*	6	Lance	10,252.3	.67	.144	.47	.12	445	610	70	18	.24
WW-102	6	Lance	11,018.0	.86	.136	.32	.15	448	460	38	17	.30
WW-105*	6	Lance	11,032.6	1.40	.147	.29	.11	450	550	29	8	.27
WW-108	6	Lance	11,046.0	.82	.249	.39	.12	452	640	48	15	.39
WW-111	6	Lance	11,066.0	1.85	.103	.46	.17	451	560	25	9	.18
WW-112	6	Lance	11,068.0	.24	.223	.04	.22	464	260	15	90	.86
WW-113*	6	Ericson	13,097.2	1.41	.496	.73	.10	463	1220	52	7	.41
WW-117	6	Ericson	13,114.0	1.67	.724	.94	.13	466	1670	56	8	.43
WW-137	6	Mesaverde	14,906.0	.53	.191	.10	.29	487	300	18	56	.66
WW-141*	6	Mesaverde	14,923.8	.50	.120	.07	.37	487	190	14	75	.62
WW-144	6	Mesaverde	14,937.0	.68	.174	.15	.17	485	330	22	25	.53
WW-145	6	Mesaverde	14,939.0	4.46	.463	2.11	.14	481	2570	47	3	.18
WW-151*	6	Mesaverde	16,068.5	.68	.150	.07	.13	490	220	11	19	.67
WW-162	6	Mesaverde	16,110.0	1.10	.169	.10	.22	493	270	9	20	.62
WW-164	6	Mesaverde	16,115.0	.81	.171	.08	.18	497	250	10	22	.68
WW-170*	6	Mesaverde	17,173.3	.10	.067	--	.11	--	70	--	111	1.00
WW-174	6	Mesaverde	17,189.0	.81	.196	.021	.15	478	220	3	18	.90
WW-177*	6	Hilliard	17,965.0	.55	.138	.007	.18	518	150	1	32	.95

*Sample for which there are two total organic carbon analyses.

Table 2.--Rock-eval pyrolysis data of samples from the El Paso Natural Gas, Wagon Wheel no. 1 well, Sublette County, Wyoming

[-- no data;]

Sample No.	Well No.	Strati-graphic unit	Depth (ft)	Organic Carbon (wt. %)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	$T(S_2)$ (^oC)	Genetic Potential (ppm)	H_2 Index (mg HC/gC)	O_2 Index (mg CO_2/gC)	Transformation Ratio (S_1/S_1+S_2)
WW-3*	6	Fort Union	5028.2	0.69	0.69	0.09	0.13	421	250	14	20	0.62
WW-9	6	Unnamed Tertiary	7057.0	2.80	.199	5.22	.18	426	5420	186	6	.62
WW-12*	6	Unnamed Tertiary	7083.2	.14	.023	.05	.13	436	80	38	95	.30
WW-14	6	Unnamed Tertiary	7095.0	.53	.066	.10	.17	439	170	19	32	.40
WW-15	6	Unnamed Tertiary	7100.0	.34	.143	.09	.23	430	230	27	69	.61
WW-16	6	Unnamed Tertiary	7102.0	.13	.222	.04	.20	426	260	30	155	.85
WW-22	6	Unnamed Tertiary	7120.0	.41	.023	.05	.16	431	70	12	39	.31
WW-24	6	Unnamed Tertiary	7125.0	.09	.020	--	.09	--	20	--	104	1.00
WW-27	6	Unnamed Tertiary	7134.0	2.75	.027	3.34	.23	436	336	121	8	.01
WW-28*	6	Unnamed Tertiary	7137.2	2.70	.106	2.04	0.32	438	214	76	12 -	.05
WW-38	6	Unnamed Tertiary	7384.0	1.14	.038	.41	.19	440	450	36	17	.08
WW-40	6	Unnamed Tertiary	7392.0	1.06	.123	.79	.12	443	910	74	12	.14
WW-42	6	Lance	8030.0	.14	.082	--	.13	--	80	--	92	1.00
WW-43*	6	Lance	8037.0	.28	.109	.03	.16	442	130	9	56	.75
WW-48	6	Lance	8066.0	.09	.118	--	.10	--	120	--	108	1.00

Figure 1 shows a plot of the isotopic compositions of the analyzed desorbed and test-recovered gas versus depth in each well. $\delta^{13}C$ values range from about -34 to -42^{o}/oo (parts per thousand). Although there does not appear to be any obvious compositional similarity between wells, the isotopic compositions of the desorbed and test-recovered gas within each well are very similar, lending support to the earlier work of Law and others, (1979, 1980) and McPeek (1981) that the interbedded carbonaceous rocks are the most likely sources of the gas accumulations.

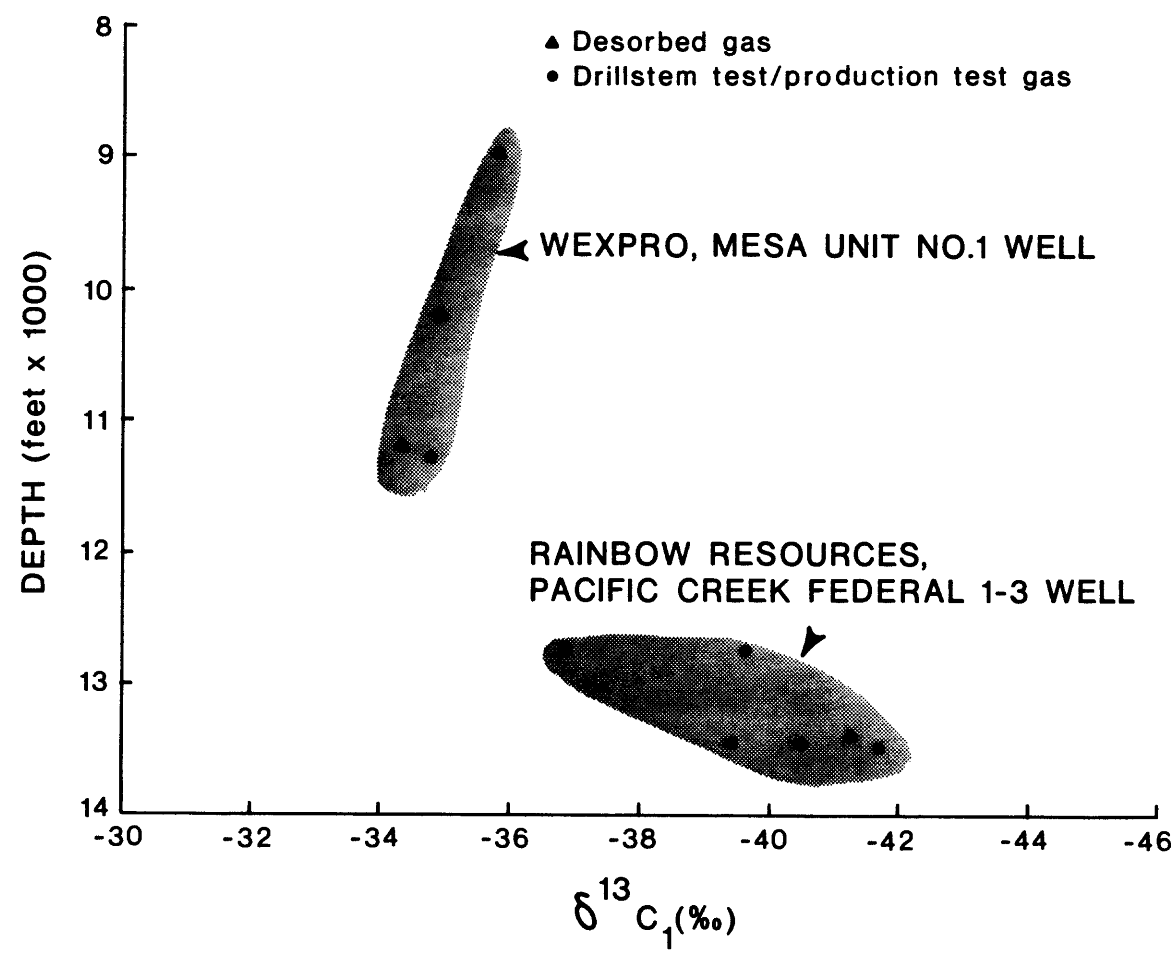

Figure 1.--$\delta^{13}C$, analyses of methane from samples of desorbed gas and gas recovered from production tests or drillstem tests in the Wexpro, no. 1 Mesa Unit and the Rainbow Resources, 1-3 Pacific Creek Federal wells.

Organic Matter Quantity

Fifty-one core samples consisting of carbonaceous sandstone, siltstone, shale, mudstone, and coal were analyzed for total organic carbon content (weight percent). These data are shown in tables 1 and 2. The core samples were collected from the El Paso Natural Gas Wagon Wheel no. 1 and the Wexpro, Mesa no. 1 wells (fig. 2 and table 1, pgs. 3-4, Law, this volume). The samples represent a wide range of depositional environments.

Excluding coal, total organic carbon contents of the analyzed samples range from 0.11 to 13.28 percent. The average content is 1.65 percent. In general, dark-colored carbonaceous mudstones and shales are more organic-rich, although carbonaceous siltstones and sandstones contain as much as 1.5 weight percent organic carbon. In most of the samples, organic matter is present as small flakes and coalified plant fragments disseminated throughout the sample, or as organic-rich concentrates in thin (<1mm) discontinuous laminae. Total organic carbon analyses of samples from the Wagon Wheel well are shown on figure 2.

There is some concern that the reported organic carbon values may not accurately reflect the organic carbon content of these samples. Thirteen samples, identified by asterisks in tables 1 and 2, from the El Paso Natural Gas, Wagon Wheel no. 1 well were analyzed for organic carbon by two laboratories. The results are significantly different. The reason for the analytical differences is unknown.

Organic Matter Quality

Immediately following the deposition of organic debris, biochemical and physicochemical processes begin to alter the organic matter. In ancient rocks, the determination of organic matter type is often obscured or obliterated by these processes and may be further complicated by sedimentological mixing and recycling. The type of organic matter is important because it determines the composition of hydrocarbons that may be generated. In general, types I and II kerogens, discussed in the following pages, are oil and gas source rocks, and type III kerogens are gas source rocks.

There are three principal types of kerogen (Tissot and Welte, 1978). Type I kerogen is most often associated with lacustrine environments, is derived from algal material, and has high atomic H/C (hydrogen/carbon) and low O/C (oxygen/carbon) ratios. Type II kerogen is usually associated with marine environments, is derived from a mixture of phytoplankton, zooplankton, and microorganisms, and has intermediate H/C and O/C ratios. Type III kerogen is usually associated with nonmarine environments, is derived from terrestrial vegetation and has low H/C and high O/C ratios.

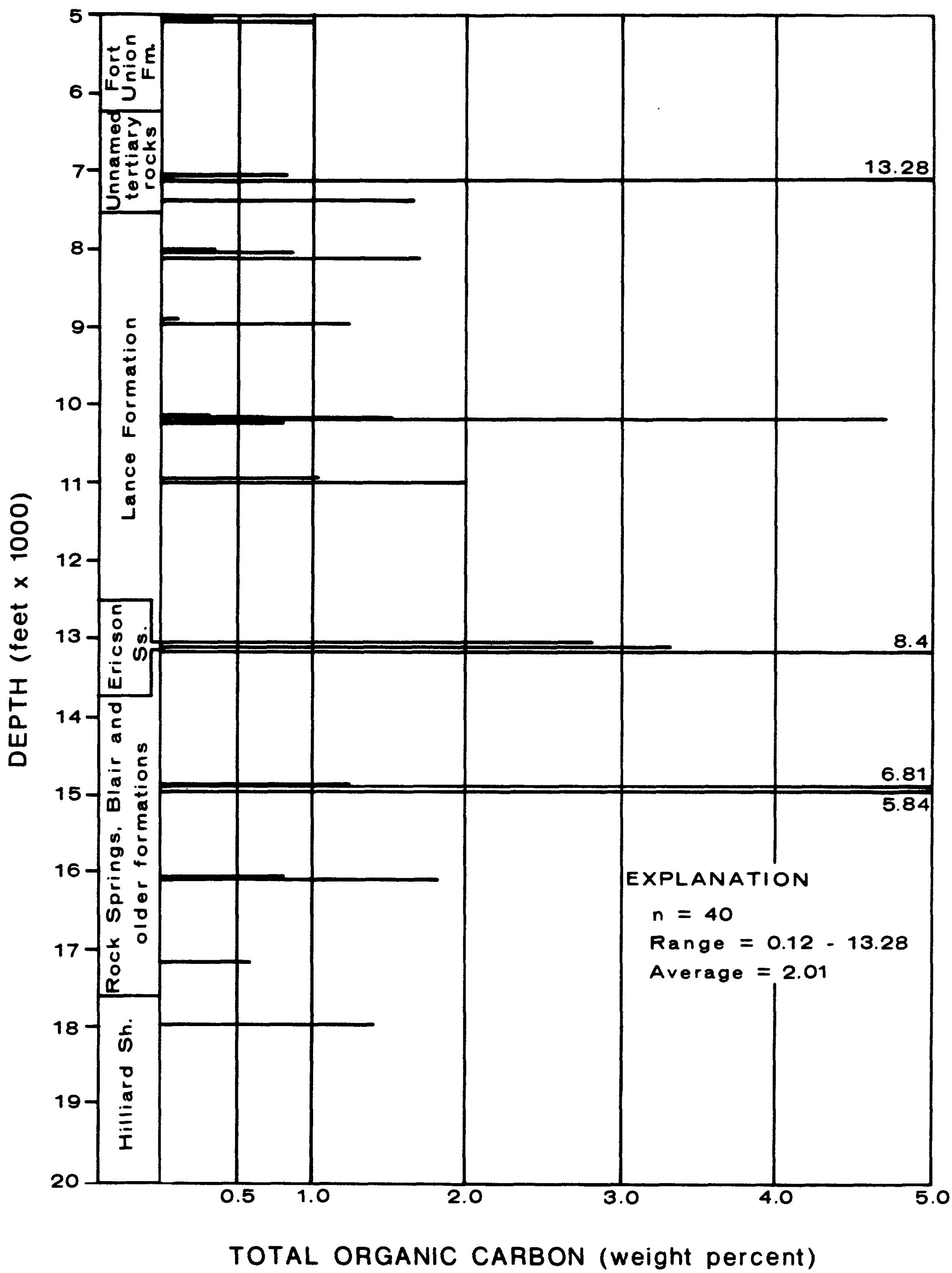

Figure 2.--Total organic carbon content of samples from the El Paso Natural Gas, Wagon Wheel no. 1 well. Only samples from table 1 are shown.

Shown in table 1 are the interpreted organic matter types as determined by reflected light microscopy of kerogen fractions. In this technique, coal macerals in the kerogen are identified and the relative abundance of macerals are estimated. According to van Krevelen (1961) and Stach and others, (1982) exinite includes fossil spores, cuticle, resins, waxes, and algal remains; vitrinite includes woody or humic material; inertinite may include charcoal and allochthonous or recycled material; and amorphous includes structureless organic matter that commonly contains hydrogen-rich material. However, because structureless organic matter can result from diagenetic processes as well, this type may include a mixture of different coal macerals.

The reflected light microscopy data in table 1 show that, in most samples, vitrinite is the dominant coal maceral, commonly in amounts greater than 50 percent. The amorphous and exinite groups, those maceral groups with a higher potential of generating liquid hydrocarbons, are generally present in amounts less than 30 percent.

Figure 3 shows a plot of the hydrogen and oxygen indices of samples from the El Paso Natural Gas, Wagon Wheel no. 1 and the Superior, Pacific Creek no. 1 Federal wells. This is a modified van Krevelen diagram (Espitalie′ and others, 1977; Tissot and Welte, 1978) in which the hydrogen index and oxygen index, as determined by Rock-Eval pyrolysis (table 2), are substituted for the atomic H/C and O/C ratios, respectively. At high levels of thermal maturity the kerogen evolutionary paths merge and a clear distinction is not apparent. However, most of the samples from these two wells are in proximity to the type III kerogen path.

Another measure of organic matter quality is provided by the genetic potential (table 2). The genetic potential is the sum of the free hydrocarbons in the rock (S_1) and the amount of hydrocarbons in the organic matter that have not yet been generated (S_2). Tissot and Welte (1978) have suggested that samples with values lower than 2000 parts per million (ppm) are poor source rocks; samples from 2000 to 6000 ppm are moderate source rocks, and samples >6000 ppm are good source rocks. Based on these criteria, most of the samples from the Wagon Wheel well are poor source rocks and only two samples are moderately good source rocks.

THERMAL MATURATION

Observations in the Pacific Creek area (Law and others, 1979, 1980) and elsewhere in the basin (Spencer and Law, 1981; Law and Spencer, 1981; Law and Smith, 1983) indicate that the initiation of significantly large volumes of thermogenic gas begins at a temperature of about 190° to 200°F (88° to 93°C) and a vitrinite reflectance ranging from 0.74 to 0.86 percent. This conclusion was originally based on observations in the Pacific Creek area, where the top of sustained gas shows, as indicated on mud logs, occurs at an uncorrected subsurface temperature of about 180°F (82°C) and a vitrinite reflectance of about 0.80 R_o. Thermally generated gas is probably produced at lower temperatures and levels of organic maturation, but not in large quantities. The interpretation assumes little or no gas has migrated, and that a thermal equilibrium condition exists--that is, present temperatures are sufficiently high to have produced the observed levels of organic maturation.

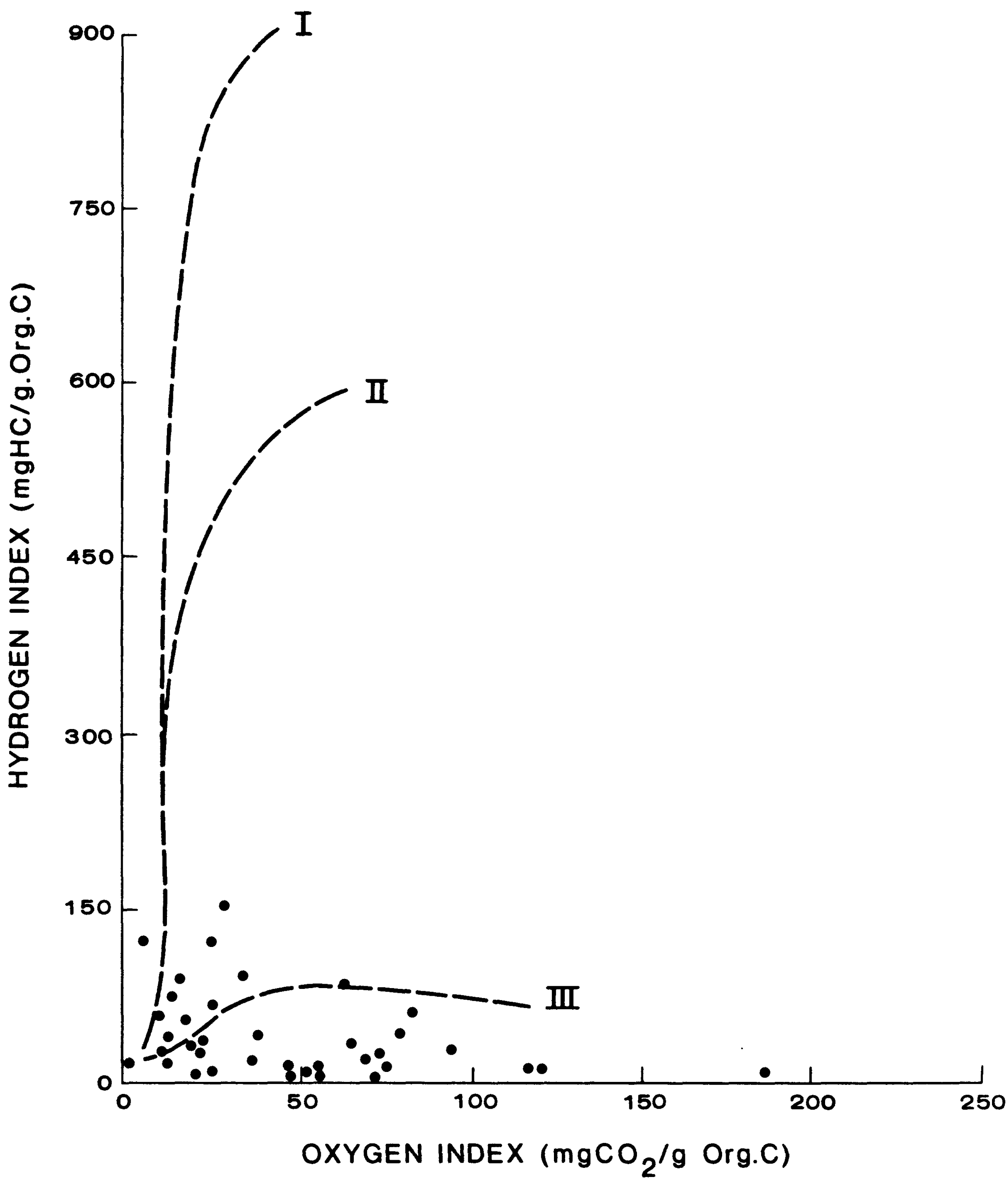

Figure 3.--Modified van Krevelen diagram (Tissot and Welte, 1978) of hydrogen and oxygen indices of samples from the El Paso natural Gas, Wagon Wheel no. 1 and Superior, Pacific Creek no. 1 well.

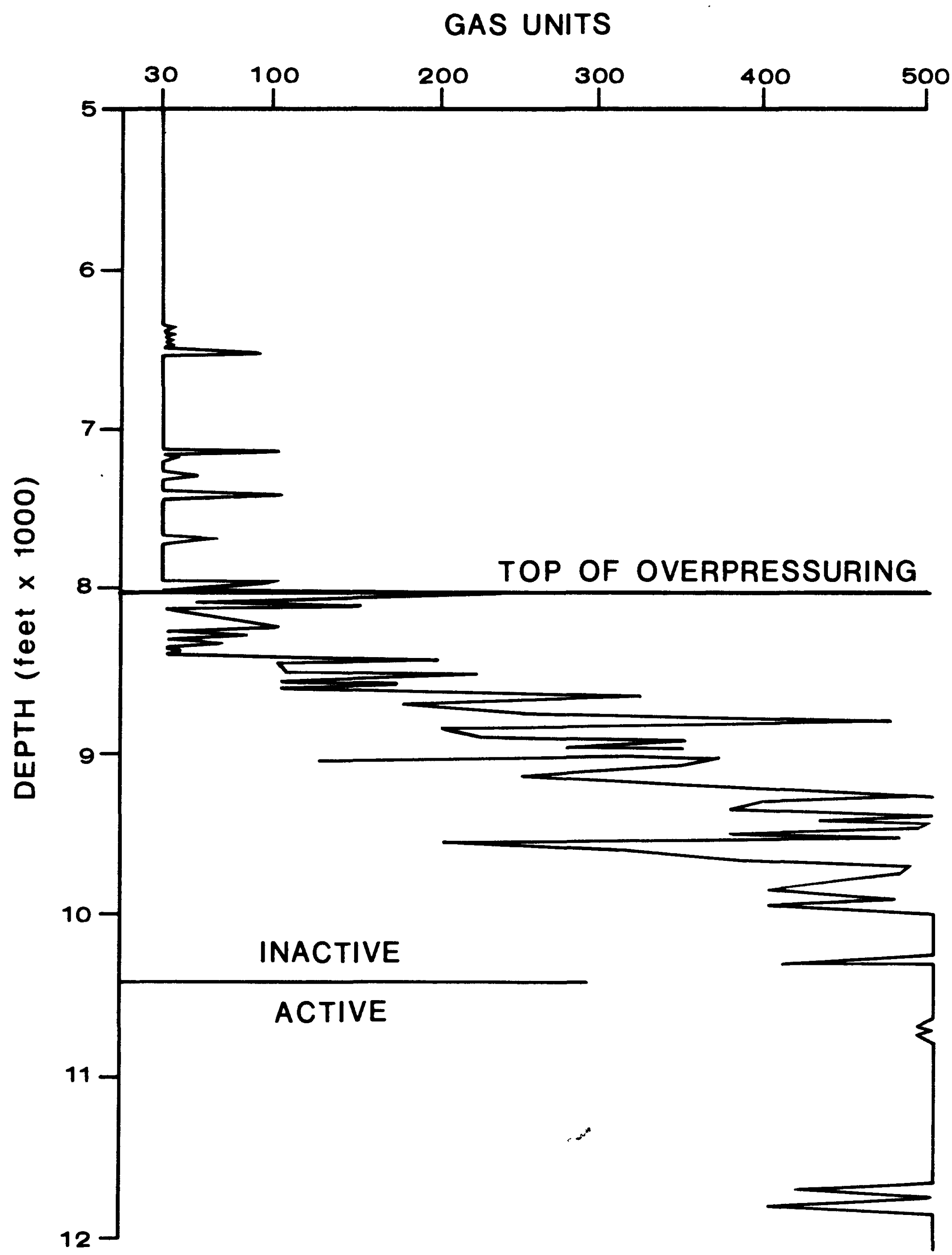

Figure 4.--Modified part of mud log from El Paso natural Gas, Wagon wheel no. 1 well showing relationship of gas occurrence to top of overpressuring and active and inactive zones of overpressuring.

