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The Fryingpan Member of the Maroon Formation—A Lower Permian(?) Basin-Margin Dune Field in Northwestern Colorado

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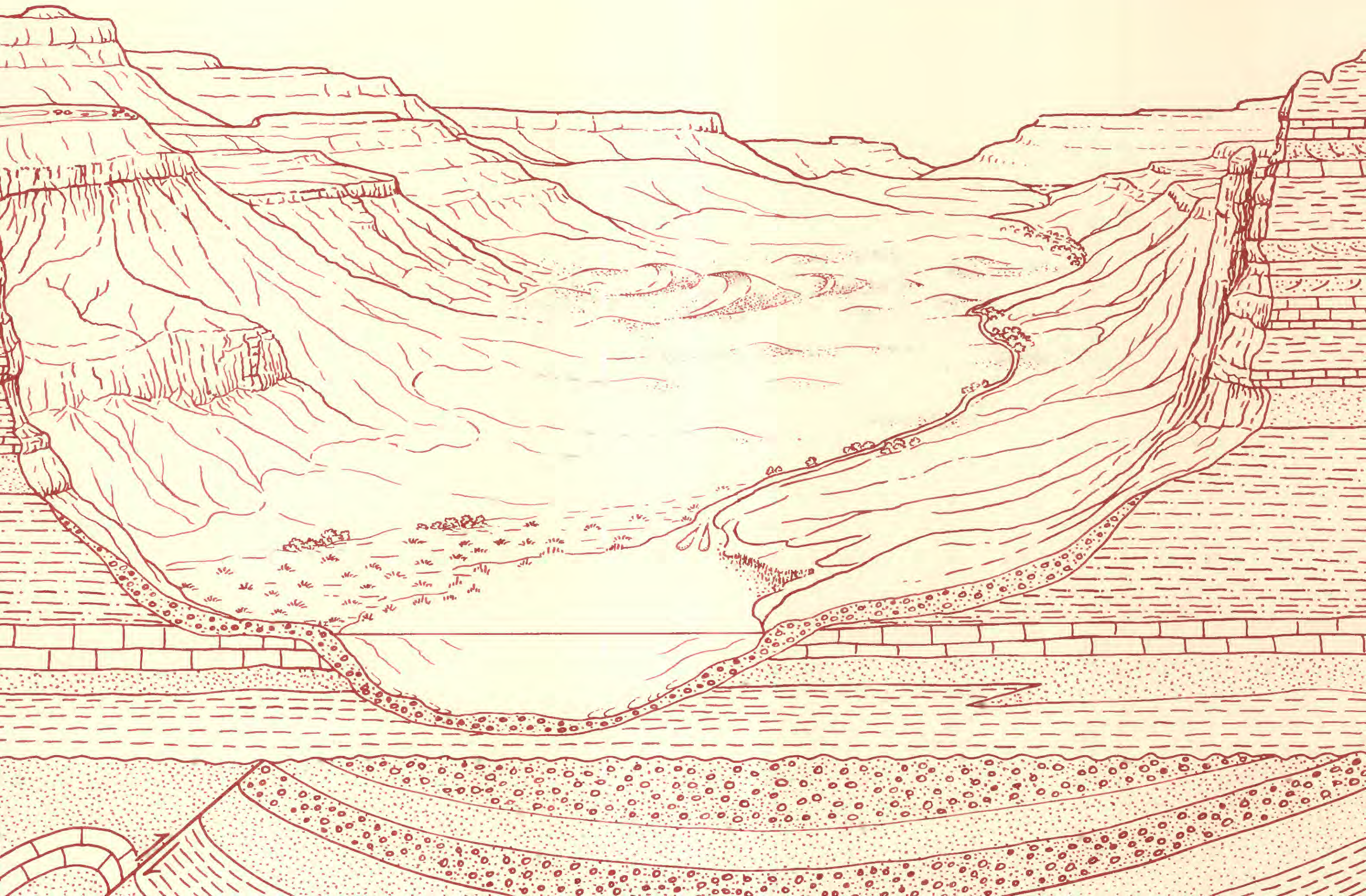

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EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U. S. GEOLOGICAL SURVEY

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Chapter H

Variations in Vitrinite Reflectance Values for the Upper Cretaceous Mesaverde Formation, Southeastern Piceance Basin, Northwestern Colorado—Implications for Burial History and Potential Hydrocarbon Generation

By VITO F. NUCCIO and RONALD C. JOHNSON

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

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

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PLATE

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FIGURES

CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C=(temp °F–32)/1.8-

Variations in Vitrinite Reflectance Values for the Upper Cretaceous Mesaverde Formation, Southeastern Piceance Basin, Northwestern Colorado—Implications for Burial History and Potential Hydrocarbon Generation

By Vito F. Nuccio *and* Ronald C. Johnson

Abstract

Analysis of vitrinite reflectance profiles and surfaces of equal vitrinite reflectance in the southeastern part of the Piceance basin, northwestern Colorado, indicates that burial histories for the Divide Creek anticline and the Grand Hogback are different from those for adjacent synclines. These two positive structures probably reached their present-day thermal maturity before late Eocene folding and before the end of the Laramide orogeny. In contrast, adjacent synclines did not reach their present-day thermal maturity until the end of the Laramide orogeny, or possibly later.

Vitrinite reflectance data suggest that most of the Upper Cretaceous Mesaverde Formation in the southeastern part of the Piceance basin is thermally mature enough to have produced hydrocarbons by thermal generation, but that only part of the Mesaverde is thermally mature enough to have expelled significant amounts of natural gas. The point at which natural gas expulsion theoretically begins varies from near the top of the Mesaverde Formation in the synclines to near the base of the Mesaverde in the Divide Creek anticline and along the Grand Hogback.

INTRODUCTION

Mean vitrinite reflectance (Rm) was determined for samples from the Upper Cretaceous Mesaverde Formation in the southeastern part of the Piceance basin (fig. 1). Samples were obtained by carefully picking coaly chips out of well-cutting samples from five wells. Vitrinite reflectance profiles were then constructed to determine the level of thermal maturity in the study area. A stratigraphic and structural cross section was constructed and the positions of several important surfaces of equal vitrinite reflectance plotted. The cross section (pl. 1) and profiles (figs. 2–5) were then studied to determine the relative burial histories of the Divide Creek anticline and the Grand Hogback and their adjacent synclines and how and when these structural elements formed. The cross section helps identify areas in which potential source rocks are thermally mature enough to have generated and expelled significant amounts of natural gas, and it indicates the locations of favorable source beds and sandstone reservoirs. The results of this study should aid in understanding low-permeability gas accumulations in the Mesaverde Formation of the Piceance basin.

Manuscript approved for publication, January 5, 1989.

GEOLOGIC SETTING

The Piceance basin is a structural and sedimentary basin created during the Laramide orogeny (Late Cretaceous through Eocene time). The basin is bounded on the northwest by the Uinta uplift, on the north by the Axial basin anticline, on the east by the White River uplift, on the southeast by the Sawatch uplift, on the south by the San Juan volcanic field, and on the southwest by the Uncompahgre uplift (fig. 1). Similar to other Laramide basins, the Piceance basin is highly asymmetric; it has gently dipping western and southwestern flanks and a nearly vertical to overturned eastern flank

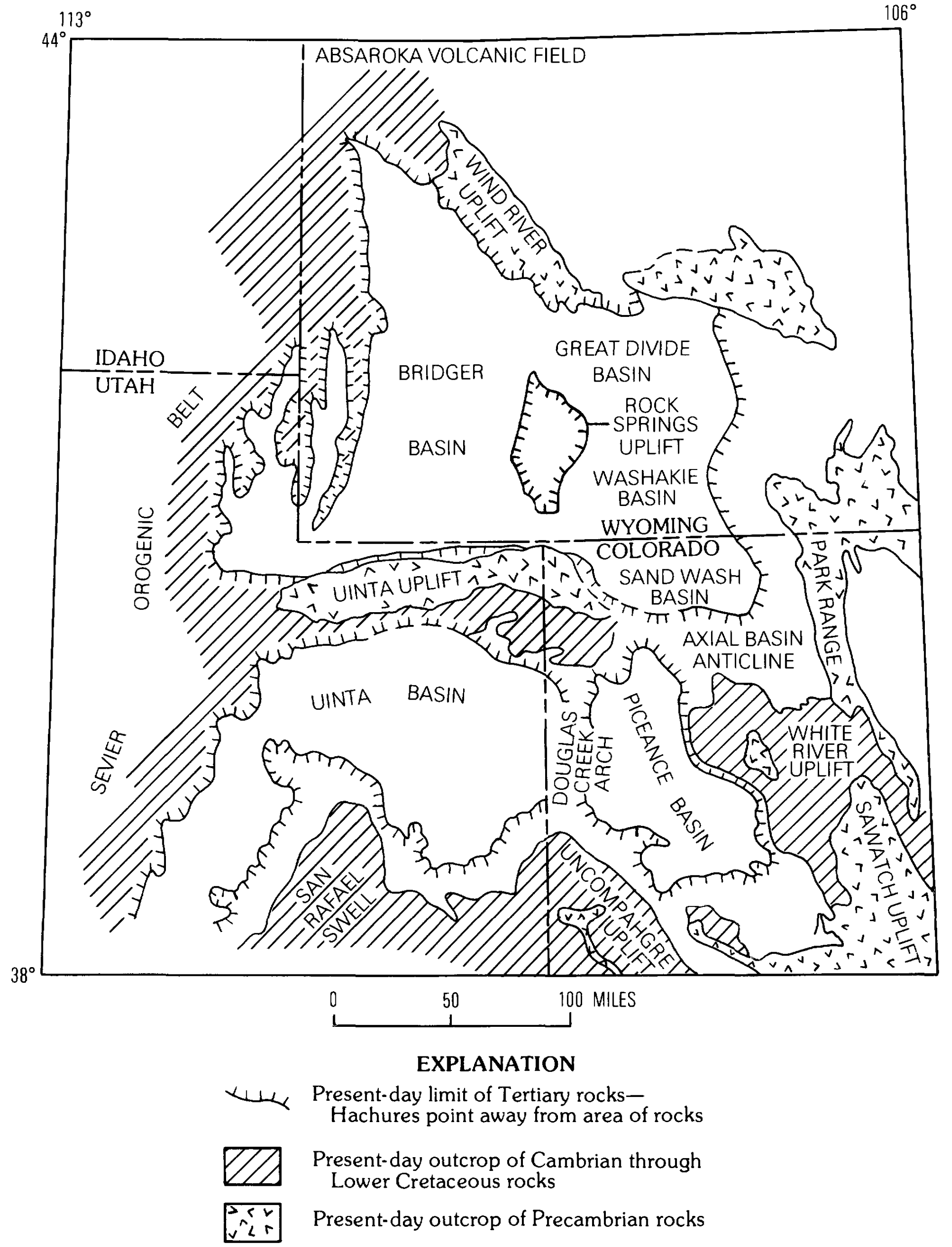

Figure 1. Outcrops of Precambrian rocks, and basins and uplifts created during the Laramide orogeny in the area of the Piceance basin, Wyoming, Utah, Colorado, and Idaho. Modified from Johnson (1989).

named the Grand Hogback. The eastern flank is believed to be underlain by a major, deep-seated reverse or thrust fault (Gries, 1983).

