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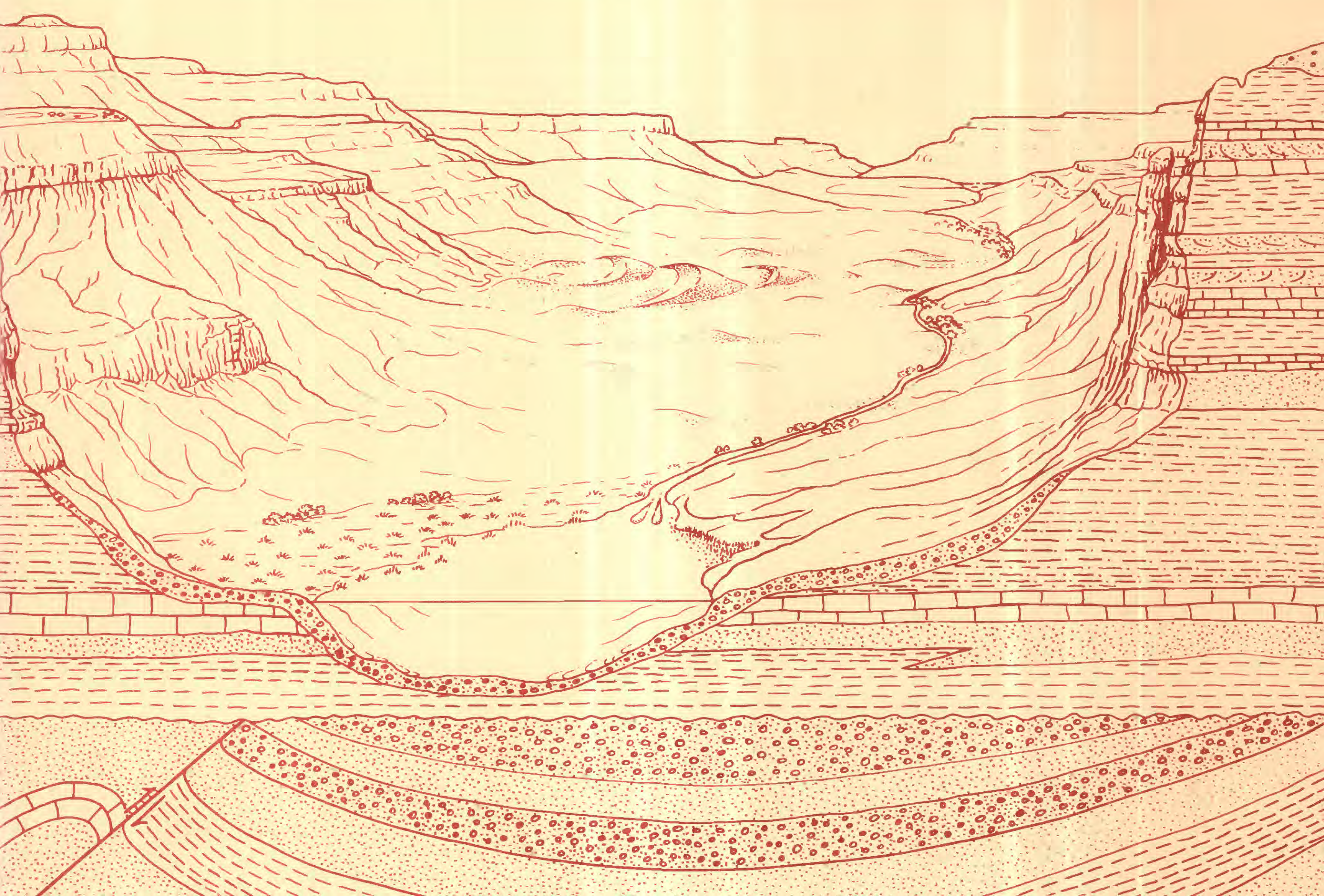
Burial Reconstruction of the Early and Middle Pennsylvanian Belden Formation, Gilman Area, Eagle Basin, Northwest Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 1787–A–C



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EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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Chapter A

Sedimentology and Paleogeographic Significance of Six Fluvial Sandstone Bodies in the Maroon Formation, Eagle Basin, Northwest 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

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PLATE

FIGURES

METRIC CONVERSION FACTORS

To convert from	To	Multiply by
Centimeter (cm)	Inch (in.)	0.39
Meter (m)	Feet (ft)	3.28
Kilometer (km)	Mile (mi)	.62
Gram (g)	Ounce avoirdupois (oz)	.03527
Kilogram (kg)	Pound avoirdupois (lb)	2.205
Degrees Celsius (°C)	Degrees Fahrenheit (°F)	Temp °F=1.8 (Temp °C+32)

Sedimentology and Paleogeographic Significance of Six Fluvial Sandstone Bodies in the Maroon Formation, Eagle Basin, Northwest Colorado

By Samuel Y. Johnson

Abstract

Architectural element analysis is used to examine the sedimentology of six fluvial sandstone bodies from the Pennsylvanian and Permian Maroon Formation in the Eagle basin, northwest Colorado. Five of these sandstone bodies were derived from the ancestral Uncompahgre uplift on the southwestern basin margin and occupy similar stratigraphic positions in the upper part of the Maroon Formation. The sixth sandstone body was derived from the ancestral Front Range uplift and, although in the lower part of the Maroon Formation section, is considered representative of the sedimentation style of the upper Maroon at its location.

The two sandstone bodies located closest to the basin margins consist of channel and gravel-barform architectural elements of conglomerate and conglomeratic sandstone and are interpreted as proximal braided-river deposits. Three medial sandstone bodies are dominated by foreset-macroform and sand-bedform architectural elements of fine- to coarse-grained sandstone and represent deposition in sandy braided streams. The most distal sandstone body comprises a laminated-sandsheet element of very fine to fine-grained sandstone and was deposited by sheetfloods over a low-relief mudflat. Facies changes suggest downstream decreases in depth, flow strength, and discharge, characteristics that have been noted for some modern and ancient fluvial systems in arid to semiarid basins. Facies and paleocurrent data indicate that during late Maroon time the depositional axis of the Eagle basin was probably strongly skewed to the northeast and located in the vicinity of the Vail-McCoy trough.

INTRODUCTION

The goal of this basin analysis study is to reconstruct the fluvial depositional system of the upper part of the Pennsylvanian and Permian Maroon Formation in the Eagle basin, northwest Colorado (fig. 1). This goal is mainly accomplished through "architectural element analysis," a method of sedimentary-facies analysis (Allen, 1983; Miall, 1985) that emphasizes recognition of the lateral characteristics of fluvial sandstone bodies and allows increased resolution of their depositional history and setting. Six fluvial sandstone bodies were analyzed and interpreted as the deposits of proximal and medial braided rivers, and mudflats. The distribution of these facies suggests that the upper Maroon fluvial system(s) generally decreased in depth, flow strength, and discharge in the downstream direction.

Acknowledgments.—This paper has benefited from constructive reviews by Thomas E. Moore and Christopher J. Schenk, U.S. Geological Survey. The work on which this report is based was done as part of the U.S. Geological Survey Evolution of Sedimentary Basins Program.

REGIONAL GEOLOGY

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). Orogenic highlands in Colorado include the ancestral Uncompahgre and Front Range uplifts, which bound the northwest-trending central Colorado trough, and the ancestral Sawatch uplift (DeVoto, 1972), which subdivided this trough into several subbasins (fig. 1). The Eagle basin, generally regarded as the area in the central Colorado trough where the Middle Pennsylvanian Eagle Valley Evaporite occurs, is one of these subbasins. In this report, the Eagle basin is defined as the part of the central Colorado trough north of the ancestral Sawatch uplift and south of the northern boundary of the Laramide White River uplift (fig. 2). The Pennsylvanian and Permian strata in Eagle basin dip to the west and northwest off the White River uplift into the subsurface below the Paleogene Piceance basin. Deposition in Eagle basin was strongly controlled by local tectonics, relative sea-level changes, and climate (Mallory, 1971, 1972; Bartleson, 1972; Walker, 1972).

The Belden Formation, mostly a dark-gray or black shale of deltaic and shallow marine origin, comprises the oldest (Early and early Middle Pennsylvanian) sediments

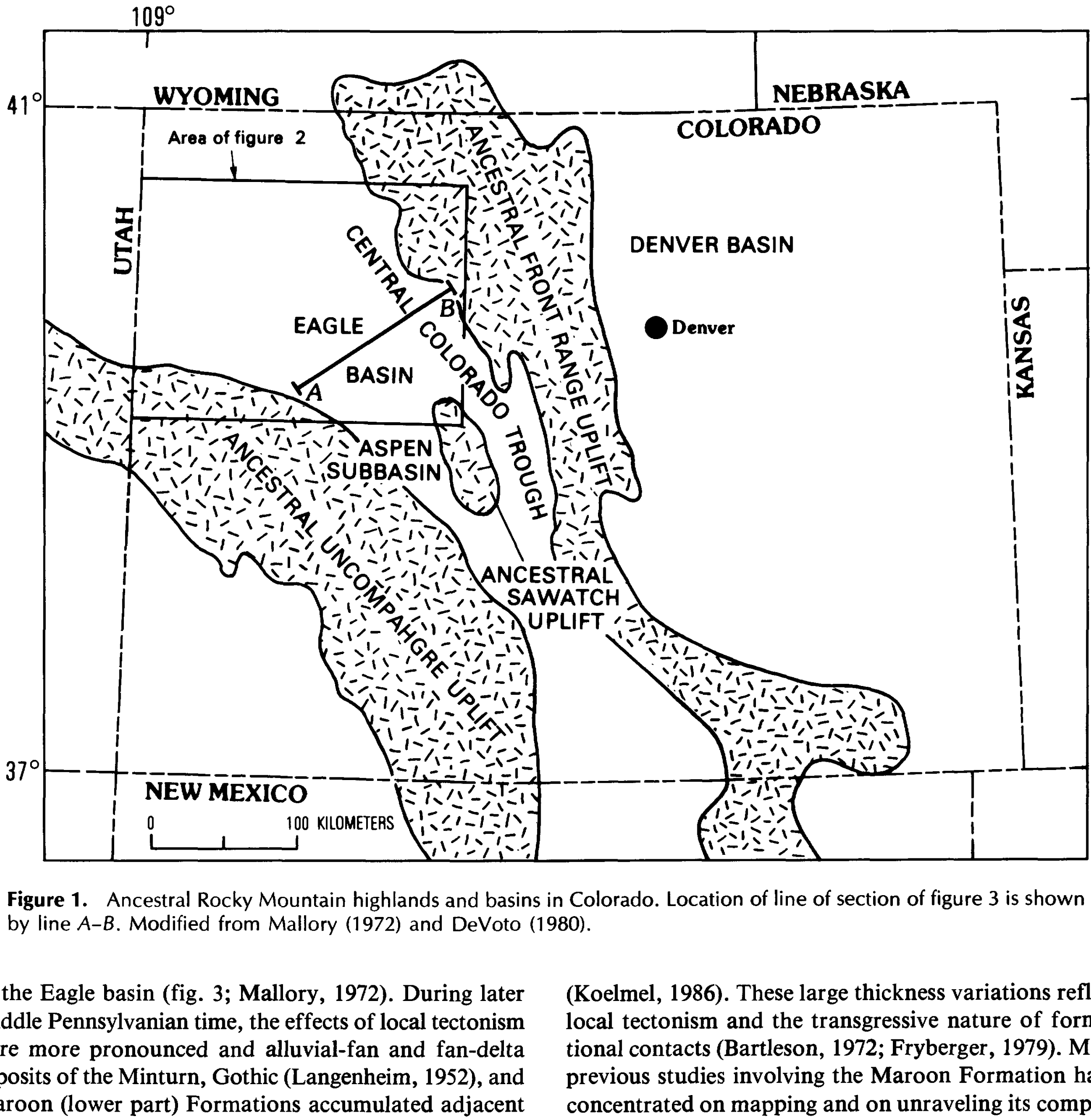

Figure 1. Ancestral Rocky Mountain highlands and basins in Colorado. Location of line of section of figure 3 is shown by line *A–B*. Modified from Mallory (1972) and DeVoto (1980).

of the Eagle basin (fig. 3; Mallory, 1972). During later Middle Pennsylvanian time, the effects of local tectonism were more pronounced and alluvial-fan and fan-delta deposits of the Minturn, Gothic (Langenheim, 1952), and Maroon (lower part) Formations accumulated adjacent to the basin margins. These basin-margin facies include shallow-marine limestones that pass laterally into evaporite and clastic deposits of the Eagle Valley Evaporite in the center of the basin (Mallory, 1971; Schenk, unpublished data, 1986). Nonmarine rocks of the upper part of the Maroon Formation comprise the Late Pennsylvanian and Early Permian part of the basin sediments and are the subject of this paper. The nonmarine Permian Schoolhouse Tongue (Brill, 1952) of the Weber Sandstone overlies and interfingers with the Maroon Formation in most of the Eagle basin.

In the Aspen subbasin, west of the Sawatch uplift (figs. 1, 2), the Maroon Formation is as thick as 4,600 m (Freeman and Bryant, 1977), whereas in the Eagle basin to the north the Maroon is only about 200–1,000 m thick (Koelmel, 1986). These large thickness variations reflect local tectonism and the transgressive nature of formational contacts (Bartleson, 1972; Fryberger, 1979). Most previous studies involving the Maroon Formation have concentrated on mapping and on unraveling its complex stratigraphic relationships (see, for example: Brill, 1944; Langenheim, 1954; Mallory, 1958, 1972; Bartleson and others, 1968; Bartleson, 1972; Freeman and Bryant, 1977; DeVoto, 1980). Detailed sedimentologic studies of the Maroon are mostly lacking.

ANALYSIS OF FLUVIAL SANDSTONE BODIES

Since the early 1960's, when fining-upward sequences were first recognized in fluvial rocks (Bernard and Major, 1963; Allen, 1964), environmental interpretation of ancient fluvial deposits has relied heavily on recognition of vertical sedimentation cycles and comparison with a proliferating spectrum of vertical-profile