In contrast to the apparent thermal equilibrium condition in other parts of the Green River Basin, the Wagon Wheel well exhibits a disequilibrium condition--that is, present temperatures are insufficient to account for the observed level of organic maturation. The top of sustained gas shows (fig. 4) and overpressuring are at a temperature of about 150°F (66°C) and a vitrinite reflectance of about 0.74 R_o (fig. 5). The observation of thermal disequilibrium is supported by two independent techniques. X-ray diffraction analyses of clay samples in the Wagon Wheel well, by Pollastro and Bader (1983) and Pollastro and Barker (this volume), indicate that these rocks have been subjected to hotter temperatures than presently observed. Results of apatite fission-track dating in cores from the Wagon Wheel well by Naeser (this volume) also indicate that present temperatures are less than maximum temperatures that have occurred in these rocks.

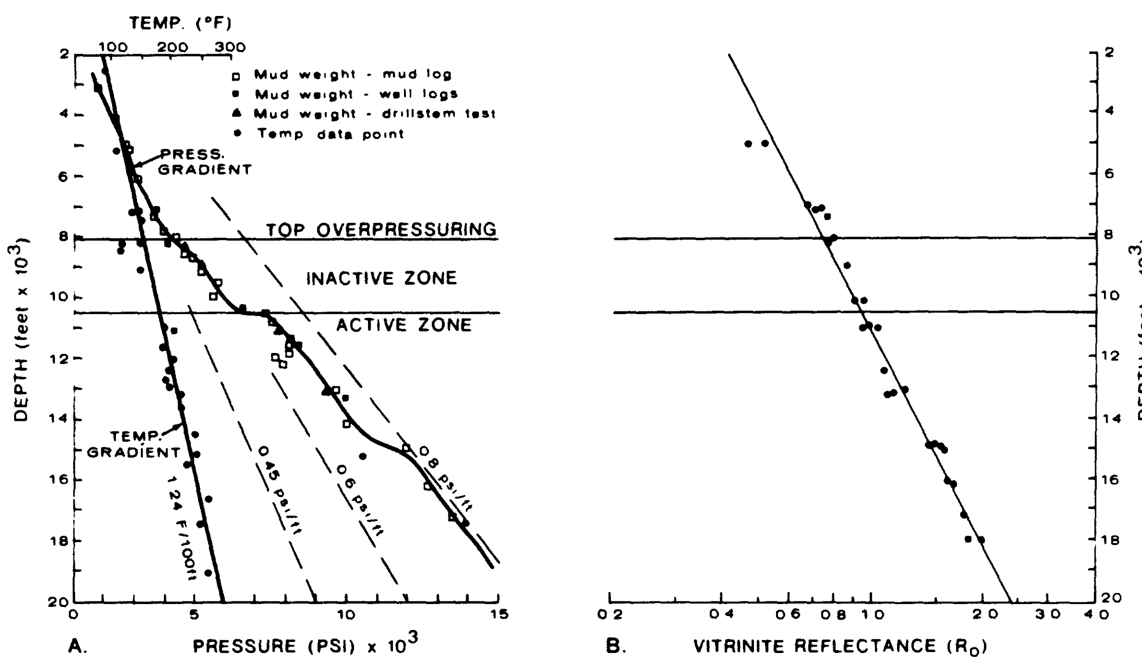

Figure 5.--(A) El Paso Natural Gas, Wagon wheel no. 1 well presssure and temperature gradients, and (B) vitrinite reflectance (R_o) profile. Temperature data from El Paso Natural Gas Wagon Wheel no. 1 and Pinedale no. 5 wells. Pressure gradient interpreted by C. W. Spencer. Vitrinite reflectance analyses by Robertson Research (U.S.) Inc., Houston, Texas.

By way of comparison, Rock-Eval pyrolysis temperatures are shown for the Wagon Wheel well on figure 6. According to Espitalie' and others, (1977), pyrolysis temperatures (T^o max in table 2) less than 435°C (752° and 815°F) correspond to the immature zone of petroleum generation, and temperatures between 435° and 460°C (815° and 860°F) correspond to the mature oil zone. On the basis of these pyrolitic temperature boundaries, the top of the oil zone in the Wagon Wheel well is at a depth of about 7,900 ft (2,408 m) and is nearly coincident with the top of overpressuring at 8,030 ft (2,450 m).

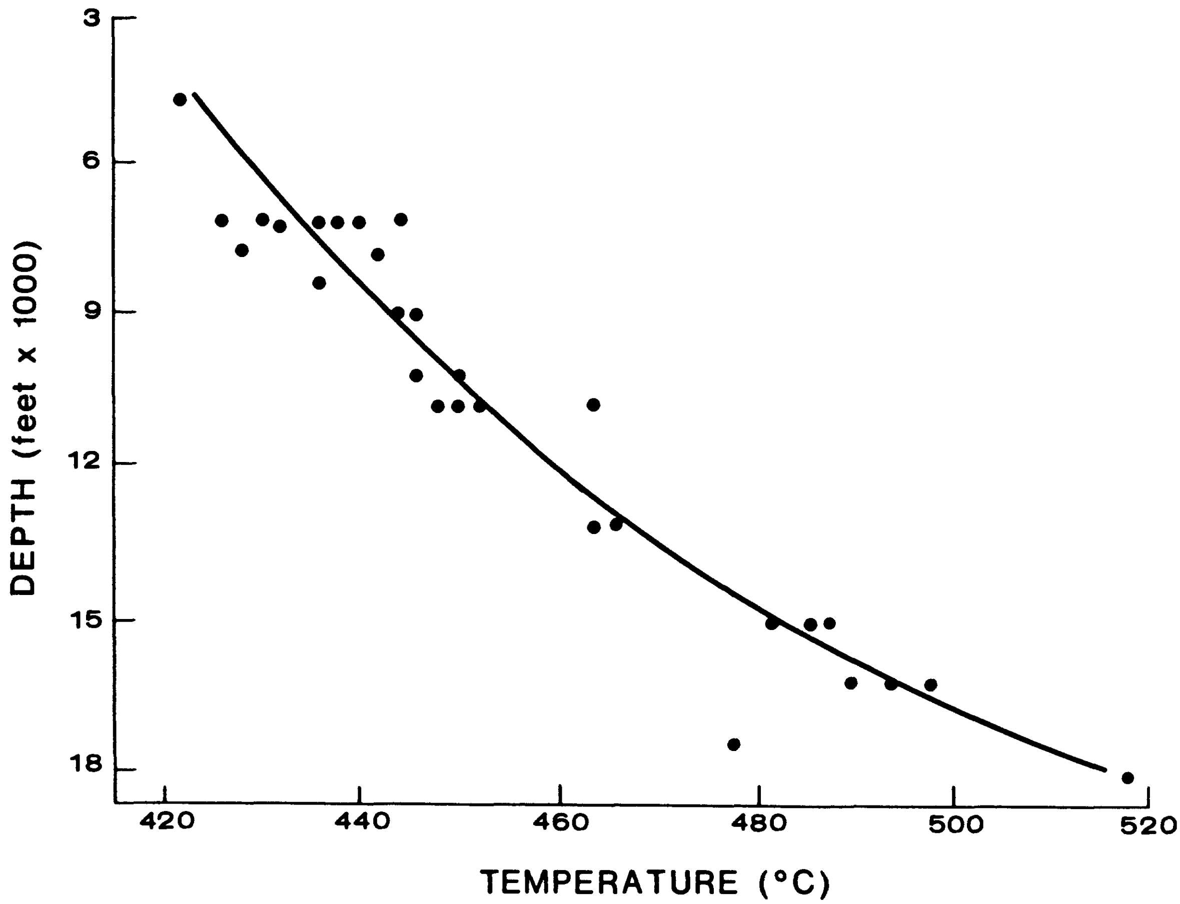

Figure 6.--Pyrolysis temperatures (T_{S_2} in table 2) of samples from the El Paso Natural Gas, Wagon Wheel no. 1 well.

SUMMARY

The source of gas contained in Upper Cretaceous low-permeability reservoirs in the Pinedale anticline area is most likely the interbedded coal and carbonaceous shale and siltstone. Based on analyses of 51 samples from two wells, the average organic carbon content of these lithologies is 1.65 weight percent, and the predominant type of organic matter is humic (type III kerogen), which is capable of generating gas and little or no liquid hydrocarbons. The top of the gas-bearing rocks occurs in the Upper Cretaceous Lance Formation at a depth of 8,030 ft (2,448 m) and a vitrinite reflectance of 0.74 percent.

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Overpressured Tight Gas Reservoirs in the Pinedale Anticline Area, Sublette County, Wyoming

By Charles W. Spencer

INTRODUCTION

Most deep (>11,000 ft, >3,353 m) wells drilled on and adjacent to the Pinedale anticline, Sublette County, Wyoming, encountered tight gas reservoirs with abnormally high-pore pressures in Upper Cretaceous rocks. Overpressuring, as used in this discussion, is reservoir pressure which is in excess of normal hydrostatic pressure. Normal hydrostatic pressure is approximately 0.43 psi/ft (9.73 kPa/m), but most of the overpressuring is in excess of 0.5 psi/ft (>11.3 kPa/m), and some reservoir pressures on the Pinedale anticline are higher than 0.8 psi/ft (>18.1 kPa/m). Overpressured reservoirs in this part of southwest Wyoming (northern Green River Basin) were first noted by Rathbun (1968, 1969). Several authors have recently discussed overpressuring in the Green River Basin (Law and others, 1979, 1980; Law and Spencer, 1981; Spencer and Law, 1981; Spencer, 1983; Law, 1984).

Overpressuring can be caused by a variety of mechanisms, and sometimes in a given area, more than one factor may contribute to the abnormally high pressure. Fertl (1976) describes many possible causes of overpressuring. The generally accepted causes of most overpressuring are dewatering (compaction) of shales (Harkins and Baugher, 1969), and alteration of "montmorillonite" (smectite) to a less hydrated mixed-layer, illite-smectite mineralogy (Powers, 1967; Burst, 1969). These concepts both assume that water is the pressuring mechanism but in the tight reservoir, oil or gas is the dominant pressuring fluid phase. In fact, rarely is any overpressured water ever encountered in Rocky Mountain reservoirs.

Rathbun (1968, 1969) interpreted that the overpressuring in the northern Green River Basin was caused by tectonic compression; however, as discussed below, other mechanisms may be more important. The northern Green River Basin is located between the southwestward thrusted Wind River uplift and the eastward thrusted Wyoming Thrust belt. Figure 1 shows the location of the Green River Basin and the Pinedale anticline. This figure also shows the distribution of overpressured tight gas reservoirs in Cretaceous and Tertiary reservoirs. The definition of areas of overpressuring was based on proprietary drillstem test (DST) data obtained from Roger L. Hoeger, publicly available copies of DST records from state oil and gas records, mud logs, and drilling mud weights. Figure 1 shows that the overpressured areas are not confined to the area between thrusts in the northern Green River Basin.

Law and others (1980) studied data from overpressured wells in the Pacific Creek area (see fig. 1) and proposed that the abnormal pressuring was caused by the active thermochemical generation of gas from organic-rich, gas-prone source beds in low-permeability reservoir sequences. This overpressuring is mostly dependent on gas being generated at a minimum present-day subsurface temperature greater than 190°F (>88°C) (Spencer and Law, 1981). Most overpressured reservoirs in the Rocky Mountains have minimum temperatures of about 200°F (93°C) (Spencer and Law, 1981). However, not all reservoirs with temperatures above 200°F (>93°C) are overpressured. Maintenance of overpressure requires not only critical temperatures, but also requires the presence of organic-rich source beds still capable of gas generation and the presence of low-permeability seals to retain the abnormal pressure (Law and others, 1980).

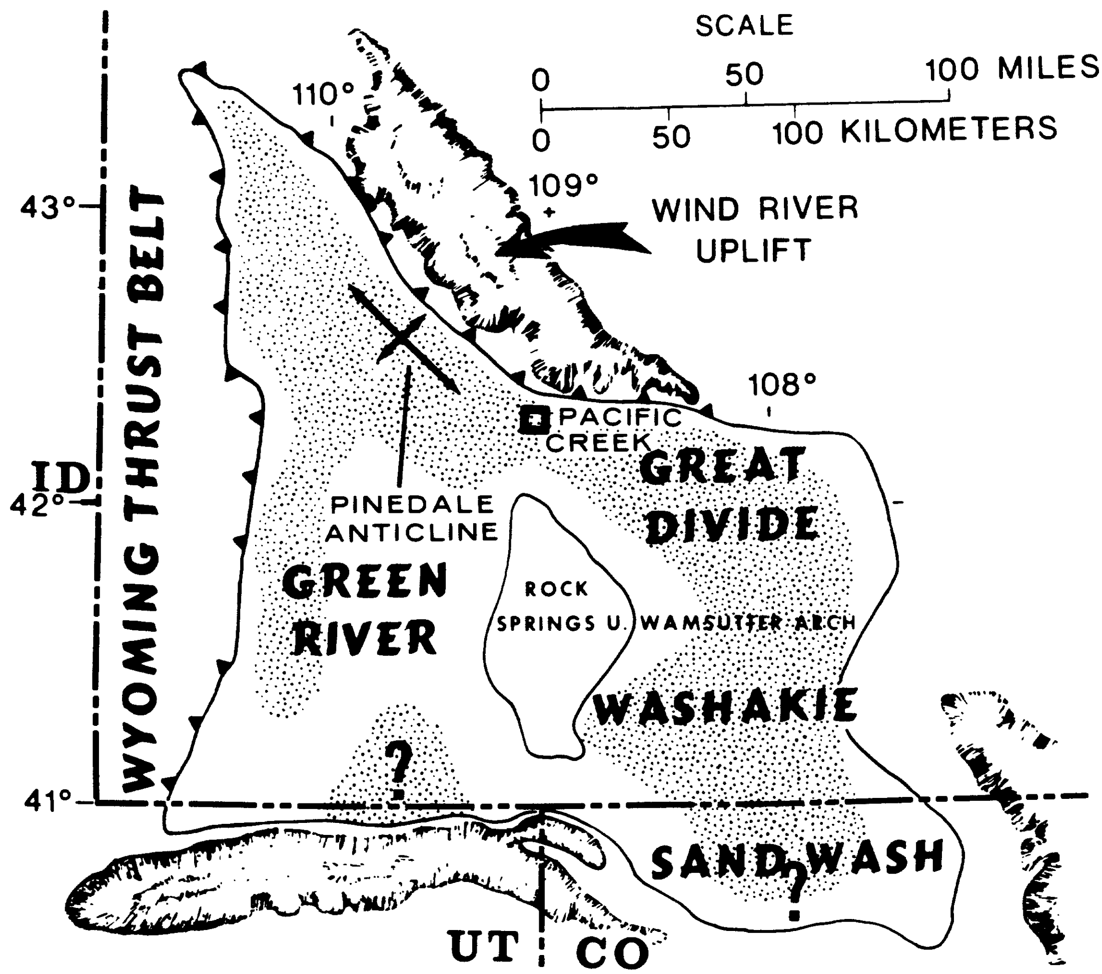

Figure 1.--Map of the Greater Green River Basin showing basin subdivisions and the distribution of overpressured (stippled) Cretaceous and Tertiary tight gs reservoirs (modified from Spencer, 1983).

METHODS OF STUDY

Accurate calculation of reservoir pressure in conventional rocks is generally easily estimated or calculated because the rocks have good permeability. However, tight gas reservoirs have very low in-situ permeability to gas (0.1 md to <.0001 md). As a result of this low permeability, the usual methods of measuring reservoir pressure are not adequate. The usual methods are (1) extrapolation of DST shut-in pressures to an undisturbed, original pressure, and (2) cased-hole, drawdown-buildup tests (similar to DST). In gas reservoirs, and especially tight gas reservoirs, accurate static pressure calculations are further impeded by the fact that gas is highly compressable. After a well is flowed (pressure drawdown) the well is shut-in and gas recompression occurs in the hole (wellbore storage) and in the formation (afterflow). This compressability factor, coupled with the low permeability problem, make very long shut-in times necessary for tight-reservoir pressure estimation. Shut-in times of many weeks or months are usually required. Therefore, most DST data can not be used to estimate pressure. However, I estimate that about 10 percent or less of the DSTs run in tight-reservoir sequences in the Rocky Mountain region evaluate rock sequences that are highly fractured. This fracture permeability greatly enhances the rock matrix permeability and the rock surface area evaluated by the test. Some of these tests in fractured reservoirs can be used to approximate true-reservoir pressure; however, all other evidences of overpressure should also be used. Other overpressure detection methods involve correlation of data from drilling mud weights, drilling-time charts, and mud-log gas shows and "kicks". To date, estimation of pore pressure from borehole geophysical logs run in Tertiary and Cretaceous rocks in the Rocky Mountain region has not been reliable (S. E. Prensky, oral commun., 1984).

Mud weights and gas-show data are the two most widely available sources of data to indicate overpressuring. With experience, one can fairly accurately identify the top of overpressuring using these data; however, caution must be used when attempting to estimate the maximum reservoir pressures within the overpressured interval. Various operators have their own approaches to drilling high-pressure, tight rocks. Some operators will drill "underbalanced"; that is, drill with mud weights that are known to be less than true-reservoir pressure. Drilling underbalanced greatly enhances bit-penetration rates. Some operators will unknowingly drill in an underbalanced condition, but most operators try to drill with mud weights equivalent to the reservoir pressure of the section being penetrated. This technique (1) permits good bit penetration rates, (2) minimizes the potential for well "blowouts", and (3) reduces the chance of accidentally fracturing the open part of the hole by mud weights that exceed the formation fracture gradient. In conclusion, all factors must be taken into consideration when estimating pore pressures in very tight rocks.

PINEDALE AREA ABNORMAL RESERVOIR PRESSURE

Overpressuring in the Pinedale area has been noted by Rathbun (1968, 1969), Law and Spencer (1981), and Law (1984). Rathbun (1968, 1969) interpreted that borehole-geophysical logs could identify a conductivity anomaly associated with overpressuring in the northern Green River Basin. However, most of his interpretation of abnormal pressure was based on drilling mud-weight data. Preliminary computer processing of well logs by S. E. Prensky (oral commun., 1984) indicates borehole geophysical logs are not a reliable means to identify overpressuring in the consolidated rocks of the northern Green River Basin.

Figure 2-A shows an interpreted subsurface temperature and pressure gradient plot of the EPNG No. 1 Wagon Wheel that I prepared for a report by Law (1984). Figure 2-B, taken from Law (this volume, fig. 5, p. 48) shows a plot of vitrinite reflectance data correlated with depth. The pressure interpretation is largely based on mud weight and other data compiled from mud logs, well logs, and borehole mud weights determined from DST hydrostatic pressures (HP). None of the DST shut-in pressure data were extrapolatable, owing to the low permeability of the reservoirs tested. However, a few DSTs had sufficient pressure buildup during initial shut-in times that the overpressure can be clearly verified even though the maximum amount of

overpressure could not be determined. Figure 3 shows a copy of a DST chart from the No. 1 Wagon Wheel, run in the Upper Cretaceous Lance Formation from 10,978 to 11,070 ft (3,346.1-3,374.1 m). The visual interpretation of the initial shut-in curve and pressure data confirms the presence of abnormally high reservoir pressure. The initial shut-in pressure (ISIP) was 6,805 psi (>46.9 MPa) at 11,066 ft (3,372.9 m). The pressure was increasing at the time the shut-in period ended. It is obvious from the chart that the true reservoir pressure is slightly higher than the mud maximum hydrostatic pressure (HP). The maximum mud HP was 7,600 psi (52.4 MPa). Even though the DST pressure data are not extrapolatable, I interpret that the well was being drilled slightly underbalanced at the time the test was run. Therefore, the true reservoir pressure is greater than 7,600 psi (52.4 MPa). Consequently, the reservoir pressure is greater than a 0.69 psi/ft (15.61 kPa/m) gradient.

The pressure-depth plot (fig. 2-A) shows several inflections in the increase in pressure gradient with depth. The first one occurs at about 8,000 ft (2,438 m) in the Lance Formation and marks the top of abnormally high pressure. Another increase in pressure is seen at about 10,500 ft (3,200 m), and the deepest increase in pressure occurs at about 15,000 ft (4,572 m) in the middle of the Rock Springs Formation. Law (1984) has described the interval between the upper pressure inflections as a zone of inactive gas generation. This interval is between 8,030 ft (2,447.5 m) and 10,400 ft (3,169.9 m). He interprets the source beds in this zone to have been formerly at a sufficiently high temperature (>190^{o}F, >88^{o}C) to have been actively generating gas and were consequently overpressured. Approximately 2,000 ft (610 m) of uplift and erosion on the Pinedale anticline has occured (Law, pg. 7, this volume). This uplift caused the source beds to cool below the 190^{o} to 200^{o}F (88^{o} to 93^{o}C) critical mimimum temperature and gas generation ceased (Law, 1984). The temperature at 8,000 ft (2,438 m) is now about 150^{o}F (66^{o}C). Therefore the inactive zone represents a residual overpressure interval.

The pressure-gradient increase at about 10,500 ft (3,200 m) occurs at a present-day subsurface temperature of approximately 200^{o}F (>93^{o}C), which, as noted earlier, is the estimated temperature necessary for the onset of significant gas generation from humic-rich source beds. An additional increase in the pressure gradient starts at a depth of about 15,000 ft (4,572 m) and continues to the total depth of the well at 19,000 ft (5,791.2 m) in the top of the Upper Cretaceous Baxter Shale. The top of the inactive zone occurs at a percent vitrinite reflectance in oil (%R_o) of about 0.75 (fig. 2-B) and the highest vitrinite value in the well is an R_o of 2.0 at about 18,000 ft (5,486 m).