Three large anticlines are in the southeastern part of the basin, the Divide Creek, Wolf Creek and Coal Basin anticlines. Although these anticlines may have been modified structurally by intrusions of Oligocene and younger age, they probably are underlain by Laramide reverse or thrust faults related to the fault beneath the Grand Hogback (Gries, 1983).

The thickness of the Mesaverde Formation (also known as the Mesaverde Group) varies from about 3,000 ft along the western margin to more than 6,000 ft along the eastern margin of the Piceance basin. Deposition of the Mesaverde Formation mostly, but not totally, predates onset of the Laramide orogeny. During deposition of most of the Mesaverde, the area of the Piceance basin was part of a much larger foreland sedimentary basin that extended across the central part of the North American continent. During the Early Cretaceous, downwarping in the foreland basin resulted in invasion by an epeiric sea. Several thousand feet of Mancos Shale was deposited over the area of the Piceance basin; then, during the Late Cretaceous, the seaway was filled by sediments derived mostly from the Sevier orogenic belt to the west (Fouch and others, 1983).

The lower part of the Mesaverde Formation consists of several transgressive and regressive cycles that were deposited while the shoreline of the epeiric sea shifted back and forth across the area of the Piceance basin. Regressive cycles (from oldest to youngest) are the Corcoran Sandstone Member of the Mesaverde Formation or of the Iles Formation of Mesaverde Group, the Cozzette Sandstone Member of the Mesaverde Formation or of the Iles Formation of Mesaverde Group, the Rollins Sandstone Member of the Mesaverde Formation, and two informal units, the middle sandstone and upper sandstone of Cullins (1969). Each successively younger regressive cycle pushed the shoreline farther east and southeast until, by Late Cretaceous (Maastrichtian) time, the seaway remained mostly east of the Piceance basin.

Source Rocks

The tongues of Mancos Shale probably contain a mixture of humic and sapropelic matter and as such would be good source rocks for petroleum; however, the organic matter in these rocks has been neither quantified nor qualified. The regressive marine rocks of the Mesaverde commonly contain coal measures and therefore are good source rocks for natural gas. The upper part of the Mesaverde Formation consists of deltaic and coastal-plain fluvial sediments deposited after the shoreline of the epeiric sea retreated east of the Piceance basin area. Rocks of the upper part of the Mesaverde include some carbonaceous shale and coal, but lenticular sandstones and gray shales predominate, and the upper part of the Mesaverde contains only fair to poor source rocks for natural gas.

Tectonic and Thermal History

In the area of the Piceance basin, the Laramide orogeny began during Late Cretaceous (Campanian) time and prior to the end of Mesaverde deposition. One of the oldest Laramide uplifts in the area is the Sawatch uplift, southeast of the Piceance basin, and radiometric dates suggest that it began to rise during the middle of fluvial Mesaverde deposition (Tweto, 1975). Volcanic rock fragments in a fluvial Mesaverde core from the southern part of the Piceance basin may have been derived from the rising Sawatch uplift (Hansley, 1981). Despite positive movement on the Sawatch and possibly other Laramide uplifts during the Campanian, fluvial Mesaverde deposition continued in the area of the Piceance basin until almost the end of the Cretaceous.

Regional uplift and erosion probably began prior to the end of the Cretaceous and affected most, if not all, of the area of the Piceance basin (Johnson and May, 1978, 1980; Johnson and Finn, 1985, 1986). As much as several thousand feet of Mesaverde rock may have been stripped away before subsidence and sedimentation began again during the Paleocene. The Piceance basin subsided throughout most of the Paleocene and Eocene, and as much as 12,000 ft of sediment was deposited along the structural trough of the basin. This thick pile of sediment increased the thermal maturity of the Mesaverde such that significant quantities of natural gas were generated by the Mesaverde in the deeper parts of the basin.

THERMAL MATURITY MODELS

Although mean random vitrinite reflectance (Rm) can be used to determine the level of thermal maturity of organic matter in sedimentary rocks, it should be noted that there are two models to explain the relationship between time and thermal maturity. In the first model, time and temperature are assumed to be interchangeable, and, if given sufficient time, even a relatively low temperature can produce a high level of thermal maturity (Lopatin, 1971; Waples, 1980). No single temperature, therefore, can be assigned to a vitrinite reflectance value. In this model, originally proposed by Karweil (1956) and further developed by Lopatin (1971), the geologic history of a unit is divided into increments of time and the average temperature for each increment estimated. Each increment is assigned a value based on both the average temperature of that increment and the length of time spent at that temperature. In Lopatin's model, the rate of reaction increases by a factor (r) for each 10 °C increase in temperature. Using the Arrhenius equation, which states that the rate of chemical reaction approximately doubles for each 10 °C increase in temperature, Lopatin assigned a value of 2 to the factor r. The sum of each increment value multiplied by r yields Lopatin's TTI index. Waples (1980) calculated TTI values for 402 samples from around the world and, despite the scatter in his data, suggested that a value for r of 2 is reasonable. Lopatin had calibrated his model to different stages in the process of oil generation by using data from the Munsterland–1 borehole in the Ruhr district of Germany. When Waples attempted to apply Lopatin's calibration to other areas, the predicted vitrinite reflectance values were higher than the observed values, apparently because of an error in the geologic reconstruction of the Munsterland borehole. Waples

(1980) then recalibrated Lopatin's TTI index by using data from 31 wells from around the world and suggested a new correlation between TTI and vitrinite reflectance.

In the second model, time is assumed to have no significant effect on thermal maturity; relatively soon (geologically speaking) after maximum temperatures are reached, organic matter stabilizes and significant reaction ceases (Neruchev and Parparova, 1972; Barker, 1983; Price, 1983). Proponents of this model believe that the Arrhenius equation does not apply to nonreversible complex reactions that occur when organic matter is converted into hydrocarbons. Suggate (1982) found a good correlation between maximum temperature and coal rank, regardless of the age of the coal, and suggested that the effects of time on the maturation of organic matter have been overemphasized. He stated (p. 385) that "***the time available (rarely less than 1 million years and commonly much longer) at maximum temperature will always be sufficient to complete the reaction, at least to the 99 percent level." If proponents of the second model are correct, then vitrinite reflectance can be used as an absolute paleothermometer and it is much easier to interpret vitrinite reflectance values. Although it is beyond the scope of this report to debate the two models, some general conclusions will be discussed in a later section.

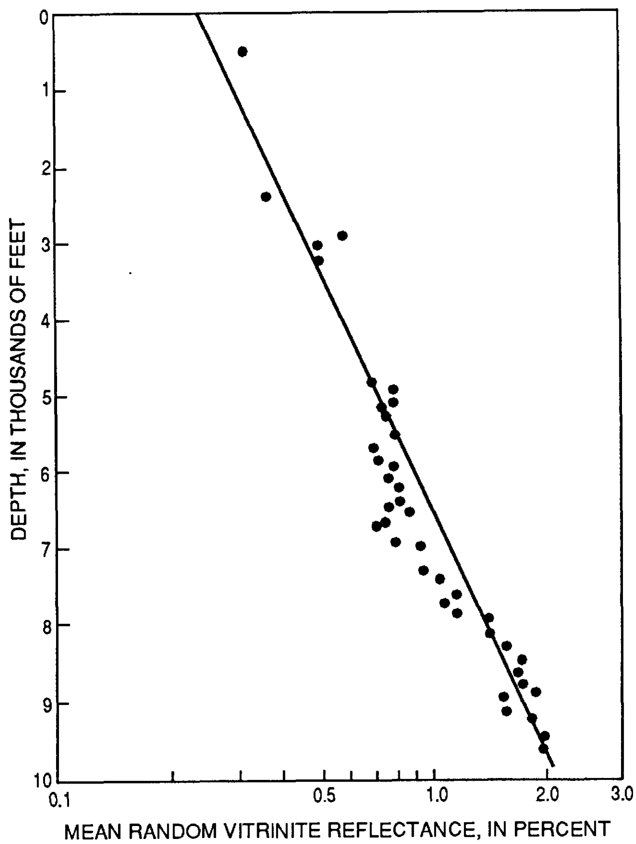

Figure 2. Vitrinite reflectance profile (with best-fit line) for Barrett Energy Crystal Creek No. A–2 well. Location of well shown on figure 6.

VITRINITE REFLECTANCE PROFILES FOR SOUTHEASTERN PART OF PICEANCE BASIN

Vitrinite reflectance was plotted as a function of depth on semilogarithmic graphs for four of the five wells (figs. 2–5) studied. (Data for the Tenneco Oil Corporation well are proprietary and are not shown.) Because vitrinite reflectance generally increases logarithmically with depth (Dow, 1977), a "best-fit" or "eyeballed" straight line was drawn through the data: the steeper the line, the slower the rate of increase in vitrinite reflectance with depth.