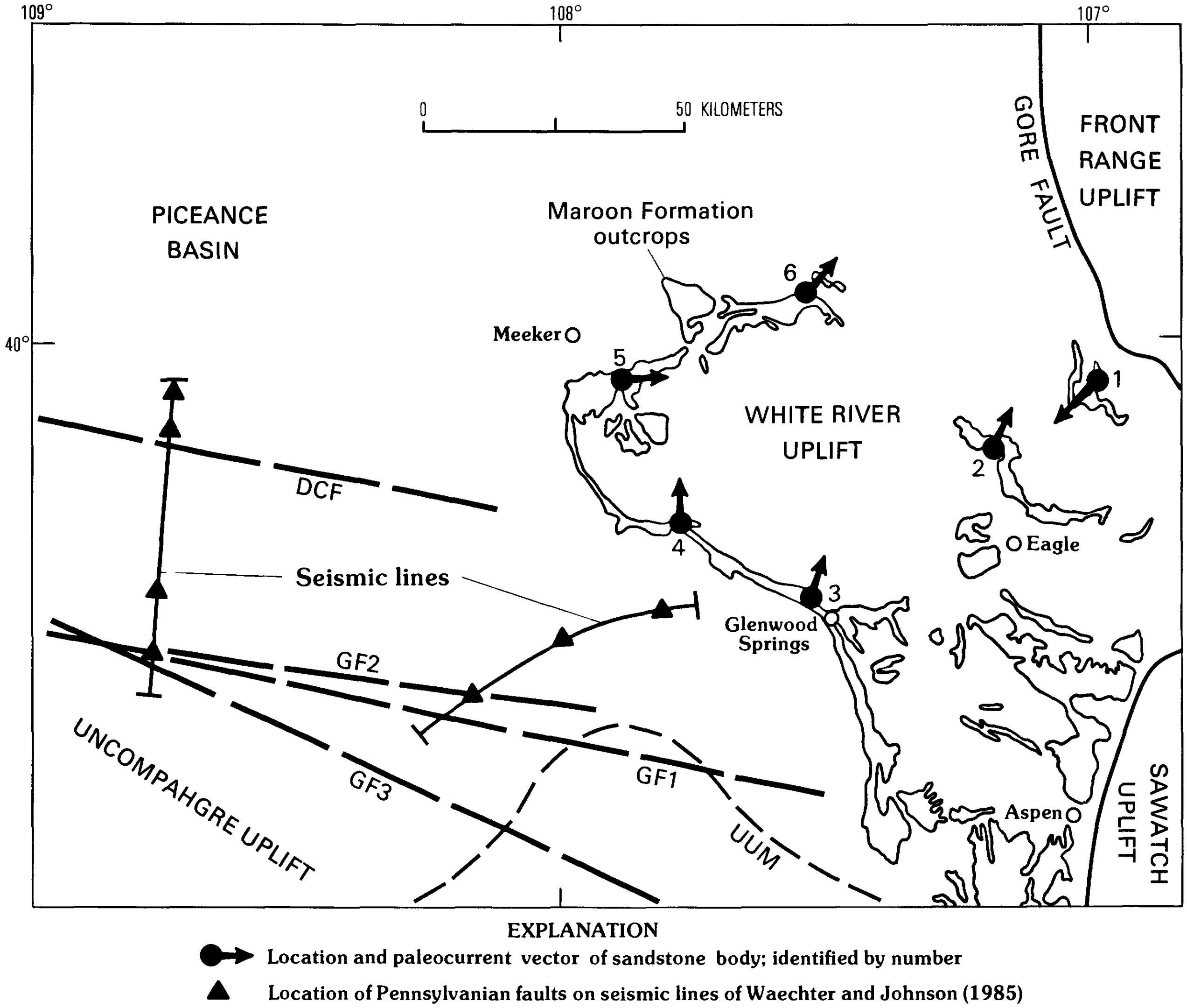

Figure 2. Locations of outcrops of Pennsylvanian and Permian Maroon Formation and sandstone bodies described in report. **DCF**, Douglas Creek fault of Stone (1969); **GF1**, Garmesa fault zone of Stone (1969); **GF2**, Garmesa fault zone, as inferred from seismic lines of Waechter and Johnson (1985); **GF3**, northeastern edge of ancestral Uncompahgre uplift, as inferred by Koelmel (1986); **UUM**, northwestern border of ancestral Uncompahgre uplift, as inferred by Mallory (1971). Area of map shown in figure 1.

facies models (see, for example: Miall, 1977, 1978; Walker and Cant, 1979). Widespread use of these models has been accompanied by growing awareness that the method does not provide sufficient consideration both of outcrop data related to the internal geometry and structure of fluvial sandstone bodies, and of the effects that variable subsidence rate, climate, and sediment supply can have on development of vertical sequences (see, for example: Allen, 1978, 1983; Jackson, 1978; Bridge and Leeder, 1979; Miall, 1985). Allen (1983) recognized these problems and erected a new methodology for analyzing sandstone bodies of the Brownstones (Old Red Sandstone) of the Welsh Borders that is based on recognition of "architectural elements" in lateral profiles. Consideration of this lateral dimension allowed recognition of large-scale, laterally and vertically accreting bedforms such as bars, bar complexes, and sand sheets, data essential for accurate reconstruction of ancient fluvial systems. Other recent significant contributions describing and interpreting the internal geometry and lateral characteristics of fluvial deposits have been made by Friend and others (1979), Allen and Matter (1982), Friend (1983), Hazeldine (1983), Allen and others (1983), and Ramos and Sopena (1983). Drawing on these studies, Miall (1985, p. 268) recently suggested that all fluvial deposits can be divided into eight architectural elements and that study of the geometry and organization of these elements provides a key to interpretation of depositional environment. Miall named this method "architectural element analysis."

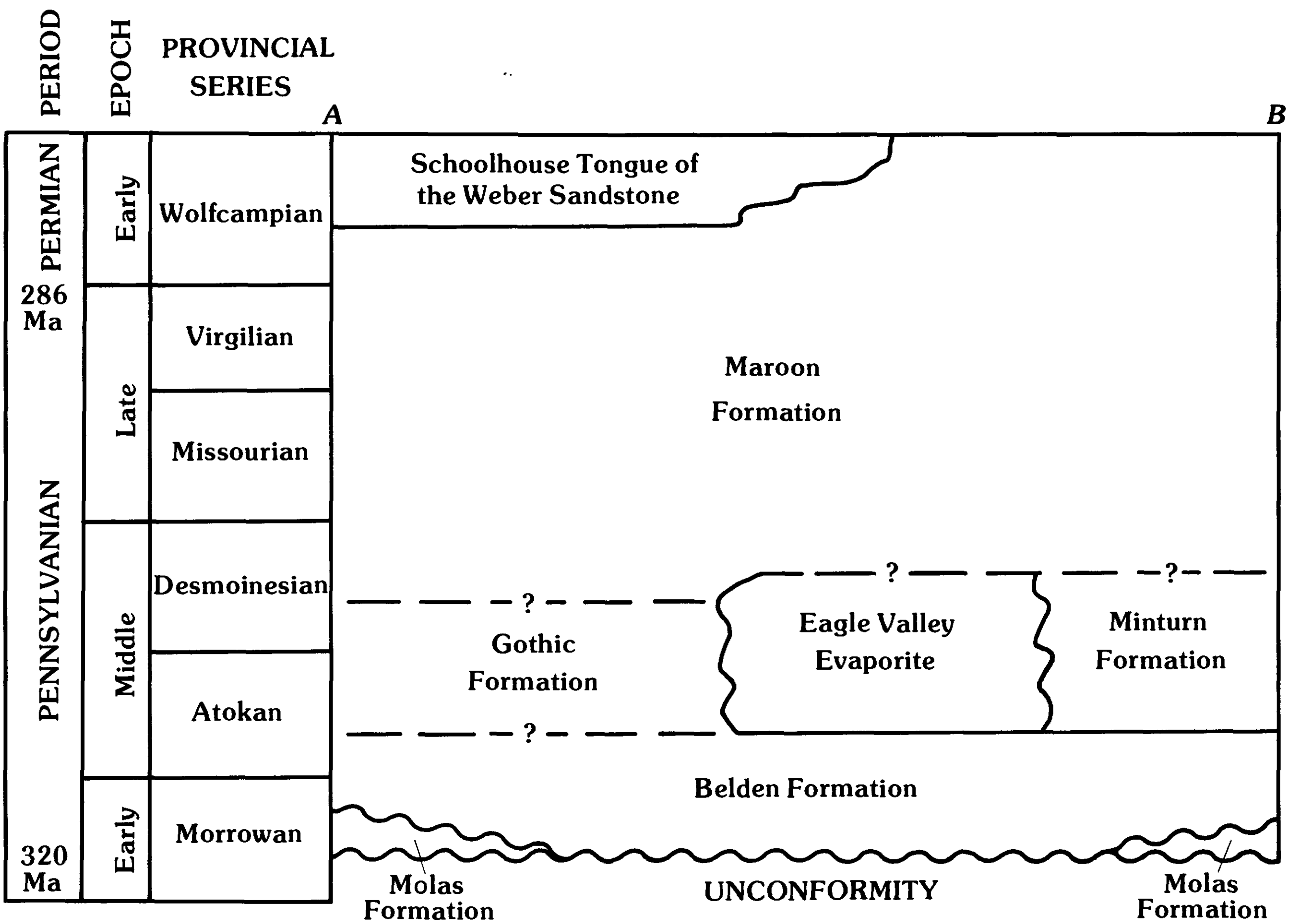

Figure 3. Schematic time-stratigraphic section of Pennsylvanian and Lower Permian rocks, Eagle basin. Dashed lines and queries indicate location of boundary is uncertain. Location of line of section is shown in figure 1.

Allen (1983) presented detailed lateral profiles of 11 sandstone bodies from the middle to upper Brownstone exposed in road cuts within a few kilometers of the town of Ross-on-Wye. These profiles provide a detailed look at sedimentation style, depositional environment, and paleohydrology at one location in the Old Red Sandstone basin. In contrast, the work presented here examines representative sandstone bodies from the Maroon Formation at six different locations in the Eagle basin (figs. 2, 4). Significant variations between these sandstone bodies highlight basin-wide changes in sedimentation style and provide important data for basin reconstruction.

METHODS

The Maroon Formation forms scattered outcrops in the northern Eagle basin on the margins of the White River uplift (fig. 2). The locations of the six sandstone bodies described in this paper were selected for their geographic distribution (fig. 4) and quality of exposure. At each location, the Maroon consists of sheetlike coarse-grained intervals of sandstone and conglomeratic sandstone (sandstone bodies) interbedded with fine-grained intervals of reddened, very fine to fine-grained sandstone and (or) mudstone. Because the thickness of the Maroon varies, its contact with the overlying Weber Sandstone was used as a datum for establishing relative stratigraphic position between locations. This contact is probably time transgressive (see, for example: Fryberger, 1979) but is nevertheless the best approximation of a time line or marker horizon for this area and stratigraphic interval.

At locations 2–6, the upper 150 m of the Maroon Formation was traversed, and the best exposed sandstone body (from 21 to 130 m below the Maroon-Weber contact) was selected for measurement and description. There is little variation in grain size, sedimentary structure, and vertical lithofacies assemblages in the sandstone bodies of the upper Maroon at each of these localities, and each sandstone body is considered representative of the upper Maroon fluvial system at its location.

At location 1, the Maroon Formation is only about 200 m thick (Koelmel, 1986), exposures are limited, and the Maroon Formation is disconformably overlain by the

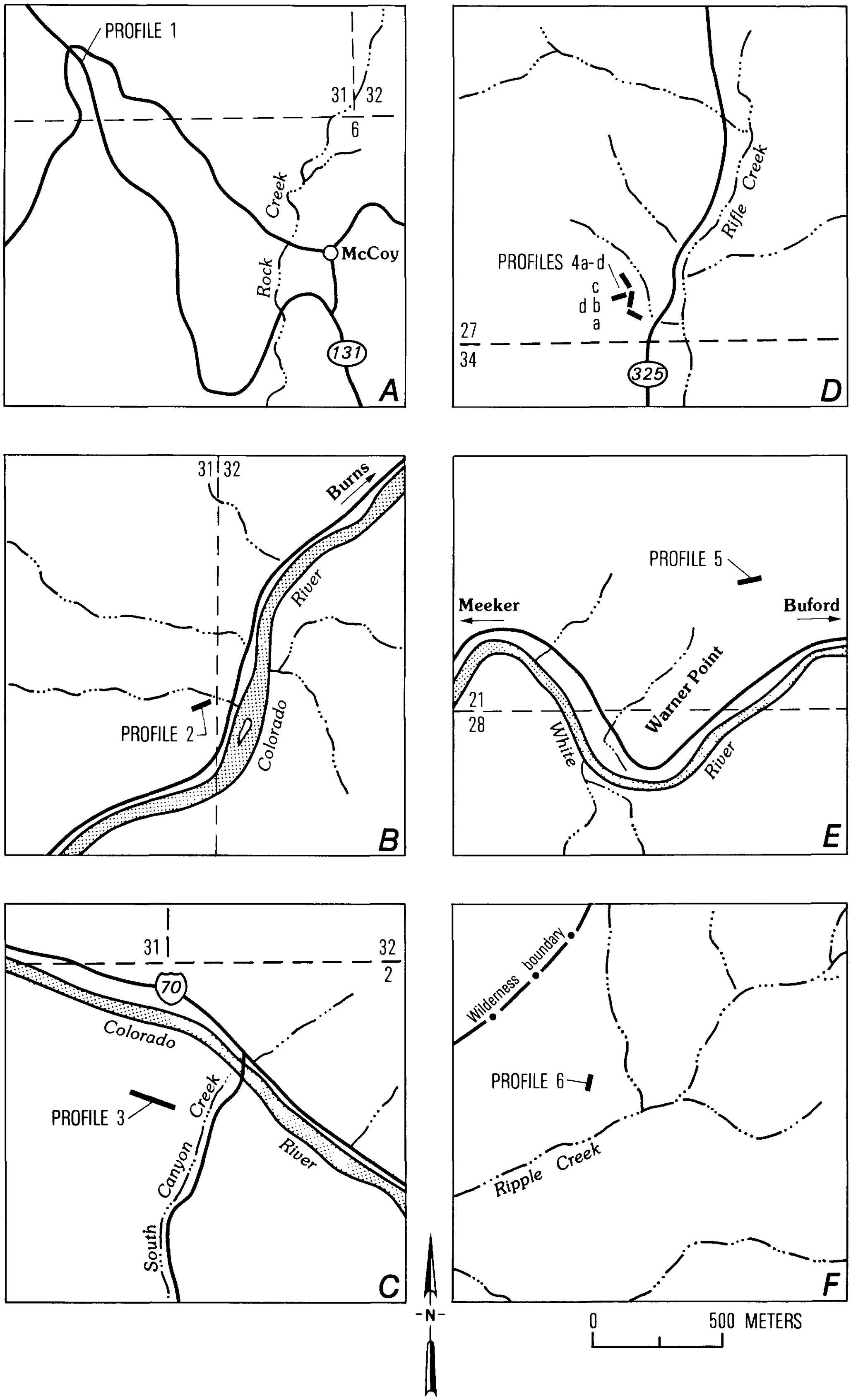

Figure 4. Locations of profiles of sandstone bodies, Eagle basin. Profiles are shown on plate 1. Views *A–F* show profiles 1–6; locations on figure 2.

Permian and Triassic State Bridge Formation. The Weber Sandstone is missing and, together with the upper part of the Maroon Formation, may have been erosionally removed (Murray, 1958). The only sandstone body suitable for description at this location is 10–20 m above the contact with the underlying Minturn Formation (as mapped by Stevens, 1956; Tweto and others, 1978) and therefore probably occupies a stratigraphically lower position than the sandstone bodies at locations 2–6. A traverse through the Maroon section in the area of location 1 suggests that this body is representative of the Maroon section, and, because this area is close to the basin margin (fig. 2), it is likely that the sedimentation style of the Maroon at this location was fairly constant.

Two methods were used to collect and record data from sandstone bodies. At locations 2, 3, 5, and 6, a grid was mapped on the outcrop using a Jacob's staff, and consecutive 6-meter-wide intervals were plotted in a field notebook at a scale of 2.54 cm = 1 m. Erosional and bedding contacts, sedimentary structures, and grain size were carefully mapped. Although key intervals and structures in the sandstone body were photographed for future reference, field notes and drawings are the principal data base. At locations 1 and 4, the primary data base is a series of overlapping photographs accompanied by field notes and sketches of selected intervals or stratigraphic relationships. Paleocurrent data (from crossbeds, scour marks, and pebble imbrications) were collected from each of the sandstone bodies. In the office, photographs, field notes, and sketches were used to create single continuous lateral profiles of the sandstone bodies (pl. 1).

Following the methods of Allen (1983), the lateral profiles of sandstone bodies were subdivided into sedimentation units, such as crossbed cosets or bundles of plane beds, on the basis of grain size, sedimentary structures, and bounding relationships. Units were numbered according to their approximate order of deposition and then grouped into "complexes," which "comprise sedimentation units that are genetically related by facies and (or) paleocurrent direction and thus distinct from adjacent groupings" (Allen, 1983, p. 250) and are inferred to represent periods of sedimentation not interrupted by significant changes in style of sedimentation or channel morphology. "First-order contacts" bound sedimentation units, whereas "second-order contacts" bound complexes and "third-order contacts" bound sandstone bodies.

Complexes were then assigned to one of the eight architectural elements of Miall (1985), which on the outcrop scale of examination in this study (pl. 1) represent large mesoforms or macroforms as defined by Miall (1985). Many of the larger complexes in the sandstone bodies regarded as channel or foreset macroform elements consist of stratified sandstones or conglomeratic sandstones that were unquestionably deposited in mesoforms such as gravel barforms or sand bedforms. Where superposition of mesoform deposits in macroform deposits could be demonstrated, the mesoform deposits were considered to be a part of the larger macroform architectural element. Similarly, many channel complexes include sedimentation units that have channelized bases, but, because these enclosed units are of smaller scale and therefore "nested" within the larger channel, they are considered part of the larger channel element. A complex is herein regarded as a channel element only if the amount of downcutting approximates or exceeds the thickness of the lowest depositional unit in the channel fill. The abundance, organization, internal structure, and texture of the sedimentation units and complexes/architectural elements form the basis for interpretation of the depositional environment.

