The Eagle Valley Evaporite, Northwest Colorado—A Regional Synthesis

GEOLOGICAL SURVEY BULLETIN 1311-E

The Eagle Valley Evaporite, Northwest Colorado— A Regional Synthesis

By WILLIAM W. MALLORY

CONTRIBUTIONS TO GENERAL GEOLOGY

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A regional study of the extent, thickness, lithology, stratigraphic relations, age, depositional environment, and tectonic history of thick sulfate deposits and associated salts of sodium and potassium

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CONTENTS

ILLUSTRATIONS

TABLE

CONTRIBUTIONS TO GENERAL GEOLOGY

THE EAGLE VALLEY EVAPORITE, NORTHWEST COLORADO— A REGIONAL SYNTHESIS

By William W. Mallory

ABSTRACT

The Eagle Valley Evaporite consists principally of gypsum and anhydrite, but it contains an appreciable quantity of halite and traces of potash salts. The enclosing rocks are conglomerate, sandstone, siltstone, shale, and limestone. The age of the formation is Middle Pennsylvanian, late Atoka, and Des Moines.

The evaporite interval (Eagle Valley Evaporite and correlative rocks of other lithologies) is divided into lower and upper parts separated by the Jacque Mountain Limestone Member of the Minturn Formation and a correlative or nearly correlative horizon, informally termed the JM datum. The thickness of the evaporite interval ranges from 9,000 feet in the vicinity of Eagle, Colo., to zero at the northeastern edge of the Eagle basin, 25 miles away. In some areas flowage has increased original depositional thickness.

Because of its pliability, the evaporite has been deformed more than other rocks in its vicinity. It shows the effects of load metamorphism, Laramide tilting, diapiric upwelling, and contortion due to flowage and hydration of anhydrite. Its geomorphic expression is anomalous in that it typically forms bluffs and low hills in spite of its high solubility and friability; this fact indicates that it probably is upwelling in some areas at a rate commensurate with solution and erosion.

The evaporite was deposited in a landlocked marine trough between the Uncompahgre and Frontrange uplifts. Marine circulation and interchange of water were impeded on the open northwest end by a broad, shallow shelf, while exceptionally thick evaporite rocks were deposited at the distal, southeast end. The climate was arid or semiarid, with occasional torrential rain.

Mineral commodities of possible future commercial value, contained in or associated with this formation, are gypsum, halite, salts of potassium, oil, and gas.

INTRODUCTION

LOCATION AND REGIONAL GEOLOGIC SETTING

The Eagle Valley Evaporite is a formation of limited areal extent. It is present in the northwest quadrant of Colorado in parts of Eagle, Pitkin, Garfield, Rio Blanco, Moffat, and Routt Counties. Physiographically, it is in the northern corner of the Colorado Plateaus province west of the Sawatch, Tenmile, Gore, and Park Ranges of the Rocky Mountains (fig. 1, pl. 3). The White River Plateau, a broad structural dome from which rocks of Pennsylvanian age have been removed by erosion, lies near the middle of the area.

Paleogeographically, the Central Colorado trough (fig. 8) of Pennsylvanian time lay between the Frontrange [1] and Uncompahgre uplifts of the Ancestral Rocky Mountains and extended from northwest Colorado to northeast New Mexico (fig. 8). The Eagle basin is the name applied in this paper to the northwestern part of the trough. The name Maroon basin has also been used. The area in which the evaporite rocks occur has an irregular outline but would fit inside a rectangle 50 miles wide by 100 miles long.

The lithology of these rocks is unusual and their stratigraphic relations are complex. The presence of halite in the basin has been known since 1949 when the Champlin Refining Co. drilled their Black 1 well near the town of Eagle. The presence of potash and other salts of commercial value was suspected for several years and has been confirmed by recent drilling.