Vitrinite reflectance profiles for the Barrett Energy (fig. 2), CER Corporation (fig. 3), and California Company (fig. 4) wells have shallower slopes than do the profiles for the Tenneco (unplotted) and TRW Company (fig. 5) wells. The Barrett and CER wells are on the gently dipping southwestern flank of the basin and relatively close to its structural axis (pl. 1). The Tenneco well is near the crest of the Divide Creek anticline. The California Company well is in the syncline between the Divide Creek anticline and the Grand Hogback, and the TRW well is located on the Grand Hogback. It is

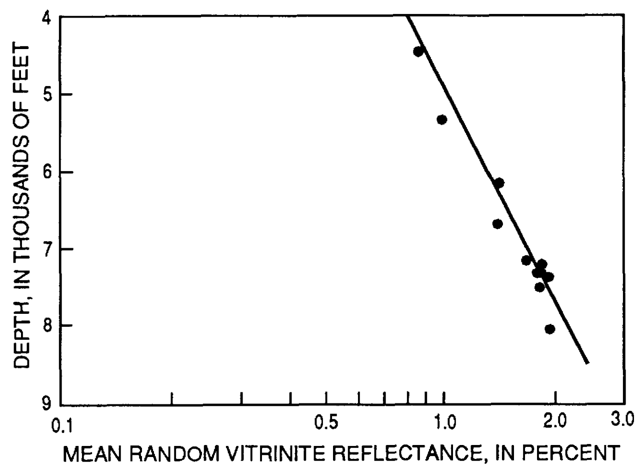

Figure 3. Vitrinite reflectance profile (with best-fit line) for CER Corporation MWX–1 and MWX–2 wells. Location of MWX site shown on figure 6.

commonly accepted that, if the best-fit line is extrapolated to a Rm value of 0.20 percent, then the original surface at maximum burial can be determined and the amount of overburden removed estimated. We have not

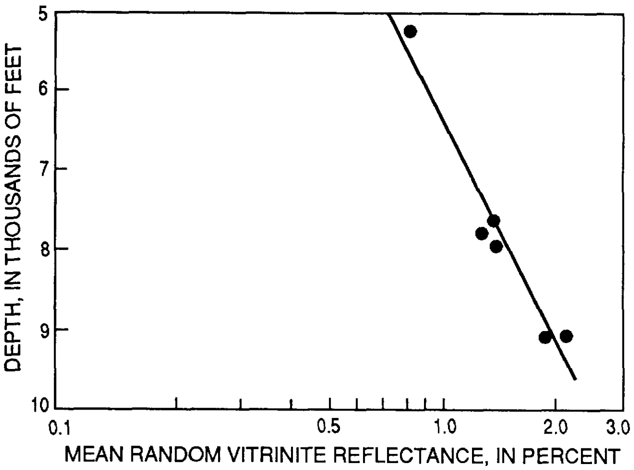

Figure 4. Vitrinite reflectance profile (with best-fit line) for California Company Baldy Creek No. 1 well. Location of well shown on figure 6.

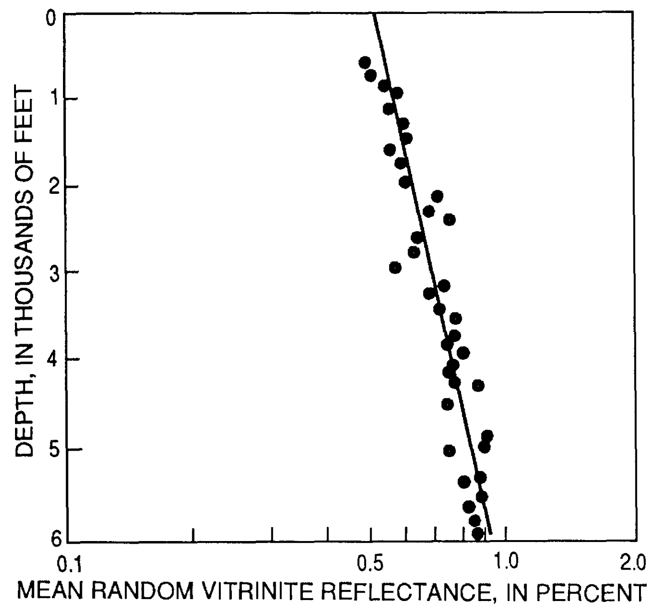

Figure 5. Vitrinite reflectance profile (with best-fit line) for TRW Company Sunlight Federal No. 2 well. Location of well shown on figure 6.

attempted this because we are studying only the Cretaceous Mesaverde Formation and Mancos Shale and we would have to make extrapolations through several thousands of feet of Tertiary section. In general, however, wells having less steeply trending Rm profiles either have or have had higher geothermal gradients or have been subjected to a certain temperature or burial depth for a longer period of time than wells having more steeply trending Rm profiles.

HYDROCARBON-GENERATION THRESHOLDS EXPRESSED BY SURFACES OF EQUAL VITRINITE REFLECTANCE

The Mesaverde Formation contains mostly terrestrial vitrinitic or humic kerogen and is capable of generating large quantities of methane gas under the proper conditions. Three important surfaces of equal vitrinite reflectance are shown on the cross section (pl. 1): 0.73, 1.10, and 1.35 percent. Although it is debatable which value corresponds to the start of methane generation in coals and carbonaceous shales, we have chosen one of the most widely accepted models, that of Juntgen and Karweil (1966), in which thermal generation begins at 0.73 percent Rm. Coals, and to some extent carbonaceous shales, are able to absorb or store methane within their microstructure, and the point at which gas is expelled depends on the degree of thermal maturation (as measured by vitrinite reflectance), temperature, and pressure. According to Juntgen and Karweil (1966) and Meissner (1984), methane begins to be expelled at Rm values between 0.73 and 1.10 percent. Although the organic matter in the Mesaverde Formation is mostly humic and will generate methane, the 1.35-percent-Rm surface is believed to be the point at which oil breaks down to gas and condensate (Dow, 1977). Oil may have migrated upward into the Mesaverde from the underlying, more liptinite rich Mancos Shale but should not be found in the area below the 1.35–percent-Rm surface, unless it migrated in after Mesaverde Formation temperatures declined. A vitrinite reflectance surface of 2.0 percent is shown between the Barrett and CER wells for reference only. Except in the Barrett and CER wells, the Mesaverde Formation has reached maturities of at least 0.73 percent Rm (pl. 1).

DISCUSSION AND CONCLUSIONS

Surfaces of equal vitrinite reflectance in the southeastern part of the Piceance basin generally are parallel with structure, though at a lesser angle. Vitrinite reflectance surfaces diverge over the positive structures and converge toward the synclines, and they are steep on the positive structures and less steep in the synclines (pl. 1). These observations suggest that the rate of increase in vitrinite reflectance with depth is less on the Divide Creek anticline and the Grand Hogback than in the adjacent synclines.

In this study, we assume that paleogeothermal gradients are the same as present-day gradients because we have insufficient data to determine either how geothermal gradients have changed through time or what they were at a given time in the past. Geothermal gradients for the wells in this study were calculated by using uncorrected bottom-hole temperatures and are fairly consistent with regional geothermal gradient trends constructed by using similar data from hundreds of wells in the Piceance basin (fig. 6) (Johnson and Nuccio, 1986). Regional trends suggest that geothermal gradients vary only modestly along the line of section. The Tenneco well on the Divide Creek anticline has an uncorrected geothermal gradient of 1.98 °F/100 ft, a gradient slightly higher than the regional study would suggest. This higher gradient may be the result of an extensive fracture system in the anticline that allows relatively hotter fluids to circulate upward through the section. Temperatures in this well were not recorded until 17 hours after circulation stopped, and, as a result of this unusually long recovery time, borehole temperatures were probably able to equilibrate with formation temperatures. The Tenneco well geothermal gradient is still less than the estimated corrected geothermal gradient of 2.0–2.2 °F/100 ft for the area of the Divide Creek anticline (Johnson and Nuccio, 1986).

If thermal gradients have been fairly constant through time along the line of section (pl. 1), then observed thermal maturity differences must result mostly from differences in burial histories. Burial histories near the axial trough of the basin are fairly well understood (Nuccio and Johnson, 1984; Johnson and Nuccio, 1986), but burial histories of structures such as the Grand Hogback and the Divide Creek anticline are less well understood. Several episodes of movement during the Laramide orogeny produced multiple unconformities over these structures, and burial histories are difficult to reconstruct because detailed stratigraphic studies are not available for either the Divide Creek anticline or the area of the Grand Hogback studied in this report. Considerable uplift apparently occurred on the Divide Creek anticline and along the Grand Hogback late in the Laramide orogeny during the middle and late Eocene. Although middle and late Eocene rocks have been eroded from the tops of the two structures, rocks of this age are preserved along the flanks and dip at fairly high angles. Movement on both structures is mostly Laramide and probably stopped by the end of the Eocene.

Prior to structural uplift of the Divide Creek anticline and the Grand Hogback, thermal maturities had not reached their present levels along the line of section. If they had, then the surfaces of equal vitrinite reflectance would be parallel with stratigraphic units across these structures (fig. 7*A*). In a like manner, thermal maturities were not completely determined after structural movement stopped; if they had been, then the surfaces of equal vitrinite reflectance would be almost horizontal and pass through structures (fig. 7*B*). In order to explain the position of surfaces of equal vitrinite reflectance in the southeastern part of the Piceance basin, we suggest that late Eocene uplift and erosion over the Divide Creek anticline and the Grand Hogback significantly cooled the Mesaverde Formation over these structures and "froze" the steep vitrinite reflectance profiles in place. If our hypothesis is correct, then vitrinite reflectance values over these two structures have changed little since the period of folding began sometime before the end of the Eocene. The adjacent synclines were not affected by late Eocene uplift and continued to subside and receive sediments until almost the end of the Laramide orogeny, near the end of the Eocene. This additional depth of burial allowed the maturation process in the synclinal areas to continue, as evidenced by the shallower vitrinite reflectance profile.

The structural complexities of the southeastern part of the Piceance basin make it an ideal area in which to test the validity of the two contrasting models of organic metamorphism. The line of section (pl. 1) was extended east along the Grand Hogback and west to near the southwestern margin of the basin, and schematic cross sections were drawn for two time periods: 46 m.y. ago, during deposition of the late Eocene Mahogany oil shale zone, a time in which the Piceance basin was actively subsiding (fig. 8*A*); and 10 m.y. ago, just prior to downcutting of the Colorado River Canyon system (fig. 8*B*).

The time of deposition of the Mahogany oil shale zone was chosen because the zone is the stratigraphically highest marker unit that can be traced throughout most of the Piceance basin (fig. 8*A*). Because the Mahogany zone has been eroded from the crest of the Divide Creek anticline and the Grand Hogback, the position of the Mesaverde in these areas during this period is speculative. Surfaces of equal vitrinite reflectance are shown on figure 8*A*, but specific values are not assigned. Regardless of whether the time-dependent or time-independent model is correct, the surfaces of equal vitrinite reflectance should dip and fan out somewhat toward rapidly subsiding areas of the basin during active basin subsidence because, during active subsidence, organic matter has less time to equilibrate in the rapidly subsiding areas than in the slowly subsiding areas. Fanning out of the surfaces of equal vitrinite reflectance toward the synclines is opposite of what is observed today.