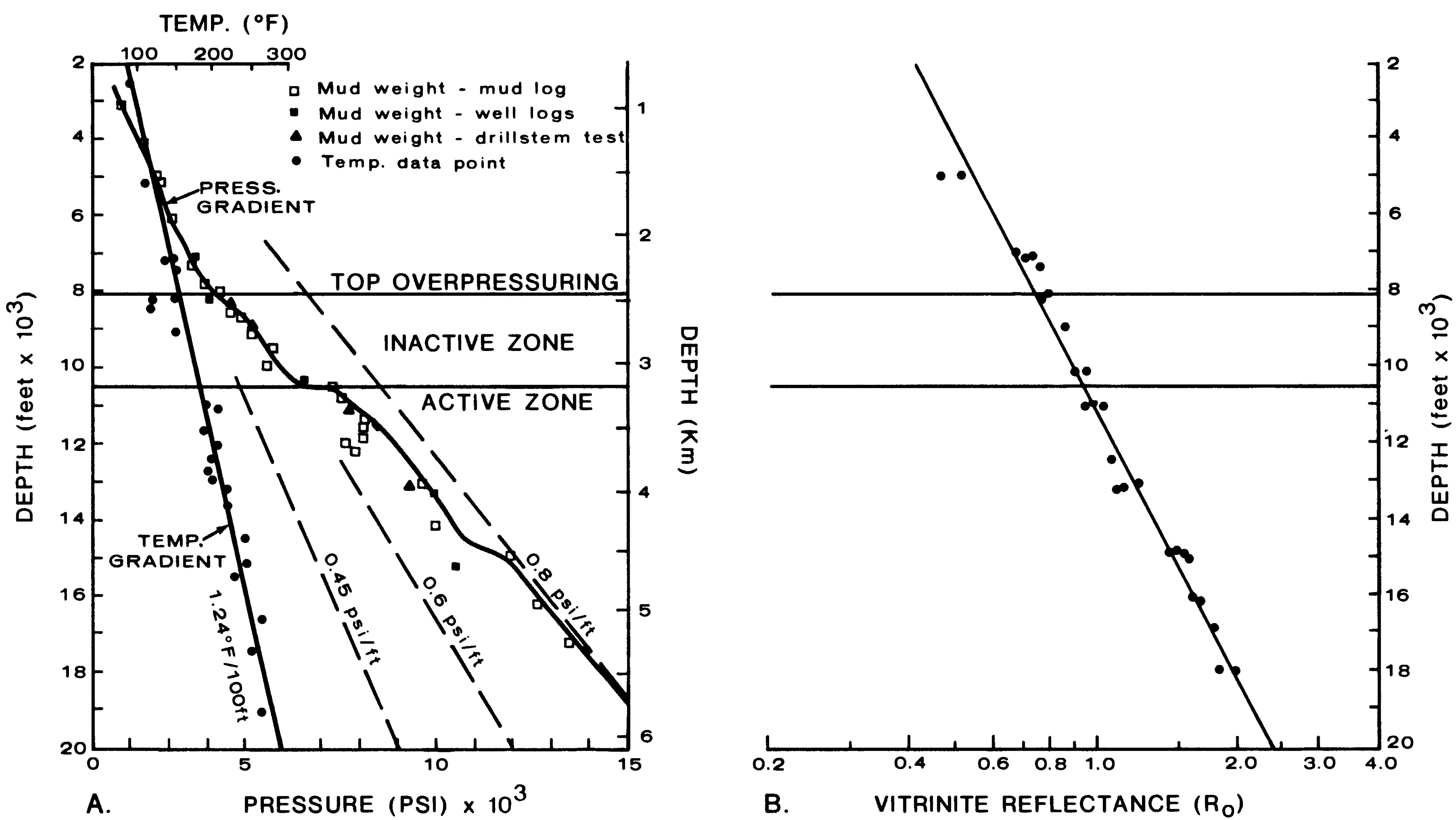

Figure 2.--Pressure, temperature, and vitrinite reflectance data for EPNG No. 1 Wagon Wheel well (Sec. 5, T. 30N., R. 108W., Sublette Co., Wyo.) The vitrinite data were obtained from core samples.

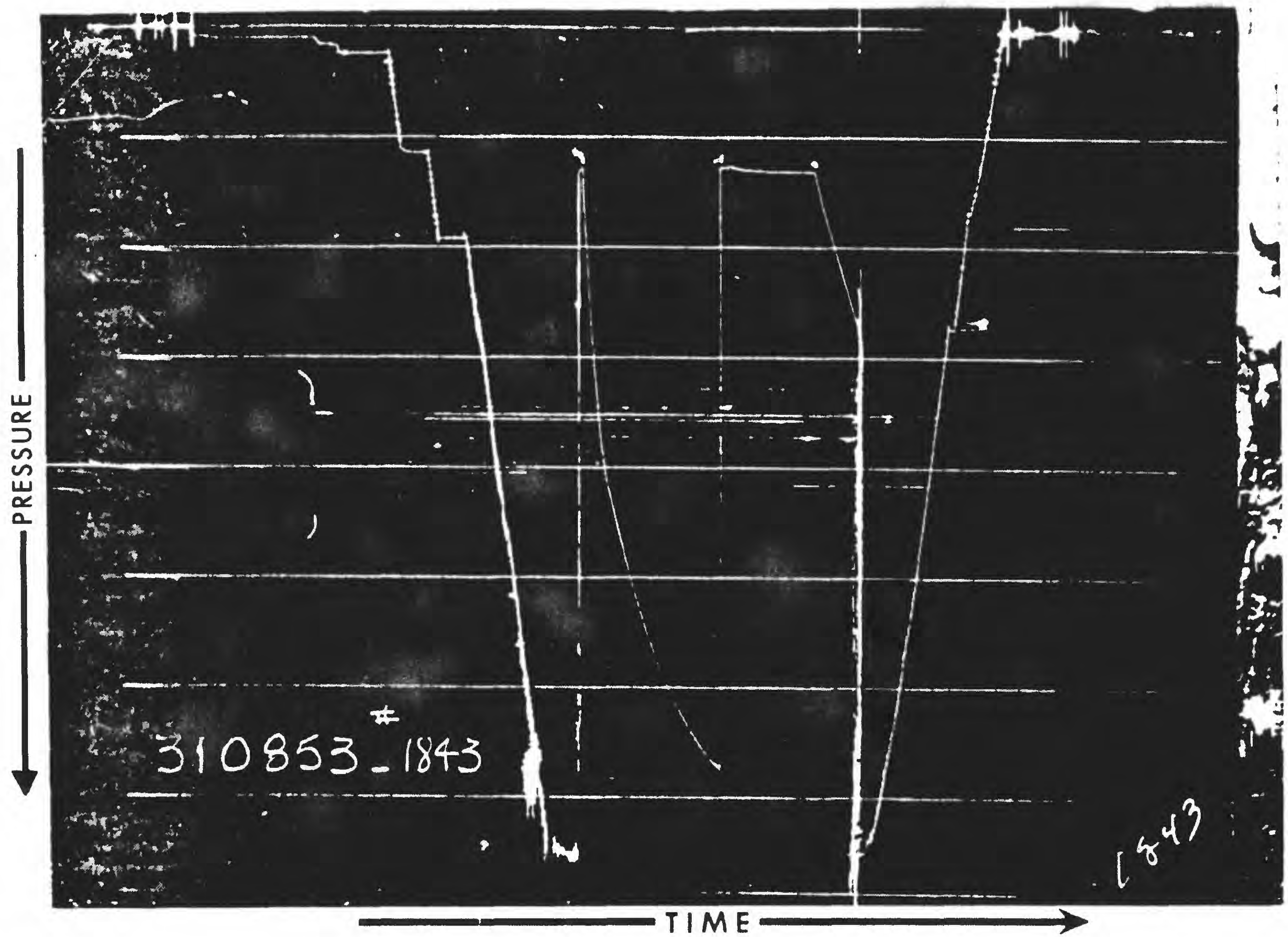

Figure 3.--Copy of DST chart from test run in Upper Cretaceous Lance Formation in EPNG No. 1 Wagon Wheel from 10,978 to 11,070 ft (3,346. 1-3374.1 m). Pressure increases from top to bottom and time increases from left to right. Initial shut-in pressure was 6805 psi (46.9 MPa). The maximum mud hydrostatic pressure was 7600 psi (52.4 MPa).

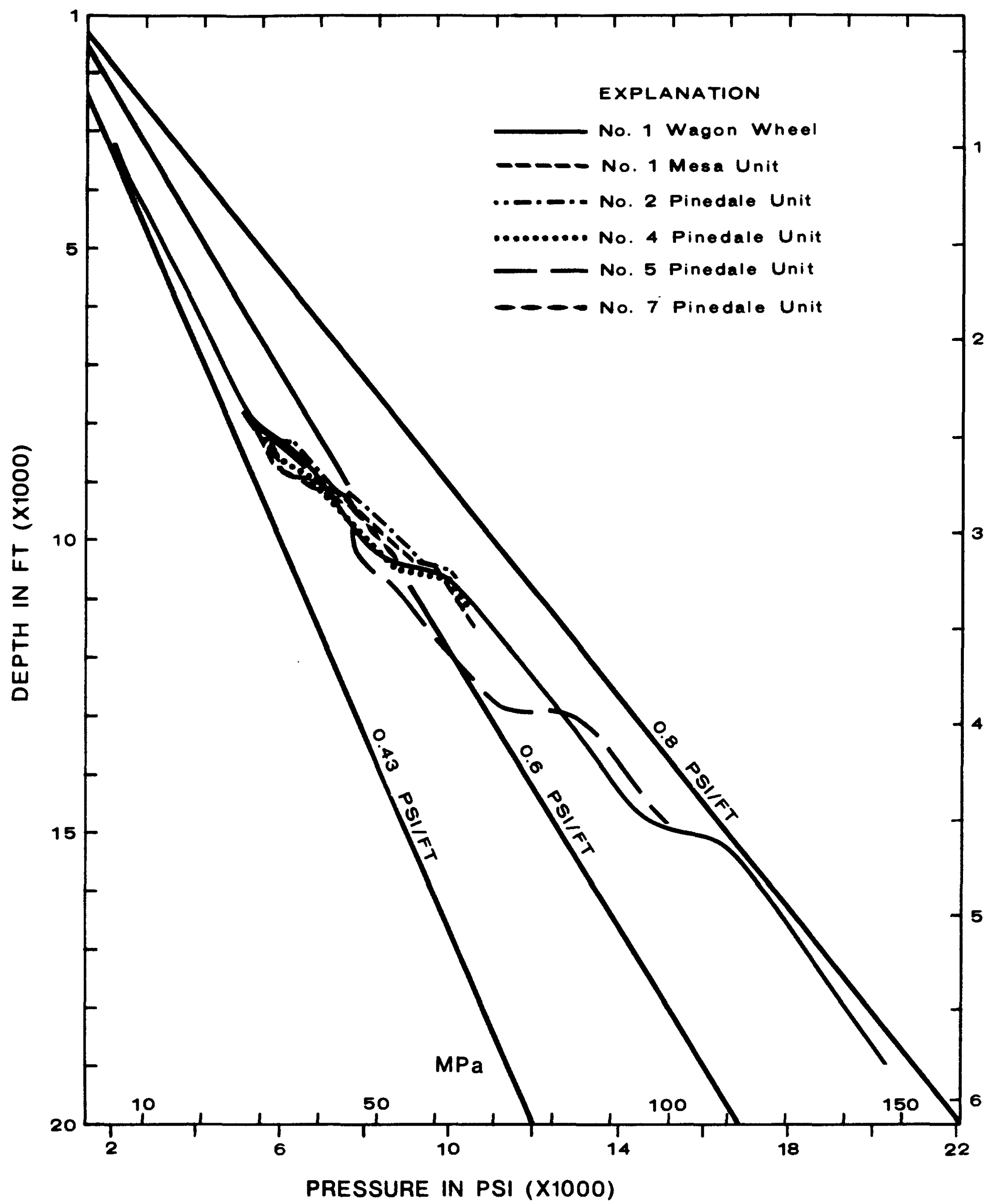

Figure 4.--Cross plot of interpreted reservoir pressures versus depth for six wells drilled on the Pinedale anticline. Data mostly compiled from drilling mud weights.

The No. 1 Wagon Wheel well was drilled as a proposed site for nuclear stimulation. Consequently, the well was drilled with considerable concern to keep reservoir pressures and mud weights in balance. For this reason, the general pressure profile (fig. 2-A) for the Pinedale anticline is shown best by this profile. This does not mean that other wells in the area may not have some differences in reservoir pressure. Figure 4 shows mud-weight profiles for most of the wells in the anticline area. For the location of the wells used in figure 4 see Law fig. 2 and table 1 (p. 3-4, this volume). This compilation shows that most of the well mud weights were adjusted to the pressure variations in a similar manner. The only significant exception appears to be the low mud weights used to drill the EPNG No. 5 Pinedale Unit well from about 9,300 ft to 13,900 ft (2,834-4,237 m). The well was drilled underbalanced to 13,060 ft (3,980.7 m) and casing was set, at which point drilling was resumed in an apparently balanced condition to total depth.

SUMMARY AND CONCLUSIONS

All the wells drilled on or near the Pinedale anticline encountered overpressured tight gas reservoirs to varying degrees. The maximum reservoir pressure encountered, based on mud weights in the No. 1 Wagon Wheel, was about 14,800 psi (102 MPa) at 19,000 ft (5,791.2 m). This is equal to a gradient of about 0.8 psi/ft (18.1 kPa/m). This pressure gradient approximates a typical fracture gradient (or pressure) needed to artificially fracture wells in most Rocky Mountain Cretaceous-age rocks. Meissner (1978) and Law and others (1979, 1980) have proposed that the hydrocarbons are generated in low-permeability sequences until the fracture gradient of the rocks is exceeded, allowing the gas to migrate out of the reservoirs thereby reducing the pressure and then the pressure bleeds down to the closure stress.

The analysis of wells in the Pinedale area confirms the concepts developed by Law and others (1980) in the Pacific Creek area (fig. 1). Using these concepts, the depth to the top of overpressuring in tight gas reservoirs is predictable. The degree of overpressuring is less predictable.

The value of this research is that (1) one can locate the main interval of gas saturation (almost all reservoirs in overpressured zones are gas saturated), (2) it is possible to predict the approximate depth at which overpressuring will occur and thereby predict at what depth intermediate casing should be set, (3) drilling engineers can anticipate the maximum pressure that might be encountered (maximum pressure equals fracture gradient), (4) high pressure provides more reservoir energy to produce hydrocarbons, and (5) reservoir pressure is a very critical factor in estimation of gas resources.

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Thermal Maturity Map, Northern Green River Basin, Wyoming

By M. R. Lickus, M. J. Pawlewicz
B. E. Law and W. W. Dickinson

INTRODUCTION

In recent years studies of thermal maturity have been increasingly utilized in basin analysis. These kinds of investigations are most often used in studies of hydrocarbon generation and migration. However, they also provide insight into the structural and burial history of a basin. There are several thermal maturity indices that are used in these studies. The most commonly used index is vitrinite reflectance (R_o).

In oil-prone source rocks there is a thermal maturation window for oil generation that ranges from 0.6 to 1.3 percent R_o (Tissot and Welte, 1978). In gas-prone source rocks the R_o for the initiation of thermogenic gas is poorly known; values from 0.55 to 0.80 have been reported (Law and others, 1979, 1980; Magoon and Claypool, 1983; Monnier and others, 1983; Law, 1984; Pitman and others, 1984). Law and others (1979, 1980) have observed that the generation of significantly large volumes of thermogenic gas begins at a vitrinite reflectance of about 0.8 percent in the Pacific Creek area of the Green River Basin. Subsequent investigations in the Greater Green River Basin by Spencer and Law (1981), Law and Spencer (1981), and Law (1984) support this observation.

As a consequence of this empirical observation and to gain a better understanding of the thermal and structural history of the Pinedale anticline area, the purposes of this study are to (1) determine the depth at which the 0.8 percent R_o occurs, and (2) provide information that may have a bearing on the understanding of the thermal and structural history of the area.

METHOD

Figure 1 shows a thermal maturity map of the northern part of the Green River Basin which is part of a thermal maturity map of the Greater Green River Basin by Pawlewicz and others (in preparation). In the northern part of the Green River Basin, samples were obtained from 27 wells, where the number of samples per well varied from 1 to 45. Coal samples were preferentially collected for analysis in order to expedite sample preparation and to minimize the possibility of including recycled organic matter in the analysis. Where only drill cuttings of shale and sandstone were available, they were processed by an acid maceration technique (King and others, 1963; Saxby, 1970). Samples were collected by B. E. Law, W. W. Dickinson, M. R. Lickus, and M. J. Pawlewicz and were analyzed by M. J. Pawlewicz and N. H. Bostick of the U.S. Geological Survey, Denver, Colorado, and by Robertson Research (U.S.) Inc., Houston, Texas.

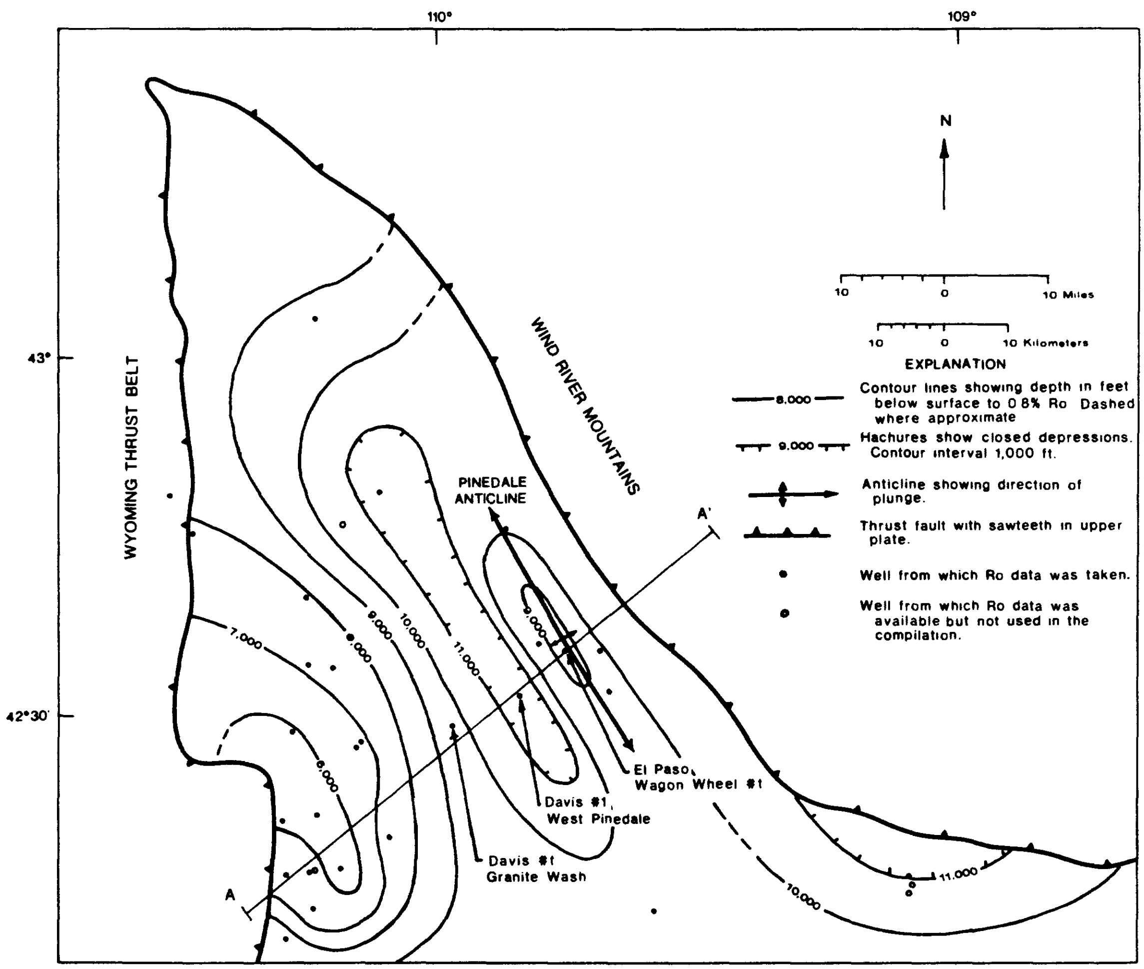

Figure 1.--Map of northwestern Greater Green River Basin showing location of the Pinedale anticline, cross section A-A′ (fig. 2), the wells along the cross section (fig. 2) and the contours representing depth, in feet, to the 0.8 percent R_o level.

Samples for the reflected light analyses were prepared by taking the concentrated organics from the maceration technique and the coal samples and casting them in epoxy resin on frosted petrographic slides. These were leveled and subsequently ground and polished using fine sandpaper and succesively finer polishing abrasives. The reflectance was done, under oil immersion, using a Zeiss universal microscope.

Samples processed from cores present few problems but cuttings samples can contain contaminants from uphole sloughing and from lignite drilling mud additive, if used. This necessitates that the operator alter the method of scanning the sample and be selective of the organics from which R_o readings are taken. For core samples, the lowest reflecting organic material is read indiscriminantly. However, with cuttings samples the operator must choose the most common material or the modal population; sometimes between several populations or ranges of Ro values. The mean reflectance value was used as an estimate of the indigenous vitrinite population. When the mean value did not accurately represent the vitrinite population, such as when the R_o readings were few and wide ranging, a pick was determined by the operator. The pick was based on consideration of the polish of the slide and the quality of the organic matter. In almost all of the samples the mean reflectance and pick are the same or nearly the same value.

Construction of the thermal maturity map required the determination of a regional vitrinite reflectance gradient. R_o data from wells within the area were plotted on a graph of depth versus vitrinite reflectance. Depth was plotted on a linear scale and vitrinite reflectance was plotted on a logarithmic scale (Dow, 1977). A best-fit line was drawn using a linear regression calculation, and the slope of this line was used as the reflectance gradient, which in the northern part of the Green River Basin is 0.0898 percent R_o/1000 ft. For wells having less than five samples this regional gradient was then used to determine the depth at which the 0.80 percent R_o occurs. For wells having more than five samples distributed over a significantly thick stratigraphic interval, an R_o gradient was constructed using data within the interval of interest. The contouring was initially done with a computer contouring program and subsequently modified by hand in areas where the data points were widely spaced.

DISCUSSION

The thermal maturity map (fig. 1) shows the depth at which the 0.80 percent R_o occurs. The selection of the 0.80 percent R_o was based on the observations in the Greater Green River Basin by Law and others (1979, 1980), Law and Spencer (1981), and Law (1984) that significantly large volumes of gas begin to occur at depths corresponding to vitrinite reflectance values in the range of 0.74 to 0.86 percent. The occurrence of the top of sustained gas shows is also commonly associated with the top of overpressuring and an uncorrected subsurface temperature of about 180°F (82°C). Cross section A-A' (fig. 2) shows the 0.80 isoreflectance line and the top of overpressuring. The depth to 180°F (82°C) has been previously mapped by Law and Smith (1983).

In the vicinity of the Pinedale anticline the top of overpressuring occurs within the upper part of the Lance Formation at an R_o of about 0.74 percent. On the La Barge platform, the top of overpressuring is not well known but apparently occurs within the lower part of the Hilliard Shale at an R_o greater than 0.80 percent. The relationships between thermal maturity and overpressuring in the Wagon Wheel no. 1 well have been discussed by Law (1984).

The configuration of the thermal maturity contours (fig. 1) in the vicinity of the Pinedale anticline is similar to the structural configuration shown by Law (fig. 2, pg. 8, this volume). Cross section A-A' (fig. 2) shows the relationship more clearly. The stratigraphically highest position of the 0.80 percent isoreflectance line, along the cross section, occurs on the Pinedale anticline. Along the northeastern part of the cross section, the 0.80 percent isoreflectance line is parallel to structure. In the La Barge platform area, along the southwestern part of the cross section, reflectance and structure are discordant. Assuming that the thermal gradients along the line of section have been nearly the same through time, these structural and thermal maturity relationships indicate that the Pinedale and La Barge areas have had different structural and burial histories. With respect to cross section A-A′ it appears that (1) maximum burial depths occurred in the Pinedale anticline area, (2) structural deformation in the Pinedale anticline area occurred after the development of the presently observed levels of thermal maturity, (3) structural deformation in the La Barge platform area occurred during the development of the presently observed levels of thermal maturity, and (4) structural deformation in the La Barge platform is older than that in the Pinedale anticline.