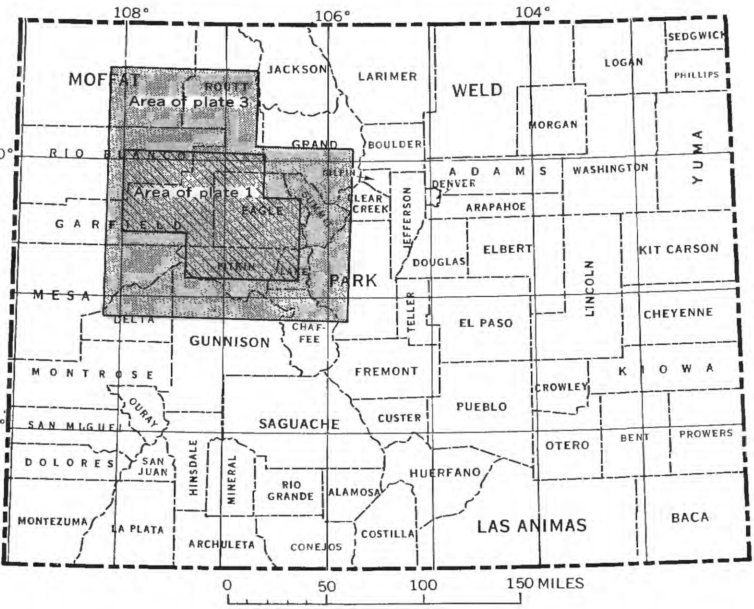


FIGURE 1.—Index map of Colorado showing area of investigation.

[1] This spelling is used to distinguish the Pennsylvanian uplift from the now-existing Front Range of Laramide origin.

PREVIOUS WORK AND OBJECTIVES OF THIS REPORT

The earliest speculations on the gypsum in the Eagle Valley Evaporite concerned its age; Permian was a general consensus by analogy with widespread evaporites in the midcontinent region. A. R. Marvine (in Peale, 1876, p. 119), however, suggested that at least part of the gypsum north of the Eagle River was of Carboniferous age. Little was written on the subject until Brill (1942, p. 1391), in a study of the Gore area, recognized the Des Moines age of at least part of the gypsum, described a local intertonguing of the evaporite rocks with the Battle Mountain Formation, and inferred the lateral equivalence of these two formations. In 1944 he listed (p. 631, 632) localities where gypsum is exposed and discussed at greater length the physical relation of these rocks to other formations. In 1952 Brill published a comprehensive discussion of the Pennsylvanian rocks in the Central Colorado trough of western Colorado and north-central New Mexico in which he showed the approximate surface extent of gypsum on a generalized regional map. This is the earliest publication of the extent of the evaporite basin, but the scale of the map was small and his data were limited to a few surface sections. Benson and Bass (1955) recognized the anticlinal structure of the Eagle River valley east of Dotsero; their recognition was the earliest implication that structures involving salt flowage might be present in the Eagle basin.

In 1958 Murray (p. 50–53) discussed the Pennsylvanian rocks of the Maroon (Eagle) basin in northwest Colorado and showed a detailed section of the evaporitic rocks between Pando and Sweetwater Creek. This work clearly indicated the intertonguing of his Eagle Evaporite Member of the Minturn Formation in this area but did not include discussion of other parts of the Eagle basin. Bass (1958, p. 92) discussed briefly in a review article the evaporitic rocks on the south flank of the White River Plateau (pl. 1) and used the name Paradox Formation. Other authors in the same volume used such terms as Eagle Evaporite Member (Murray, 1958) or Eagle Evaporites (Katich, 1958; Bissell and Childs, 1958). Katich (1958) discussed the Eagle Evaporites and presented a small-scale regional map (his fig. 1) showing the thickness and extent of the evaporitic rocks; subsurface data were included.

Mallory (1960, fig. 5) showed on a small scale the evaporite rocks of the Eagle and Paradox basins in a regional paleogeographic setting and included (1960, fig. 8) a longitudinal section of Pennsylvanian rocks of the Central Colorado trough. Lovering and Mallory (1962) introduced the name Eagle Valley Evaporite to formalize current usage and selected a type section near Avon where the relation of the Minturn, Maroon, and Eagle Valley Formations can be studied on the surface. Bass and Northrop (1963, pl. 1) mapped the surface extent of the evaporite rocks in the Glenwood Springs quadrangle and discussed (p. J42–J46) the lithology and age of these beds. Their map is the earliest representation on a large scale of the location of outcrops of the evaporite. It has been reduced and incorporated without alteration in plate 1 of this report.