Figure 8*B* shows the Piceance basin as it appeared 10 m.y. ago. The positions of the surfaces of equal vitrinite reflectance probably have changed little during the last 10 m.y. because of the rapid rate of erosion and subsequent cooling in the basin, and the present-day positions of these surfaces are used. In the southeastern part of the Piceance basin, an erosional surface at a present-day elevation of 10,000±1,000 ft probably formed during the final stages of the Laramide orogeny and shortly thereafter, a time period in which basin

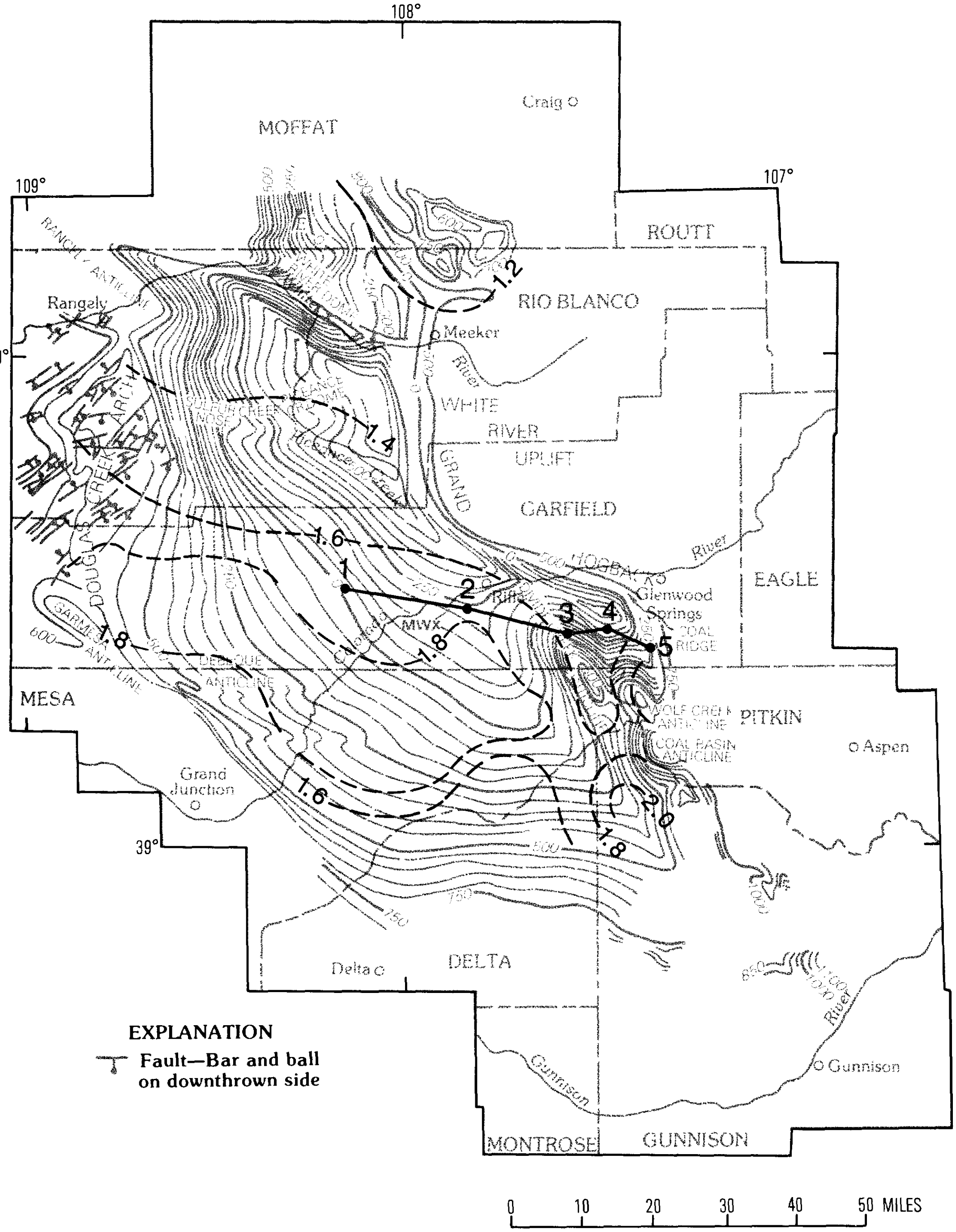

Figure 6. Structure contours for the top of the Rollins Sandstone Member of the Mesaverde Formation or the Trout Creek Sandstone Member of the Iles Formation of the Mesaverde Group, Piceance basin, and contours of geothermal gradients (uncorrected). Structure contours in feet times 10, interval variable; geothermal gradient contour interval 0.2 °F/100 ft. Line of section of plate 1 also shown: location 1, Barrett Energy Crystal Creek No. A–2 well; location 2, CER Corporation MWX–1 and –2 wells; location 3, Tenneco Oil Corporation No. 1 Cameo 20–4 well; location 4, California Company Baldy Creek No. 1 well; location 5, TRW Company Sunlight Federal No. 2 well. Modified from Johnson (1989); geothermal gradient contours from Johnson and Nuccio (1986).

subsidence gradually diminished and erosion occurred along the margins of the basin and in the structurally positive areas of the basin such as the Divide Creek anticline (Johnson and Nuccio, 1986). This erosional surface is now partly buried by basalt flows, and the Mahogany oil shale zone has been eroded from all but the lower part of the western flank of the Divide Creek anticline, where it dips away from the anticline. The

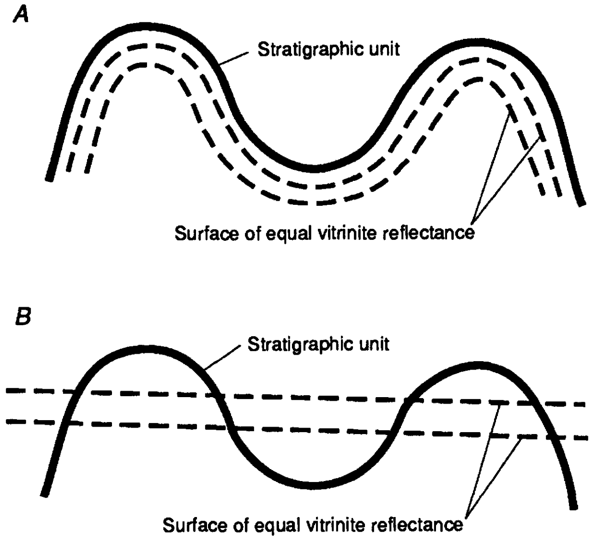

Figure 7. Schematic cross sections of a folded area, showing courses of surfaces of equal vitrinite reflectance. *A*, Surfaces of equal vitrinite reflectance established prior to folding. *B*, Surfaces of equal vitrinite reflectance established subsequent to folding.

considerable amount of erosion indicates that significant post-Mahogany, late Eocene movement occurred on the anticline. Even in this relatively low structural position, the elevation of the Mahogany is 9,500 ft, very close to the 10,000±1,000-foot erosional surface. Post-Mahogany, late Eocene uplift on the Divide Creek anticline probably resulted in the removal of many thousands of feet of Paleocene and Eocene sediments from the top of the Divide Creek anticline. If thermal gradients remained unchanged, then this amount of erosion would have lowered formation temperatures over the Divide Creek anticline by as much as 50–100 °F. Because erosion appears to have been confined to the uplifted areas and probably did not affect the adjacent synclines, formation temperatures probably remained higher in the synclines until downcutting of the Colorado River began about 10 m.y. ago.

Application of Thermal Maturity Models to Southeastern Part of Piceance Basin

Observed variations in vitrinite reflectance values in the study area can be easily explained by using a time-dependent model. In such a model, the rate of vitrinite metamorphism after uplift and erosion would have been comparatively slow on the Divide Creek anticline and the Grand Hogback and vitrinite reflectance would be established by late Eocene time. In the adjacent synclines, on the other hand, little erosion has occurred and temperatures remained close to maximum values until 10 m.y. ago; as a result, vitrinite metamorphism would have continued at a comparatively rapid rate. This rapid rate of metamorphism would explain the presently observed, less steep vitrinite reflectance profiles in the synclines.

Observed variations in vitrinite reflectance can be explained by using a time-independent model if late Eocene uplift and erosion over the Divide Creek anticline and Grand Hogback occurred very rapidly. This rapid uplift would have frozen vitrinite reflectance values before they could equilibrate to maximum burial temperatures. The shift along the margins of the basin and over the Divide Creek anticline from slow subsidence to rapid uplift and erosion would have occurred in less than the equilibration period of from 10,000 to 1 million years; otherwise present-day vitrinite reflectance profiles would be the same on the Divide Creek anticline and the Grand Hogback as in the synclines.

SUMMARY

A more complete understanding of the burial history of the Divide Creek anticline may help determine the most appropriate thermal maturity model. Although lower Tertiary rocks have been eroded from the crest of the Divide Creek anticline, they are still preserved along the flanks, and careful mapping of key units along the flanks may better define thickening trends and help determine when the anticline was most active. Additional vitrinite reflectance data are needed to determine if the vitrinite reflectance profiles in this study are representative of the entire Piceance basin area. Additional vitrinite reflectance data are also needed for structurally higher levels on the Divide Creek anticline. In summary, the southeastern part of the Piceance basin provides considerable opportunities to investigate the processes of organic-matter metamorphism.