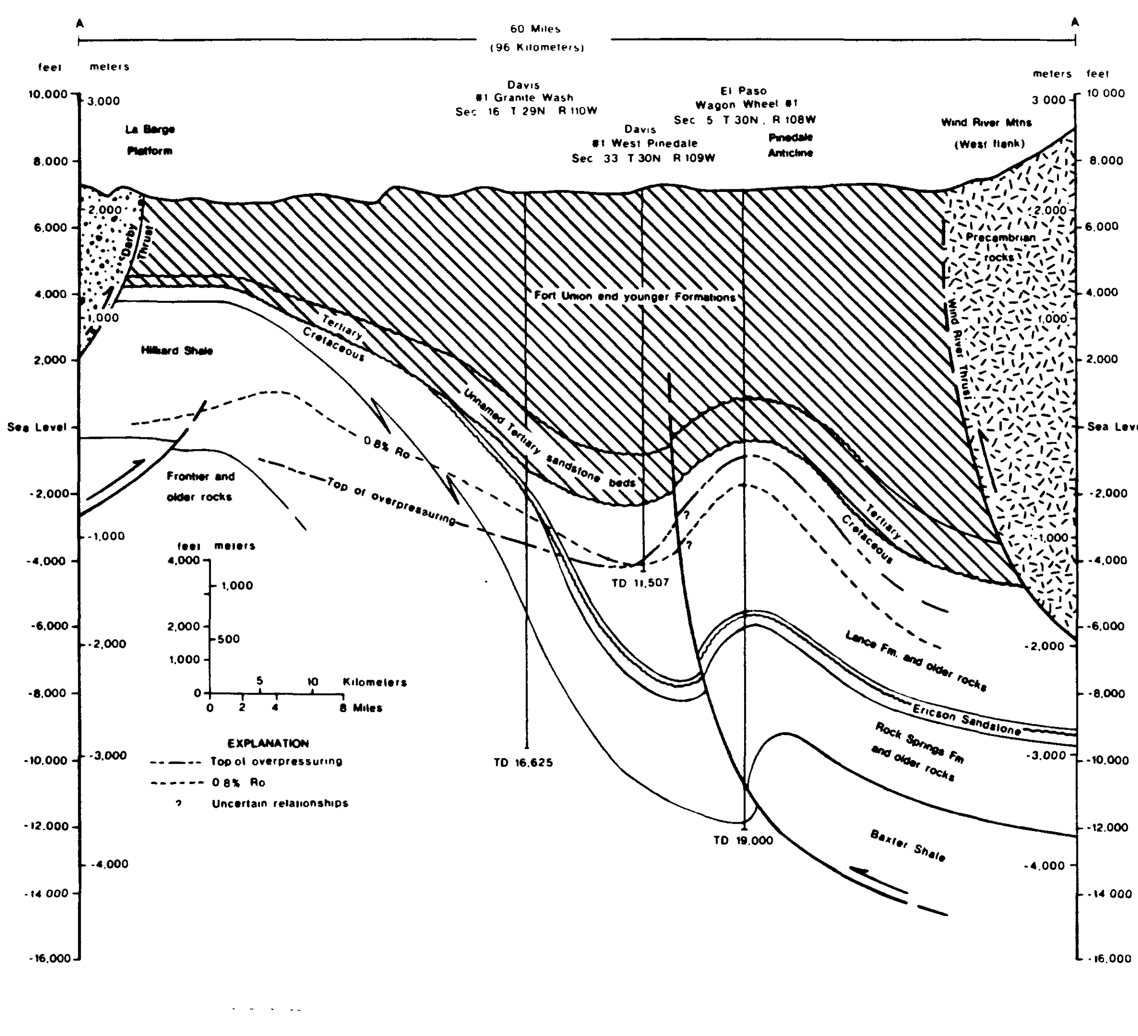

Figure 2.--Structural cross section A-A′ (see fig. 1) showing relationships between structure, top of overpressuring and 0.8 percent R_o line.

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Fission-Track Ages from the Wagon Wheel No. 1 Well, Northern Green River Basin, Wyoming: Evidence For Recent Cooling

By Nancy D. Naeser

INTRODUCTION

Fission tracks are the zones of intense damage formed when fission fragments pass through a solid. Several naturally occurring isotopes undergo spontaneous fission, but only ^{238}U, which is present in trace amounts in many minerals and glasses, has a fission half-life that is sufficiently short to produce a significant number of tracks over geologic time. Because the spontaneous fission of ^{238}U, takes place at a constant rate, the age of a mineral or glass can be calculated by determining its spontaneous track density and the amount of uranium which it contains. Details of the fission-track method are given in Naeser (1976; 1979a).

Once fission tracks are formed, they are stable in most common minerals at temperatures below about 80°C. However, if a mineral containing spontaneous fission tracks is heated at high enough temperature, the tracks fade and disappear, resulting in an anomalously young fission-track age. The temperature at which this "annealing" occurs depends on (1) the mineral involved--different minerals anneal at different temperatures, and (2) the duration of heating--the longer a mineral is heated, the lower the temperature that is required to totally anneal its tracks. Annealing temperatures have been determined for many minerals by short-term laboratory experiments. However, temperature-time relationships more directly applicable to heating durations of geologic interest have been obtained empirically by determining the temperature at which minerals are totally annealed (i.e., yield a zero age) in deep drill holes in several areas where the approximate duration of heating is known. The most complete drill-hole data available are for apatite (fig. 1). They indicate that total annealing of tracks in apatite occurs at temperatures that range from ca. 150°C (for 10^5 yr heating duration) to ca. 105°C (10^8 yr). The annealing temperatures of zircon are not as well known, but limited drill-hole data suggest that it is totally annealed at temperatures of 200°C ± 25°C over periods of 10^5 to 10^8 yr.

Fission-track annealing offers a powerful tool for studies of thermal, tectonic, and burial history, in both basement and sedimentary rocks. Application to sedimentary rocks poses special problems because they can be composed of detrital grains of widely divergent ages, which are equal to, or more commonly greater than, the stratigraphic age of the rock. The theoretical basis for the application of fission-track dating to sedimentary basins and the expected distribution of fission-track ages with depth in sediments were first described by Naeser (1979b). For a sedimentary sequence in which burial temperatures are maximum, the expected distribution of apatite ages is as follows. Ages obtained on apatite grains from shallow samples at relatively low temperatures will not be annealed and will still reflect the age(s) of the source rock for the detrital grains ("zone of no annealing"; fig. 2). Sediments subjected to progressively higher temperatures give progressively younger apparent apatite ages ("zone of partial annealing").

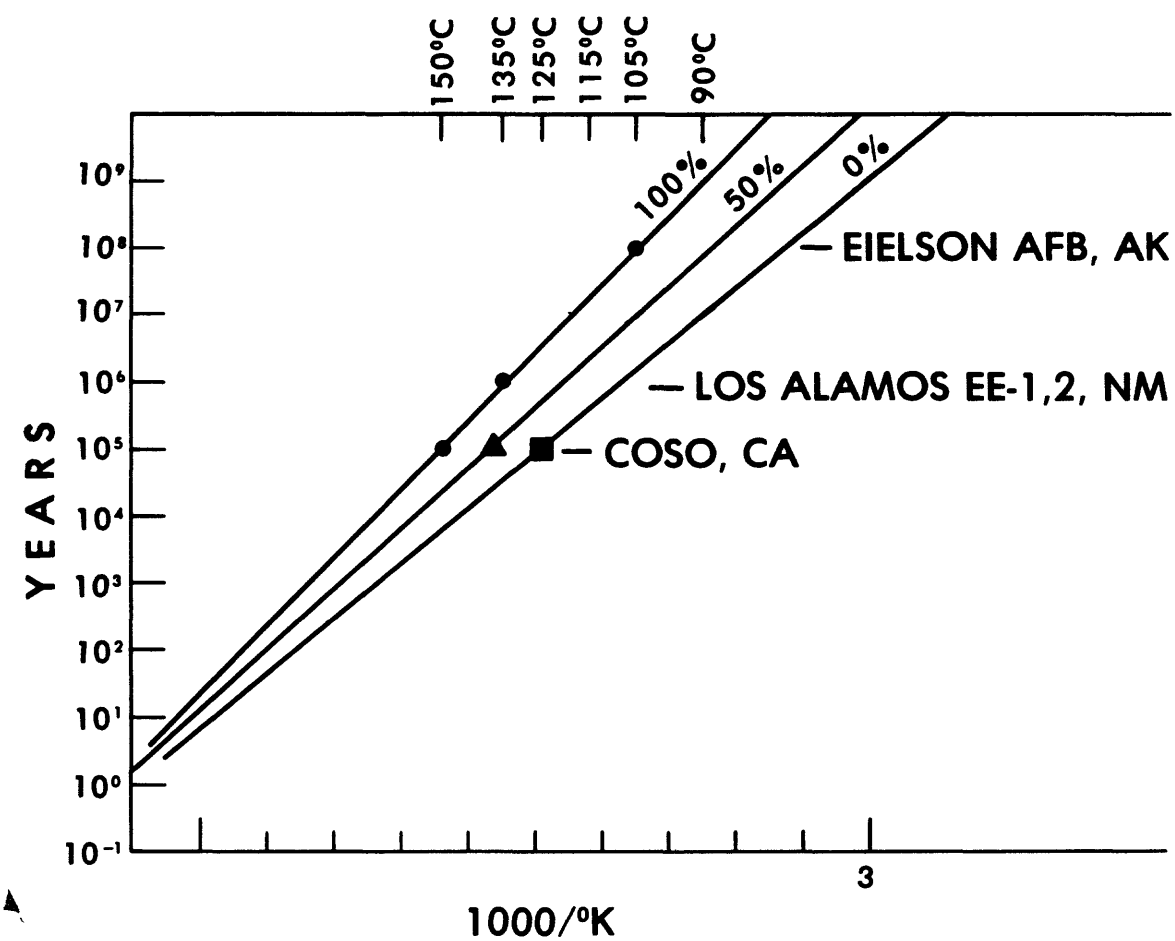

Figure 1.--Temperatures required to anneal fission tracks in apatite for heating of 10^5 to 10^8 yr duration (from Naeser, 1981). Temperatures were determined empirically from drill-hole data (see text).

Within this zone, the apparent apatite ages become younger than the stratigraphic age of the sediments, and finally decrease to zero at the depth where the temperature for total annealing is attained for sufficient exposure time (see fig. 2) ("zone of total annealing"). Naeser's data (1981; fig. 1) suggest that, for geologic rates of annealing, the zone of partial annealing (from total track retention to total track loss) is 20°C to 30°C wide.

When sediments cool from their maximum paleotemperature, apatite from the zone of total annealing once again begins to accumulate tracks and record a fission-track age (fig. 3). The recorded apatite age, the slope of the depth (or temperature) versus age plot, and the thickness of the zone of cooling ages give information on the time, rate, and amount of cooling, respectively.

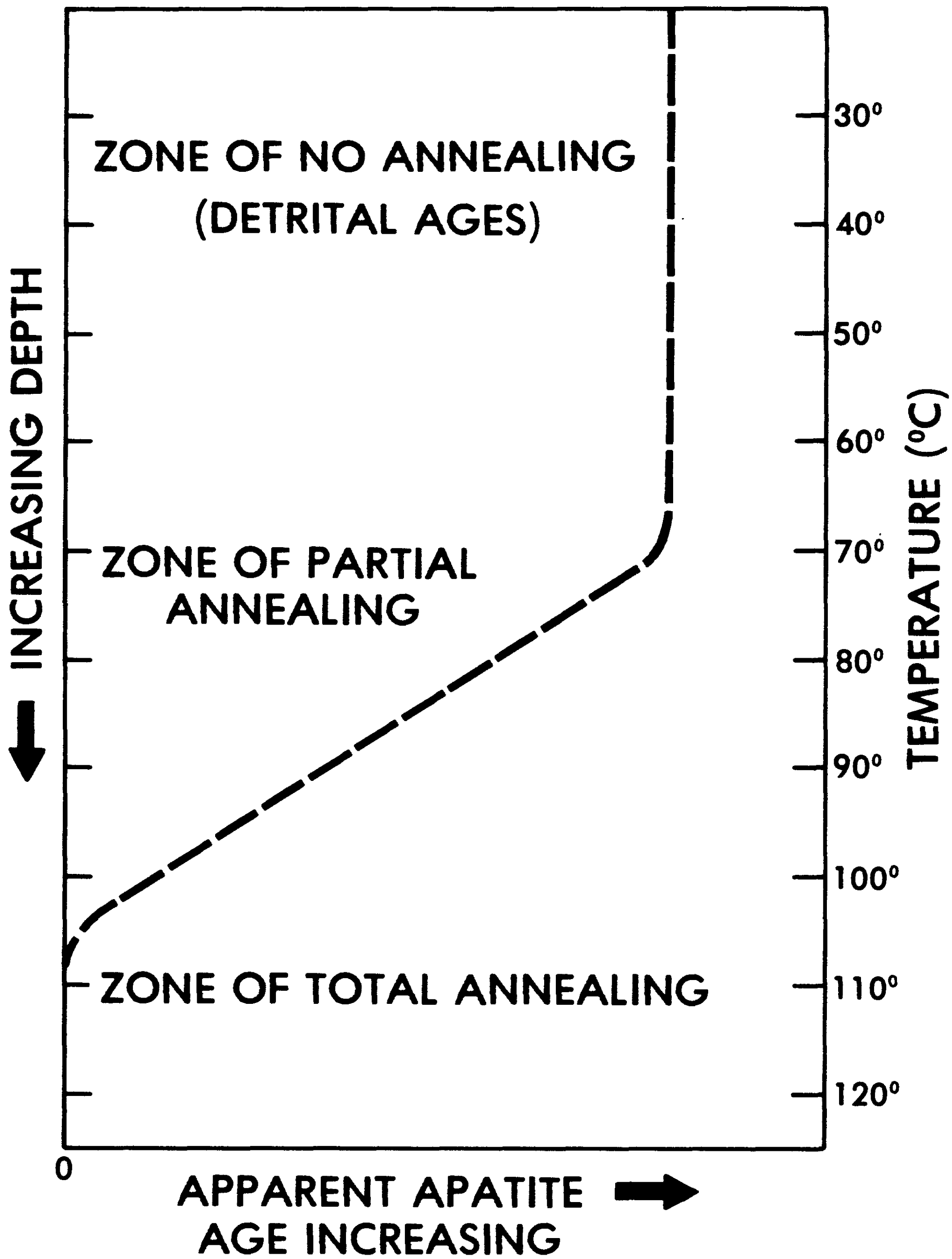

Figure 2.--Expected distribution of apparent apatite ages in sediments at the time of maximum burial heating (modified from Naeser, 1979b). The apparent age decreases to zero at the depth where the temperature for total annealing is attained for sufficient time (see fig. 1). In this example, total annealing occurs at just over 105°C, which indicates heating of 10^8 yr duration. See text for further explanation.

Zircon fission-track ages should generate similar curves, but at higher temperatures than apatite.

The fission-track method has been used to study the thermal history of the Wagon Wheel no. 1 well, in the northern Green River Basin. The geologic setting of this part of the basin and in particular the stratigraphy and structure in the area of Wagon Wheel no. 1 are discussed by Law (this volume).

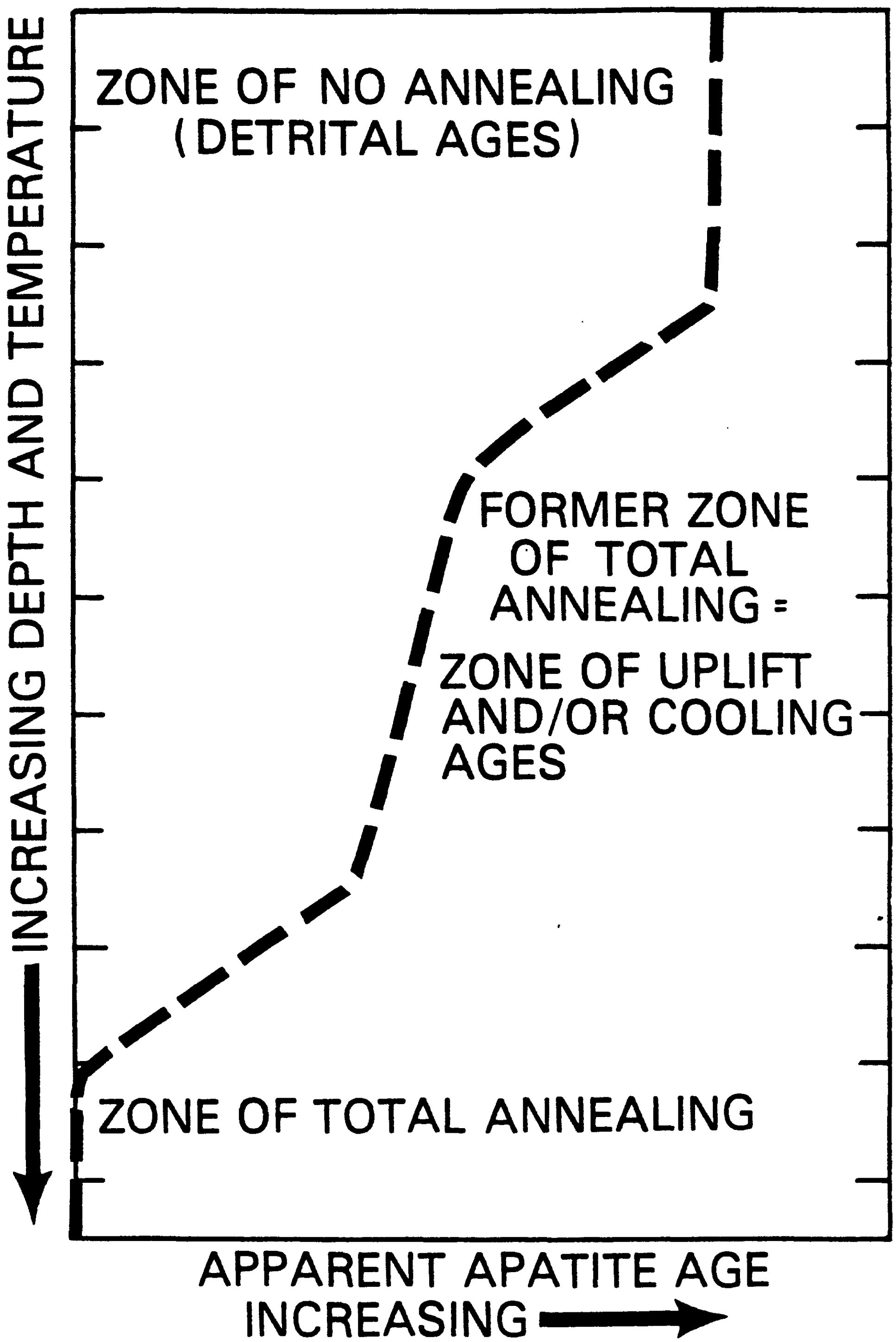

Figure 3.--Expected distribution of apparent apatite ages with depth in sediments after uplift and (or) cooling (modified from Naeser, 1979b).

METHODS

Fission-Track Dating

Apatite and (or) zircon have been separated from eleven selected lower Tertiary and Upper Cretaceous sandstone core samples recovered from Wagon Wheel no. 1 over a depth interval of approximately 1536 to 4557 m (table 1).

Table 1.--Depth, stratigraphic position, and present temperature of samples in Wagon Wheel no. 1, Green River Basin, Wyoming

[Lance Fm., the interval described as Lance Formation and older rocks in Law (this volume); Rock Springs Fm., Rock Springs Formation and older rocks]

Sample	Depth		Stratigraphic unit[1]	Present temperature (°C)	
	feet	meters (approx.)		measured	corrected[2]
WWH 1	5038	1536	Fort Union Fm.	44	50
WWH 3	7061	2152	unnamed Tertiary	59	66
WWH 5	7340	2237	unnamed Tertiary	61	68
WWH 9	8087	2465	Lance Fm.	67	74
WWH 13	10165	3098	Lance Fm.	81	90
WWH 16	11027	3361	Lance Fm.	84	96
WWH 24	11057	3370	Lance Fm.	87	96
WWH 17	13100	3993	Ericson Ss.	101	109
WWH 25	13141	4005	Ericson Ss.	102	109
WWH 26	13197	4022	Ericson Ss.	102	110
WWH 21	14950	4557	Rock Springs Fm.	114	121

[1]From Law (this volume).
[2]See text for explanation.

Apatite and zircon were separated from the samples using the heavy liquid and magnetic separation techniques outlined in Naeser and others (1984). Grains coarser than about 75 μm (200 mesh; fine sand size) can be dated by the fission-track method. Samples from Wagon Wheel no. 1 were sieved to 75 to 180 μm or 75 to 850 μm (-80+200 or -20+200 mesh) size fractions before treating with heavy liquids. This entire fraction was used when possible, but in several samples only the 75-125 μm (-115+200 mesh) size fraction yielded a sufficiently pure separation (i.e., greater than 50 percent apatite or zircon) for dating. In all samples, the methylene iodide light fraction required further treatment with a bromoform-methylene iodide mix (sp. gr.=3.037) to improve the segregation of apatite from contaminating grains. Most samples required a further step of hand picking to isolate the apatite. The amount of core available for processing varied from 64 to 195 g.

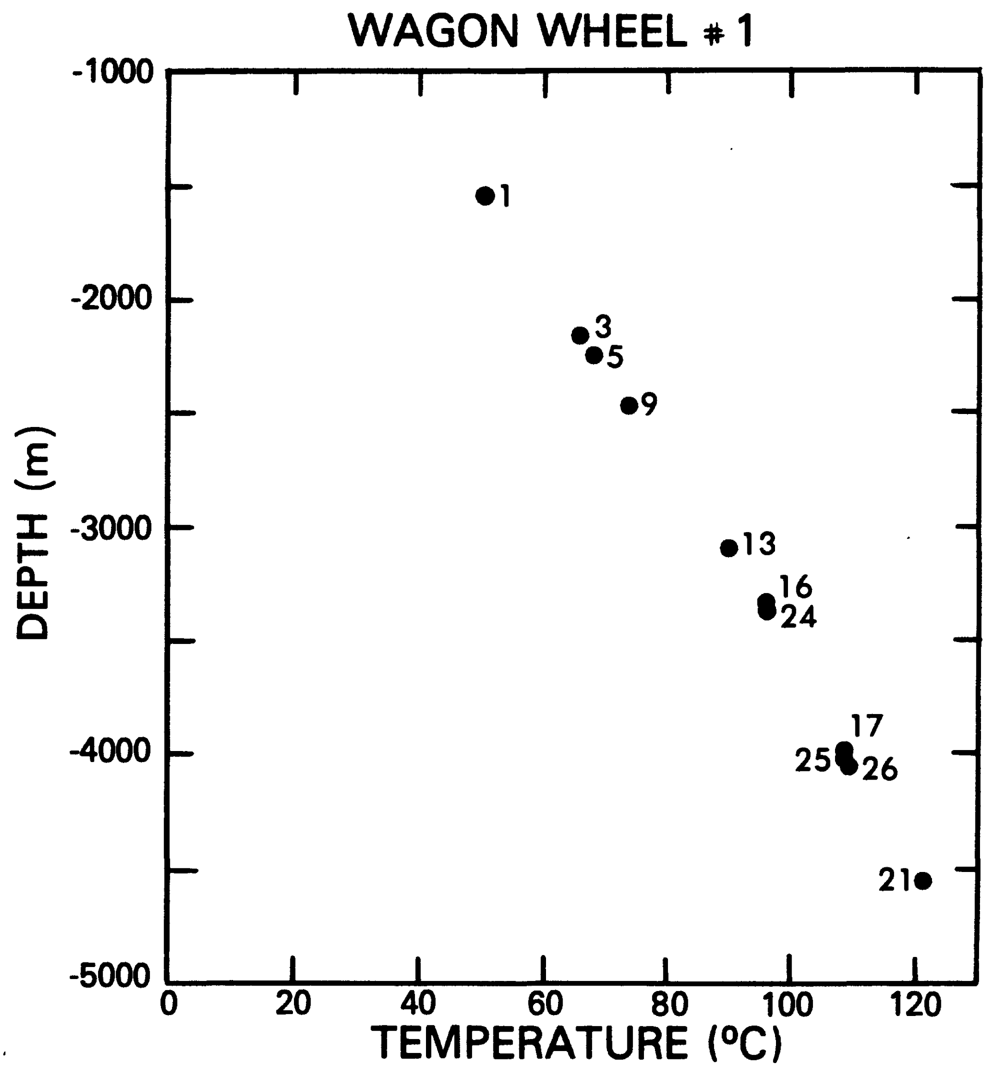

Figure 4.--Depth plotted against present temperature (corrected) of the samples from Wagon Wheel no. 1. Sample numbers correspond to numbers in table 1.

Both apatite and zircon were dated by the external detector method (Naeser, 1976), using a low uranium muscovite as the detector. The fission-track ages quoted for apatite and zircon from the Wagon Wheel no. 1 samples were calculated by the conventional method of using the sums of the spontaneous and induced tracks counted in the individual grains in the sample (Fleischer and others, 1965; Naeser, 1967). The uncertainty in the ages was calculated by combining the Poisson errors on the spontaneous and induced counts and the counts in the dosimeter (Lindsey and others, 1975). It should be recognized that the "ages" calculated for sediment samples are in fact a composite of the individual detrital grain ages and as such have no real meaning in a stratigraphic sense. The range in the age of individual grains counted in each sample is given in table 2.

Present Day Temperatures, Wagon Wheel No. 1 Well

Two sets of temperatures are given in table 1:
(1) "measured" temperatures interpolated from log data, and
(2) corrected temperatures that have been adjusted using the procedure outlined in McCulloh and Beyer (1979) (fig. 4).