DESCRIPTION OF THE SANDSTONE BODIES

Sandstone Body 1

Location

Sandstone body 1 (pl. 1) was measured at the northern end of a long road cut on the east side of Colorado Route 131, approximately 1.2 km northwest of McCoy (figs. 3, 4*A*; T. 2 S., R. 83 W., sec. 31, SE¼; elevation, 6,960 ft). The attitude of the body is 165° 20° NE. As previously discussed, the Maroon Formation is probably only about 200 m thick in this area (Koelmel, 1986) and the sandstone body is about 10–20 m above the top of the underlying Minturn Formation.

Description

Neither the top nor the base of the sandstone body is exposed. The 55-meter-long lateral profile (pl. 1; fig. 5) is as thick as 7.5 m, but only the lower 3–5 m is well exposed. The profile is tentatively (because of limited exposure) divided into 10 sedimentation units and grouped into 10 complexes (A–J) that are considered channel and gravel-barform elements. Strata consist of conglomerate and conglomeratic to coarse-grained sandstone. Clasts are subrounded and have a maximum diameter of 20 cm. Many sedimentation units show slight normal grading, but grain-size does not systematically vary either within complexes or in the profile as a whole. The mean paleocurrent direction is 228°; thus the body is oriented at a high oblique angle (63°) to paleoflow. Given this orientation, channel outlines should be accentuated, whereas foreset surfaces of bedforms and barforms should be less visible.

Complex A (unit 1; pl. 1) is a gravel-barform element comprising a laterally continuous (>35 m) sheet of

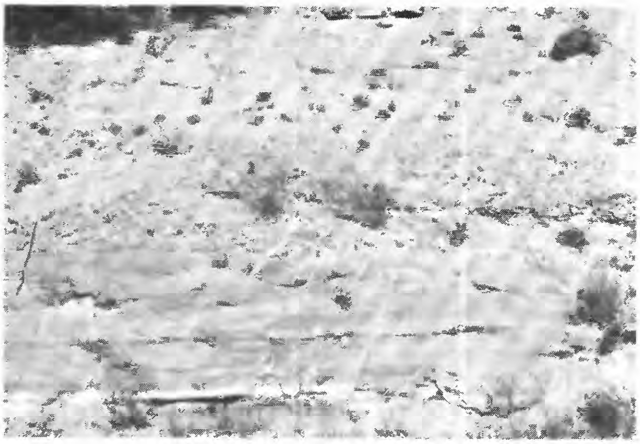

Figure 5. Parts of several channel elements in sandstone body 1 between 21 and 33 m. Jacob's staff (150 cm long) shown for scale.

coarse-grained to conglomeratic plane-bedded and cross-bedded conglomeratic sandstone. Complex B (units 2–3) is a channel element that erodes into complex A (50 cm of erosional relief) and similarly consists of a sheet of plane-bedded conglomeratic sandstone. Complex C (unit 4) is a poorly exposed channel element having more than a meter of erosional relief at its base.

Complex D (units 5–7) is the southern part of a broad (>29 m), deep (>150 cm of erosional relief), partly exposed channel element that cuts into complexes A and B. Unit 5 may have been laterally accreted to the southern margin of the channel. Complex D was eroded prior to deposition of the 30-meter-wide complex E (units 8–11) channel element. Complexes F (unit 12) and G (unit 13) are 7- to 8-meter-wide channel elements that are coarser than complex E and cut into it with as much as 100 cm of erosional relief.

Complex H (units 14–15) is a channel element that extends laterally for more than 50 m and consists of massive to plane-bedded conglomeratic sandstone. The lower erosion surface is more than 40 m long and as deep as 180 cm. Complex I (unit 16) is a 20-meter-wide channel element. Complexes G and H are cut by a broad (>20 m), deep (>160 cm) channel, the fill of which forms complex J (unit 17). Complex J consists of north-dipping beds of conglomeratic sandstone that appear to have accreted laterally to the southern margin of the channel. Complex K (units 18–20) is the highest complex and the most poorly exposed. It is floored by a 15-meter-wide channel fill unit (unit 18), and its upper part consists mostly of plane-bedded and crossbedded conglomeratic sandstone.

Interpretation

Sandstone body 1 consists predominantly of intersecting sheetlike channel elements of conglomerate and conglomeratic sandstone. This architecture and texture indicate that it was deposited in a mobile-channel, bedload-dominated fluvial system (see models 2 or 3 of Miall, 1985). These types of braided fluvial systems are characterized by low to intermediate sinuosity and intermediate to high braiding. Comparable modern rivers are most commonly in proximal basinal settings and include stream-dominated alluvial fans (Miall, 1977, 1985; Rust, 1978; Rust and Koster, 1983).

By analogy with these modern rivers, the most extensive channel scours (at the base of complexes D, H–K) probably formed during major channel-shifting events at high flood stage. The smaller channels may have a similar origin, or they may have formed by bar- or bed-dissection while floods waned. Plane-bedded units within broad channels were probably deposited in aggrading sand-gravel sheets and low-relief bars (see, for example: Rust, 1972; Hein and Walker, 1977). The low relief on channel margins mostly reflects the noncohesive nature of bank materials. Although deposition was dominated by vertical aggradation, units 5 and 17 may have been laterally accreted to the margins of the channels that they fill. Similar conglomeratic lateral-accretion deposits have been described from braided river deposits by Bluck (1976) and Ramos and Sopena (1983) and are thought to represent bar modification during waning flood stages. The water-escape structures noted in unit 1 are generally uncommon in coarse-grained sediments and suggest rapid deposition and aggradation (Johnson, 1986).

Crude estimates of paleodischarge can be made by following the methods of Allen (1983, p. 289). The bankfull channel depth cannot be less than the vertical range of the largest scours, that is, about 180 cm. Based on analogy with modern braided rivers of roughly comparable sediment load (see, for example: Doeglas, 1962; Williams and Rust, 1969; Rust, 1972; Church, 1983), an overall channel width 50 to 150 times greater than depth would not be exceptional. If an arbitrary factor of one-half is adopted to cover the proportion of bars blocking the flow, then a cross-section area of 83–250 m^2 is estimated. Based on the maximum clast diameter of 20 cm, maximum flow velocities were probably about 5 m/s (Sundborg, 1956). Minimum bankfull discharge was therefore about 417–1,250 m^3/s.

Sandstone Body 2

Location

Sandstone body 2 (pl. 1) forms resistant outcrops on east-facing slopes along the west side of the Colorado River, approximately 6.6 km southeast of Burns (figs. 3, 4*B*; T. 2 S., R. 65 S., sec. 31, SE¼; elevation, 6,620 ft). The attitude of the body is 95° 20° N., and the top of the body is 25 m below the contact with the overlying Schoolhouse Tongue of the Weber Sandstone.

Description

Sandstone body 2 has a maximum thickness of about 240 cm and can be traced laterally for about 110 m. The mean paleocurrent direction is 28°, thus the body is oblique (52°) to paleoflow and has sheet geometry (width:height>35:1, measured perpendicular to paleoflow; after Friend and others, 1979). For the entire Maroon section in this area, the mean paleocurrent direction is 41° (n=47). The lateral profile (pl. 1) is about 40 m long, but the eastern part is only partly exposed. The sandstone body consists of fine- to coarse-grained sandstone having no systematic grain-size change from its base to its top. The sandstone body is bounded above and below by poorly exposed, massive, mottled, reddish-brown mudstone and very fine grained sandstone.

The sandstone body consists of more than 65 lenticular to sheetlike, unnumbered units of predominantly trough crossbedded sandstone (figs. 6, 7). These units form one complex, a sandy bedform element (see discussion below). Most crossbed cosets are bounded by very low angle erosion surfaces. The crossbed sets typically are from 15–25 cm thick but may be as thick as 60 cm. Convolute lamination and water-escape structures are common (fig. 8), particularly in the eastern 15 m of the sandstone body where primary stratification in the lower 100–130 cm has been either deformed or obliterated.

Interpretation

The dominance of trough crossbedding reflects deposition in migrating dunes (Middleton and Southard, 1977). These dunes may have migrated across channel floors, or they may have been superimposed on macroforms such as large bars or sandflats (see, for example: Cant and Walker, 1978). Distinctive features such as ascending or descending second-order contacts (see, for example: Allen, 1983; Hazeldine, 1983) or a coarsening-upward trend within the sandstone body (see, for example: Crowley, 1983) needed to document a macroform origin are not present. Minimum depth of flow was about 60 cm, the thickness of the largest crossbed cosets. Abundant convolute lamination and water-escape structures indicate sediments were originally loosely packed and probably rapidly deposited. The thickness of the deformed intervals suggests intervals of rapid vertical aggradation.

The sandstone body lacks characteristics of meandering river deposits such as lateral accretion surfaces, fine-grained drapes, a fining- and thinning-upward trend, or significant paleocurrent dispersion. These characteristics and the sandy bedform-dominated architecture are therefore most consistent with deposition in a wide (based on the sheet geometry of the sandstone body), low-sinuosity channel. Miall (1985) suggested that

Figure 6. Crossbedded sandstone in westernmost 5 m of sandstone body 2. Detail shown in figure 7; hammer shown for scale.

Figure 7. Stacked crossbedded sedimentation units in sandstone body 2. Hammer in same location as in figure 6.

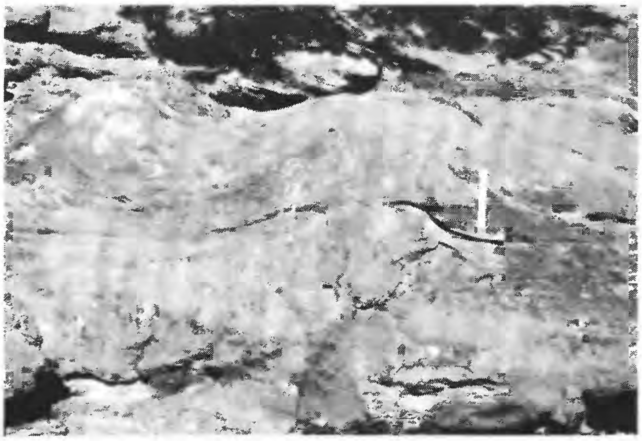

Figure 8. Large-scale convolute laminations and water-escape structures in the eastern part of sandstone body 2.

this architectural style typifies sand-dominated braided fluvial systems characterized by low to intermediate sinuosity and intermediate to high braiding and cited the Platte River (Smith, 1970; Blodgett and Stanley, 1980; Crowley, 1983) and the South Saskatchewan River (Cant and Walker, 1978) as modern analogs.

Sandstone Body 3

Location

Sandstone body 3 was measured in resistant outcrops on east-facing slopes on the west side of South Canyon Creek Road, approximately 8 km west of Glenwood Springs along the south side of the Colorado River (figs. 2, 4*C*; T. 6 S., R. 90 W., sec. 2, NW¼; elevation, 5,920 ft). The attitude of the body is 115° 60° SW. The top of the body is approximately 27 m below the contact with the overlying Schoolhouse Tongue of the Weber Sandstone.

Description

This sandstone body is 3.3–4.2 m thick and extends along strike for more than 500 m. The mean paleocurrent direction is 15° for the 48-meter-long profile (pl. 1; fig. 9); thus, the body is almost perpendicular (85°) to paleoflow and has sheet geometry (width:height>119). For the entire Maroon section in this area, the mean paleocurrent direction is 53° ($n = 104$). The body consists mostly of coarse-grained to conglomeratic sandstone. Conglomerate clasts are typically subrounded and in most beds have a maximum diameter of 2–14 cm. The sandstone body is bounded above and below by reddish-brown, massive, plane-bedded, or ripple-laminated, very fine to medium-grained sandstone and minor mudstone.

The lateral profile comprises 29 sedimentation units grouped into 10 complexes (A–J) that form channel and gravel-barform architectural elements. Because the lateral profile is oriented almost perpendicular to paleoflow, channel outlines are accentuated and foreset surfaces of migrating bedforms or barforms are not apparent. Many of the sedimentation units show slight normal grading, but there is no systematic grain-size variation within complexes or within the sandstone body as a whole.

Complex A (unit 1) is a channel element of plane-bedded conglomeratic sandstone that is laterally continuous for at least 25 m at the base of the eastern half of the profile. Complex B (unit 2) forms the base of the western part of the profile and likewise comprises a laterally continuous (about 18 m) channel element that is filled by trough crossbedded, coarse-grained sandstone. Complex C (units 3–6) is also a sheetlike channel element and consists of massive to horizontally stratified conglomeratic sandstone deposited over an erosion surface that has as much as 60 cm of relief above complex A.

Figure 9. Sheetlike channel elements in sandstone body 3. View looking west; photographed from 10-meter mark of profile (pl. 1). Hammer shown for scale (handle barely visible in center of photograph).

Complex D (units 7–9) is a gravel-barform element. Unit 7 formed the core of a bar that had as much as 120 cm of relief above the stream bed. Unit 8 appears to have been laterally accreted on the flanks of this bar and was in turn onlapped by unit 9. Complex E (units 10–16) is a thick (as much as 200 cm), sheetlike (>37 m wide) channel element that consists almost entirely of low-angle to horizontally stratified conglomeratic sandstone in shallow, nested channels. Complex F (units 17–19) is a broad (>27 m) channel element that has more than 200 cm of erosional relief at its base. Unit 17 is the lowest and most coarse grained unit in the complex. Units 18 and 19 form relatively small channel fills that are nested in the larger channel of unit 17.

Complex G (units 20–21) is a 8-meter-wide channel element consisting of two nested channel units. Complex H (unit 22) is also a relatively narrow (<10 m) channel element. Three broad, shallow (erosional relief <90 cm) channels form complex I (units 23–25) at the top of the western end of the profile. Similarly, complex J (units 26–29) is a channel element consisting of four sedimentation units that form channels at the top of the eastern end of the lateral profile.

Interpretation

Similar to sandstone body 1, sandstone body 3 consists of intersecting sheets of conglomerate and conglomeratic sandstone that form channel and gravel-barform architectural elements. This architecture and texture are most consistent with deposition in a mobile-channel, bedload-dominated, braided fluvial system that resembles models 2 or 3 of Miall (1985). As previously discussed, comparable modern rivers are most commonly in proximal basin settings (Miall, 1977, 1985; Rust, 1978; Rust and Koster, 1983).

There is a continuum in channel size from the major complex-bounding scours (as much as 25 m wide and 200 cm deep) to smaller, unit-bounding (intracomplex) scours. The larger channels were probably cut during the largest flood events. Smaller channels probably formed in smaller floods or by bed or bar dissection during falling water stages. The dominance of plane bedding above erosive contacts suggests rapid clast-by-clast accretion above the scour surface and incipient development of low-relief bars (Rust, 1972; Hein and Walker, 1977). Some of the major channels (such as complexes B and F) have a relatively fine grained and well stratified fill that was probably deposited at low flood stage long after the channel-cutting event.

Minimum paleodischarge can be calculated by using the method outlined for sandstone body 1. Using 200 cm (the depth of the deepest scour) as minimum channel depth, a factor of 50 to 150 for width/depth ratio, a factor of one-half for flow-blocking bars, and a velocity of 4.5 m/s (for clasts as large as 14 cm; Sundborg, 1956), then the minimum bankfull discharge is 458–1,375 m^3/s, very similar to that inferred for sandstone body 1.

Sandstone Bodies 4–1 and 4–2

Location

Sandstone bodies 4–1 and 4–2 are located approximately 125 m west of Colorado Route 325, on the west side of Rifle Creek (figs. 2, 4*D*; T. 4 S., R. 92 W., sec. 27, SW¼; elevation, 6,450 ft). The lateral profiles (pl. 1) include three panels from sandstone body 4–1 (4a, 4b, 4c) and one profile (4d) from sandstone body 4–2, which overlies and is separated from sandstone body 4–1 by about 60 cm of very fine grained sandstone and mudstone. Four profiles are presented because their different orientations provide an important three-dimensional perspective of sedimentation style. Profile 4a is 7 m long and trends northeast (125°); profile 4b is 5 m long and trends north (10°); profile 4c is 29 m long and trends north-northwest (155°); and profile 4d from sandstone body 4–2 is 6 m long and trends east-northeast (75°). The attitude of master bedding is 90° 10° S. The top of sandstone body 4–1 is 60 m below the base of the overlying Schoolhouse Tongue of the Weber Sandstone.