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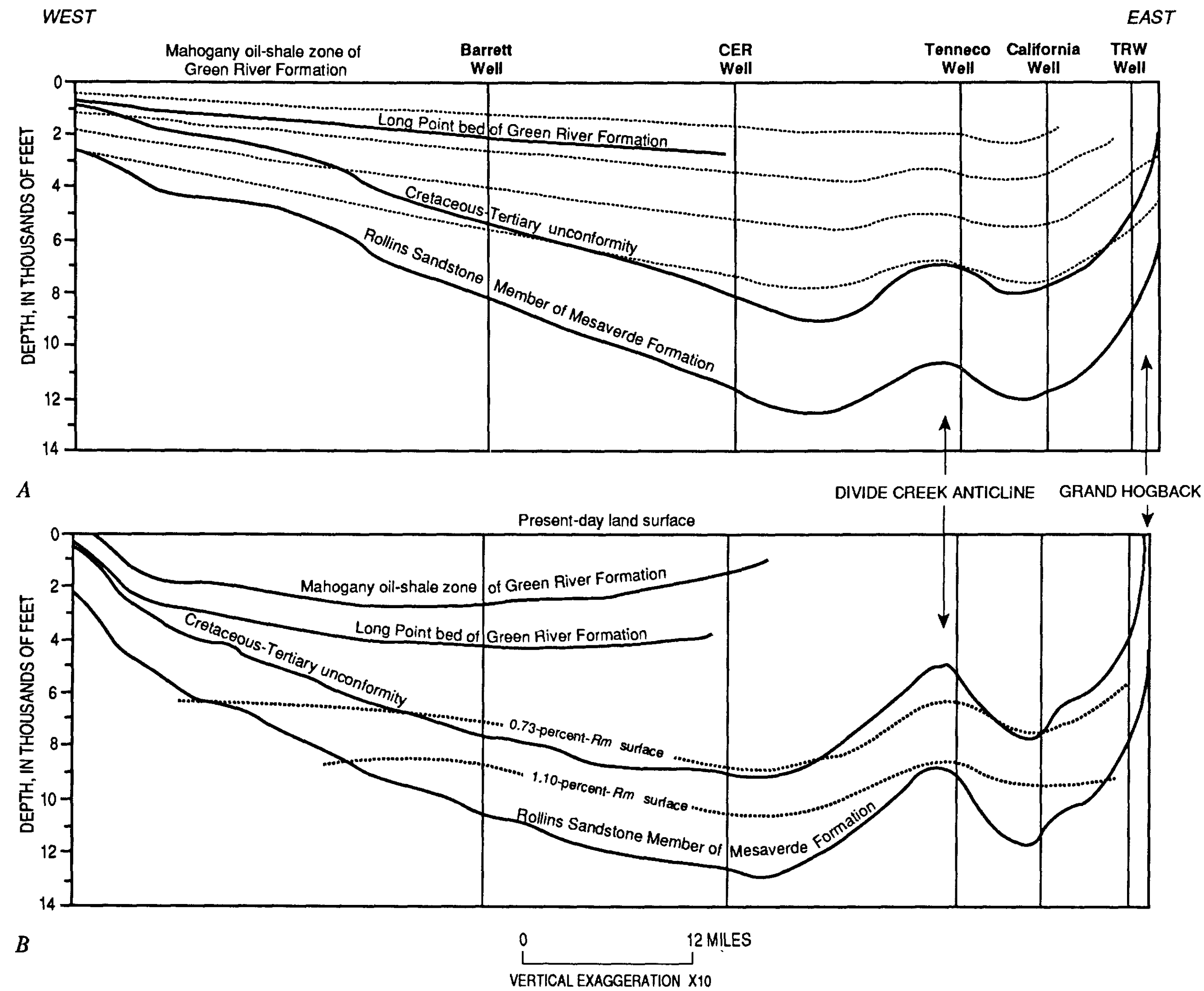

Figure 8. Cross sections showing traces of surfaces of equal vitrinite reflectance (Rm) (dotted lines) in relation to structure, Piceance basin, Colorado. *A*, 46 m.y. ago, during deposition of the middle Eocene Mahogany oil-shale zone. *B*, 10 m.y. ago, immediately prior to downcutting of the Colorado River. Line of section is that of plate 1 (shown on fig. 6), except that it extends farther east along Grand Hogback and farther west to near southwestern margin of Piceance basin.

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Chapter I

The Fryingpan Member of the Maroon Formation—A Lower Permian(?) Basin-Margin Dune Field in Northwestern Colorado

By SAMUEL Y. JOHNSON

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

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

CONTENTS

FIGURES

CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C = (temp °F–32)/1.8

The Fryingpan Member of the Maroon Formation— A Lower Permian(?) Basin-Margin Dune Field in Northwestern Colorado

By Samuel Y. Johnson

Abstract

The Early Permian(?) Fryingpan Member of the Maroon Formation mainly consists of quartz-rich, very fine to fine grained sandstone deposited in eolian dune and interdune environments. The unit has a maximum thickness of 123 meters and a restricted occurrence (about 80 square kilometers) adjacent to the northern flank of the Sawatch uplift in the northern part of the Aspen subbasin. The facies, dimensions, and basin-margin location of the Fryingpan Member dune field are similar to those of the modern dune field in the Great Sand Dunes National Monument in south-central Colorado. Eolian sand sheets and fluvial deposits of the Maroon Formation and the Schoolhouse Tongue of the Weber Sandstone to the north in the Eagle basin are the inferred sediment source. On the basis of stratigraphic, sedimentologic, and paleogeographic criteria, the Fryingpan Member (formerly called the sandstone of the Fryingpan River) is removed from the State Bridge Formation and assigned to the Maroon Formation.

INTRODUCTION

Freeman (1971a, 1972a,b) recognized a distinctive sandstone unit in the Woody Creek, Ruedi, Toner Reservoir, and Red Creek 7½-minute quadrangles of Eagle and Pitkin Counties, northwest Colorado. Freeman named this unit the sandstone of the Fryingpan River, mapped its restricted occurrence, inferred its eolian origin, and defined its stratigraphic position. He noted that its contact with the underlying Maroon Formation (Middle Pennsylvanian to Early Permian) was sharp and might be a very low angle unconformity, and he therefore proposed that the sandstone of the Fryingpan River be considered the lowest part of the overlying Permian and Early Triassic State Bridge Formation. Recently Johnson (1987a,b,c) showed that the Maroon Formation contains extensive eolian deposits and that the sandstone of the Fryingpan River has much closer affinity to the Maroon Formation than to the State Bridge Formation, which mainly consists of siltstone, sandstone, and claystone deposited in fluvial, marginal-marine and lacustrine environments (Freeman, 1971a; Freeman and Bryant, 1977). Accordingly, the sandstone of the Fryingpan River is here formally renamed the Fryingpan Member of the Maroon Formation. The purposes of this report are to define the stratigraphy of the Fryingpan Member and designate type and reference sections, to describe its lithology, and to interpret its sedimentology and paleogeography. These data and interpretations suggest that the Fryingpan Member formed as an ancient basin-margin dune field analogous to the modern basin-margin dune field in the Great Sand Dunes National Monument of south-central Colorado.

Acknowledgments.—Research for this paper was supported by the U.S. Geological Survey Evolution of Sedimentary Basins Program. Discussions with Val Freeman and with Christopher Schenk provided important input. Reviews by Freeman, Fred Peterson, and Karen Franczyk led to improvements in the manuscript and are greatly appreciated.

GEOLOGIC SETTING

Pennsylvanian and Early Permian tectonism in the Western United States resulted in development of the ancestral Rocky Mountains (Curtis, 1958; Mallory, 1972;

Tweto, 1977; Kluth and Coney, 1981; Kluth, 1986). Orogenic highlands in Colorado included the ancestral Uncompahgre and Front Range uplifts, which bounded the northwest-trending central Colorado trough, and the ancestral Sawatch uplift (DeVoto, 1972; DeVoto and others, 1986), which subdivided this trough into several subbasins (fig. 1). The Eagle basin, generally regarded as the area in the central Colorado trough north of the northern margin of the Sawatch uplift, is one of these subbasins. The Aspen subbasin (DeVoto and others, 1986) forms the area west of the Sawatch uplift and is a southern extension of the Eagle basin. During the Tertiary, both the Front Range and Sawatch blocks were uplifted (Tweto, 1977; Wallace and Naeser, 1986), whereas the Uncompahgre uplift was partly buried. The locations of the margins of these uplifts may have shifted from the Pennsylvanian to the Tertiary; as a result, the exact configurations of Pennsylvanian basins are not known.

Late Paleozoic deposition in the Eagle basin and the Aspen subbasin was strongly controlled by local tectonics, relative sea level changes, and climate (Mallory, 1971, 1972; Bartleson, 1972; Walker, 1972; Johnson, 1987a). The Maroon Formation, the Schoolhouse Tongue of the Weber Sandstone, and the State Bridge Formation form the late Middle Pennsylvanian to Early Triassic fill of these subbasins (fig. 2).

The Maroon Formation is mostly a sequence of nonmarine red beds. It may be as thick as 4,500 m in the Aspen subbasin (Freeman and Bryant, 1978); whereas, to the north in the Eagle basin, its thickness is considerably less, about 300 to 1,000 m (Johnson, 1987a). The diachronous contact between the Maroon Formation and underlying strata in part explains the major thickness variations. The Maroon Formation was

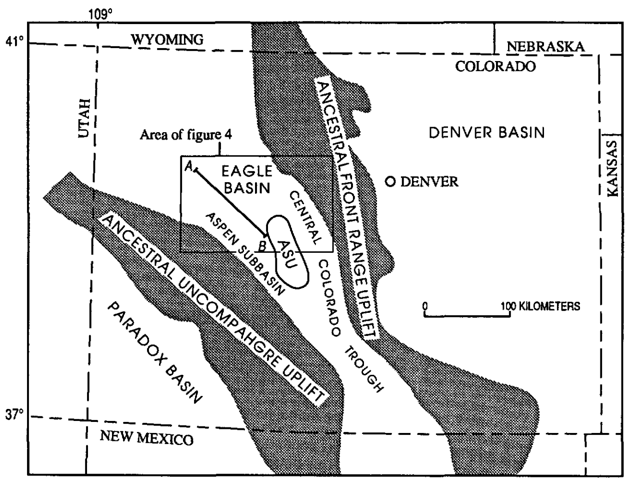

Figure 1. Location of ancestral Rocky Mountain highlands (hatching) and basins in Colorado. ASU, ancestral Sawatch uplift. Line of section *A–B* (fig. 2) also shown. Modified from Mallory (1972).