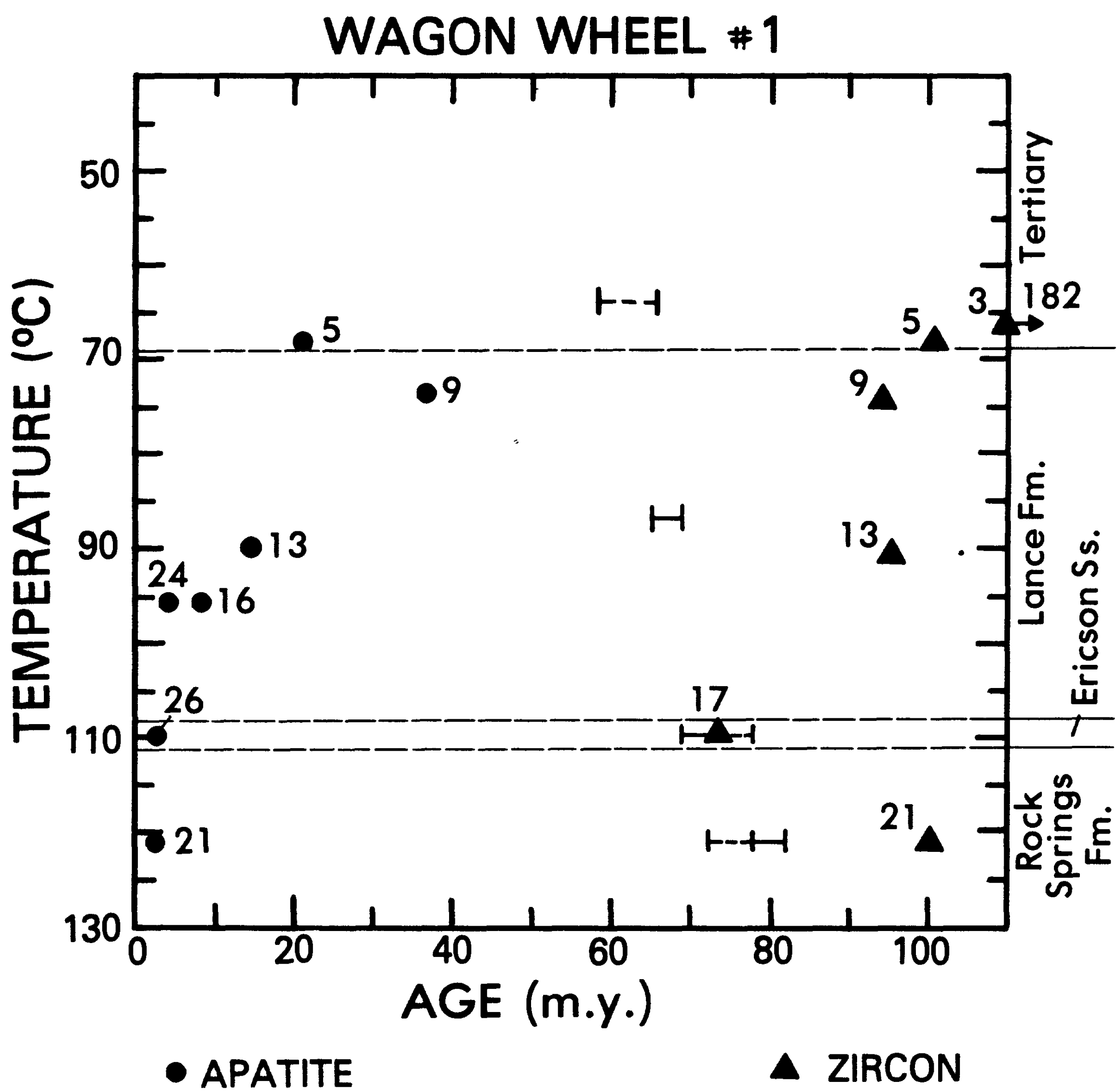

Figure 5.-Fission-track ages of detrital apatite and zircon separated from sandstones in Wagon Wheel no. 1 plotted against present temperature (corrected). Sample numbers correspond to numbers in table 1. Bars in each stratigraphic unit indicate the approximate time of deposition of the unit, as determined from K-Ar ages of Cretaceous ammonite zones (Obradovich and Cobban, 1975) and the correlations shown in Weimer (1961) and Law (fig. 5, p. 12, this volume).

In Wagon Wheel no. 1, the McCulloh and Beyer (1979) correction yields temperatures that match very closely those that would be obtained using the correction procedures of the AAPG Geothermal Survey of North America (Kehle and others, 1970; Kehle, 1972). The uncertainty associated with any individual corrected temperature is probably ca. ± $3^{o}C$ from the surface to 10,000 ft (3,048 m) and ca. ± $5^{o}C$ from 10,000 ft to T.D. (18,992 ft; 5,789 m) (T. H. McCulloh, oral commun., 1982). The corrected temperatures vary from $6^{o}C$ to $12^{o}C$ higher than the "measured" temperatures.

ZIRCON AGES

Zircon ages have been determined for six of the Wagon Wheel no. 1 samples (table 2; fig. 5). Sample WWH 16 contains insufficient zircon for an age determination, and WWH 1 cannot be dated because the zircon is metamict.

Zircon does not appear to have undergone significant annealing in any of the samples because, as discussed below, (1) only a few grains are significantly younger than the age of the sediments, and (2) through most of the Cretaceous section there is no correlation between the depth (or temperature) of the samples and the zircon ages.

The ages of the sedimentary units sampled in Wagon Wheel no. 1 are known with some confidence because the units can be correlated to ammonite zones whose ages have been determined by K-Ar dating of associated bentonite layers (Obradovich and Cobban, 1975; Weimer, 1961; Law, this volume; fig. 5). Comparison of these ages to the zircon fission-track ages (table 2; fig. 5) shows that the calculated fission-track ages of all of the Wagon Wheel no. 1 samples, as well as all but a few of the individual grain ages, are equal to or greater than the age of the unit where they were sampled.

Through most of the Upper Cretaceous section in Wagon Wheel no. 1, the calculated zircon ages are statistically indistinguishable from one another. There is some variation in the range of ages of the individual zircon grains in these samples, but there is no obvious correlation between this variation and the depth (or temperature) of the samples. A possible exception is WWH 17, from the "upper part of the Ericson Sandstone" (terminology of Law, this volume). This sample appears to contain a lower percentage of old zircons than other Cretaceous rocks in Wagon Wheel no. 1 and it yielded a significantly lower age than many of the units. This may be related at least in part to the fact that the upper Ericson Sandstone, including the interval where samples WWH 17 and WWH 25 were collected, has a distinctive composition, and has been interpreted as having a different provenance than the bulk of the Cretaceous sandstone in the Western Interior (Law, this volume; Rice and Gautier, 1983, p. 4-24; D. L. Gautier, oral commun., 1984). In the present study, the upper part of the Ericson Sandstone is also distinguished by containing little or no apatite (see below).

The upper part of the sampled Tertiary section appears to contain an older suite of detrital zircons than the Cretaceous rocks. Zircons in WWH 1 are metamict, which implies that they are of considerable age, and the calculated zircon age of WWH 3 is significantly older than the underlying samples.

Table 2.--Apatite and zircon fission-track ages from Wagon Wheel no. 1, Green River Basin, Wyoming

[ρ_s, spontaneous track density; ρ_i, induced track density. Number in parentheses = number of tracks counted.]

Sample[1]	Number of grains counted	ρ_s x10^6 t/cm^2	ρ_i[2] x10^6 t/cm^2	ϕ[3] x10^{15} n/cm^2	Range in individual grain ages[4] x10^6 yr	Apparent age[4] x10^6 yr	±2s[5] x10^6 yr
Apatite							
WWH 5	8	0.299 (94)	5.73 (902)	6.72 (2354)	9-67	20.9	4.6
WWH 9	10	0.213 (91)	2.31 (494)	6.61 (2354)	6-81	36.3	8.4
WWH 13	9	0.093 (28)	2.53 (380)	6.51 (2354)	0-35	14.3	5.6
WWH 16	6	0.047 (5)	2.23 (119)	6.40 (2354)	0-19	8.0	7.4
WWH 24	6	0.036 (8)	2.05 (230)	3.67 (2726)	0-17	3.8	2.8
WWH 26	11	0.023 (8)	2.03 (354)	3.61 (2726)	0-36	2.4	1.8
WWH 21	9	0.025 (5)	3.50 (357)	6.30 (2354)	0-10	2.6	2.4
Zircon							
WWH 3	5	22.33 (394)	7.43 (65)	1.03 (4424)	106-530	181.9	48.9
WWH 5	9	12.48 (1578)	6.53 (413)	0.889 (6340)	57-581	100.9	11.4
WWH 9	9	10.28 (1078)	6.60 (346)	1.01 (4424)	63-288	94.4	12.0
WWH 13	9	11.04 (1472)	6.92 (461)	1.01 (4424)	46-322	95.8	10.6
WWH 17	9	9.69 (931)	7.91 (380)	1.01 (4424)	44-649	73.6	9.2
WWH 21	4	13.55 (477)	10.12 (142)	1.01 (4424)	47-275	100.7	19.5

(1) Sample locality data given in table 1.

(2) Reported induced track density = 2 x measured density.

(3) Thermal neutron fluence (ϕ) determined from calibrated muscovite detector covering glass dosimeters (for zircon: NBS glass standard SRM 962: 37.38 ± 0.08 ppm U; for apatite: U.S.G.S. glass standard calibrated against NBS glass standard SRM 963: 0.823 ± 0.002 ppm U) placed at top and bottom of each irradiation tube. Fluences were calibrated against the Cu value determined at NBS (Carpenter and Reimer, 1974). The fluence for each sample was calculated by interpolation between values determined for the standards.

(4) Calculated from the fission-track age equation (Fleischer and others, 1965; Naeser, 1967), using the sums of the spontaneous and the induced track counts obtained for all grains in the sample, and the following values: λ_D = 1.551 x 10^{-10} yr^{-1}; λ_F = 7.03 x 10^{-17} yr^{-1} (Roberts and others, 1968); σ_F = 580 x 10^{-24} cm^2; I = 7.252 x 10^{-3}.

(5) Standard error (s) calculated by combining the Poisson errors on the spontaneous and induced counts and the counts in the dosimeter (Lindsey and others, 1975).

APATITE AGES

Apatite has been dated from seven of the Wagon Wheel no. 1 samples (table 2). Samples WWH 17 and WWH 25, both from the upper part of the Ericson Sandstone (see discussion above), contain insufficient apatite for an age determination.

All of the calculated apatite ages for the Wagon Wheel no. 1 samples, as well as almost all of the individual grain ages, are younger than the stratigraphic age of the sedimentary units from which they were collected, indicating that significant annealing of the apatite has occurred during burial of the sediments. If rocks containing unannealed apatite are preserved in Wagon Wheel no. 1, they evidently are present higher in the section, since even the shallowest dated sample (WWH 5; 2237 m depth) contains partially annealed apatite (cf. fig. 2).

The apatite fission-track ages in Wagon Wheel no. 1 fall into two distinct trends (fig. 5). In the upper part of the sampled interval, apatite generally decreases in age with increasing temperature and approaches a zero age at just over 96°C. At this point, the trend in ages changes abruptly and the ages remain nearly constant, between about 2 to 4 m.y., over a temperature interval of at least 20°C, down through the lowest sample dated (WWH 21).

The time-temperature relationship in annealing (fig. 1) means that the degree of annealing observed in the upper part of the drill hole (down to the almost totally annealed apatite at ca. 96°C) could have been produced either by the rocks:

(1) being near their present temperature for a long time (at least 10^8 yr; see fig. 1), or

(2) being at a higher temperature for a shorter time, before cooling to their present temperature.

The rocks in this part of the drill hole are uppermost Cretaceous (Lance Formation) and younger in age (i.e., less than ca. 70 m.y.; Obradovich and Cobban, 1975; Weimer, 1961; Law, this volume), which means it is unlikely that they have been near their present temperature for a period of time even approaching 10^8 yr. We are thus left with the second alternative. Without knowing the exact burial history of the rocks, it is difficult to determine how much cooling has occurred on the basis of the annealing data in the upper part of the drill hole alone. However, the abrupt change in the trend of ages below 96°C (analagous to the "zone of uplift and/or cooling ages" on fig. 3) gives further evidence on the nature of the cooling. It suggests that at least the latest phase of cooling was initiated only 2 to 4 m.y. ago, was relatively rapid, and has involved a decrease in temperature of at least 20°C.

Pollastro and Barker (1984) have studied the temperature history in Wagon Wheel no. 1, using several other paleotemperature indicators. They have demonstrated that mean random vitrinite reflectance measured on thin coaly seams in the rocks and illite-smectite transformation in sandstone and clay layers increase in a similar way down the drill hole from 5,000 to 18,000 ft (1524 to 5486 m), and together imply a maximum paleotemperature of ca. 190°C at 18,000 ft. By comparison, the present (corrected) temperature at this depth is 141°C (using the McCulloh and Beyer (1979) correction method).

CONCLUSIONS

Vitrinite reflectance and illite-smectite transformation measurements in Wagon Wheel no. 1 suggest that sediments in this area of the northern Green River Basin have cooled by ca. 50°C (Pollastro and Barker, 1984).

Fission-track data also support higher paleotemperatures in the past and suggest that at least the latest phase of cooling was initiated in the Pliocene (2 to 4 m.y. ago), has been relatively rapid, and has produced at least a 20°C decrease in temperature.

ACKNOWLEDGMENTS

I wish to thank T. H. McCulloh for providing the corrected temperatures for the Wagon Wheel no. 1 well.

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Geothermometry From Clay Minerals, Vitrinite Reflectance, and Fluid Inclusions - Applications to the Thermal and Burial History of Rocks Cored From the Wagon Wheel No. 1 Well, Green River Basin, Wyoming

By Richard M. Pollastro and Charles E. Barker

INTRODUCTION

A number of geochemical and mineralogical techniques have been applied to sedimentary rocks and basins to determine the burial and paleotemperature history (see Scholle and Schluger, 1979, for an excellent review and examples). For example, clay-mineral assemblages in sedimentary rocks are commonly used to determine the extent of diagenesis. Numerous studies of shales and related rocks have demonstrated specific depth-dependent mineralogical changes (see reviews by Weaver, 1979, and Hower, 1981). These changes or transformations in the clay-mineral assemblages appear to be strongly dependent on temperature. Provided that there is good documentation on the temperatures at which such clay-mineral transformations occur, these clay-mineral phases can be used as maximum recording geothermometers.

Vitrinite reflectance (mean random measurement, R_m in %) is a popular technique for assessing the level of thermal maturity of organic matter in sedimentary rocks. The thermal evolution of dispersed sedimentary organic matter (OM) and coal with increasing temperature and burial depth is commonly referred to as catagenesis (Vassoevich and others, 1974; Welte, 1974). Provided that a sufficient number of samples are analyzed, R_m allows inferences on the maximum depth of burial of sediments, their tectonic history, and the geothermal development of a particular region (Stach and others, 1982). A sequence of progressively increasing R_m values in a well results from increasing thermal maturity with depth due to a rise in temperature in response to the geothermal gradient (Dow, 1977). Price (1983) and Barker and Price (in preparation) have demonstrated that R_m has a strong correlation (r=0.96 and r=0.8, respectively) with temperature in over 75 geologic systems that are now at maximum burial temperature or where the maximum paleotemperature is known. They suggest that such a strong temperature dependence of R_m indicates that reaction duration (burial time) has little influence on kerogen thermal maturation and that vitrinite reflectance, if used carefully, may be a geothermometer that records the maximum temperature reached during the burial history of a rock.

The study of fluid inclusions in sedimentary rocks provides information about the composition of the fluid phase present during diagenetic events, the evolution of authigenic mineral growth, and the temperature and pressure conditions of diagenesis. Therefore, fluid inclusions can give information on both the peak burial conditions of a rock and on later events, such as during cooling and uplift. The use of fluid inclusions in sedimentary rocks has been reviewed by Roedder (1979, 1984), and by Crawford (1981).

The present study uses geothermometry from changes in clay-mineral phases and composition, R_m, and homogenization temperatures (T_h) from fluid inclusions to access the thermal history in gas-bearing rocks of Upper Cretaceous and lower Tertiary age of the Pinedale anticline, northern Green

River Basin, Wyoming (fig. 1). This paleotemperature data and present-day temperature records for the Wagon Wheel well in conjunction with stratigraphy, have provided significant details concerning the thermal and burial history for the Pinedale area.

METHODOLOGY

Clay-mineral Studies

The clay minerals from approximately 180 sandstone and shale samples were analyzed in this study. The samples were taken from 12 sections of core recovered from the Wagon Wheel well and over depths ranging from 5,000 to 18,000 ft (1,525 to 5,483 m) (fig. 1). The clay mineral assemblages were initially characterized through X-ray diffraction (XRD) analyses of both the whole-rock and <2 micron clay-mineral fraction. Qualitative identification of the clay minerals was aided with the scanning electron microscope (SEM).

Composition and ordering of mixed-layer illite/smectite (I/S) clay was determined on oriented, glycol-saturated specimens, prepared using the method described by Pollastro (1982), of the <0.5 micron (equivalent spherical diameter) fraction. The patterns were intepreted using the methods of Reynolds and Hower (1970). Ordering types were defined using the "Reichwiete" (R) notation, as described by Reynolds (1980), where "R" signifies the most distant layer in an interstratified sequence that affects the probability of occurrence of the final layer. Most diffractograms of natural occurring I/S clay can be categorized as falling into one of three ordering types of interstratification (Reynolds and Hower, 1970). These three types are 1) random I/S (R=0), 2) allevardite or short-range ordered I/S (R=1,2), and 3) kalkberg or long-range ordered I/S ($R \geq 3$).

Vitrinite Reflectance

Mean vitrinite reflectance (R_m in %) was measured on samples from 12 thin coaly laminae in cores distributed over a depth interval from 5,000 to 18,000 ft (1,525 to 5,483 m). Coaly material was used for vitrinite reflectance measurements in this study because, if it is available, coal tends to provide more reliable R_m data than dispersed organic matter (OM) in sedimentary rocks. OM samples from sedimentary rocks frequently contain a wide population of vitrinite which could lead to difficulties in selecting indigenous, first-cycle vitrinite and result in less reliable measurements. Coaly samples, however, usually contain a single, dominant population of vitrinite without a significant amount of recycled vitrinite. These characteristics allow for a more consistent selection of vitrinite that produces a smaller variation in reflectivity and, therefore, a smaller operator bias in determining R_m.

The coaly samples were ground to <0.25 mm mesh and then mounted and polished using the method of Baskin (1979). Reflectance was measured by B. L. Crysdale (U.S. Geological Survey, Denver) on a Zeiss Universal microscope fitted with a MPM-01 microphotometric system. The system was restricted with a pinhole diaphram to read a 3 micron spot on the sample using a 40x/0.85 n.a. lens under oil immersion at a total magnification of 400x.

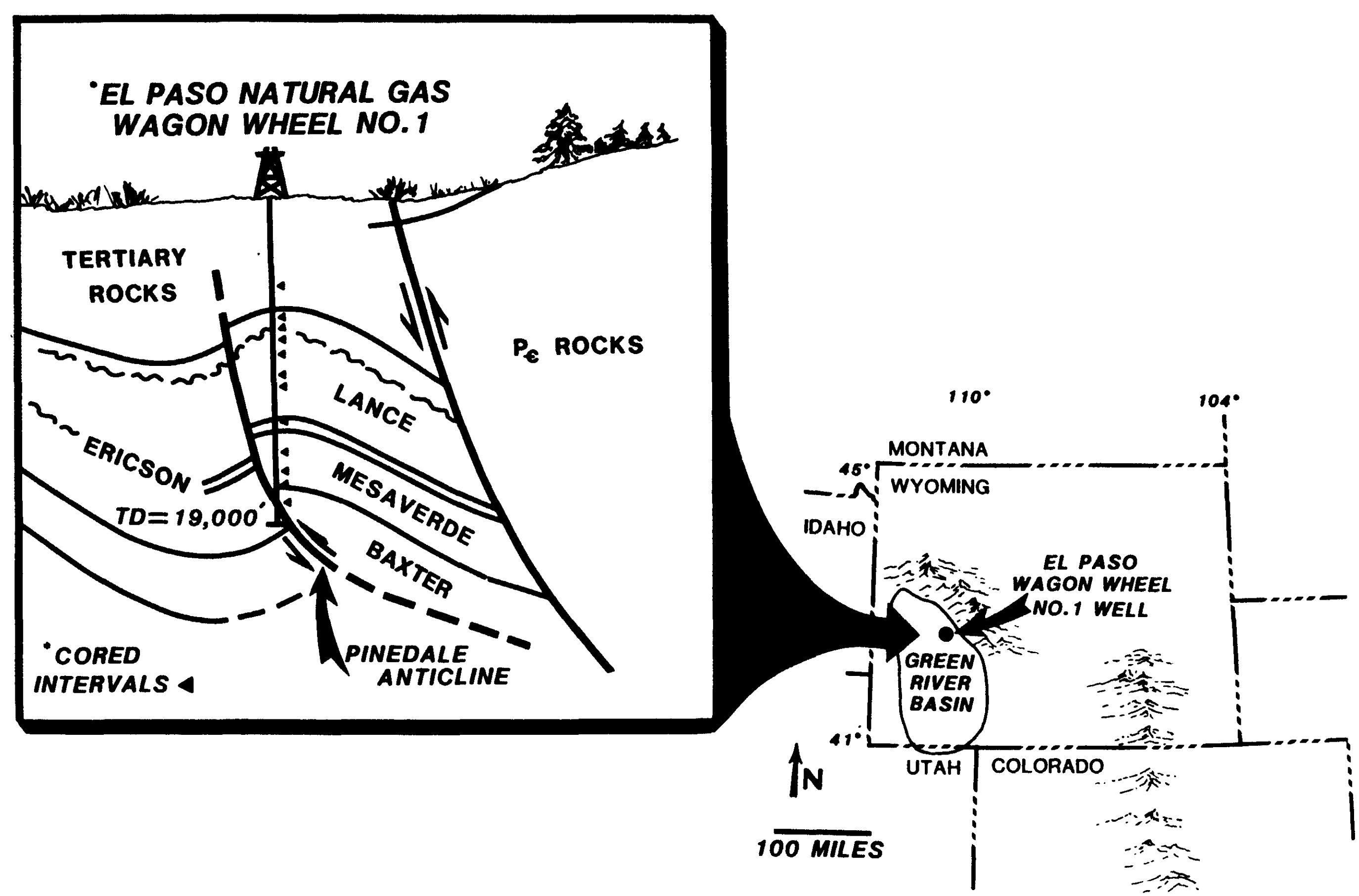

Figure 1.--Location map and generalized stratigraphic cross section of the El Paso Natural Gas, Wagon Wheel No. 1 well. Figure also shows approximate distribution of cored intervals. Stratigraphic section modified from Law (1984).

The system was calibrated using a Zeiss leucosapphire standard that has a reflectance of 0.58 precent when illuminated by filtered, 546 nm light. The standards and samples were analyzed in immersion oil having a refractive index of n_e=1.518.

A maturation gradient for the Wagon Wheel well was calulated from a logarithmic (R_m) versus linear (depth) plot. A least squares regression was run on this plot (Dow, 1977). A paleoburial temperature gradient was then calculated by converting R_m to temperature using the vitrinite reflectance models of Dow (1977), Price (1983), and Barker and Price (in preparation).

Fluid Inclusions

Fluid inclusions were present in authigenic calcite and autigenic quartz grains, occurring as fracture-fillings in the cores. Samples were prepared as doubly-polished sections using the method of Barker and Reynolds (1984). Fluid inclusion homogenization temperatures (T_h) were determined in a USGS, gas-flow, heating/cooling stage (Werre and others, 1979). The heating/cooling stage was calibrated using artificial fluid inclusions having known T_h and composition. These standards allow direct measurement of temperature gradients within the stage and necessary temperature corrections. Calibration with standards were made in the range of -57^o to 400^{o}C. The heating stage thermocouple was calibrated to a digital thermometer, using the freezing point of mercury, water, zinc, tin, and aluminum from -39^o to 660^{o}C. Repeated calibrations indicated a reproducibility in temperature measurements of $\pm 1^o$C for heating and +/-0.2^{o}C for freezing. At a gas flow of 40 standard cubic feet per hour, the horizontal temperature gradient in a 1 cm diameter circular section of the stage was about 0.2^{o}C/mm at 230^{o}C.