Description

Strata in sandstone bodies 4–1 and 4–2 consist of medium-grained to conglomeratic sandstone (diameter of largest pebble <3 cm), and coarse-grained sandstone is dominant. Some of the sedimentation units are normally graded, but there is no grading within complexes or in the sandstone bodies as a whole. The two sandstone bodies are bounded above and below by massive, reddish-brown, mottled, very fine grained sandstone and mudstone. Sandstone body 4–1 is laterally continuous for more than 60 m; sandstone body 4–2 is mostly covered and cannot be traced laterally. The mean paleocurrent direction for the entire Maroon Formation section along Rifle Creek is 18° (n=73), indicating that sediment transport was to the north-northeast. The mean palocurrent direction for the four profiles is 1° (n=41; pl. 1).

Sandstone body 4–1 is 230–330 cm thick. Profile 4a (fig. 10) is at an oblique angle (56°) to the mean paleocurrent direction. Nine sedimentation units, consisting of crossbedded and plane-bedded conglomeratic sandstone, are recognized in the 7-meter-long profile. These units form a single complex that is considered a sandy bedform element. Crossbed sets are as thick as 70 cm (unit 3).

Profile 4b (fig. 11) is almost parallel with the mean paleocurrent direction. Strata are divided into 13 sedimentation units that consist mainly of trough and planar crossbedded sandstone. Crossbed foresets and trough axes dip north and northeast and are enclosed by larger scale erosion surfaces that dip south (top of unit 2, top of units 4 and 5, top of units 6 and 7, top of units 8 and 9), the upstream direction. The opposing dips of the foresets (for example, units 6 and 8) and the enclosing erosion surfaces suggest migration of sand bedforms up and across a large foreset macroform and rule out a lateral accretion origin. Outcrop data are insufficient to determine if units 11–13 are part of this foreset-macroform element or form a separate, higher complex.

Profile 4c is 10 to 35 m north of profile 4b and is oblique (26°) to the mean paleocurrent direction. This profile is composed of 11 sedimentation units consisting of plane-bedded and crossbedded (maximum amplitude=40 cm), coarse-grained sandstone. Maximum crossbed height is 40 cm. An erosional surface, locally overlain by a pebble lag, is at the base of units 5 and 6. If viewed independently, the sedimentation units in this profile would be grouped into two complexes (units 1–4, 5–11) that would be considered sand-bedform elements. However, the profile is only 10–35 m downstream from profile 4b (fig. 4*D*), where strata were clearly deposited on the upstream flank of a foreset macroform. Based on this spatial relationship, strata in profile 4c are considered a single complex that was a part of the foreset macroform element of profile 4b.

Profile 4d (fig. 12) from sandstone body 4–2 provides a second example of a foreset-macroform architectural element. The profile is 3 m thick and is highly oblique (74°) to the mean paleocurrent direction. Thirteen sedimentation units and three complexes are recognized.

Figure 10. Plane-bedded and crossbedded sandstone in sandstone body 4–1 (profile 4a).

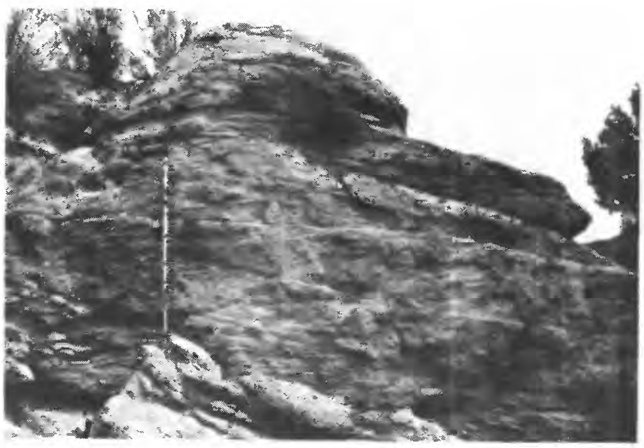

Figure 11. North-directed crossbed cosets enclosed by south-dipping (to right) erosional bounding surfaces in sandstone body 4–1 (profile 4b). Jacob's staff (150 cm long) shown for scale.

Figure 12. Deformed interval at the base of sandstone body 4–2 overlain by foreset-macroform element (profile 4d).

Complex A (unit 1) is tentatively considered a sandy bedform element, but primary sedimentary structure has been mostly obliterated by soft-sediment deformation. Complex B (units 2–13) is a foreset-macroform element that contains west-dipping erosion surfaces that bound east-dipping crossbedded units. Similar to profile 4b, the opposing dips of the erosion surfaces and the crossbeds rule out a lateral accretion origin. Complex C (unit 13) is a channel element that cut into the top of the foreset macroform; the axis of this channel element is almost parallel with the mean paleoflow direction.

Interpretation

Sandstone bodies 4–1 and 4–2 consist mostly of foreset-macroform and sandy bedform architectural elements. The geometry of the foreset-macroform elements, characterized by opposing crossbed foresets and erosion surfaces, has been previously recognized by Allen (1983), who referred to these macroforms as composite-compound bars. Periods of rapid sedimentation in the foreset macroform of profiles 4b and 4c are indicated by the high angle of climb on erosion surfaces between crossbed cosets. The scour surface at the base of units 5 and 6 in profile 4c probably represents erosion of the top of the macroform during a major flood event.

The dominance of foreset-macroform and sandy bedform architectural elements and the recognition of bar-top deposits suggest a fluvial system most similar to that of Miall's (1985) model 10, for which the South Saskatchewan river (Cant and Walker, 1978) is cited as a modern example. The South Saskatchewan is characterized by low to intermediate sinuosity, intermediate to high braiding, the development of sand flats and cross-channel (transverse) bars, and relatively deep (3–5 m) flow. The South Saskatchewan River macroforms are at diverse oblique orientations to paleoflow and resemble the pattern noted for the foreset macroforms of profiles 4b and 4d. Stratification types and sequences in sandstone bodies 4–1 and 4–2 are not identical, however, to those of the sand flats and cross-channel bars of the South Saskatchewan River. The vertical range of the upstream-dipping erosion surfaces (only partly exposed) within the foreset-macroform element of profile 4b provides a minimum value (about 130 cm) for paleochannel depth.

Sandstone Body 5

Location

Sandstone body 5 was measured on south-facing slopes north of the White River and the Meeker-to-Buford road (figs. 2, 4*E*; T. 1 S., R. 92 W., sec. 21, SE¼; elevation, 7,280 ft). The attitude of the body is 65°8°N., and the outcrops trend nearly east-west (80°). The top of the body is 45 m below the base of the overlying Schoolhouse Tongue of the Weber Sandstone.

Description

The mean paleocurrent direction of sandstone body 5 (fig. 13) is 90° (pl. 1); thus the 32-meter-long profile is nearly parallel with paleoflow. The mean paleocurrent direction for the entire Maroon Formation section at this location is more northeasterly (53°, $n=43$). The sandstone body profile has a maximum thickness of 2.8 m and consists of fine-grained and rare medium- to coarse-grained sandstone. It is bounded by massive, mottled, reddish-brown, very fine grained sandstone and mudstone.

The lower erosional contact of the sandstone body (fig. 13) descends about 90 cm from west to east, the downstream direction. This irregular contact is overlain by complex A (units 1–3), a channel element consisting of massive to stratified sandstone containing abundant mudstone rip-up clasts. Complex B (units 4–18) comprises the upper portion of the sandstone body. Sedimentation units are dominantly plane bedded in the lower and western (upstream) parts of the profile, whereas units in the upper and eastern (downstream) parts of the profile are both plane bedded and crossbedded. Sedimentation units are separated by horizontal to east-dipping erosion surfaces, a relationship that indicates the migrating foreset bedforms were superimposed on a larger macroform and therefore form a part of a foreset-macroform element. There is a prominent east-dipping mudstone drape in the eastern part of the sandstone body (fig. 13; thickness exaggerated in pl. 1).

Interpretation

The sandstone body 5 profile is dominated by the large foreset macroform of complex B. Segregation of stratification types in this macroform provide important data concerning its genesis and morphology. Plane-bedded sandstone of unit 5 may have formed the nucleus of the macroform. Once unit 5 was deposited, sediment was added to the macroform as fields of bedforms migrated over it and down its slope, which is defined by the east-dipping, unit-bounding erosion surfaces. Similar downstream-dipping erosion surfaces in foreset macroforms have been described by Allen (1983), Hazeldine (1983), and Kirk (1983). The transition from plane bedding in the upstream part of the macroform to crossbedding on the downstream slope of the macroform may reflect increasing depth of flow (see, for example: Middleton and Southard, 1977, fig. 7.18a).

Both the macroform architectural element and the mixed sediment load of sandstone body 5 suggest a fluvial

Figure 13. Channeled base and shale drape (indicated by arrow) in the eastern part (26–31 m) of sandstone body 5. Jacob's staff (150 cm long) shown for scale.

system similar to the previously discussed models 9 or 10 of Miall (1985), for which the Platte and South Saskatchewan Rivers are cited as modern analogs. Paleocurrent data for sandstone body 5 diverge 37° from the mean paleocurrent direction for the entire Maroon Formation section at this location and suggest that, as in the South Saskatchewan River, macroforms had variable orientations relative to paleoflow. Minimum depth of flow, based on the maximum thickness of crossbed sets (unit 14), was about 70 cm.

Sandstone Body 6

Location

Sandstone body 6 (pl. 1) was measured at an elevation of 9,520 ft on southwest-facing slopes above Ripple Creek in northernmost Garfield County (unsurveyed T. 1 N., R. 88 W.), about 425 m inside the wilderness boundary (figs. 2, 4*F*). The attitude of the bedding is 150° 9° N., and the top of the sandstone body is 130 m below the base of the overlying Schoolhouse Tongue of the Weber Sandstone.

Description

The profile is 26 m long, and the sandstone body has a maximum thickness of 4.1 m (fig. 14). Limited paleocurrent data ($n=11$) from the upper part of the Maroon Formation at this location are northeasterly (44°); thus, the sandstone body is probably at an acute angle (about 30°) to paleoflow. The body consists of fine- and very fine grained sandstone and is bounded above and below by mostly massive, reddish-brown mudstone interbedded with a few thin (<20 cm) marine limestone beds. No erosional relief is visible at the base of the sandstone body.

Figure 14. Plane-bedded and ripple-laminated, fine- to very fine grained sandstone in sandstone body 6.

Three sedimentation units separated by parallel to locally discordant contacts form a single complex interpreted as a laminated-sandsheet element. Units 1 and 2 are plane bedded. Plane beds at the base of unit 3 pass upward to interstratified plane-bedded, ripple-laminated, and rare trough crossbedded (at 17 m) strata. Convolute lamination and water-escape structures are common in all three sedimentation units.

Interpretation

Lack of channeling at the base of and within the laminated-sandsheet element of sandstone body 6 probably reflects unconfined flow. Common convolute lamination and water-escape structures suggest rapid aggradation. Couplets of plane-bedded and ripple-laminated strata (unit 3) probably represent deposition under progressively waning flow. Bounding red mottled mudstone and marine limestone suggest deposition on a low-relief playa or mudflat near a marine interface.

Depositional units of this kind are found in crevasse splays of major rivers (Elliot, 1986) and in sandy sheetfloods that have prograded onto muddy floodflats in arid regions (Williams, 1970a, b; Hardie and others, 1978; Turnbridge, 1981). A sheetflood origin for this sandstone body is most likely because there are no major channel sandstone bodies in the upper Maroon Formation section in this area that could be regarded as parent channels for crevasse splays. Sand-sheet architectural elements are characteristic of model-12 fluvial systems of Miall (1985), which are described as streams with flashy discharge that are subject to short-lived, high-energy floods.

PALEOGEOGRAPHY

The sedimentology of the six sandstone bodies and the characteristics of their bounding strata may be used to reconstruct the style of fluvial deposition in the upper part of the Maroon Formation in the Eagle basin. This type of paleogeographic reconstruction requires accurate location of basin margins. The northern Eagle basin was bounded to the east by the Gore fault and the ancestral Front Range uplift (figs. 1, 2, 15), which are located on the basis of surface mapping (Tweto and others, 1978; Tweto, 1979). The ancestral Uncompahgre uplift formed the southwestern margin of the basin and is a buried tectonic feature that apparently had an irregular and complex northern boundary. Stone (1969, 1977) recognized and described the Garmesa fault zone as being the northern margin of the ancestral Uncompahgre uplift. Waechter and Johnson (1985) showed faults on two seismic profiles that represent this fault zone, and a line connecting these two faults is here regarded as the northern margin of the ancestral Uncompahgre (fig. 2). Note that this trend diverges slightly from that shown by Stone (1969) and is well north of that shown by Koelmel (1986). Regardless of exact location, if the Garmesa fault is projected eastward (Stone, 1969), then it extends into the Eagle basin. The border of this highland (and basin-margin faults) therefore probably bent sharply to the south in the area west of Aspen (as shown by Mallory, 1972). Waechter and Johnson's (1985) seismic lines also show at least two other uplifted fault blocks and zones north of the Garmesa fault zone that were probably active during Pennsylvanian time, including the Douglas Creek fault of Stone (1969). For some time periods, as discussed later, these fault blocks may have served as the uplifted southwestern margin of Eagle basin.

Of the six sandstone bodies, sandstone body 1 contains the largest clasts and is located closest to an inferred basin margin (fig. 3). Sediment was derived from the ancestral Front Range uplift, about 5 km to the east (fig. 15). As noted, the dominance of channel architectural

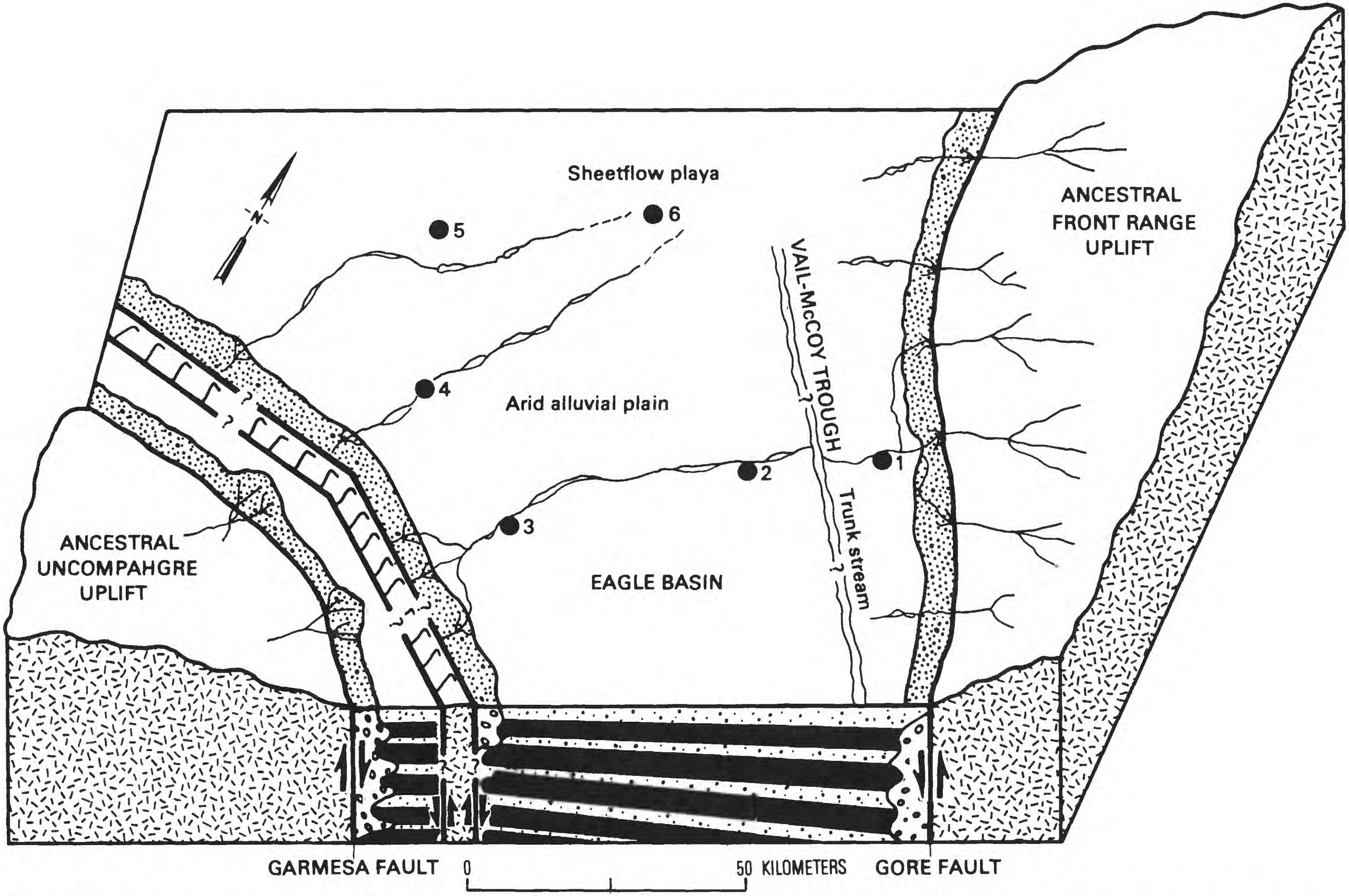

Figure 15. Paleogeographic model of fluvial sedimentation in the Eagle basin during late Maroon Formation time. Depositional axis of basin is inferred to be strongly skewed to the northeast and to lie in the vicinity of Vail–McCoy trough (Walker, 1972). Fault blocks north of Uncompahgre uplift (noted on seismic lines by Waechter and Johnson, 1985) may have been uplifted sediment sources for the upper Maroon. Numbered solid circles indicate locations of sandstone bodies 1–6.

elements and the coarse texture of this sandstone body are characteristics of proximal braid-plain settings (see, for example: Rust and Koster, 1984). Paleohydrologic calculations suggest that minimum bankfull discharge was probably 417–1,250 m^3/s, comparable to that of the modern South Platte River (Smith, 1970; Crowley, 1983), which drains the Colorado Front Range. This inferred discharge is suprisingly large and suggests that sandstone body 1 was deposited downstream from the confluence of several tributaries and (or) near the mouth of a major intra-ancestral Front Range uplift drainage system (fig. 15).