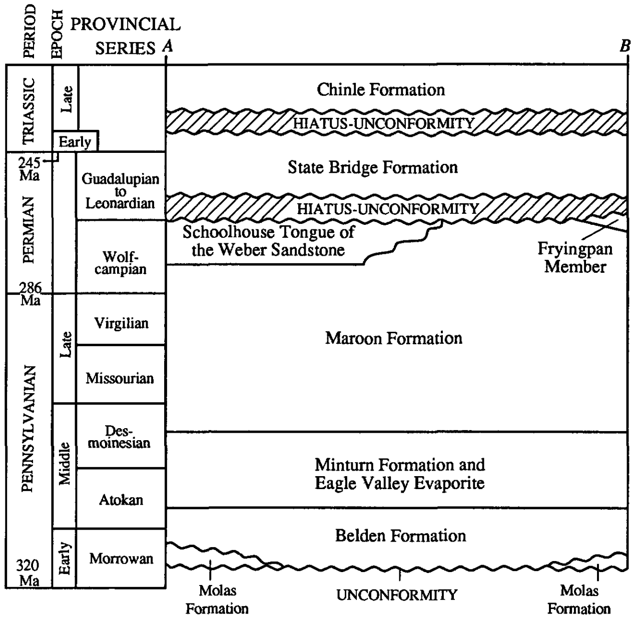

Figure 2. Stratigraphy of Pennsylvanian to lower Mesozoic deposits in Eagle basin and northern Aspen subbasin. Line of section *A–B* shown in figure 1.

deposited in mixed fluvial and eolian environments under strong climatic control (Johnson, 1987a,b,c,d). Fluvial sediments were deposited during more climatic humid intervals in braided river channels, in sheetfloods, and on floodplains. Eolianites are mainly sand-sheet deposits that formed by reworking of fluvial sediments during more arid climatic intervals. The sand-sheet deposits consist of plane- and low-angle-bedded, very fine to fine grained sandstone; abundant scattered granules and coarse sand grains are interpreted as deflation lags. These eolianites are abundant and typically compose 20–30 percent of Maroon stratigraphic sections (Johnson, 1987a). Paleowind directions determined from uncommon dune deposits indicate eolian sediment transport was mainly to the southeast (fig. 3). Some of the silt and very fine grained sand eroded from the Maroon sand sheets during major windstorms was deposited as loess along the northwest margin of the ancestral Sawatch uplift. This loessite is well exposed in the northern part of the Aspen subbasin near the Ruedi Reservoir (fig. 4), where it underlies the Fryingpan Member.

The Schoolhouse Tongue of the Weber Sandstone (as thick as 66 m) overlies and interfingers with the Maroon Formation over much of Eagle basin (fig. 4) but is not in the Aspen subbasin. The Schoolhouse Tongue is also mainly an eolian sand-sheet deposit of very fine to fine grained sandstone (Johnson, 1987a). It is differentiated from the Maroon Formation on the basis of its distinctive white or yellow-gray bleached color and its characteristic hydrocarbon staining. Freeman (1971b,

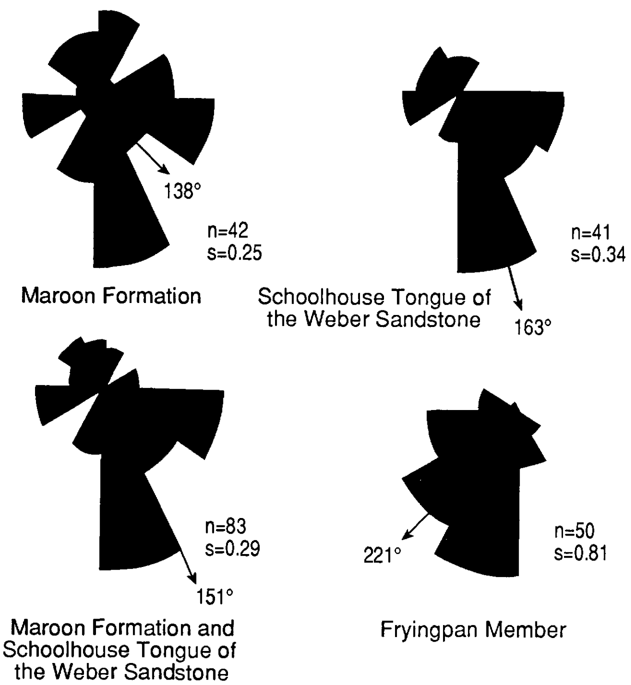

Figure 3. Paleowind indicators for Maroon Formation (exclusive of Fryingpan Member), Fryingpan Member, Schoolhouse Tongue of the Weber Sandstone, and Maroon Formation and Schoolhouse Tongue combined. Data from crossbed foresets (arrow is vector mean; n is number of observations; s is vector strength).

p. D80) pointed out that, in the central part of Eagle basin near Eagle (fig. 4), the contact between the Maroon Formation and the Schoolhouse Tongue of the Weber Sandstone is diagenetic in that it juxtaposes bleached and unbleached rock of otherwise similar lithologic character. This contact is similar in character throughout most of Eagle basin (Johnson, 1987a). Paleowind indicators (fig. 3) similarly indicate sediment transport to the south-southeast.

The Fryingpan Member has a restricted occurrence at the top of the Maroon Formation near Ruedi Reservoir on the west flank of the ancestral Sawatch uplift (fig. 4). It was first recognized by Freeman (1971a), who mapped it, named it the sandstone of the Fryingpan River, and considered it the basal part of the State Bridge Formation. It has a maximum thickness of about 123 m and consists mainly of reddish-orange, very fine to fine grained sandstone. Its stratigraphy, lithology, sedimentology, and distribution are discussed in following sections.

The Maroon Formation (including the Fryingpan Member) and the Schoolhouse Tongue of the Weber Sandstone are overlain by the State Bridge Formation (Brill, 1944) over most of the Eagle basin and the Aspen subbasin. The State Bridge varies in thickness from about 100 to more than 1,000 m (Freeman, 1971a; Tweto and others, 1978) and mainly consists of reddish-brown claystone and siltstone and minor sandstone. Beds are typically massive, ripple laminated, or plane laminated. Wavy bedding, lenticular bedding, flaser bedding, symmetric and asymmetric ripple marks, mudcracks, sole marks, flute casts, burrows, and thin (< 10 cm) horizons of rip-up clasts are all common. Thin (<1 m), lenticular sandstone bodies are common in the lower part of the State Bridge Formation in the Aspen subbasin. A thin dolomite bed, the South Canyon Creek Dolomite (Bass and Northrop, 1950), is in the lower part of the State Bridge Formation (23 m above the contact with the Maroon Formation in Box Canyon, about 15 km west of Ruedi Reservoir; fig. 4) over much of the Eagle basin and Aspen subbasin (Freeman and Bryant, 1977). Freeman (1971a) recognized and defined the Sloane Peak Member and the coarse unit of Toner Creek as discrete members in the upper part of the formation. The State Bridge Formation was mainly deposited in fluvial, marginal-marine, and lacustrine(?) environments (Freeman, 1971a).

The Maroon Formation and the Schoolhouse Tongue of the Weber Sandstone lack fossils that yield diagnostic ages. Limestones in the underlying Minturn and Gothic Formations and Eagle Valley Evaporite contain Middle Pennsylvanian (Desmoinesian) fossils (Tweto, 1949; Boggs, 1966; Mallory, 1971; Bartleson, 1972), and the South Canyon Creek Dolomite of the State Bridge Formation has yielded early Late Permian (Guadalupian) fossils (Bass and Northrop, 1950; M.E. MacLachlan, oral commun., 1987). A Middle Pennsylvanian to Early Permian age has therefore been assumed for the Maroon. In that the Schoolhouse Tongue of the Weber Sandstone and the Fryingpan Member are at the top of the Maroon, they are probably of Early Permian age. The contact between the Maroon Formation, or the Schoolhouse Tongue of the Weber Sandstone, and the State Bridge Formation, however, is locally unconformable (Freeman, 1971b). This unconformity has local angularity (as much as 60°; Freeman, 1971a, p. F6) and may represent a significant hiatus. If this is the case, then the Schoolhouse Tongue and the Fryingpan Member might conceivably be of Pennsylvanian age.

STRATIGRAPHY AND OCCURRENCE

The Fryingpan Member has a restricted occurrence in the northern part of the Aspen subbasin adjacent to the Sawatch uplift (Freeman, 1971a, 1972a,b; Freeman and Bryant, 1977) (fig. 4). It generally is resistant to erosion, typically forms vertical cliffs or underlies dip slopes, and commonly is covered by moss and other vegetation. The regional dip varies from about 5° to 25°. The best exposures are in slopes and roadcuts north of the Fryingpan River, about 1–5 km west of the Ruedi Dam. The unit thins from about 123 m in these

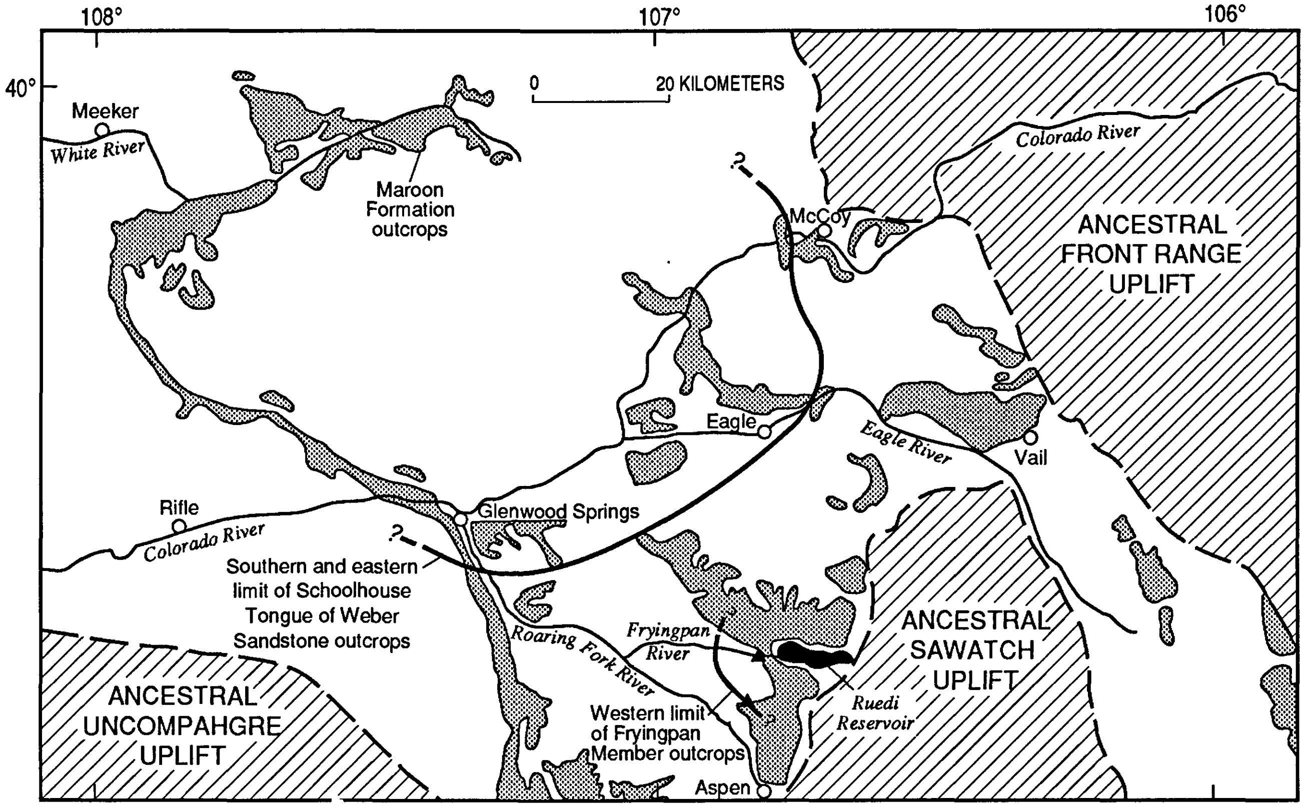

Figure 4. Location of outcrops of the Maroon Formation (screen pattern) and inferred extent (dashed lines) of occurrence of Fryingpan Member and Schoolhouse Tongue of Weber Sandstone in Eagle basin and Aspen subbasin. Northern triangle (west of Ruedi Reservoir) shows location of Fryingpan Member type section (fig. 5*A*); southern triangle shows location of reference section (fig. 5*B*).

outcrops to a pinchout about 5–6 km to the south-southwest and about 7–8 km to the west-northwest (Freeman, 1971a, 1972a,b; this study). These outcrops encompass an area of about 70 to 80 km^2. To the east and north of these outcrops, the Fryingpan Member has been eroded.