RESULTS AND INTERPRETATION

Clay Mineralogy

I/S clay from both sandstone and shale show a progressive increase in the amount of illite layers with increasing depth in the Wagon Wheel well (fig. 2). As the amount of illite layers in I/S increase with increasing depth in the well, I/S proceeds from a randomly interstratified phase (R=0, fig. 3A), to an ordered, allevardite-like mineral (R=1). On the glycol-saturated XRD pattern, this is recognized by the disappearance of the 17 angstrom reflection, characteristic of glycol-smectite, and the appearance of a reflection at 13-14 angstroms, indicative of the short-range ordered (allevardite-like) I/S phase (fig. 3B). This transformation occurs in the Wagon Wheel core at about 7,800 ft (2,375 m). The transformation from allevardite-like I/S to the kalkberg-like ($R \geq 3$) I/S form (>85 percent illite layers in I/S, fig. 3C), occurs at about 15,000 ft (4,570 m). The exact nature of the I/S transformation in the cores of the Wagon Wheel well has been discussed by Pollastro (1983, 1984).

Corrensite, a regularly interstratified chlorite-smectite clay mineral, coexists with I/S clay in a portion of the Wagon Wheel core (fig. 4). Corrensite is also useful as a geothermometer in sandstones. Corrensite first occurs in the Wagon Wheel core at approximately 7,200 ft (2,195 m) and persists to about 8,300 ft (2,530 m).

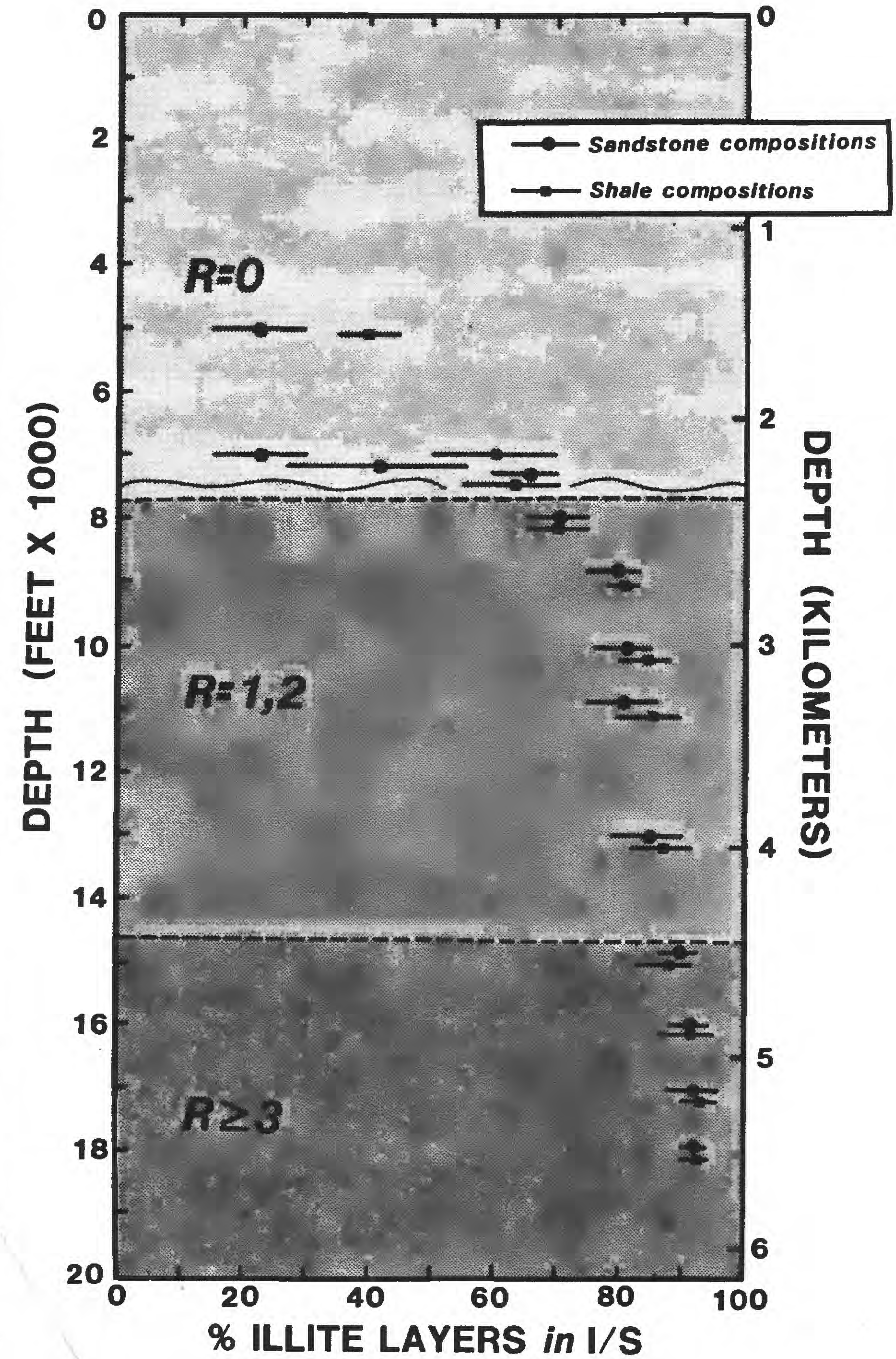

Figure 2.--Composition of mixed-layer illite-smectite (I/S) clay from <0.5 micron fraction versus present burial depth in sandstones and shales of the Wagon Wheel No. 1 well. Figure also shows depths where changes in ordering of I/S occur in the well. 180 samples are represented in the diagram. Bars indicate composition range of I/S in a group of samples analyzed; dots and squares on bars show average value for that group. R=0, random I/S; R=1,2, short-range ordering; R>3, long-range ordering.

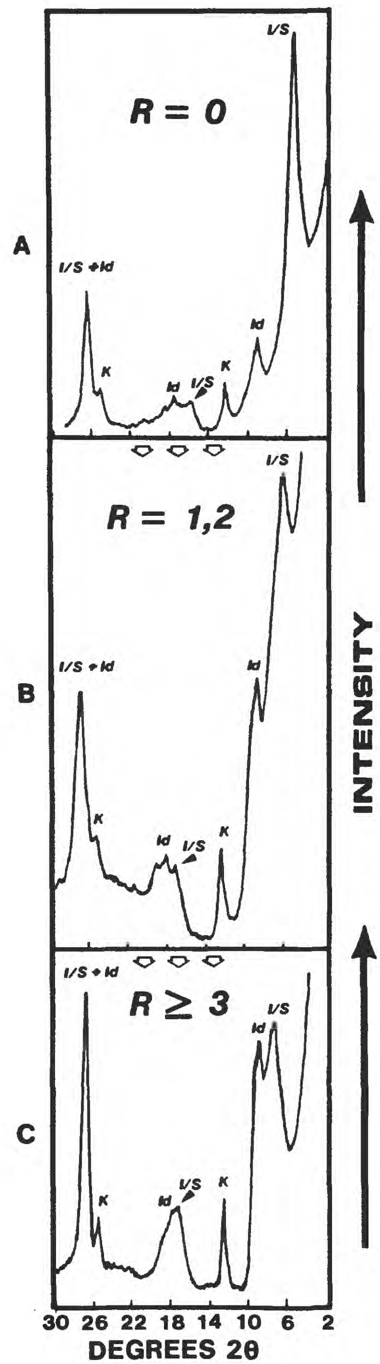

Figure 3.--X-ray diffraction patterns showing changes in ordering of mixed-layer illite-smectite (I/S) clay. Patterns produced from oriented, glycol-saturated mounts of <0.5 micron clay. A) Random I/S. B) short-range ordered I/S. C) long-range ordered I/S. Id, discrete illite; K, kaolinite; CuKα radiation.

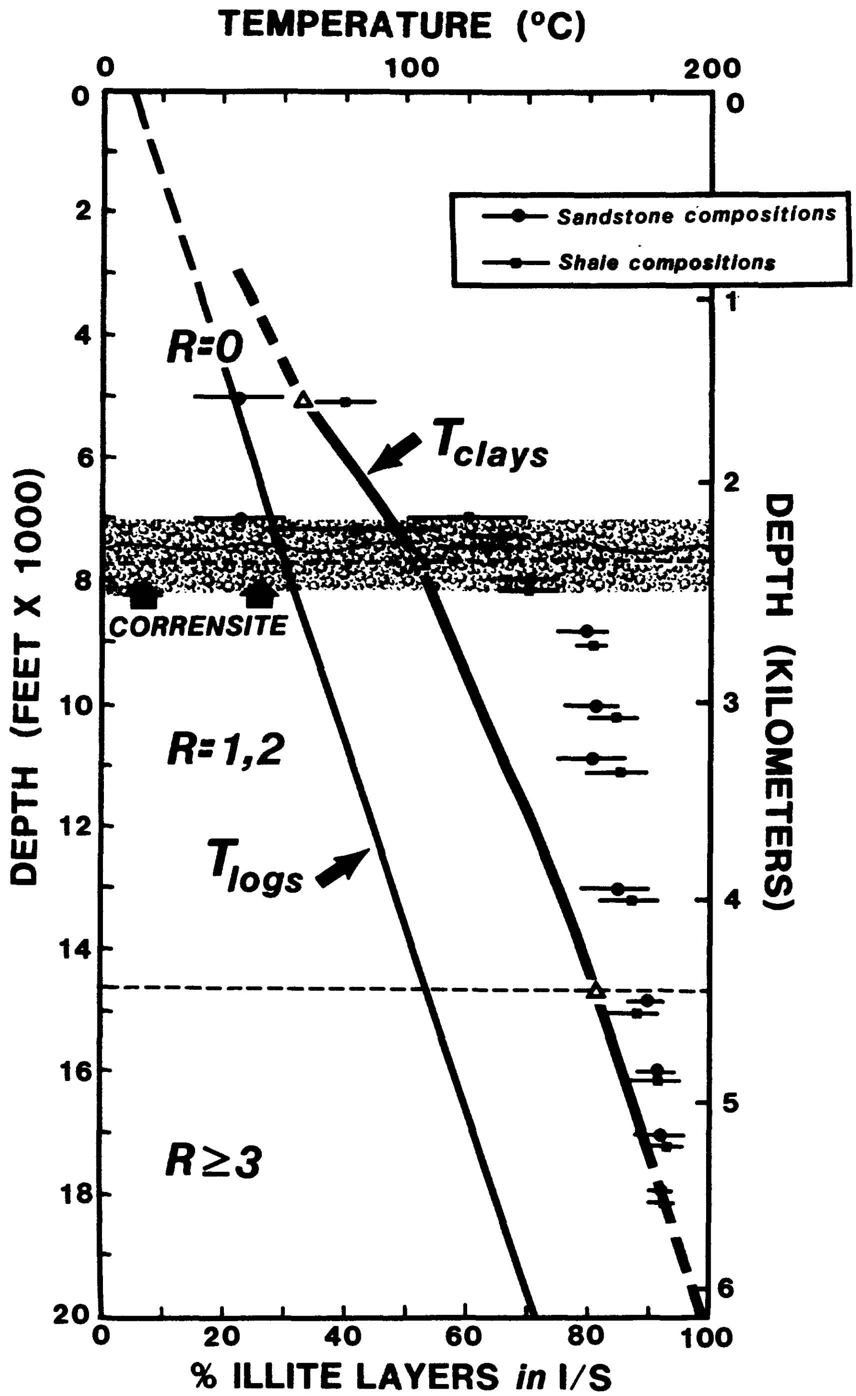

Figure 4.--Paleotemperature gradient as determined by clay-mineral geothermometers (T_{clays}) and present-day thermal gradient (T_{logs}) from uncorrected borehole temperatures. Clay-mineral geothermometry was determined from changes in ordering and composition of mixed-layer illite-smectite (I/S) clay and the appearance of corrensite in the cores. Temperatures of formation of these clay phases were taken from those established by Hoffman and Hower (1979).

Based on the first occurrence and disappearance of different ordering types of I/S clay, and corrensite, as well as the temperature estimates for stability of these mineral phases published by Hoffman and Hower (1979, figure 13 in their paper), a paleotemperature curve was calculated for the Wagon Wheel well (fig. 4). This curve is compared to the present-day geothermal gradient from uncorrected borehole measurements for the Wagon Wheel well in figure 4. The data of figure 4 suggests that these rocks were subjected to higher burial temperatures in the past, and probably on the order of 30^{o} to 50^{o}C. The slope of the paleotemperature curve established by the clay-mineral indicators is in fairly good agreement with the present-day geothermal gradient at depths below 8,000 ft (2,438 m). The disagreement in slope at shallower depths is due to the recovery depth of the first core and, therefore, the first group of samples analyzed. The onset of the I/S reaction likely begins at a shallower depth in the well, however, no core samples are available.

Vitrinite Reflectance

The coaly samples contained large monomaceralic and bimaceralic grains; structured vitrinite was rare. The quality of the polish on the specimens varied from good to poor and was attributable, in part, to variations in the amount of fine-grained, disseminated pyrite in the coals. R_m values had a range of about 0.30 percent or less, and a standard deviation of 0.10 percent. The lean organic content of the whole-rock samples (ranging from 0.09 to 4.46 percent; averaging 0.86 percent total organic carbon; W. Dickinson, U.S. Geological Survey, written commun.) and gas-prone character of the OM (type III kerogen, Law, 1984), indicates that supression of R_m due to diagenetic conditions is not a significant factor (Price and Barker, 1984). Therefore, the R_m values were not corrected to compensate for either operator bias (single operator) or suppression effects.

R_m measurements from the Wagon Wheel coals show a strong linear relationship (r^2=0.86) with depth (fig. 5). The intersection of the straight line, calculated from linear regression analysis of the data, with the present-day surface intercept in figure 6 occurs at a R_m value of 0.33 percent. Vitrinite reflectance models indicate that, in an uneroded terrain, R_m values should range from 0.20 percent (Dow, 1977; Barker and Price, in preparation) to 0.225 percent (Price, 1983). If these models are applied to the Wagon Wheel data, an R_m value of 0.33 percent would suggest that about 2,950 to 5,575 ft (900 to 1,500 m) of section has been eroded.

The R_m data was also used to calculate maximum burial temperatures for the rocks of the Wagon Wheel well. The calibration of Barker and Price (in preparation) was used to convert R_m values to maximum burial temperatures. A linear regression analysis was then run on the plot of maximum burial temperature versus depth (fig. 6). The slope of this line represents the paleogeothermal gradient at maximum temperature, and is about 25^{o}C/km (fig.6).

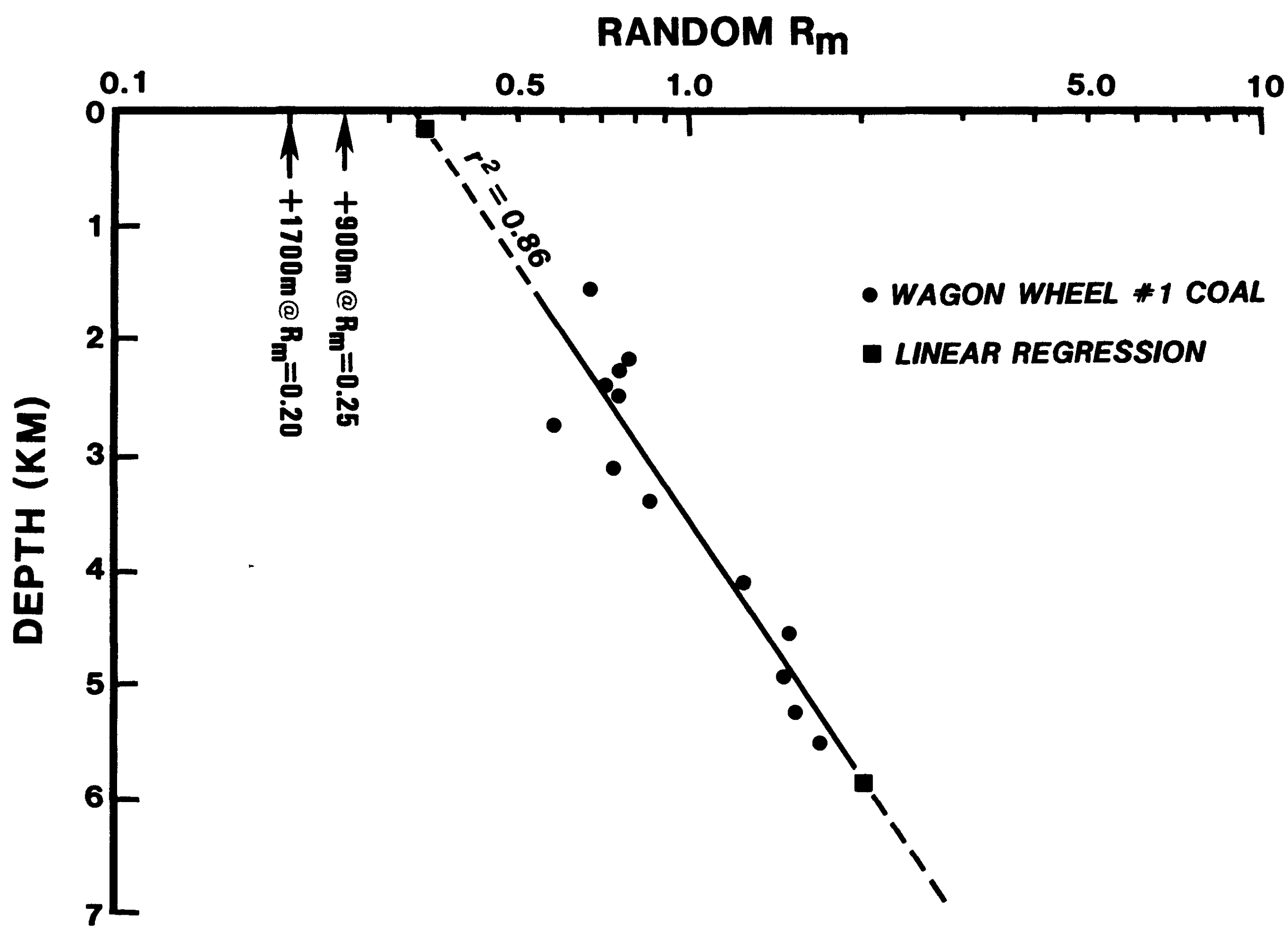

Figure 5.--Semilogarithmic plot and linear regression line for mean vitrinite reflectance (R_m) versus depth for coaly partings of the Wagon Wheel core. Intersection of regression line with surface occurs at R_m=0.33 percent. Figure shows erosion estimates from vitrinite reflectance models for surface intersections of R_m=0.20 percent and 0.25 percent.

This data indicates a maximum temperature of about 196°C at 18,000 ft (5,483m) and is in good agreement with the maximum paleotemperature curve established from clay-mineral geothermometry (fig. 4). Comparison of the maximum paleogeothermal gradient curve to the present-day geothermal gradient curve established from uncorrected borehole measurements (fig. 6) shows that the two curves plot almost parallel. This suggests that burial temperatures in the Pinedale area have been reduced by uplift and erosion, as suggested by Pollastro and Barker (1984) and Law (1984) rather than by a major decrease in the geothermal gradient.

Fluid Inclusions

Aqueous inclusions, liquid- and vapor-rich, fluorescent hydrocarbon inclusions, and methane-bearing inclusions were found in the rocks of the Wagon Wheel core. However, aqueous inclusions, found in authigenic quartz grains in the lower part of the Wagon Wheel core, were the only inclusions that provided good Th measurements. The authigenic quartz crystals occurred as fracture-fillings that coexist with calcite (fig. 7) at approximately 17,000 ft (5,181 m). These sparse aqueous inclusions were non-fluorescent, approximately 2 to 5 microns in longest dimension, and had T_h values of 130° to 150°C. Present-day, uncorrected, borehole temperature measured in Wagon Wheel at 17,000 ft (5,181 m) is about 125°C. This fluid inclusion data suggests that these fracture-fillings were formed at temperatures much lower than the paleomaximum temperatures as determined by clay-mineral indicators and R_m. The fractures, and their fracture-filling minerals, were probably formed during late uplift and erosional unloading of the Pinedale anticline.

THERMAL HISTORY AND BURIAL RECONSTRUCTION

The interpreted geothermometry of the Wagon Wheel well from the data of the present study are summarized on figure 8. From these profiles, and available information on the stratigraphy and structure of the Pinedale area, a preliminary burial reconstruction (fig. 9) was made largely based on the stratigraphy and structure from Shaughnessy and Butcher (1974), Reynolds (1976), and Law (1979, 1984) and Law (this volume). Absolute ages of the formation boundaries were taken from the K-Ar dates of Reynolds (1976). Where no absolute ages were available for this area, dates were assigned from the Geological Society of America, North American Geologic Time Scale (1983). Several unconformable boundaries were considered insignificant in relation to time and sediment contributions (Law, this volume; and B. E. Law, USGS, oral commun.). It was also assumed that no net deposition of sediment has occurred in the Pinedale area since the Eocene, approximately 37 m.y. B.P. (Schuster and Steidmann, 1983).

A study of the annealing of fission tracks in minerals from the Wagon Wheel core by Naeser (1984, this volume) has shown that a major cooling event occurred in the Pinedale area 2-4 m.y. B.P. This information was also used in our reconstruction (see fig. 9).

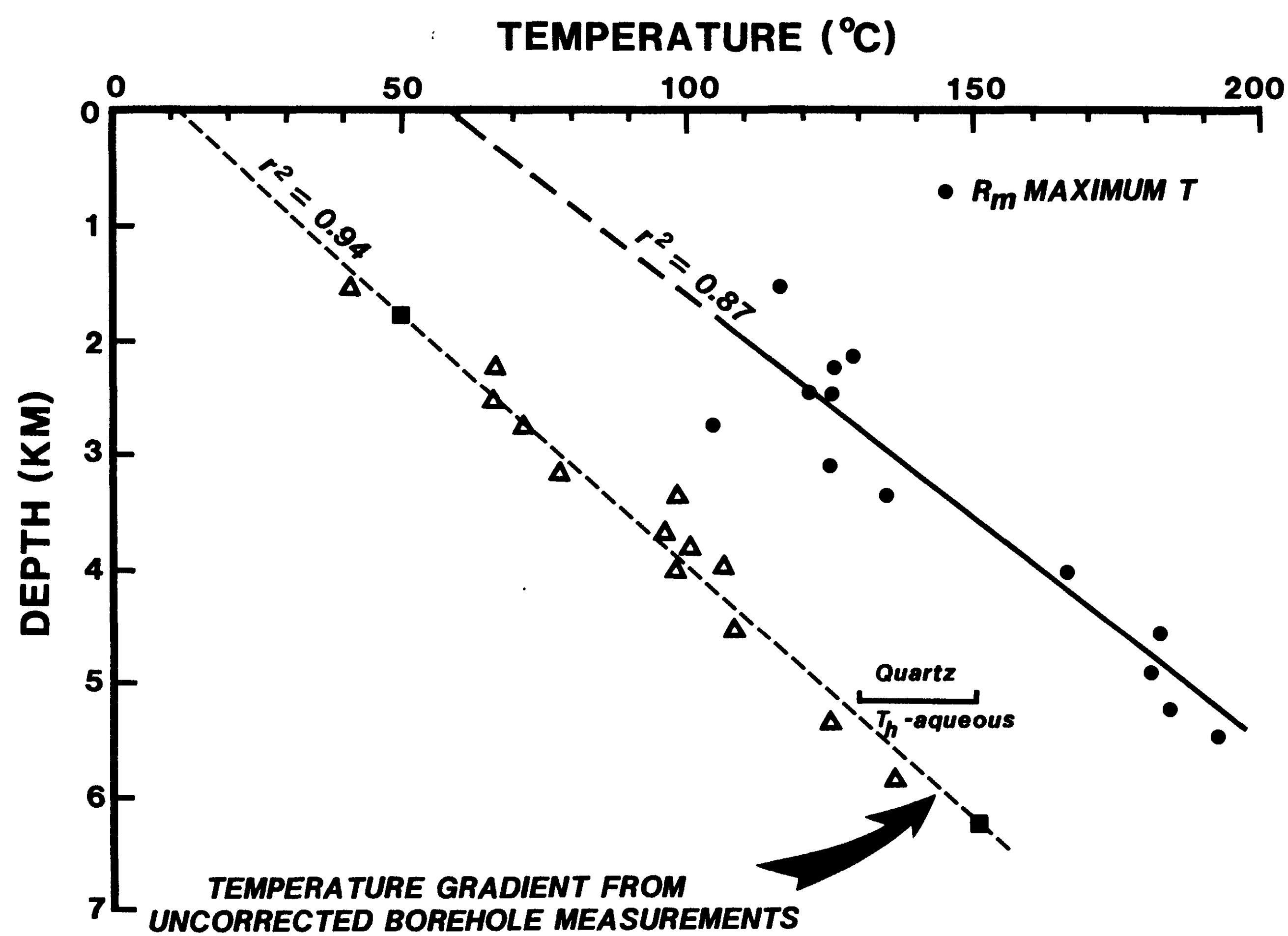

Figure 6.--Linear regression lines for maximum temperature (determined from R_m) versus depth and for present-day, uncorrected borehole temperatures versus depth in the Wagon Wheel No. 1. Conversions of R_m to maximum temperature are based on the vitrinite reflectance model of Barker and Price (1984). Range of temperature measurements from aqueous fluid inclusions in quartz (T_h aqueous) at 17,000 ft (5,181 m) also plotted on diagram.