Sandstone bodies 2–6 all have east- to north-directed paleocurrents and were derived from the Uncompahgre uplift and associated fault blocks on the southwestern basin margin. Sandstone body 3 (present locations) is no farther than 40 km from the basin margin. Although not as coarse grained as sandstone body 1, it similarly consists of channel elements of conglomeratic sediment interpreted to be deposits of braided, mobile-channel, bedload-dominated fluvial systems. Minimum paleodischarge estimates are similar to those for sandstone bodies 1 and 3, and it seems likely that sandstone body 3 also was downstream from the confluence of several tributaries. Sandstone body 4 is only a few kilometers farther from the basin margin than sandstone body 3 but is finer grained and consists of foreset-macroform and sand-bedform architectural elements. These differences are consistent with a downcurrent facies change within a braided fluvial system (Miall, 1985); however, the locations and paleocurrent data for the two sandstone bodies suggest they may have been deposited in different, parallel drainage systems (fig. 15).

Sandstone bodies 5 and 2 are a maximum of 65 and 80 km from the ancestral Uncompahgre uplift, respectively. These bodies consist of foreset-macroform and sandy bedform elements of fine- to medium-grained sandstone and are interpreted to be deposits of sandy braided rivers. Significantly, sandstone body 2 is considerably closer (about 30 km) to the Front Range uplift than to its source in the Uncompahgre uplift. Sandstone body 6 is about 90 km from its inferred source in the Uncompahgre uplift and is the most distal of the sandstone bodies. It consists of a laminated sand-sheet architectural element that formed on a low-relief plain near a marine interface.

The proximal to distal changes in architecture and grain size noted for the Uncompahgre-derived sandstone bodies and, especially, the development of the laminated-sandsheet element in sandstone body 6 suggest progressive decreases in depth, flow strength, and discharge in the downcurrent direction. Several modern and ancient fluvial systems show the same trends. Friend (1978) summarized four examples from the Devonian of Spitzbergen and Greenland and the Tertiary of the Ebro Basin, and Tunbridge (1981) described comparable facies changes from the Devonian Old Red Sandstone in southwest Wales. Modern examples of fluvial systems that decrease in size and discharge downsystem have been described from the Sahara piedmont (Williams, 1970a), the Australian Eyre basin (Williams, 1970b; Hardie and others, 1978), and the Indo-Gangetic plain (Mukerji, 1976; Parkash and others, 1983). Arid or semiarid climates characterize (or are inferred to characterize) each of these modern and ancient analogs, and the decrease in discharge is attributed to loss of water into permeable alluvium and (or) evapotranspiration coupled with lower precipitation in the basin than in mountainous source areas. In the Eagle basin, the evaporite-rich Eagle Valley Evaporite underlies and interfingers with the Maroon Formation, providing strong evidence of aridity during the Pennsylvanian. On the basis of clay mineralogy, Raup (1966) also has inferred an arid or semiarid climate for Eagle basin during Pennsylvanian time. Orographic effects attributable to the ancestral Front Range and Uncompahgre uplifts probably created a rain-shadow desert in the Eagle basin during this interval (Mack and Suttner, 1977; Mack and others, 1979).

The locations and paleocurrent data for sandstone bodies 2–6 indicate that, during late Maroon time, the Eagle basin had an asymmetric drainage pattern. Rivers draining the ancestral Uncompahgre uplift (and possibly the related fault blocks) flowed a considerable distance to the northeast across the geometric center of the basin. In a nonmarine basin, rivers flow toward and along the axis of maximum subsidence (Bridge and Leeder, 1979; Read and Dean, 1982). Mallory (1972) and DeVoto (1980) have shown on isopach maps a thick section of Pennsylvanian rocks along the northeast flank of the Eagle basin (between locations 1 and 2) that may represent the zone of relatively high subsidence toward which the Maroon rivers flowed. Boggs (1966) inferred a Middle Pennsylvanian trough in this zone on the basis of facies patterns in the Minturn Formation, and Walker (1972) named this feature the Vail–McCoy trough. Major trunk streams draining both the ancestral Front Range and Uncompahgre uplifts may have merged in this trough and then flowed northwestward (fig. 15).

The amount of basin asymmetry is dependent on the uplift history of fault blocks (Waechter and Johnson, 1985) north of the Uncompahgre during sedimentation (fig. 2). Sandstone body 3 is about 30 km north of the ancestral Uncompahgre front and is sedimentologically and texturally similar to sandstone body 1, which formed about 5 km from the ancestral Front Range uplift. The noted similarities between the two bodies might indicate that they were deposited about the same distance from their source. If so, then the fault-bounded basement blocks noted by Waechter and Johnson (1985; fig. 2) were likely uplifted sediment sources for the upper Maroon and the degree of asymmetry, although still pronounced, is less.

CONCLUSIONS

Architectural element analysis reveals significant facies changes in six fluvial sandstone bodies representative of deposition in the upper part of the Maroon Formation in the Eagle basin. The two sandstone bodies located closest to the basin-margin ancestral Uncompahgre and Front Range uplifts are dominated by channel and gravel-barform architectural elements of conglomerate and conglomeratic sandstone and are interpreted as proximal braided-river deposits. Three medial sandstone bodies derived from the Uncompahgre uplift consist of foreset-macroform and sand-bedform elements of fine- to coarse-grained sandstone and are interpreted as the deposits of sandy braided rivers. The most distal sandstone body is composed of a laminated sand sheet element of very fine to fine-grained sandstone and was probably deposited in sheetfloods on a playa or mudflat. These facies changes suggest that the late Maroon Formation fluvial system(s) was characterized by downstream decreases in flow strength, flow depth, and discharge. Similar characteristics have been noted for other modern and ancient fluvial systems in arid to semiarid basins. Facies and paleocurrent data indicate that, during upper Maroon time, the depositional axis of the Eagle basin and therefore the locus of subsidence was strongly skewed to the northeast and in the vicinity of the Vail–McCoy trough.

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Chapter B

Sedimentology of an Eolian Sandstone from the Middle Pennsylvanian Eagle Valley Evaporite, Eagle Basin, Northwest Colorado

By CHRISTOPHER J. SCHENK

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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Sedimentology of an Eolian Sandstone from the Middle Pennsylvanian Eagle Valley Evaporite, Eagle Basin, Northwest Colorado

By Christopher J. Schenk

Abstract

A coset of cross-stratified sandstone in the upper part of the evaporitic interval of the Middle Pennsylvanian Eagle Valley Evaporite, northwest Colorado, is interpreted as eolian in origin. The sandstone is composed predominantly of parallel-stratified, fine-grained sandstone interpreted as eolian ripple deposits. The eolian ripple strata were probably deposited in a dune apron, the low-angle slope that forms along the base of the foreset on most sand dunes. The bounding surfaces separating sets of cross-strata within the coset probably represent changes in the shape of the dune associated with changes in local wind direction and strength. Lenses of coarser sand intercalated with eolian ripple deposits overlie the dune sandstone and may have formed in interdune or sand-sheet environments by the migration of granule ripples.

The presence of eolian deposits in a sequence containing marine black shales and evaporites indicates the importance of sea-level changes on the deposition of the Eagle Valley Evaporite. Environmental conditions in the Eagle basin during deposition of the Eagle Valley Evaporite cannot be described as simply deep or shallow but may have been strongly influenced by cyclic changes in sea level.

INTRODUCTION

The purpose of this report is to describe a sandstone from the clastic interval below the uppermost thick gypsum of the Middle Pennsylvanian Eagle Valley Evaporite in the Eagle basin near Red Canyon, northwest Colorado (fig. 1), and to present evidence that the sandstone is eolian in origin. This interpretation has implications for Middle Pennsylvanian paleogeography because it is the first interpretation of a subaerial sandstone from this part of the Eagle basin. The presence of nonmarine as well as marine sediments in the central part of the basin suggests that environmental conditions during deposition of the Eagle Valley Evaporite were not simply basinal (Mallory, 1971; Irtem, 1977) or a shallow evaporite pan or sabkha (Boggs, 1966; Tillman, 1971; Bartleson, 1972; Walker, 1972).

GEOLOGIC SETTING

The Eagle Valley Evaporite is a sequence of fine-grained clastic rocks, evaporites, and thin layers of carbonate rocks that formed in the central part of the Eagle basin during the Middle Pennsylvanian. The Eagle Valley Evaporite is underlain by the Early and Middle Pennsylvanian Belden Formation, composed mostly of black shale, and intertongues with and is overlain by the Pennsylvanian and Permian Maroon Formation, composed predominantly of sandstone. In general, the Eagle Valley exhibits a gradual change upward from mudstone, shale, and evaporite to sandstone and evaporite. Conglomerate, sandstone, and carbonate rocks of the Minturn and Gothic Formations were deposited along the margins of the basin and are coeval with the Eagle Valley.

The sandstone described in this report was studied in a section measured through part of the Eagle Valley Evaporite near Red Canyon, approximately 7 km northeast of Eagle, Colo. (fig. 1). In this part of the basin, the Eagle Valley Evaporite contains numerous gypsum beds, some of which are as thick as 50 m or more. Many clastic units are intercalated with the evaporite beds, and the sandstone described here is part of a clastic interval directly below the stratigraphically highest thick marine gypsum unit in the Eagle Valley Evaporite (fig. 2).

GENERAL DESCRIPTION OF SANDSTONE SEQUENCE

The clastic interval below the uppermost thick gypsum of the Eagle Valley Evaporite is composed predominantly of sandstone but also contains mudstone, siltstone, and thin layers of carbonate rocks. A partial section that includes the eolian deposits is shown in figure 3. The lowest strata in this partial section contain small-scale trough cross-strata produced by the migration of asymmetrical ripples. The ripple strata commonly contain

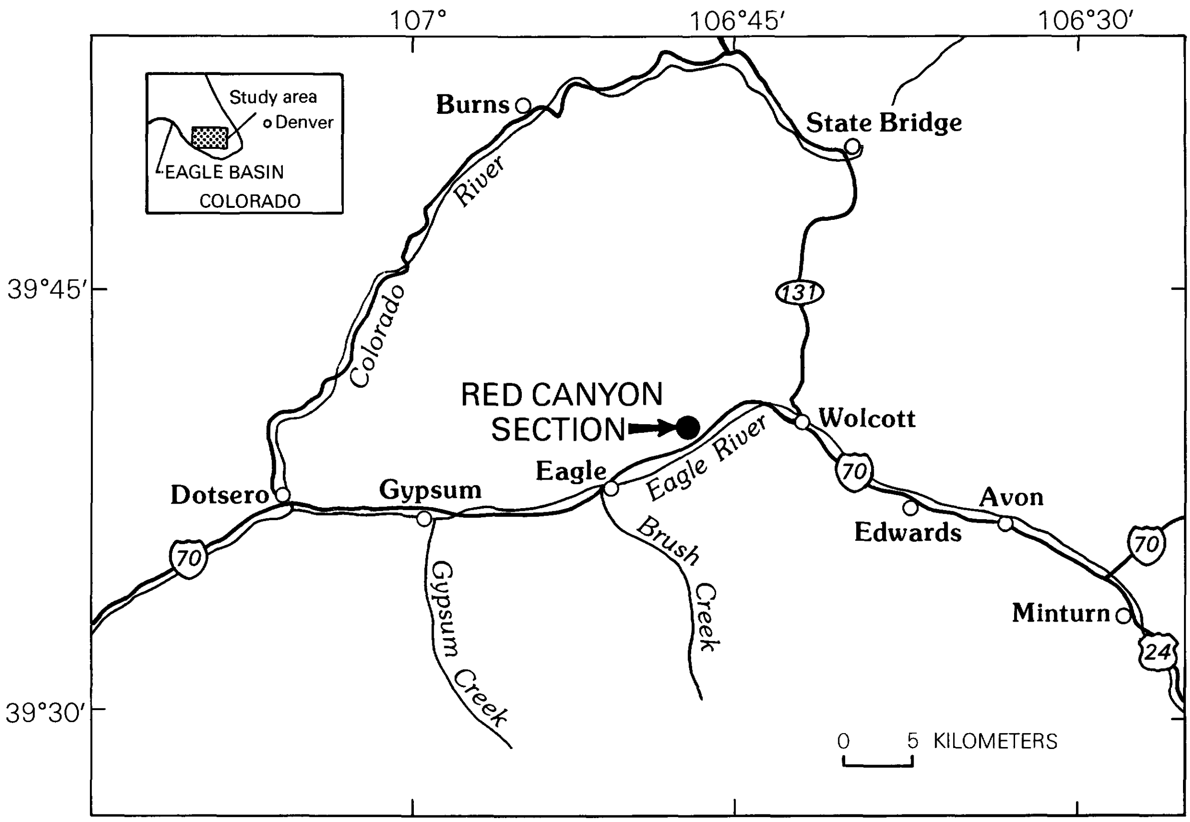

Figure 1. Location of the study area and measured section near Red Canyon, Eagle basin, northwest Colorado.

mud flasers, thin layers of mud preserved in the ripple troughs. These ripple- and flaser-stratified sandstones are overlain by irregularly to undulatory-stratified sandstones that in turn pass upward into a set of cross-strata characterized by inversely graded laminae. These strata are overlain by a 2-meter-thick coset of sandstone that is the subject of this paper. This cross-stratified sandstone is erosionally overlain by 50 cm of irregularly to parallel-stratified sandstone. The base of this sandstone fills in erosional relief on top of the underlying cross-stratified sandstone. The sequence shown in figure 3 is capped by flaser-stratified sandstone and dense, thinly laminated, gray to black carbonate beds that have mudcracks on their upper surfaces.

DESCRIPTION OF THE CROSS-STRATIFIED SANDSTONE

The cross-stratified sandstone in the clastic interval at Red Canyon comprises several sets of cross-strata that form a coset (fig. 4*A*). The sets of cross-strata are separated by low-angle, even bounding surfaces that outline the wedge-shaped sets within the coset. The upper bounding surface of the coset exhibits 5 cm of relief, and the sandstone above fills in this relief (fig. 4*B*).