There is no continuous, well-exposed section of the Fryingpan Member near the Ruedi Dam where it has its maximum thickness. As a result, a composite section of the unit was measured (fig. 5*A*) and is here designated as the type section. The lower 84 m of the section was continuously measured in steep outcrops north of the Fryingpan River approximately 1,350–1,800 m west of the Ruedi Reservoir Dam (SW¼ sec. 12, NW¼ sec. 13, T. 8 S., R. 85 W.). The upper 39 m of the section was measured in a small, abandoned quarry north of the Fryingpan River about 820 m east of the mouth of Saloon Gulch (SE¼ sec. 11, T. 8 S., R. 85 W.). The locations of the lower 46 m and the upper 39 m of the type section are essentially the same as those measured by Freeman (1971a, p. F12) in less detail.

The contact between the Fryingpan Member and the underlying Maroon Formation in the Ruedi Dam area is locally well exposed (fig. 6). Below the contact at the type section, the upper Maroon consists of massive to faintly crossbedded and flatbedded siltstone to very fine grained sandstone interpreted as loessite (Johnson, 1987a,b,c). Above the contact, the Fryingpan Member consists of plane-bedded and crossbedded, very fine to fine grained sandstone also of eolian origin (Freeman, 1971a; this report). The contact itself is concordant, fairly abrupt, and characterized by gentle, low-angle, undulating relief. Similar relief is common between beds in the underlying Maroon Formation loessites. No evidence was found to support Freeman's (1971a, p. F8) suggestion that this contact might be an angular unconformity of very low angle. The contact between the Fryingpan Member and the overlying and less resistant reddish-brown siltstone and claystone of the State Bridge Formation is generally marked by a break in slope. This contact appears sharp and probably is disconformable.

A reference section of the Fryingpan Member (fig. 5*B*) was measured about 5 km south-southwest of the type section above a logging road in the Dry Woody Creek drainage (NE¼ sec. 34, T. 8 S, R. 85 W). The section is 1,360 cm thick and is complete; its thickness demonstrates the rapid thinning of the unit away from the type section. The contact between the Fryingpan

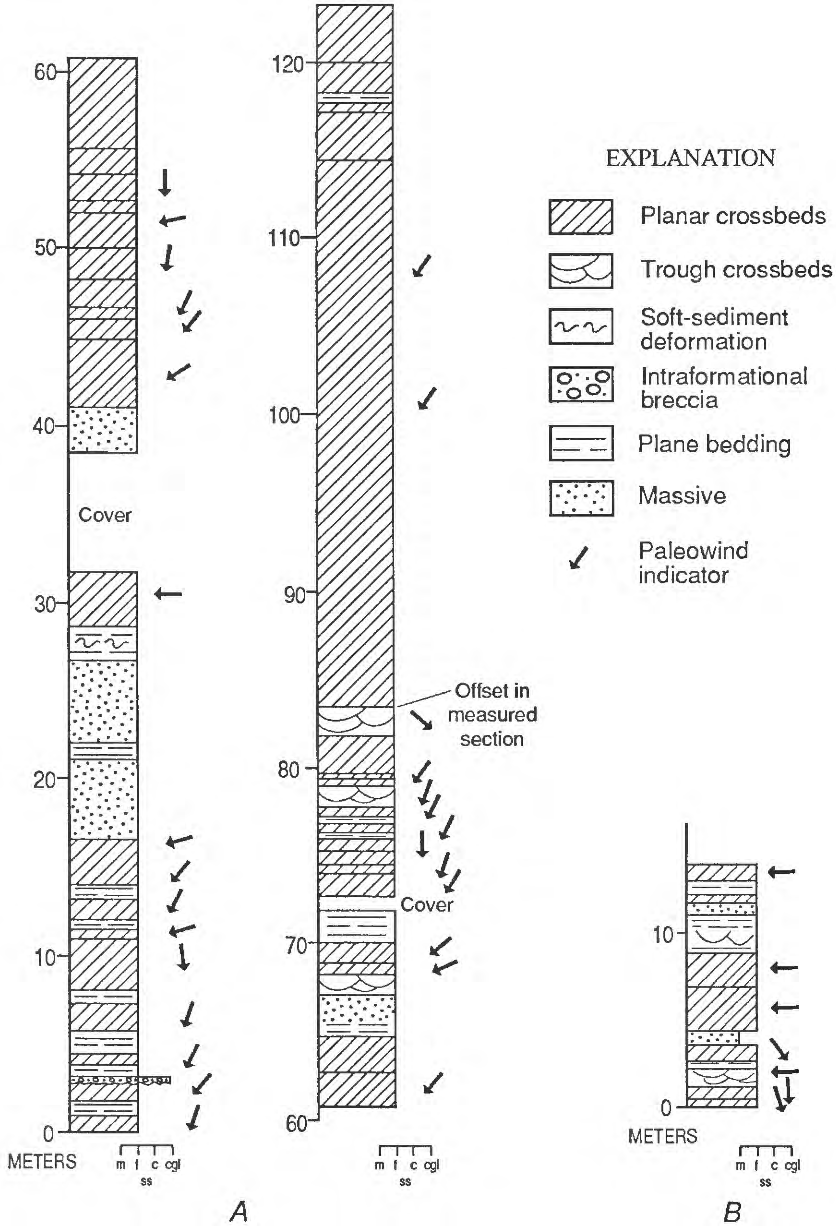

Figure 5. Stratigraphic column showing type section (*A*) and reference section (*B*) for the Fryingpan Member of Maroon Formation. Grain size (sections are almost completely homogeneous, very fine to fine-grained sandstone) shown on horizontal scale (m, mudstone; f, fine-grained sandstone; c, coarse-grained sandstone; cgl, conglomerate). Geographic locations of sections described in text.

Member and the underlying Maroon Formation is well exposed (fig. 7); massive siltstone and very fine grained sandstone of the Maroon are gradationally overlain by plane-bedded and crossbedded, very fine to fine grained sandstone of the Fryingpan Member. The contact between the Fryingpan Member and the overlying State Bridge Formation is covered, marked by a break in slope, and probably disconformable.

SEDIMENTOLOGY

The Fryingpan Member consists of well-sorted, moderate-reddish-orange, very fine to fine grained sandstone, and less common siltstone, medium- to coarse-grained sandstone, and breccia. Crossbedded sandstones interpreted as eolian dune deposits and plane-laminated to massive sandstones interpreted as

Figure 6. Contact between siltstone of Maroon Formation and the Fryingpan Member, exposed at base of Fryingpan Member type section.

Figure 7. Contact between very fine grained sandstone of Maroon Formation and fine-grained sandstone of Fryingpan Member exposed at base of Fryingpan Member reference section. View looking northeast.

interdune deposits comprise the two principal facies in the type section. The eolian interpretation is based mainly on the thickness of crossbed sets and on the abundance of diagnostic eolian stratification types.

Thick sets of planar crossbeds and scarce trough crossbeds (planar:trough = 18:1) dominate the type section. Sets are typically 0.5–3 m thick (figs. 8, 9); however, a 30-m-thick set of crossbeds (fig. 10) is in the upper part of the section. If this thick set of crossbeds is not considered, the mean set thickness is 1.65 m. Trough crossbedded strata form three intervals (1.2–2.4 m thick); trough widths are as much as 3–5 m and heights are as much as 1.0 m. Planar and trough crossbed foresets typically dip 15° to 30°; dip orientations indicate sediment transport to the southwest (fig. 3).

Foreset laminae of eolian grainflow, grainfall, and ripple origin (Hunter, 1977) were all observed, but the variable quality of outcrop exposures precludes accurate determination of the relative proportion of these diagnostic eolian stratification types. Grainflow laminae (figs. 8, 9) are abundant, particularly in thicker (< 1 m)

Figure 8. Crossbedded dune deposits and plane-bedded interdune deposits. Sandflow toes at base of two crossbed sets in center of photograph form tangential contacts with lower bounding surfaces. Note planar to undulating character of bounding surfaces (marked with arrows). Hammer (right center) shown for scale. View looking northwest, Fryingpan Member type section.

Figure 9. Planar crossbedded dune deposits and plane- to low-angle-bedded interdune deposits (top of photo). Note sandflow toes at base of crossbed sets. Bounding surfaces marked with arrows. Hammer shown for scale. View looking northwest, Fryingpan Member type section.

crossbed sets having relatively steep (< 25°) dips. Grainflow laminae typically form lenses having slightly convex-up upper contacts; sandflow toes whose bottom sets form tangential contacts with underlying bounding surfaces are common. Laminae of inferred grainfall origin are less conspicuous and generally form relatively tabular strata that thin down the foreset surface or that evenly drape irregular, low-angle (15°–25°) foreset surfaces. Eolian ripple laminae (fig. 11) are most common in relatively thin sets of crossbeds (< 150 cm) as well as in interdune deposits. These laminae are thin (< 1 cm) and inversely graded, generally lack ripple-form laminae, and resemble the subcritical translatent laminae of Hunter (1977).

Crossbed bounding surfaces are generally planar to slightly undulatory and juxtapose sets of crossbeds with one another or with interdune deposits. Crossbed sets can generally be traced laterally to the limits of the outcrops (as much as a few tens of meters). In a few cases, crossbeds are laterally continuous with low-angle beds of inferred interdune origin.