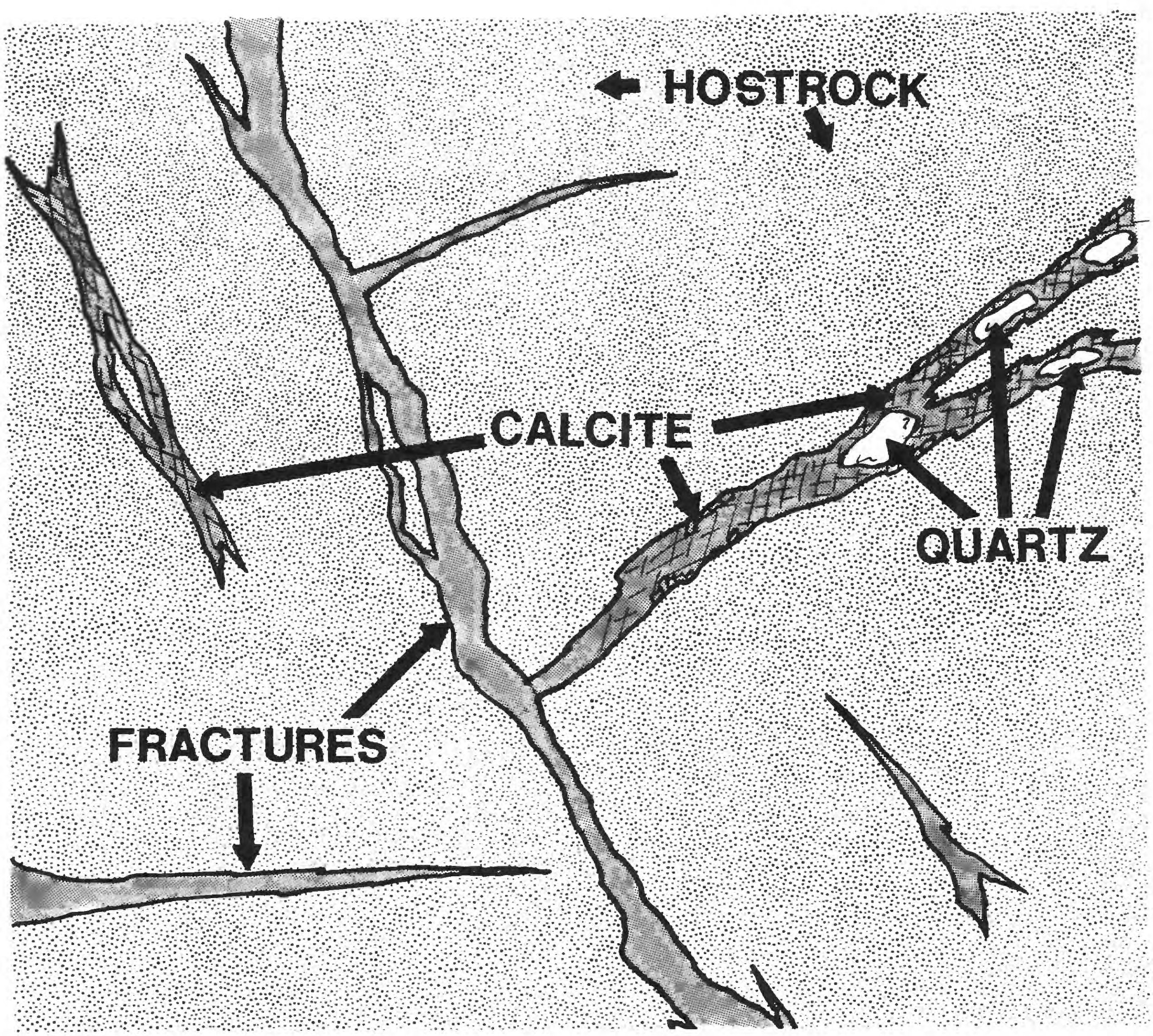

Figure 7.--Diagram showing textural relationships between fractures and calcite- and quartz-infillings in core of sandstone from Wagon Wheel No.1 at 17,000 ft (5,181).

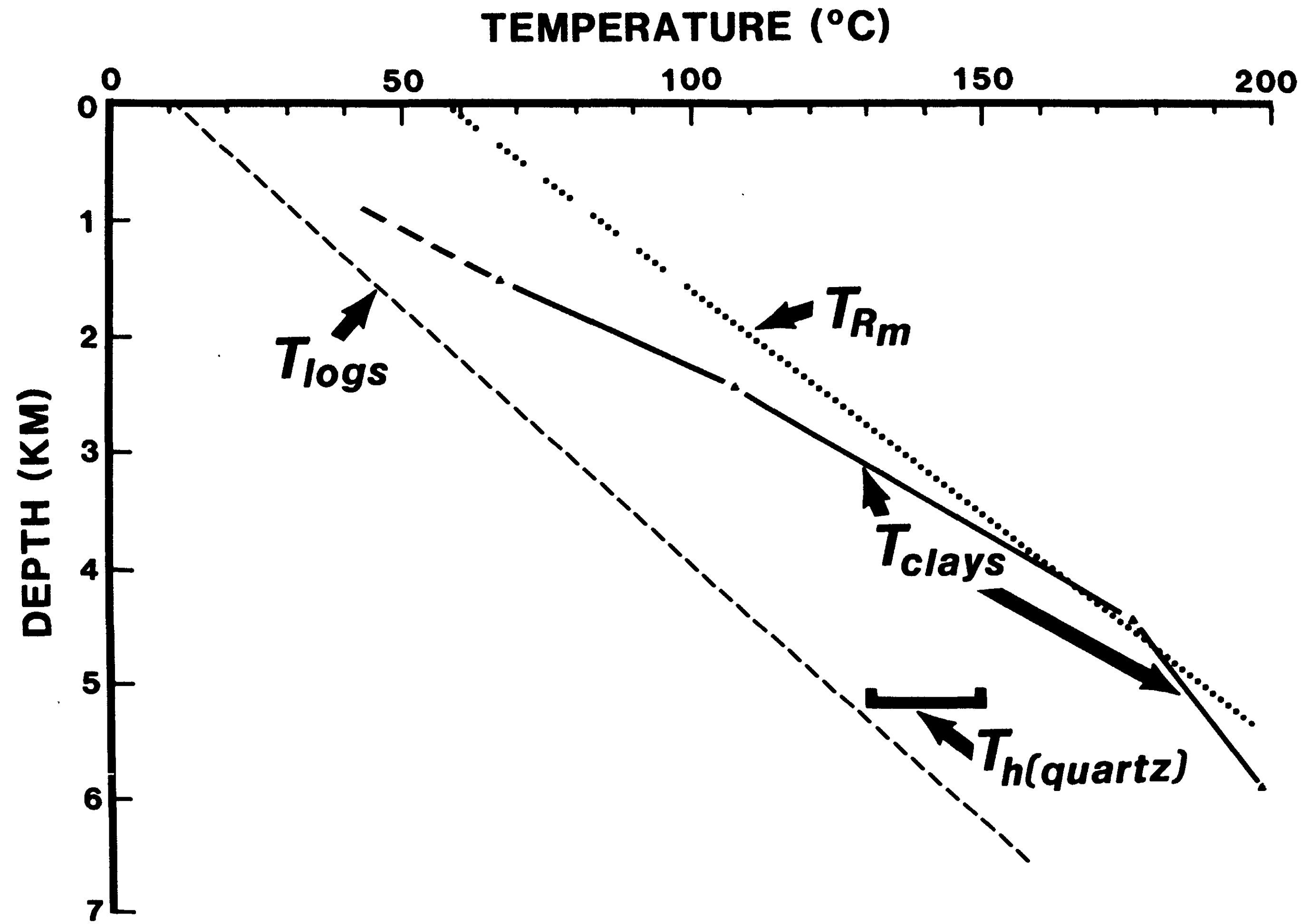

Figure 8.--Composite diagram of temperature versus depth showing profiles from present-day borehole temperatures (T_{logs}), clay-mineral (T_{clays}), and vitrinite reflectance (T_{Rm}) geothermometry. Range of homogenization temperatures ($T_{h-quartz}$) from aqueous fluid inclusions in fracture-filling quartz grains also shown.

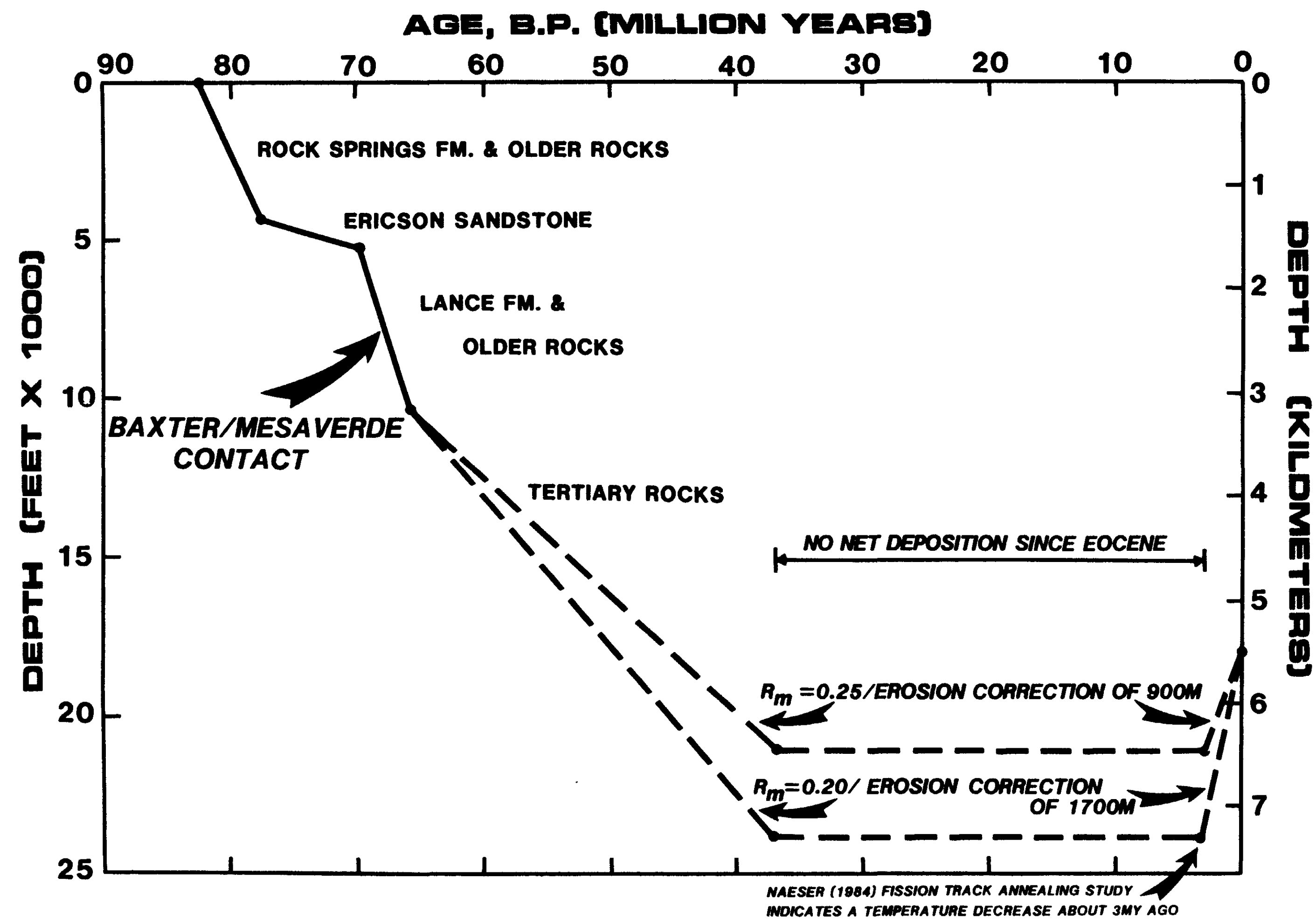

Figure 9.--Burial reconstruction profile of Pinedale anticline from paleotemperature, stratigraphic, geochronological, and structural records. Reconstruction was made on Baxter/Mesaverde contact.

SUMMARY

A multidicipline study of organic and inorganic diagenesis in the Tertiary and Cretaceous rocks of the Pinedale anticline, northern Green River Basin, Wyoming, has established the following--qualitative and compositional analyses of I/S clay from sandstones and shales from the Wagon Wheel core show a progressive increase in ordering and in the amount of illite layers with increasing depth (and temperature).

--depth/temperature curves extrapolated from both the occurrence or disappearance of diagenetic clay-mineral phases and vitrinite reflectance are in good agreement and indicate that the rocks from the Wagon Wheel well were subjected to greater temperatures (probably 30^{o} to 50^{o}C higher) sometime in the past.

--the paleogeothermal gradient for the rocks of the Wagon Wheel well is in good agreement with the present-day geothermal gradient established from borehole temperatures. The apparent temperature decrease can, therefore, be explained by uplift and erosion of the Pinedale anticline. A vitrinite reflectance profile for the well indicates that 2,950 to 5,575 ft (900 m-1,700 m) of section have been eroded.

--T_h data from aqueous fluid inclusions in authigenic quartz crystals, occurring as fracture-fillings in the Wagon Wheel core suggests that these minerals formed in equilibrium with temperatures similar to those of today.

--a major recurrent growth of the Pinedale anticline occurred after the apparent maximum burial temperatures were established. Later recurrent growth and erosional unloading probably caused fractures that were later filled by quartz and calcite in a temperature regime much like that of the present.

ACKNOWLEDGEMENTS

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Isotope Geochemistry of Carbonate Minerals in Upper Cretaceous and Tertiary Sandstones from the Pinedale Anticline, Wyoming

By Warren W. Dickinson

INTRODUCTION

Calcite and dolomite are present in various amounts throughout most of Upper Cretaceous and Tertiary gas-bearing sandstones in the Pinedale area. Because significant amounts of secondary porosity may result from the dissolution of these minerals (Schmidt and McDonald, 1979), information about carbonate may help exploitation of low-permeability gas reservoirs.

Stable isotopes of carbon and oxygen are useful in understanding the occurrence of carbonate cements. All modern evidence indicates that carbonate diagenesis takes place by dissolution and reprecipitation, which involves an intermediate transfer step by solution (Land, 1980). Because of this, stable isotopes in authigenic carbonate minerals contain a history of the fluids and temperatures of precipitation.

In general, it is not convenient to measure absolute isotopic ratios of a mineral. Instead, the δ (delta) notation is used to compare the isotopic composition of the sample to an accepted standard. For example, $\delta^{18}O$ is defined as

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}}{(^{18}O/^{16}O)_{standard}}$$

where $\delta^{18}O$ is the relative difference in parts per thousand ($^{o}/oo$) between the isotopic ratio in a sample and the ratio in a standard. In this paper, oxygen isotopic ratios for carbonates are reported in ($^{o}/oo$) relative to the PDB standard. Similarly, $^{13}C/^{12}C$ ratios are reported as $\delta^{13}C$ with PDB also as the reference standard. Standard mean ocean water (SMOW) is the reference standard conventionally used to report oxygen isotopic ratios of water.

The stable isotope of carbon (^{13}C) is most useful in identifying the source of carbon and hence the origin of carbonate minerals. In general, $\delta^{13}C$ allows distinction between light carbon (^{13}C depleted) derived from organic matter, and heavy carbon (^{13}C enriched) derived from limestones and dolomites. Organic matter (plant and animal) in sedimentary rocks has a $\delta^{13}C$ value that is usually more negative than $-20^{o}/oo$ (PDB), while marine carbonates have $\delta^{13}C$ values near $0^{o}/oo$ (PDB). The carbon in atmospheric CO_2 has a $\delta^{13}C$ value of about $-7^{o}/oo$ (PDB). The isotopic compositions of sedimentary carbonates reflect the mixing or dominance of carbon from these three sources.

Oxygen isotopes are useful in determining temperatures of precipitation if the $\delta^{18}O$ values of two minerals of interest (includes water) are known. The $\delta^{18}O$ of water can also be used to help identify the probable source of water and the extent to which it has been modified by diagenetic reactions (Longstaff, 1983). For example, mineral-water reactions will have little effect on the isotopic composition of waters that flow rapidly through a pore network. On the other hand, such reactions should cause a significant shift in the $\delta^{18}O$ of stagnant pore waters. The $\delta^{18}O$ of diagenetic minerals reflects not only temperature but also shifts in the $\delta^{18}O$ of pore water.

In the Pinedale area only near-surface waters are available for analysis, and minerals other than calcite and dolomite have not been isotopically analyzed. These facts limit the effective use of oxygen isotopes in this study. However, assuming that some portion of the carbonate minerals recrystallize with burial, shifts in the $\delta^{18}O$ of pore waters may be reflected in the $\delta^{18}O$ of the diagenetic carbonates. Such a shift is observed in $\delta^{18}O$ between carbonate cements that precipitated from the hydrologically open waters in the normally pressured sandstones and those that precipitated from the restricted waters in the low-permeability, overpressured sandstones. This chapter will discuss the implications of this shift and the occurrence of carbonate minerals in the Upper Cretaceous and Tertiary sandstones of the Pinedale area.

METHODS

A major problem in studying the stable isotopic composition of carbonates in clastic rocks is the separation of an adequate quantity of a particular phase for analysis. One way to partly avoid this problem is to correlate a large number of bulk isotopic analyses with their carbonate mineralogy, which has been petrographically determined.

Carbonate-rich sandstones were sampled from core in the Wagon Wheel and Mesa no. 1 wells (Law, this volume, fig. 1, table 1 p. 3-4) and from three outcrops near these wells. Thin sections of the samples were stained for carbonate using Dickson's (1966) method and characterized by 300 point counts. A small amount from each sample was sawed within 5 mm from the thin section and crushed for X-ray and isotopic analyses. Part of the crushed sample was reacted at 25°C with 100 percent phosphoric acid to liberate CO_2 for mass spectrometer measurement of carbon and oxygen isotopic ratios (McCrea, 1950). A double extraction technique (Epstein and others, 1964; Walters and others, 1972), which is based on solubility differences between carbonates, was used to separate the CO_2 that evolved from mixtures of calcite and dolomite.

Where possible, detrital carbonate grains were isolated by hand and isotopically analyzed. These samples provide a good check on bulk isotopic values of samples in which the carbonate consists mostly of detrital grains. Seven samples of ground water less than 200 ft deep in the Pinedale area have an average $\delta^{13}C$ = -8.6 (°/oo, PDB) and $\delta^{18}O$ = -20 (°/oo, SMOW) (Briant Kimball, USGS unpubl. data, 1984).

MINERALOGY AND STABLE ISOTOPES

In the Upper Cretaceous and Tertiary sandstones, carbonates consist of detrital limestone and dolomite grains; calcite cements, which contain various amounts of iron; and rhombic dolomite grains, which are monocrystalline detrital grains with authigenic overgrowths. Total carbonate of the study samples ranges between 3 and 45 percent and averages 18 percent, which, because of sampling bias, is higher than the surrounding rocks. Petrographic work indicates that in the Tertiary arkosic sandstones, total carbonate is less than 2 percent, while in the Upper Cretaceous lithic sandstones, it is about 10 percent.

Because of different source rocks, total carbonate in the sandstones increases from the Eocene to Late Cretaceous. In the Late Cretaceous and Early Paleocene, large volumes of carbonate detritus came from thick Paleozoic marine rocks west of the basin. Small amounts also came from the erosion of a thin Paleozoic sequence during the initial uplift of the Wind River Mountains. With continued uplift and erosion of the granitic core of these mountains, transport directions changed and Upper Paleocene and Eocene sediments in the Pinedale area were inundated with arkose.

Variation in source rocks also caused a major shift in the composition of the carbonate. With increasing depth or stratigraphic age, total calcite decreases while total dolomite increases (fig. 1). Petrographic data indicate this is due mainly to a decrease in calcite cement with a subsequent increase in monocrystalline detrital dolomite.

Calcite

In general, pore-filling calcite cements contain numerous inclusions and have a mottled, coarse-crystalline texture. Total cement in the study samples ranges from 0 to 41 percent, but averages about 8 percent. Where it constitutes more than 20 percent of the sandstone, the cement commonly has a poikilotopic texture. Sandstones with poikilotopic cement characteristically have high minus-cement porosities and floating grains, indicating that cementation occurred before significant compaction. Most quartz overgrowths predate all generations of calcite cement. Calcite replacement of feldspar grains is common in the Tertiary arkosic sandstones, whereas replacement of detrital limestone grains is common in the recycled sandstones of Late Cretaceous age.

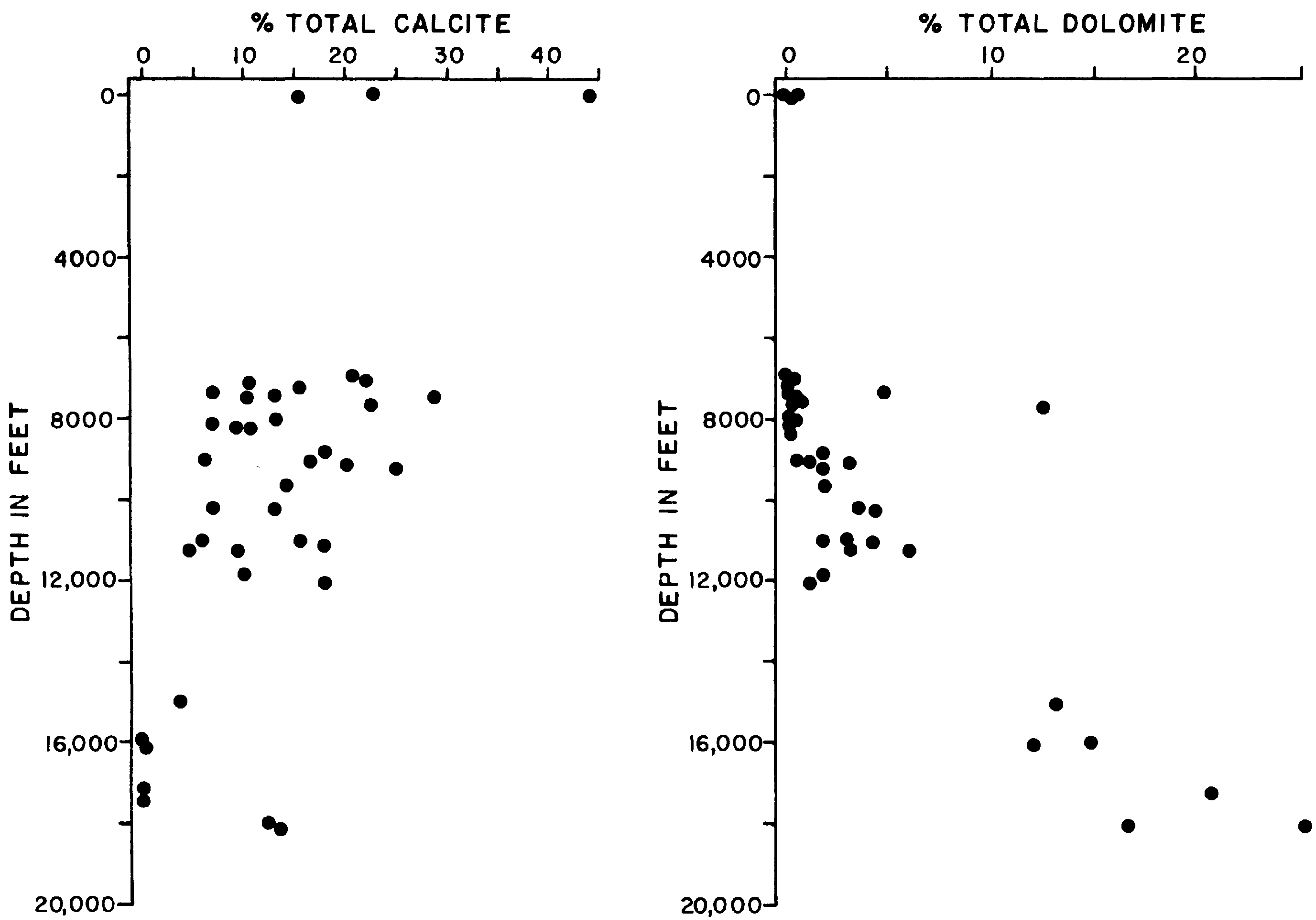

Figure 1.--Petrographic data from sandstones in Wagon Wheel no. 1 and Mesa no. 1 show a decrease in calcite and increase in dolomite as a function of depth. These trends are largely the result of variations in the composition of the source rocks.