The sets of cross-strata form long, curving tangential foresets that consist of two types of stratification. The most common type comprises thin, parallel laminae of fine-grained sandstone. Each of the lamina is inversely graded (fig. 5). The less common type of cross-strata comprises medium- to coarse-grained, ungraded sandstone, and each stratum wedges out downslope into parallel-stratified sandstone (fig. 6). The sandstone above and beneath the coset is irregularly and parallel stratified. The parallel strata are inversely graded and fine grained, and the irregular strata (fig. 7) contain discontinuous lenses of coarse-grained sandstone.

INTERPRETATION

The inversely graded, parallel strata in the sweeping tangential foresets are interpreted as being the deposits of eolian ripples. Numerous studies document the details of this type of stratification (Hunter, 1977; Fryberger and Schenk, 1981; Kocurek and Dott, 1981). The inverse grading is produced during ripple migration as the coarser grains on the crest of each ripple prograde over and cover the finer sand in the ripple trough. Eolian ripples typically climb at a very low angle, such that only a fraction of the ripple thickness is preserved, and each ripple produces

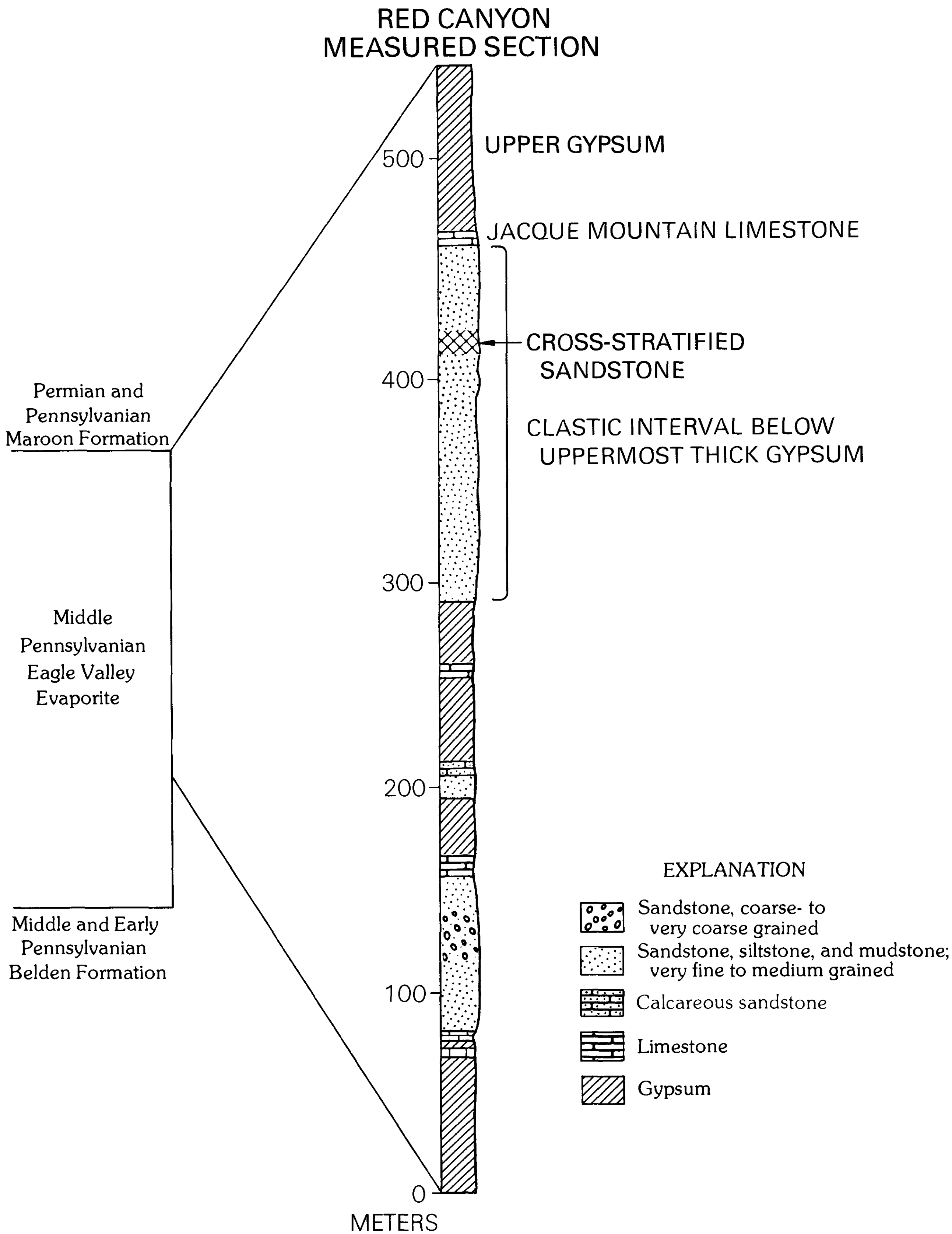

Figure 2. Stratigraphic section of the Middle Pennsylvanian Eagle Valley Evaporite near Red Canyon. The cross-stratified sandstone described in this report is in the clastic interval below the uppermost thick gypsum. Query, contact uncertain.

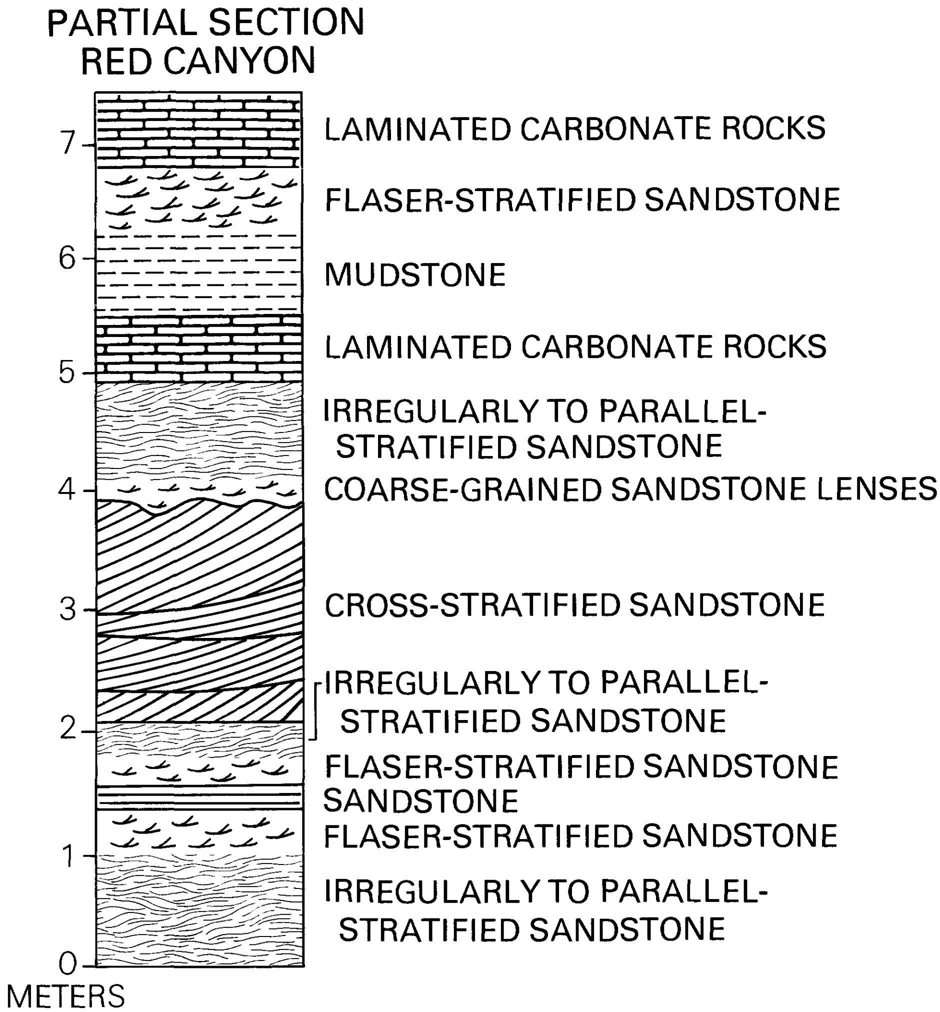

Figure 3. Stratigraphic section of part of the clastic interval below the uppermost thick gypsum of the Eagle Valley Evaporite. Flaser-stratified sandstones are both above and below the cross-stratified sandstone. Thinly laminated, black carbonate rocks at the top of the section have mudcracks on their upper surfaces.

a thin, inversely graded stratum. A train of migrating ripples results in a parallel-stratified set in which each stratum is thin and inversely graded.

The second, less common type of cross-strata forms by sand flow down the foreset of a dune. Each sand flow produces a stratum that is more coarse grained than, and wedges out downslope into, eolian ripple stratification. The coarser grained sand-flow strata exhibit a marked textural contrast to the finer grained, inversely graded ripple strata (fig. 6). The intercalation of sand-flow toes and inversely graded ripple strata provide excellent criteria for eolian deposition (Hunter, 1977; Fryberger and Schenk, 1981).

The wedge-shaped sets of ripple strata represent the deposits of a dune apron, the low-angle slope that forms at the base of the dune foreset (Fryberger and Schenk, 1981). The low-angle, tangential ripple deposits of the dune apron are commonly all that is preserved as a dune migrates (Rubin and Hunter, 1982). The low-angle bounding surfaces that separate sets of cross-strata within the coset probably represent erosion associated with either shifts in wind direction or changes in the shape or position of the dune with respect to the existing wind conditions.

The relief on the upper bounding surface of the cross-stratified sandstone is common in eolian deposits (Kocurek, 1981) and may have several causes. The relief may represent scour pits in the remnant of the dune, or it may represent differential deflation controlled to some extent by the local water table. Early diagenesis is common in dune sands, and differential cementation may result in the localization of scouring and the relief at the bounding surface (Simpson and Loope, 1985).

The intercalation of parallel-stratified eolian-ripple strata and irregular strata above the bounding surface

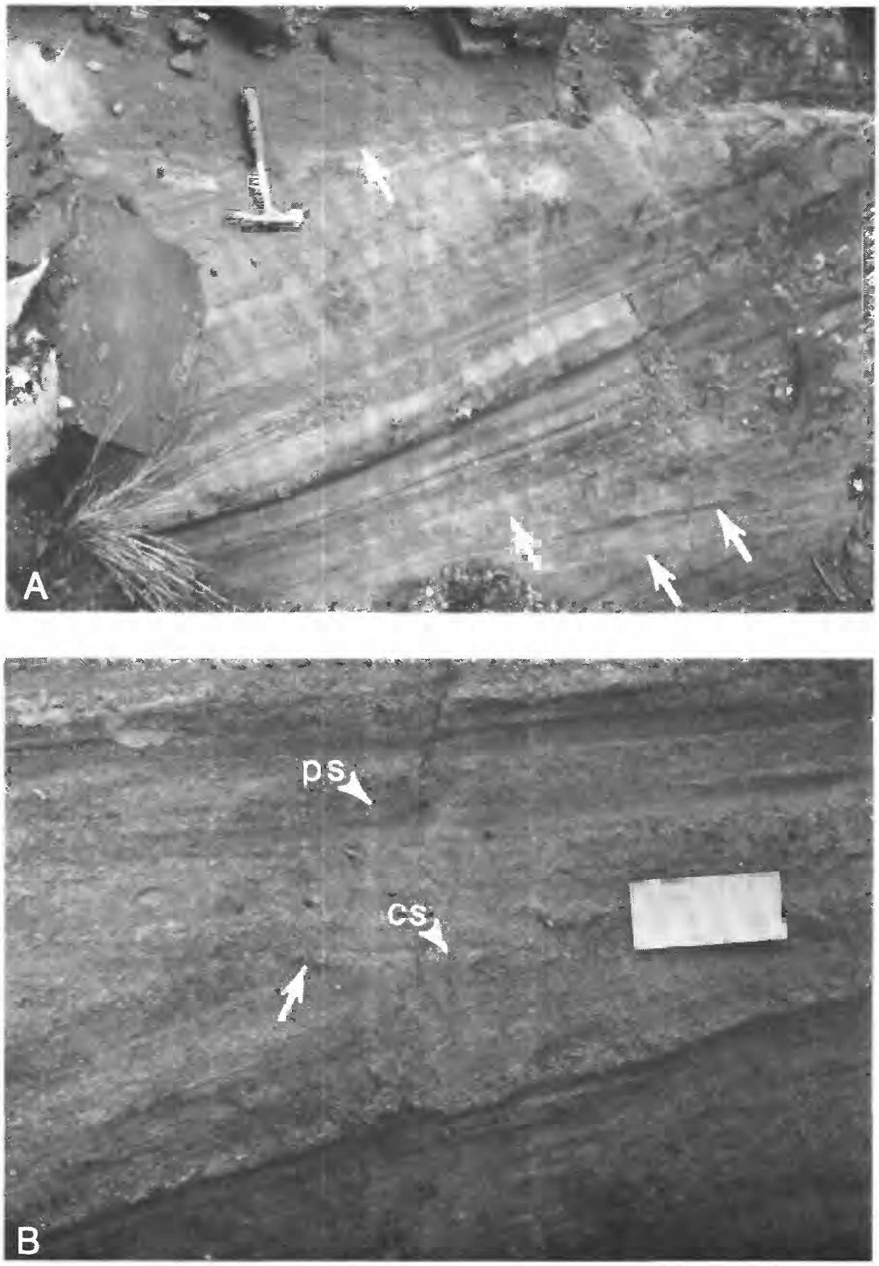

Figure 4. Features of cross-stratified sandstone. *A*, Coset of cross-stratified sandstone. Lower arrows point to bounding surfaces that separate sets of parallel-stratified sandstones. Upper arrow points to upper bounding surface of coset, which has 5 cm of relief. *B*, Detail of upper bounding surface. Note relief on top of coset (arrow) and lenses of coarse sandstone (**cs**) and parallel-stratified sandstone (**ps**) above the bounding surface.

supports the idea that the bounding surface and its relief were produced by eolian processes. The migration of coarse sand and granule ripples is a common phenomenon in and adjacent to dune fields, and these bedforms can produce this type of irregular stratification (Fryberger and others, 1979) in both interdune and sand-sheet environments.

The sandstones in this part of the sequence that contain small-scale ripple cross-strata and mud flasers probably were deposited in sandy intertidal environments (Reineck and Singh, 1973), and the dark, thinly laminated carbonate rocks probably accumulated as stromatolitic deposits in the intertidal zone (Shinn, 1983). In many areas today, dunes migrate across upper intertidal and

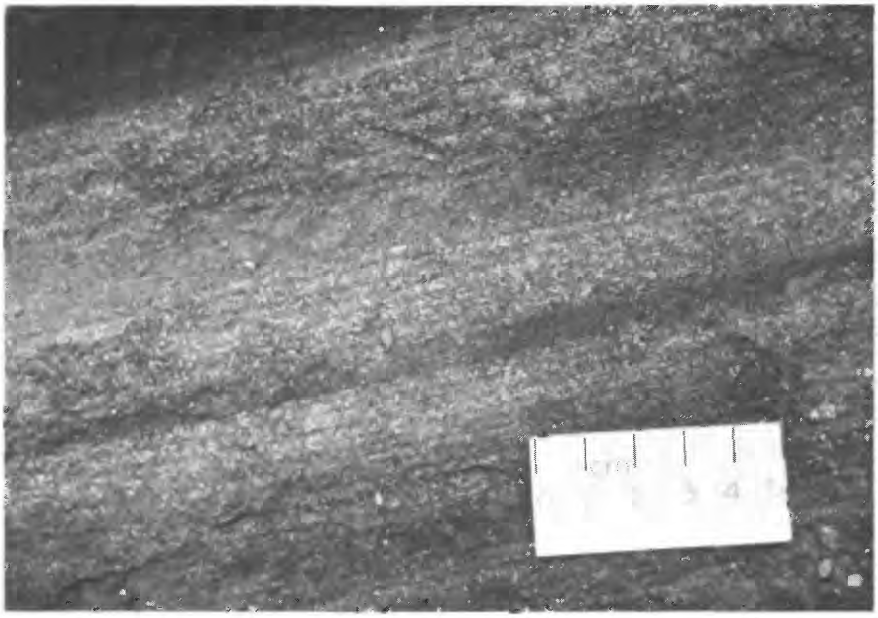

Figure 5. Detail of parallel-stratified sandstone that comprises most of the coset of cross-stratified sandstone. Note evenness and thinness of each stratum. Each stratum is inversely graded.