Strata interpreted as interdune deposits are generally plane laminated or massive. These facies are common in the lower part of the type section and decrease upward in abundance (fig. 5). Plane laminations (fig. 11) are thin (< 1 cm) and inversely graded and rarely include low-angle ripple-form laminae; they resemble the subcritical translatent laminae of Hunter (1977) and almost certainly formed by migration of eolian ripples. Soft-sediment deformation structures (figs. 12, 13), rare bioturbation traces (burrows and trails), irregular carbonate-cemented nodules (figs. 13, 14), and asymmetric ripple marks suggest that interdune areas were periodically wet and (or) saturated. The massive character of some beds might either reflect deposition of eolian detritus from suspension in shallow standing bodies of water or destruction of primary stratification by bioturbation and phytoturbation. A 30–cm-thick discontinuous lens of intraformational breccia is 2.5 m above the base of the type section (fig. 5) and probably formed in a small ephemeral stream channel. Clasts are mainly carbonate cemented siltstone.

Facies identical to those described above for the type section compose the 1,360-cm-thick reference section (fig. 5*B*). Sets of crossbeds interpreted as dune deposits are as thick as 250 cm and include foreset laminae of inferred grainflow, grainfall, and eolian origin. Strata interpreted as interdune deposits are similarly plane laminated or massive and include an 80-cm-thick siltstone bed.

PETROLOGY

Sand grains are dominantly (> 85 percent) quartz. Grains are rounded to well rounded and contain abundant vacuoles. Nonquartz grains are mainly orthoclase feldspar; plagioclase feldspar is present but uncommon. In samples characterized by thin, graded laminae, feldspar is common in the fine-grained layers and nearly absent in the coarser layers. Grains form an interlocking mosaic, due mostly to quartz overgrowth cementation. Feldspar overgrowths were observed on a few orthoclase grains but are rare. Primary interparticle porosity estimated from thin sections varies from about 5 to 15 percent.

DISCUSSION

The Fryingpan Member is here removed from the State Bridge Formation and assigned to the Maroon Formation on the basis of related stratigraphic, sedimentologic, and paleogeographic criteria. First, the contact between the Maroon Formation and the Fryingpan Member is conformable. Second, the Fryingpan Member has an eolian origin and therefore has greater affinity

Figure 10. Thick (30 m) set of crossbeds forming dune deposit at top of Fryingpan Member type section. Planar surfaces in foreground are crossbed foresets. Regional dip about 5°. View looking northeast, top of Fryingpan Member type section.

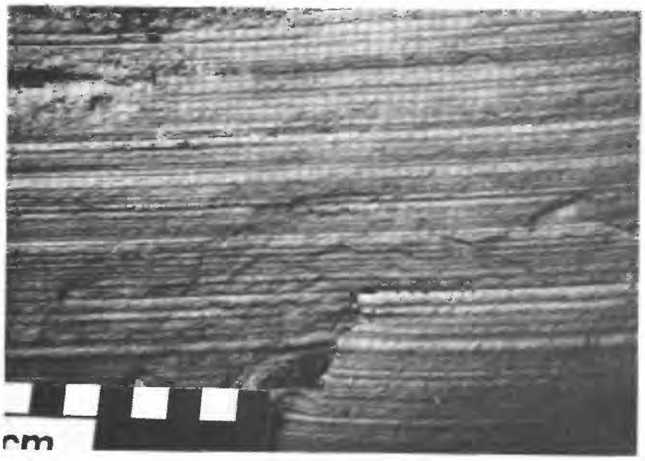

Figure 11. Thin, inversely graded, planar laminations in inferred interdune deposits, Fryingpan Member type section. Laminations were probably produced by migration of eolian ripples and represent subcritical translatent stratification of Hunter (1977).

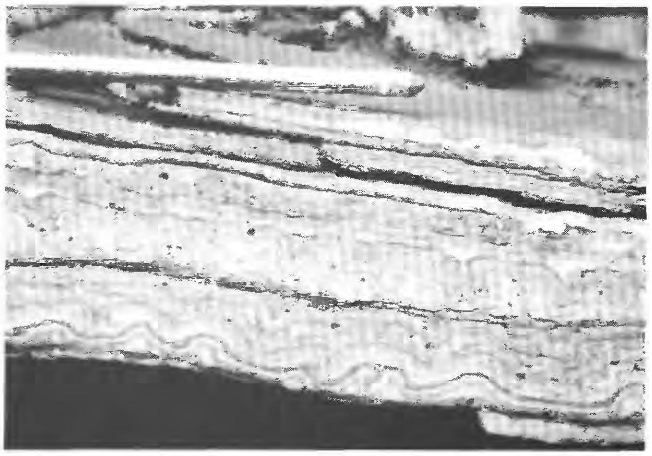

Figure 12. Two deformed horizons of convolute laminations in interdune deposits, Fryingpan Member type section. Structures in the two horizons are not connected, indicating that the deformation occurred in two discrete events. Overlying plane-laminated strata are undeformed. Pencil shown for scale.

with the partly eolian Maroon Formation than with the fluvial, marginal-marine, and lacustrine(?) State Bridge Formation. The sedimentologic discontinuity between the State Bridge Formation and the Fryingpan Member is much greater than that between the Maroon Formation and the Fryingpan Member. Third, paleowind data from the Maroon Formation and the Schoolhouse Tongue of the Weber Sandstone indicate sediment transport toward the Fryingpan Member outcrop belt, and thus provide a source of dune sand for these eolianites. In contrast, there is no obvious source for well-rounded dune sands in the siltstone- and claystone-

Figure 13. Irregular carbonate-cemented lens in deformed interval of interdune deposits, Fryingpan Member type section. Beds at top and top right of photograph show regional dip. Hammer in the same location in figure 14.

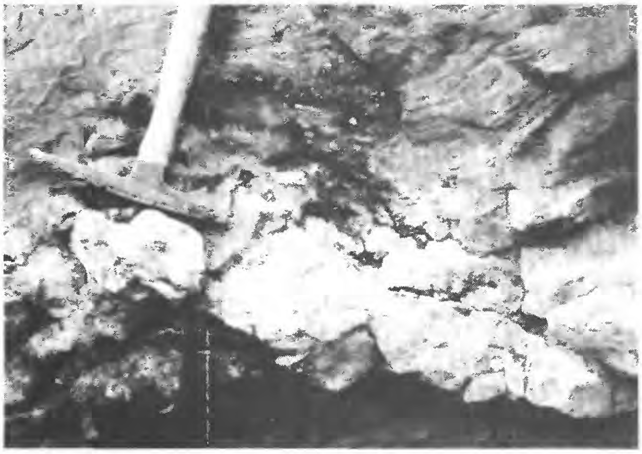

Figure 14. Closeup view of carbonate-cemented lens shown in figure 13.

dominated marine and lacustrine deposits of the State Bridge Formation.

As with loessites in the Maroon Formation (Johnson, 1987a,b,c), the ancestral Sawatch uplift probably formed the topographic barrier needed to halt transport of sediment derived from northern sources and to initiate deposition. The geographic setting for the dune deposits of the Fryingpan Member is therefore similar to that of the modern dune field at Great Sand Dunes National Monument in south-central Colorado (Johnson, 1967; Andrews, 1981). This modern dune field fills an embayment in the Sangre de Cristo Mountains through which the prevailing southwesterly winds are funnelled.

In addition to a comparable basin-margin location, the dimensions, facies, and sediment sources of this modern dune field are similar to those of the inferred Fryingpan Member dune field. The dune field at Great Sand Dunes (Province III of Andrews, 1981, fig. 1) consists of deposits 100–180 m thick and occupies about 100 km^2. The Fryingpan Member has a maximum thickness of 123 m and its outcrop belt encompasses 70–80 km^2. The stratigraphic level of the Fryingpan Member has been eroded to the east, and if it is assumed that the dune field extended eastward to the margin of the Sawatch uplift and that the modern margin of this uplift matches its Pennsylvanian margin, then the Fryingpan Member dune field may have covered as much as 200 km^2. At Great Sand Dunes and in large parts of the Fryingpan Member section, the proportion of interdune deposits is relatively low. Andrews (1981) attributed this phenomenon to close spacing of dunes resulting from proximity to the topographic obstacle presented by the uplifted basin margin, the Sangre de Cristo Mountains. Finally, the sediment source for both the Fryingpan Member and the dune field at Great Sand Dunes is inferred to be fluvial and sand-sheet deposits in the main part of the basin.

Paleowind patterns for the Fryingpan Member (fig. 3) are parallel with the inferred trend of the flanking basin margin, whereas Andrews (1981, fig. 8) reported that cross beds in the dune field at Great Sand Dunes National Monument have highly variable orientations but a dominant eastward dip toward the basin margin. The discrepancies between the two systems and the paleowind directions for the Fryingpan Member are perplexing because, for each system, the uplifted basin margin provides (or is inferred to have provided) the obstruction needed for concentrating sand derived from upwind sources and for dune development. The exact relief and configuration of the ancestral Sawatch uplift are not known, however, and the modern Sawatch uplift protrudes westward a few kilometers south of the Fryingpan Member outcrop belt. If this protrusion is a late Paleozoic relict, it may have restricted eolian sediment transport or helped generate a local wind cell that created conditions favorable for development of south-southwest-facing dunes.

The Fryingpan Member at the type section overlies loessites of the Maroon Formation. The termination of loess deposition and the initiation of dune deposition were probably forced by a cessation or slowing of subsidence in the Eagle basin and Aspen subbasin, the source area for Fryingpan Member sands. Rather than being rapidly buried beneath the Maroon alluvial-eolian plain, sands in this source area were exposed at the surface and made susceptible to eolian erosion and transport for longer time intervals. Consistent with this interpretation, thick beds of coarse to granular sand interpreted as deflation lags are present at inferred correlative stratigraphic horizons (the uppermost

Maroon Formation and the Schoolhouse Tongue of the Weber Sandstone) in the Eagle basin to the north. It is possible that deposition of the upper part of the Fryingpan Member occurred in the time gap represented by the unconformity between the Maroon and State Bridge Formations in the rest of the basin.

CONCLUSIONS

The Early Permian(?) Fryingpan Member mainly consists of quartz-rich, very fine to fine grained sandstone deposited in eolian dune and interdune environments. This unit has a restricted occurrence adjacent to the northwest flank of the Sawatch uplift and likely formed as a basin-margin dune field analogous to the modern dune field in the Great Sand Dunes National Monument in south-central Colorado. Eolian sand sheets of the Maroon Formation and the Schoolhouse Tongue of the Weber Sandstone to the north in the Eagle basin are the sediment source. On the basis of stratigraphic, sedimentologic, and paleogeographic criteria, the Fryingpan Member is here assigned to the Maroon Formation.

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