The evolution of carbonate cements from iron-free to later iron-rich varieties is a commonly reported paragenetic sequence (Boles, 1978; Land and Dutton, 1978; Pitman and others, 1982), and one that is observed at all depths in the Pinedale wells. Commonly, where cements with different iron content occupy the same pore, relict iron-free calcite is surrounded by a younger generation of iron-bearing calcite. Often the relict calcite has a corroded texture, suggesting that it once occupied the entire pore before dissolution and the subsequent precipitation of iron-bearing calcite. These observations are significant because they provide the best evidence for showing that calcite cements inherit new geochemical characteristics by a process of dissolution and precipitation.

In sandstones, the amount of calcite cement is a major factor in controlling bulk isotopic compositions. Samples containing a high percentage of cement have a wide range of isotopic values, whereas samples containing a high percentage of detrital grains have a relatively narrow range of values (fig. 2). Most samples have isotopic compositions that are more negative than the average value for the hand-picked, detrital limestone grains. The reason for the triangular shape of the points in figure 2 becomes more clear when samples that have more than 90 percent cement are plotted versus depth (fig. 3). With increasing depth, $\delta^{13}C$ and $\delta^{18}O$ values of the cements become less negative and approach the values of the detrital grains. Thus, while the isotopic composition of the detrital grains remains about the same, the composition of the cement changes with depth.

Although isolated and analyzed from only a few thin zones, detrital limestone grains are assumed to have similar isotopic compositions at all depths. The fact that maximum and minimum isotopic values of the bulk samples converge near the average value of the detrital grains supports this assumption (fig. 2). Note that $\delta^{18}O$ for the average detrital grains is slightly more positive than the convergence point. This suggests that partially replaced detrital grains are the isotopic end members in most sandstones. At any depth there is a continuum in isotopic compositions from the detrital end member to the cement end member. Although this leads to a triangular plot of data in figure 2, it causes most of the scatter in figure 3.

There is no apparent relationship between the amount of iron in the cements and their isotopic composition. Low iron concentrations and small differences in isotopic values may prevent recognition of such a relationship. However, it is more likely that the iron content and isotopic composition of the cements change in noncorresponding ways with depth. For example, both $\delta^{13}C$ and $\delta^{18}O$ generally become less negative with depth, but iron concentrations increase down to about 10,000 ft and then decrease below this depth.

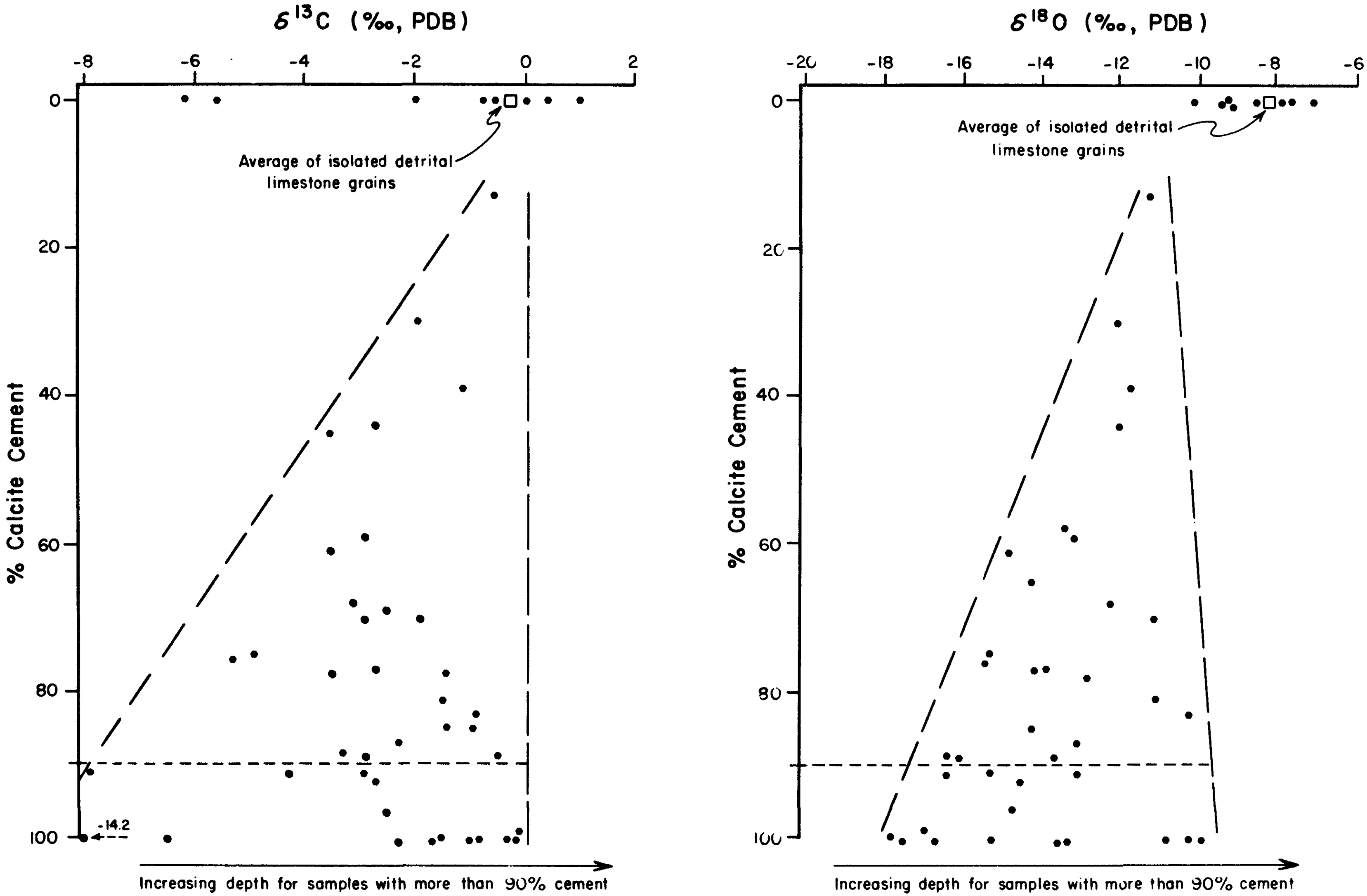

Figure 2.--Plots show percent calcite cement (petrographically determined) versus $\delta^{13}C$ and $\delta^{18}O$ of bulk calcite in sandstones from Wagon Wheel #1 and Mesa #1. Dashed lines are the approximate limits of lightest and heaviest isotopic compositions. Samples containing over 90 percent calcite cement are represented by large dots in figure 3.

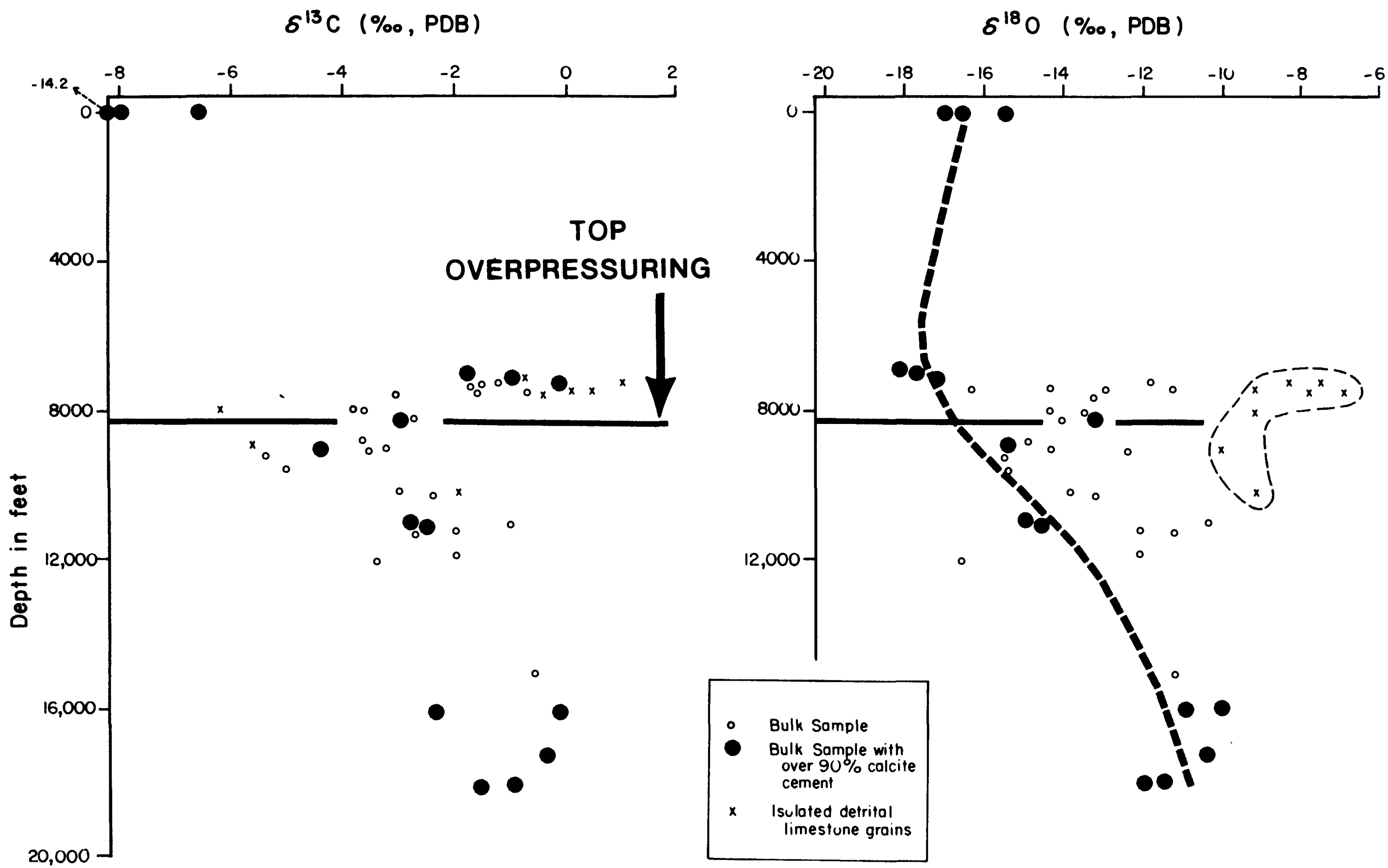

Figure 3.--Relationship of depth to $\delta^{13}C$ and $\delta^{18}O$ in calcites from sandstones in Wagon Wheel no. 1 and Mesa no. 1. Isolated detrital limestone grains were separated by hand before analysis. Dashed line shows the approximate trend in $\delta^{18}O$ for cement-rich samples. The $\delta^{13}C$ and $\delta^{18}C$ of the cement-rich samples generally become less negative with depth. The reversal in $\delta^{18}O$ near the top of overpressuring reflects the difference between open and restricted hydrochemical systems.

Dolomite

The amount of total dolomite increases with depth or formation age to a maximum of about 26 percent but averages around 8 percent, which is less than that for total calcite. Morphologically, two types of dolomite are distinguished for the purpose of interpreting isotopic data: (1) Grains of detrital dolomite show visible evidence of transportation prior to deposition. They consist mostly of well rounded polycrystalline grains which are common in the coarse-grained, Tertiary sandstones. However, monocrystalline detrital grains are common in the finer grained Upper Cretaceous sandstones. (2) Grains of rhombic dolomite are monocrystalline detrital grains that have been diagenetically modified by the addition of dolomitic overgrowths. Because monocrystalline dolomite provides the best substrate for the precipitation of authigenic dolomite, rhombic dolomite is most common in the fine-grained Upper Cretaceous sandstone.

There is a distinct absence of either dolomitic or ankeritic cement, and with few exceptions all authigenic dolomite occurs as overgrowths on grains of detrital dolomite. It is virtually impossible to obtain actual isotopic values for the overgrowths because they comprise only a small percentage of total dolomite. Instead, rhombic dolomite (detrital core with authigenic overgrowth) is used to characterize relative shifts in the isotopic values of authigenic dolomite.

The relationship of depth to the isotopic composition of dolomite is complex because rhombic-rich and detrital-rich samples form two distinct groups (fig. 4). The lack of detrital dolomite below about 12,000 ft is largely the result of the fine-grained sedimentation, which favors rhombic dolomite in Upper Cretaceous sandstones. With increasing depth, $\delta^{13}C$ of both the detrital and rhombic groups remains nearly constant and close to the average value of the hand-picked detrital grains. However, $\delta^{18}O$ of the detrital group becomes slightly more negative with depth but slightly less negative with depth for the rhombic group.

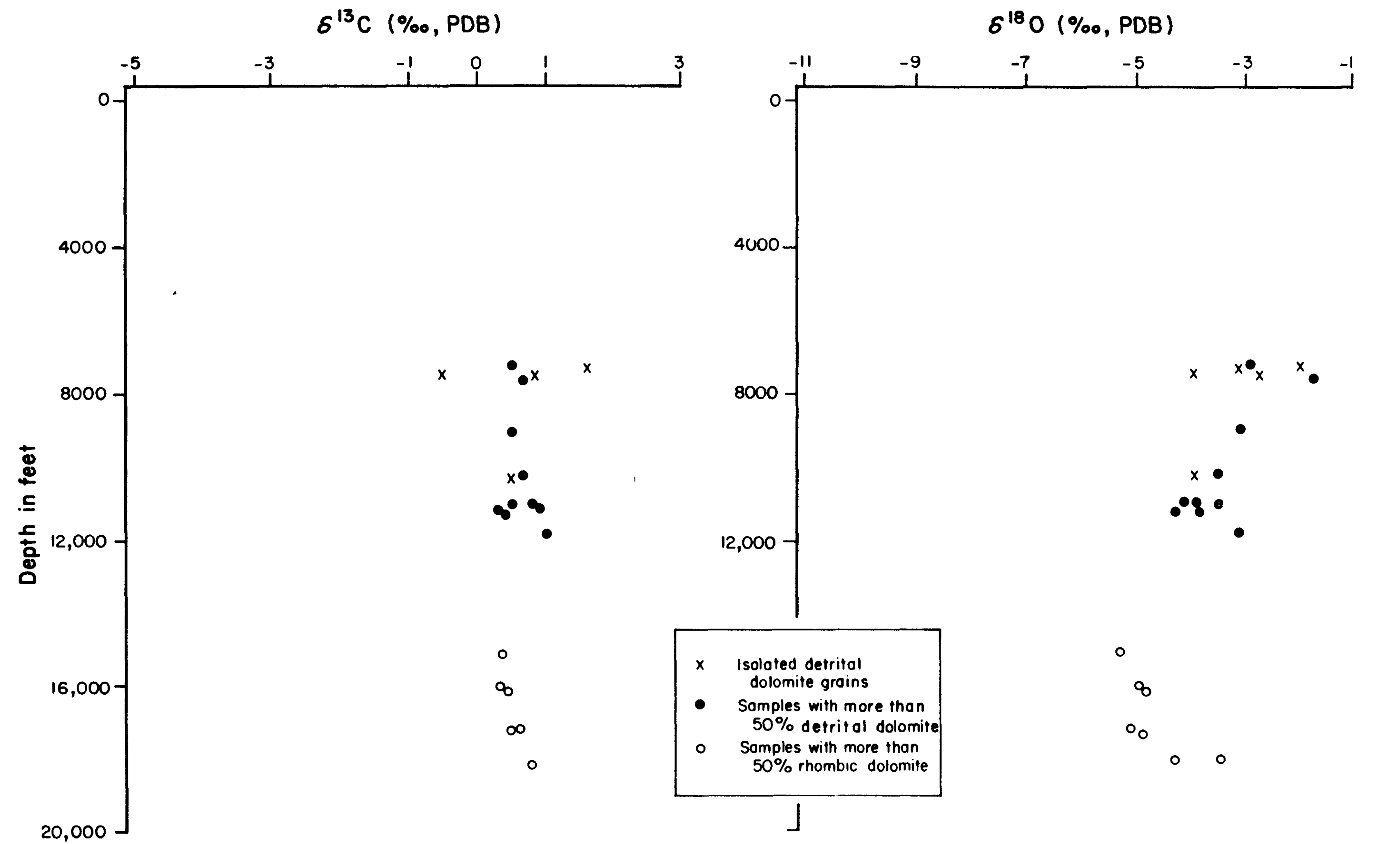

Figure 4.--Relationship of depth to $\delta^{13}C$ and $\delta^{18}O$ in dolomites from sandstones in Wagon Wheel no. 1 and Mesa no. 1. Rhombic-rich and detrital-rich samples were determined petrographically. Isolated detrital dolomite grains were separated by hand before analysis. Variations in $\delta^{18}O$ are difficult to interpret but indicate partical re-equilibration with burial.

The positive shift with increasing depth in $\delta^{18}O$ of the rhombic group (fig. 4) is interpreted as resulting from changes in the isotopic composition of the overgrowths on the rhombic grains. A plot of $\delta^{18}O$ versus percent overgrowth shows that the overgrowths are generally more negative than the polycrystalline and monocrystalline detrital grains. If it is assumed that the detrital monocrystalline cores of the rhombic grains have nearly the same $\delta^{18}O$, then with increasing depth, $\delta^{18}O$ of the overgrowths must become more positive (enriched). The trend for calcite cement is similar but greater in magnitude.

DISCUSSION

In this discussion I will demonstrate that the variations with depth in $\delta^{13}C$ and $\delta^{18}O$ of the authigenic carbonate cements result from predictable changes in temperature and isotopic composition of pore waters in the area. To make this interpretation, it is necessary to assume that some portion of the total carbonate undergoes recrystallization by a process of dissolution and reprecipitation. Thus, with burial, the bulk composition of carbonate cement is continually modified, either by the addition of new cement or by the recrystallization of old cement. Modification of isotopic composition occurs mainly by isotopic exchange between pore fluids and authigenic precipitates (Land, 1980).

The Pinedale area is unique because of two hydrochemical regimes that are relatively predictable in the subsurface. With increasing depth there is a transition from a normally pressured, open hydrochemical system to an overpressured, restricted hydrochemical system. Between these two systems, there is a predictable shift in the isotopic composition of the pore waters. This is because when water/rock ratios are high, as in the normally pressured zone, water-rock diagenetic reactions cause little modification to the isotopic composition of the aqueous fluids. However, with increasing depth, drastic reductions in porosity and permeability cause increased stagnation of the pore waters and lower the water/rock ratio. In the overpressured zone water-rock diagenetic reactions are expected to cause significant modification to the isotopic composition of the pore fluids.

The positive shift with depth in $\delta^{13}C$ of calcite cements may be interpreted as resulting from a similar shift in $\delta^{13}C$ of the pore waters. The $\delta^{13}C$ values of calcite cements sampled from outcrops are similar to the $\delta^{13}C$ values for near-surface waters. In these waters, the average $\delta^{13}C$ (-8.6 $^{o}/oo$) suggests that most of the carbon in the dissolved species comes from atmospheric CO_2. This is supported by the fact that only minor amounts of carbon are available either from detrital carbonate, which is scarce in the arkosic aquifers, or from organic carbon, which is not abundant in the thin soils of the Pinedale area. With increasing depth two things happen to change the $\delta^{13}C$ of carbon species in the pore waters. 1) The percentage of detrital carbonate increases in the sandstones, and 2) there is a decrease in the volume of meteoric water which penetrates to deep sandstones. Thus, dissolved carbon becomes diluted with ^{13}C from the dissolution of detrital carbonate and $\delta^{13}C$ becomes more positive with depth. The carbon in the deep calcite cements is essentially redistributed carbon from detrital carbonate grains.

It is surprising that there is no evidence of isotopically light carbon in the calcite cements of the gas-bearing sandstones. At depth, significant amounts of ^{12}C could be expected from CO_2 produced during organic matter maturation and gas generation. The lack of dissolution features in the overpressured rocks also suggests that carbonic acids are not present in significant volumes. Perhaps the volume of CO_2 produced from type III kerogens in these rocks during late stage maturation is simply too small to be recognized or found.

The congruity of $\delta^{13}C$ in dolomite indicates either a lack of recrystallization with burial or recrystallization with aquisition of carbon from local detrital carbonate grains. However, the slight modification in $\delta^{18}O$ of dolomite argues for some recrystallization with burial. The variability in isotopic composition of dolomite is expected to be less than calcite because dolomite is much less susceptible to recrystallization in water than is calcite (Epstein and others, 1964).

Variations with depth in $\delta^{18}O$ of the authigenic carbonates reflect changes in temperature of precipitation and changes in $\delta^{18}O$ of pore waters. Although deep pore waters from the Pinedale area have not been recovered, the low water/rock ratio implied by the low permeability of overpressured rocks strongly suggests that $\delta^{18}O$ of the pore waters becomes more positive with increasing depth. There are two reasons for this: (1) Near-surface waters, which have a relatively negative $\delta^{18}O$ (-20°/oo, SMOW), are excluded from the overpressured sandstones. (2) With increasing temperatures during progressive burial, the isotopic fractionations of most carbonate and silicate diagenetic reactions cause a net transfer of ^{16}O to diagenetic products and ^{18}O to water. Because of low circulation rates, pore waters in the deep sandstones should be isotopically modified by these reactions.

For calcite, the simplified relation between $\delta^{18}O$ of water and temperature is

$$\delta^{18}O_{calcite} - \delta^{18}O_{water} = 2.78\ (10^{6}\ T^{-2}) - 2.89$$

(Friedman and O'Neil, 1977) where T is in degrees K. Using this equation, the mean annual surface temperature (4°C) and $\delta^{18}O$ for near-surface water (-20°/oo, SMOW) in the Pinedale area, the calculated $\delta^{18}O$ for an equilibrated calcite cement is -17°/oo, PDB--a value that closely agrees with (-16.4°/oo), the average of measured $\delta^{18}O$ in calcite cements from outcrops. This is good evidence that calcite cements at the surface are in equilibrium with present near-surface conditions.

Unfortunately, the above exercise can go no further because $\delta^{18}O$ of deep pore waters are not available. However, assuming equilibrium, $\delta^{18}O$ of these waters can be calculated from the above equation, measured formation temperatures, and $\delta^{18}O$ of the calcite cements. At 7,000 and 17,000 ft deep, $\delta^{18}O_{water}$ is -9.5 (^{o}/oo, SMOW) and 4.8 (^{o}/oo, SMOW), respectively. Because the above equation is nonlinear, the shift in $\delta^{18}O_{water}$ from -20 (surface) to -9.5 (7,000 ft deep) is much less in magnitude than the shift from -9.5 to 4.8 (17,000 ft deep). In short, the trend in $\delta^{18}O$ for calcite cements, which appears to support the geological evidence, strongly suggests that pore waters are modified less in the normally pressured rocks than in the overpressured rocks. This is graphically illustrated in figure 3 by the reversal near the top of overpressuring. It is emphasized that such a trend can only be interpreted by assuming the calcite cements reequilibrate with burial.

The trend with depth for $\delta^{18}O$ in dolomite is difficult to interpret for two reasons. 1) The relation between $\delta^{18}O_{water}$ and diagenetic temperatures (less than 300^{o}C) is poorly understood for dolomite (Land, 1980). 2) Bulk isotopic compositions obscure absolute values of $\delta^{18}O$ for authigenic dolomite. From figure 4 it appears that the addition of authigenic dolomite causes the composition of bulk samples to become isotopically lighter. Although this says nothing about variations of $\delta^{18}O$ in authigenic dolomite, it does imply that a small portion of the total dolomite reequilibrates with burial.

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