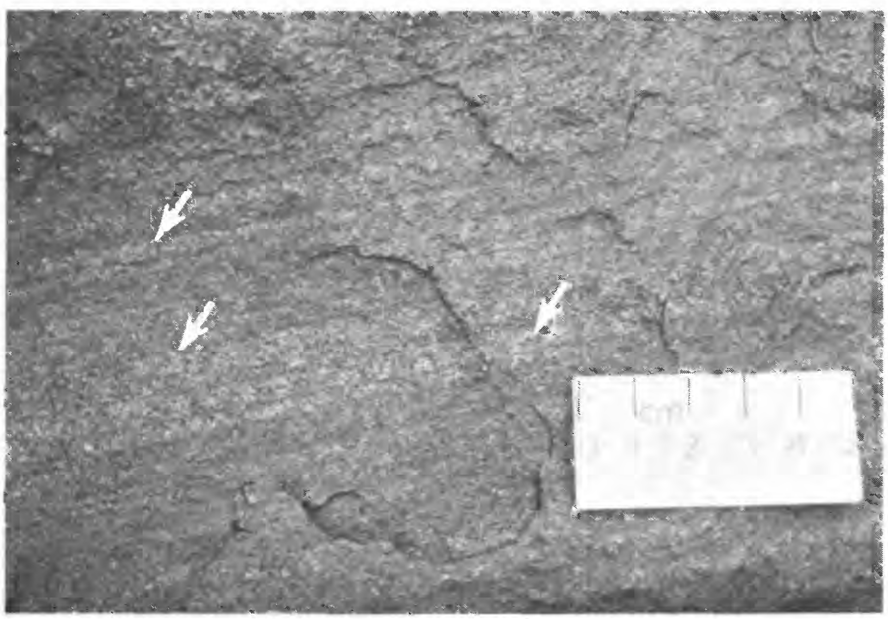

Figure 6. Coarser grained cross-strata (arrows) intercalated with inversely graded strata. The coarser grained cross-strata are ungraded and wedge out down slope into parallel-stratified sandstone.

supratidal flats (Inman and others, 1966; Shinn, 1973; Fryberger and other, 1983), and, as they migrate, only fractions of the dunes are preserved. The thin dune remnants are associated with tidal and interdune deposits, a situation considered viable for the deposits in the Eagle Valley described here.

PALEOGEOGRAPHIC IMPLICATIONS

The presence of black shales and evaporites in the Eagle Valley Evaporite led Mallory (1971) and Irtem (1977) to conclude that the Eagle Valley was deposited in relatively deep water. Boggs (1966), Tillman (1971),

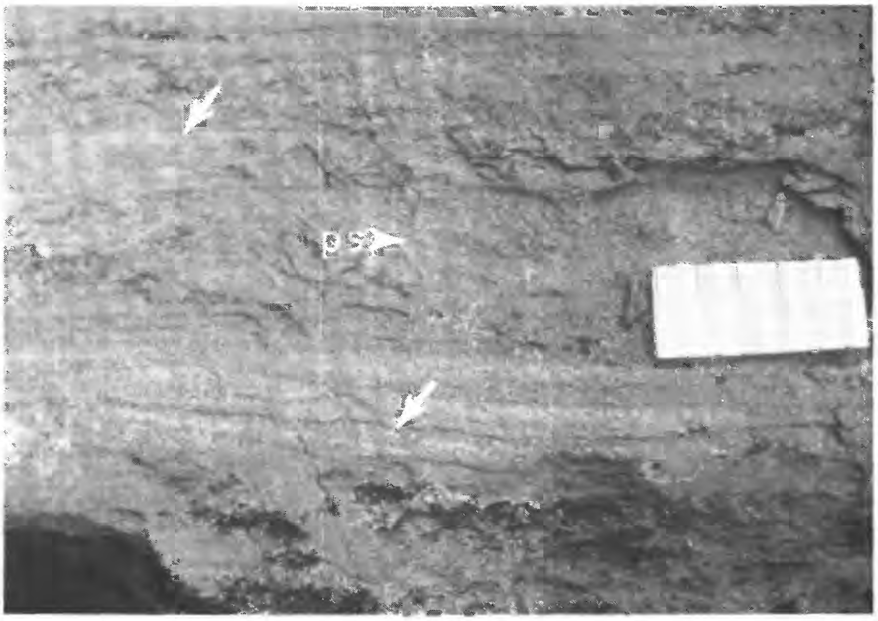

Figure 7. Irregularly and parallel-stratified sandstone above upper bounding surface of the coset. Note coarse-grained sandstone (arrows) and parallel-stratified sandstone (ps).

Walker (1972), and Bartleson (1972) believed, however, that facies changes in carbonate rocks of the coeval Minturn and Gothic Formations are more consistent with shoaling toward the center of the basin and that, by inference, the evaporites were deposited in shallow "pans" or sabkhas. The thickness, style of lamination, and lateral extent of the gypsum strongly argue for a basinal rather than shallow pan-environment (Schenk, 1987); however, the presence of eolian deposits in a clastic sequence situated between two such thick evaporite units indicates that major sea-level changes occurred during deposition of the Eagle Valley Evaporite.

During the Middle Pennsylvanian, sea-level variations were controlled by glacio-eustatic processes associated with Gondwana glaciation (Crowell, 1978; Ramsbottom and others, 1979; Boardman and others, 1984). Several studies (Heckel, 1980; Hite and Buckner, 1981) discuss the effects of sea-level changes on sedimentation in the Paradox basin and other nearby basins and in the North American mid-continent, and recognition of the role of sea-level changes may reconcile past interpretations of Eagle basin paleogeography. The presence of black shales and thick evaporites do suggest relatively deep water sedimentation, though only for restricted intervals. Evidence observed in Minturn and Gothic carbonate rocks for shoaling or sabkha conditions and in the eolian deposits described in this report may represent the other extreme of the sea-level cycle.

SUMMARY

The presence of eolian deposits and marine evaporites and black shales in the Eagle Valley suggests that sea-level changes were important in the evolution of the sedimentary sequence in the Eagle basin. During the Middle Pennsylvanian, the Eagle basin was not always a relatively deep basin nor was the center of the basin continuously occupied by a shallow evaporite pan. Sea-level changes probably resulted in an alternation of relatively deep marine and, in some cases, subaerial conditions. Additional work is necessary to outline the influences of sea-level changes on sedimentation in the center of the basin and to clarify facies relationships between sea-level cycles in the Eagle Valley Evaporite and the coeval Minturn and Gothic Formations.

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Chapter C

Burial Reconstruction of the Early and Middle Pennsylvanian Belden Formation, Gilman Area, Eagle Basin, Northwest Colorado

By VITO F. NUCCIO and CHRISTOPHER J. SCHENK

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

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Burial Reconstruction of the Early and Middle Pennsylvanian Belden Formation, Gilman Area, Eagle Basin, Northwest Colorado

By Vito F. Nuccio *and* Christopher J. Schenk

Abstract

Burial reconstruction, time-temperature index (*TTI*) modeling, and mean random vitrinite reflectance (*Rm*) determinations of the Early and Middle Pennsylvanian Belden Formation in the area around Gilman, Colorado, suggest that hydrocarbon generation could have occurred during the Late Pennsylvanian to Permian. The Belden contains sufficient quantities of both marine and nonmarine organic matter to make it an excellent source rock for both oil and gas.

TTI values calculated using a geothermal gradient of 2.4 °F/100 ft (43.7 °C/km) compare well with measured vitrinite reflectance values. If this gradient is used, then the Belden passed the lower limit of oil generation (*TTI* 10, 0.60 percent *Rm*) about 286 Ma and remained in the field of oil generation until 214 Ma, at which time oil became thermally unstable (*TTI* 80, 1.35 percent *Rm*); methane gas generation (*TTI* 25, 0.73 percent *Rm*) probably began about 278 Ma. The Belden entered the condensate field (*TTI* 1,500, and 2.2 percent *Rm*) about 102 Ma. Maximum burial and maximum temperature (*TTI* 40,000–50,000) occurred about 68 to 65 Ma and correlate with an average measured vitrinite reflectance of 3.70 percent.

The postulated high geothermal gradient of 2.4 °F/100 ft in the Gilman area probably reflects proximity to the Colorado mineral belt, and the thermal trend associated with the belt affected both the maturation of surrounding rocks and the regional geothermal gradient.

INTRODUCTION

The Belden Formation is a sequence of gray to black shale, mudstone, lime mudstone, mixed skeletal wackestone, and packstone and gray to buff sandstone deposited in the Eagle basin of northwestern Colorado during Early and Middle Pennsylvanian time. At most locations, sediments of the Belden were deposited directly on top of the Mississippian Leadville Limestone and locally on the regolithic Lower Pennsylvanian Molas Formation (Tweto and Lovering, 1977), after formation of the Eagle basin by tectonic events along the southern part of the craton (Kluth and Coney, 1981). The gray to black shale and mudstone in the Belden were first described by Brill (1944), who assigned the Belden to the Battle Mountain Formation and later (1958) raised it to formation status.

Recently, several authors have suggested that the shale and mudstone of the Belden may have been adequate source rocks for petroleum (Dodge and Bartleson, 1986; Nuccio and Schenk, 1986; Waechter and Johnson, 1986). The purpose of our study is to present data on the thermal maturity and source rock potential of the Belden Formation in the area around Gilman, Colo. (fig. 1),

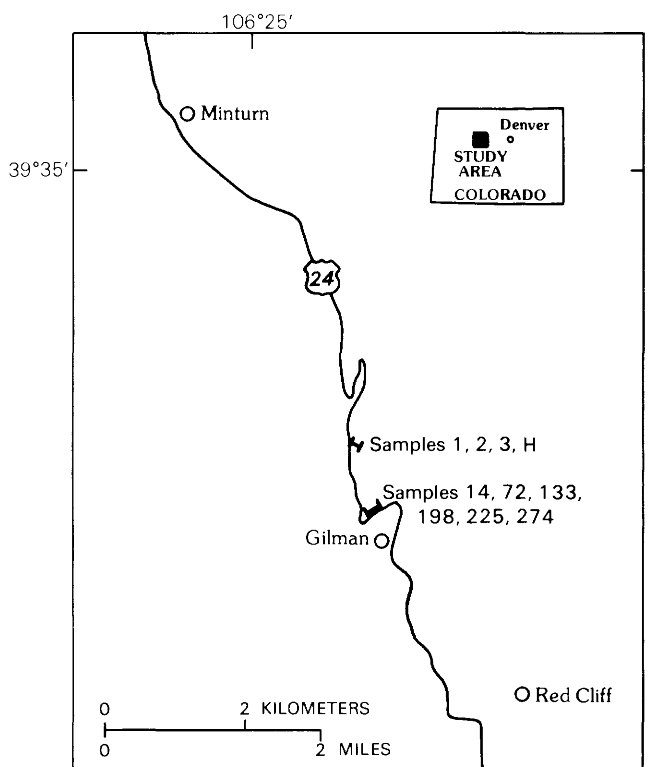

Figure 1. Location of measured sections (barred lines) and sample localities, Gilman area, Eagle basin, northwest Colorado.

where a complete section of the Belden is exposed. In addition, we use Lopatin modeling calibrated with mean random vitrinite reflectance values to reconstruct the burial history of the Belden in the area and to predict when hydrocarbons may have been generated.

A complete section of the Belden Formation is exposed on south- and east-facing slopes along U.S. Highway 24, immediately west of the abandoned town of Gilman (fig. 1). In this area, the contact of the Belden with the underlying Mississippian Leadville Limestone and with the overlying Minturn Formation is exposed. The type section of the Belden Formation is at this location (Brill, 1944), and a detailed stratigraphic section has been described by Tweto and Lovering (1977). The Belden is thinner in this area than in the western part of the Eagle basin and may represent only the Atokan part of the section, instead of the thicker Morrowan and Atokan section exposed farther to the west (Tweto and Lovering, 1977).

Acknowledgments.—The studies on which this report is based are part of the U.S. Geological Survey's Evolution of Sedimentary Basins and Thermal Maturity of the United States projects.

METHODS

Organic matter in samples of black shale, mudstone, and limestone from the Belden Formation was analyzed by using mean random vitrinite reflectance (*Rm*) and Rock-Eval pyrolysis (table 1). Two samples of mudstone from the overlying Minturn Formation were also studied. Mean vitrinite measurements can be used to define the maximum level of thermal maturity attained in the rock, and Rock-Eval pyrolysis yields data on the quantity and quality of organic matter. Most of the data used in the burial reconstruction (table 2) are from Tweto and others (1978), Tweto (1980), and our own measured stratigraphic section of the Belden. Figure 2 illustrates the stratigraphy of Pennsylvanian- to Cretaceous-age rocks in the Gilman area and complements the data shown in table 2.

The burial reconstruction was made by using the time-temperature index (*TTI*) model of Lopatin (1971). This model is one of the methods used to predict when a stratigraphic unit entered or passed through the limits of oil generation or "oil window." In Lopatin's *TTI* model, time and temperature are interchangeable, and, given sufficient time, a relatively low temperature can produce a high level of maturity (Lopatin, 1971; Waples, 1980). No single temperature, therefore, can be assigned to a vitrinite reflectance value. A second model postulates that time has no effect on thermal maturity and that, relatively soon (geologically speaking) after maximum temperatures are attained, organic matter stabilizes and reaction ceases (Neruchev and Parparova, 1972; Barker, 1983; Price, 1983). If the second model is correct, then vitrinite reflectance can be used as an absolute paleogeothermometer. It is beyond the scope of this paper to debate the two models, and we will use Lopatin's *TTI* model because it allows us to estimate the timing of important thermal events.

In the *TTI* 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 is estimated by using a present-day geothermal gradient and mean annual surface temperature. We estimated the mean annual surface temperature through time by starting with a present-day temperature of 50 °F (10.1 °C) and increasing it linearly to a temperature of 70 °F (21.3 °C) 320 Ma (table 2). Each increment of time is assigned a value based on both the average temperature of that increment and the length of time of that increment. In Lopatin's model, the rate of reaction of thermal alteration of organic matter increases by a factor *r* for each 10 °C (18 °F) increase in temperature. By 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*, and therefore his *TTI* is equal to the sum of each increment value multiplied by *r*.

Waples (1980) calculated *TTI* values for 402 samples of organic-rich rock from around the world and, despite the scatter in his data, suggested that a value for *r* of 2 is reasonable. He 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. Because *TTI* calculations yield values that can be related to our vitrinite reflectance measurements of the Belden, the two sets of values can be matched by simply adjusting the geothermal gradient.

HYDROCARBON-GENERATION THRESHOLDS AS EXPRESSED BY MEAN VITRINITE REFLECTANCE AND TIME-TEMPERATURE INDEX VALUES

Burial reconstruction of the Belden Formation shows four important hydrocarbon-generation thresholds (fig. 3): (1) *TTI* of 10 and *Rm* of 0.60 percent, the point at which oil generation begins (Waples, 1980); (2) *TTI* of 25 and *Rm* of 0.73 percent, the approximate point at which methane gas generation begins (Juntgen and Karweil, 1966); (3) *TTI* of 180 and *Rm* of 1.35 percent, the point at which liquid hydrocarbons break down to gas and condensate and the upper limit of the "oil window" (Waples, 1980); (4) *TTI* of approximately 1,500 and

Table 1. Vitrinite reflectance and Rock-Eval pyrolysis data, Eagle basin, northwest Colorado

[Sample numbers 14 to 274 also represent distance (in feet), as measured from the base of the Belden. Samples 1, 2, 3, and H are from sec. 12, T. 6 S., R. 81 W., Eagle County; all others are from sec. 13. Sample localities are shown on figure 1. Leaders (--), data not available]

Formation	Age	Lithology	Sample No.	*TOC*	*Rm*	*N*	*σ*	T_{max}	*HI*	*OI*	*PI*	*PC*	Sample weight	*S1*	*S2*	*S3*	*S2/S3*
Belden	Early and	Mudstone	1	2.03	3.37	11	0.33	0	0	38	0	0	160.9	0.01	0	0.78	0
	Middle	Sandstone	2	.49	3.72	80	.23	0	0	40	0	0	235.8	.01	0	.20	0
	Pennsylvanian	Carbonate	3	.91	4.09	19	.29	0	4	23	.25	0	250.0	.01	.04	.21	.19
		Mudstone	H	.80	3.64	56	.24	0	0	28	0	0	243.3	0	0	.23	0
		Mudstone	14	3.60	3.72	54	.54	0	3	105	.17	.01	134.4	.02	.11	3.80	.02
		Mudstone	72	--	3.77	50	.34	--	--	--	--	--	--	--	--	--	--
		Mudstone	133	--	3.56	31	.44	--	--	--	--	--	--	--	--	--	--
		Mudstone	198	--	3.76	50	.36	--	--	--	--	--	--	--	--	--	--
Minturn	Middle	Mudstone	225	1.06	3.52	51	.33	0	0	45	0	0	143.2	0	0	.48	0
	Pennsylvanian	Mudstone	274	--	3.58	50	.21	--	--	--	--	--	--	--	--	--	--

ABBREVIATIONS AND UNITS OF MEASUREMENTS

TOC	Total organic carbon (in weight percent)
Rm	Mean random vitrinite reflectance (in percent)
N	Sample population
σ	Standard deviation
T_{max}	Temperature at which maximum yield of hydrocarbons occurs during pyrolysis of organic matter (in °C)
HI	Hydrogen index (*S2/TOC*)
OI	Oxygen index (*S3/TOC*)
PI	Production index (*S1/(S1+S2)*)
PC	Pyrolyzed carbon (recoverable carbon after pyrolysis: in weight percent)
Sample weight	In milligrams per gram
S1	Integral of first peak (existing hydrocarbons volatized at 250 °C for 5 minutes) (in milligrams per gram)
S2	Integral of second peak (hydrocarbons produced by pyrolysis of solid organic matter (kerogen) between 250 and 550 °C) (in milligrams per gram)
S3	Integral of third peak (CO_2 produced by pyrolysis of kerogen between 250 and 390 °C) (in milligrams per gram)

Table 2. Data used to reconstruct burial history of the Belden Formation, Eagle basin, northwest Colorado

Age (Ma)	Formation or event	Thickness (feet)	Thickness (meters)	Mean annual surface temperature (°F)	Mean annual surface temperature (°C)
0- 10	Uplift	-5,180	-1,579	50	10.1
10- 37	Tertiary intrusive rocks	300	91	51	10.6
37- 65	Laramide orogeny	-10,900	-3,322	57	14
65- 68	Hiatus	0	0	57	14
68-130	Cretaceous rocks	7,200	2,195	57	14
130-144	Unconformity	-100	-31	59	15.1
144-163	Morrison Formation	250	76	59	15.1
163-180	Hiatus	0	0	61	16.2
180-193	Entrada Formation	60	18	62	16.8
193-210	Unconformity	-100	-31	63	17.4
210-222	Chinle Formation	70	21	64	17.9
222-225	Hiatus	0	0	64	17.9
225-260	State Bridge Formation	600	91	66	19
260-276	Hiatus	0	0	67	19.6
276-296	Maroon Formation	1,700	259	68	20.2
296-310	Minturn Formation	6,000	1,829	69	20.7
310-320	Belden Formation	200	61	70	21.3

Rm of 2.2 percent, the point at which condensate becomes thermally unstable and is converted to methane. (Methane gas is stable at relatively high temperatures corresponding to *Rm* values as high as 4.8 percent and *TTI* values as high as 120,000–130,000 (Waples, 1980).) At high temperatures, *TTI* values become more and more approximate or relative because of the exponential increase in calculated values.

THE BELDEN FORMATION AS A HYDROCARBON SOURCE ROCK

In general terms, organic matter can be divided into three types: type I, sapropelic or fatty; type III, humic or coaly; and type II, intermediate between types I and III. Sapropelic organic matter is hydrogen rich, occurs principally in rocks of marine origin, and generates oil during thermal maturation. Humic organic matter is hydrogen poor, occurs mostly in nonmarine rocks, and generates methane gas during thermal maturation. Type II organic matter can be a source for both oil and gas (Tissot and others, 1974).

In the Gilman area, rocks of the Belden Formation comprise shale, mudstone, limestone, and minor sandstone. Tweto and Lovering (1977) described a faunal assemblage in the mudstone and limestone that includes brachiopods, cephalopods, gastropods, crinoids, and bivalves. The faunal assemblage indicates a marine origin for some organic matter in the Belden, and thus the Belden is a possible source for oil. Large amounts of vitrinitic or humic material were observed in polished sections and indicate a terrestrial origin for some organic matter in the Belden, and thus the Belden is a possible source for gas as well. Results of Rock-Eval pyrolysis

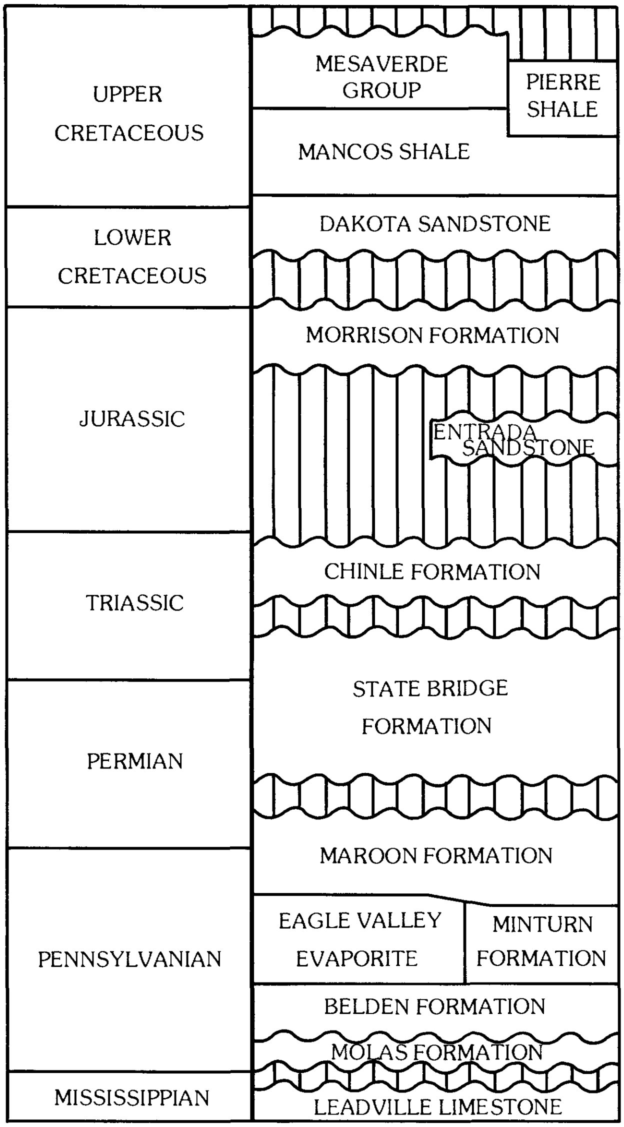

Figure 2. Stratigraphy of rocks in the Eagle basin. Tertiary rocks in the Gilman area comprise only localized occurrences of basalt and are not shown. Stratigraphy corresponds to that in table 2.

indicate that all shale samples from the Gilman section have been subjected to extremely high temperatures, and, because of these high temperatures, the method is an ineffective indicator of source rock type. Rock-Eval pyrolysis indicates high total organic carbon (*TOC*) values for shale and mudstone from the Gilman sections; these high values indicate the amount of organic matter is more than sufficient for the Belden mudstone and shale in the area to be excellent source rocks.

BURIAL RECONSTRUCTION

The burial reconstruction diagram (fig. 3) shows four important stages in the burial history of the Belden Formation. During the Pennsylvanian and Early Permian (320 to 276 Ma), 7,700 ft (2,347 m) of sediments were rapidly deposited on top of the Belden. From the Late Permian through Jurassic (276 to 130 Ma), only 780 ft (238 m) of sediments were deposited. During the Cretaceous (130 to 68 Ma), 7,200 ft (2,195 m) of sediments were deposited. The fourth stage began about 65 Ma, at the end of the Cretaceous (or at the beginning of the Laramide orogeny), and continued until the present. During this stage, the entire stratigraphic section was uplifted and eroded; approximately 15,800 ft (4,816 m) of sediments were removed and the Belden is now exposed at the surface.

If we assume the Belden reached maximum temperature during maximum burial about 68 to 65 Ma, then the maximum level of thermal maturation of organic matter should be recorded by the vitrinite reflectance values achieved at that time. From the beginning of the Laramide orogeny to the present, uplift and erosion likely caused a relative cooling and the Belden probably never experienced temperatures as high as those during maximum burial. Continued maturation of organic matter after 65 Ma was insignificant in increasing the level of thermal maturity.

Because vitrinite reflectance and *TTI* have been calibrated (Waples, 1980), we can adjust either the depth of burial or the geothermal gradient of the burial curves until *TTI* and mean vitrinite reflectance values correlate. We believe that our estimate of the depth of Belden burial is fairly accurate, and, therefore, we varied geothermal gradients in an attempt to match *TTI* values with our measured vitrinite reflectance values. Our average vitrinite reflectance value for the Belden in the Gilman area is 3.70 percent, and we assume this value represents maximum burial and temperature between 68 and 65 Ma.

TTI values correlate best to our vitrinite reflectance values if a geothermal gradient of 2.4 °F/100 ft (43.7 °C/km) is used, a gradient similar to those in the nearby southern Piceance basin (Nuccio and Johnson, 1984). Using this gradient, the Belden entered the oil window about 286 Ma and left it 214 Ma. Methane began to be generated at about 278 Ma, and the Belden passed the condensate boundary about 102 Ma. A *TTI* of between 40,000 and 50,000 occurred at maximum burial (68–65 Ma) and corresponds to our average measured vitrinite reflectance value of 3.70 percent.

We then changed the paleogeothermal gradients. A normal crustal geothermal gradient of 1.40 °F/100 ft (25 °C/km) was assumed between 320 Ma and 65 Ma, at which time the Laramide orogeny began and Tertiary intrusive rocks were emplaced. From 65 Ma until the present, geothermal gradients were chosen in order to match *TTI* and vitrinite reflectance values, and geothermal gradients much greater than 10 °F/100 ft (182 °C/km) were required. These gradients are probably much too high for

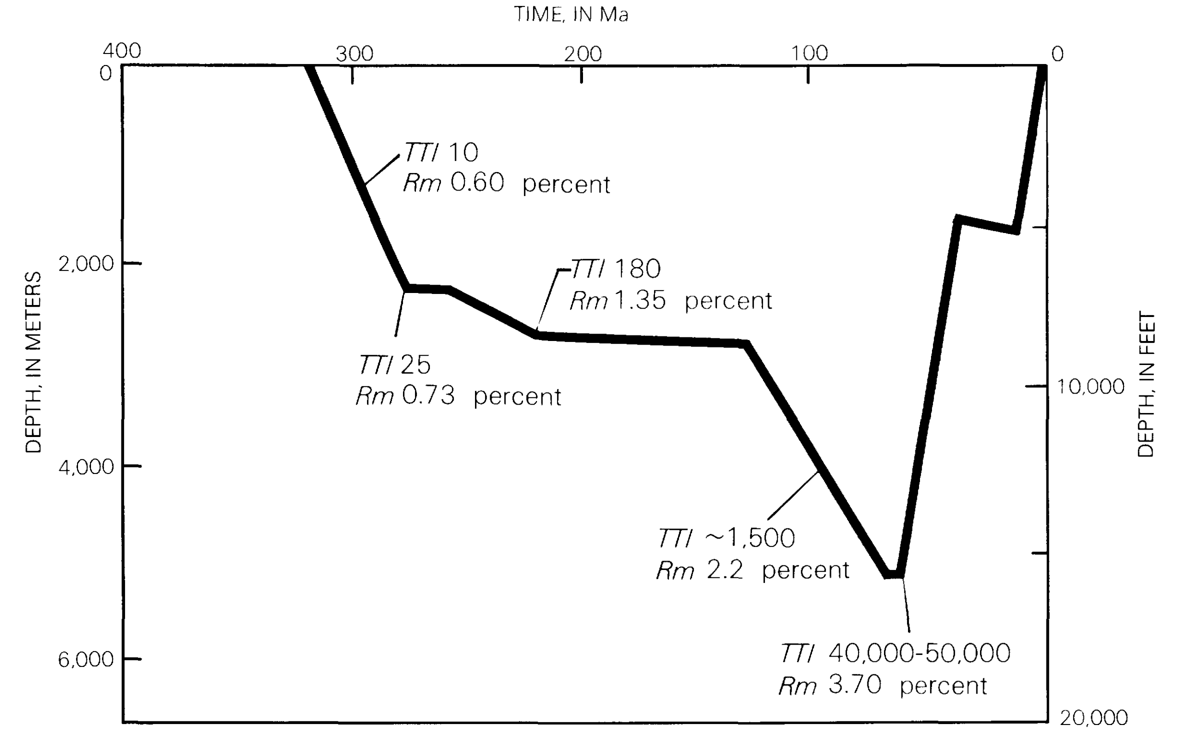

Figure 3. Burial reconstruction and stages of hydrocarbon generation in the Belden Formation, Eagle basin. A geothermal gradient of 2.4 °F/100 ft (43.7 °C/km) was used.

this area, especially because of the absence of local plutons, and we conclude that our first and simplest model, which assumes a geothermal of 2.4 °F/100 ft through time, best fits the thermal history of the Gilman area and should be used until a better method of determining paleogeothermal gradients is developed.

The relatively high geothermal gradient of 2.4 °F/100 ft used in our model for the Gilman area possibly can be explained by the presence of the Colorado mineral belt. This belt of ancient faults (2,000–1,700 Ma) can be traced from the Grand Canyon northeastward to the Rocky Mountain front near the Colorado-Wyoming border (Warner, 1980). Although heat flow in this belt may have been high throughout the history of the Belden, Laramide deformation along the belt is most pronounced wherever plutonic rocks have been emplaced, including the area of the northern San Juan basin, the southern Piceance basin, and the southern Eagle basin (Tweto and Sims, 1963; Tweto, 1975). The plutons are postulated to have had a localized heating effect on the maturation of the surrounding rocks (De Voto and Maslyn, 1977).

Another possible source of heat in the Gilman area is the Pando porphyry, a sill intruded during the Late Cretaceous near the base of the Belden Formation at the location of our measured section. Studies of dikes and sills indicate the area of thermal metamorphism around such intrusions is approximately equal to one to two times its thickness (Crelling and Dutcher, 1968; Peters and others, 1978; Bostick and Pawlewicz, 1984). If this relationship holds true for the Pando porphyry, then heat from the 50-foot-thick (15.25 m) sill affected an area of from 50 ft to 100 ft (15.24-30.48 m) outward from the intrusion. The consistency of vitrinite reflectance values in the Belden Formation both near the sill and in the overlying Minturn Formation, more than 274 ft (83.52 m) above the sill, suggests that the sill had no effect on thermal maturation and that depth of burial before the sill was emplaced controlled thermal maturation of organic matter in the Belden Formation.

SUMMARY

Burial reconstructions, time-temperature index modeling, and measured vitrinite reflectance values of the Belden Formation in the area around Gilman, Colo., suggest hydrocarbon generation may have begun as early as the Pennsylvanian as a result of both rapid burial beneath 6,000 ft (2,000 m) of the Minturn Formation and a relatively high geothermal gradient. This hydrocarbon-generation history may not be the same for the Belden Formation in other areas of the Eagle basin because the Minturn and its equivalents generally are thinner than in the Gilman area. Burial reconstructions in several areas of the basin are needed before the hydrocarbon-generation history of the Belden Formation throughout the Eagle basin can be determined.

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