The petrology of the Minturn Formation and its relation to the Eagle Valley Evaporite near Avon were discussed by Boggs (1966), who mapped a westward extension of the Jacque Mountain and Robinson Limestone Members from Avon to Squaw Creek (between Edwards and Wolcott). Careful recheck of the area failed to corroborate Boggs' mapping. The Jacque Mountain is the only identifiable limestone marker bed of the Minturn Formation that can be traced into the Eagle Valley Evaporite. On the surface it disappears by pinchout near Avon (Lovering and Mallory, 1962, fig. 132.1). In the subsurface it is identifiable in logs of the Poose Creek, Kagie, Buford, and Quiett wells (pl. 2, section *B–B′*). Elsewhere the upper surface of carbonate and evaporite units in the Morgan and Eagle Valley Formations is correlated with the upper surface of the Jacque Mountain (the JM datum) (pl. 2, section *A–A′*). Also in 1966, Mallory (p. B12–B15) described the Cattle Creek anticline, a salt diapir south of Glenwood Springs.

Previous work, therefore, described the composition, age, and extent of the Eagle Valley Evaporite in a general way and established the fact that the evaporite is laterally equivalent to the Minturn and possibly other rocks.

The objectives of this report are (1) to show in greater detail the areal extent of the Eagle Valley Evaporite, (2) to indicate which parts are exposed and which are present in the subsurface, (3) to indicate the thickness of the formation and the thickness of its contained evaporitic rocks, (4) to delineate the major facies belts of the formation and their relation to each other and to the rocks of similar age which surround them, (5) to discuss their origin and history since deposition, and (6) to point out economic aspects of the Eagle Valley Evaporite and related formations.

FIELDWORK AND METHODS OF STUDY

Field mapping, measurement and description of sections, and surface and subsurface correlations were carried out during 1962–67 on a part-time basis as other work allowed. Subsurface work was based mainly on sample logs prepared by the American Stratigraphic Co. and to some extent on other sources of data. (See table 1.) Surface sections and subsurface sections from wells are identified in the text and on maps by name. Well names are an abridgment of the full name, usually the fee name but in some instances the company name. The full name, location, and other information on wells and surface sections are shown in table 1.

TABLE 1.—*Index to surface sections and subsurface sections from wells*

[Type: 1, surface; 2, subsurface. AmStrat, American Stratigraphic Co.; Petroleum Inf. Corp., Petroleum Information Corp]

Designation on maps and in text (see pls. 2, 3)	Formal name	County	Location (section-township-range)	Type	Source of data
Amerada	Amerada Unit 1	Moffat	9-5N-94W	2	AmStrat log 781.
Avon	Avon	Eagle	8-5S-81W	1	Lovering and Mallory (1962).
Benton	California Co. Benton 1	do	14-3S-85W	2	AmStrat log 849.
Black	Champlin Refining Co. Black 1.	do	4-5S-84W	2	AmStrat log 100-R.
Boden	Reasor Boden 1	Routt	34-7N-85W	2	Petroleum Inf. Corp.
Bowen	Cameron Oil Co. Bowen 1.	Garfield	20-4S-93W	2	AmStrat log D-1257.
Buford	Buford Oil Co. Govt. 1	Rio Blanco	16-1N-91W	2	AmStrat log 725.
Chura	Gardner Bros. Chura 1	Routt	4-7N-86W	2	AmStrat log 219.
Cattle Creek Station.	West side of valley of Roaring Fork River near Cattle Creek Station.	Garfield	12-7S-89W	1	Mallory, this report.
Crosho Lake	Humble Oil & Refining Co. Crosho Lake 1.	Rio Blanco	13-2N-87W	2	AmStrat log D-2096.
Dotsero	Blowout Hill, Dotsero	Eagle	4-5S-86W	1	Mallory, this report.
Dougherty	Benedum-Trees Govt.-Dougherty 1.	Garfield	7-1N-88W	2	AmStrat log D-1253.
Dry Draw	Dry Draw	Eagle	23-5S-81W	1	T. S. Lovering (written commun., 1965).
Fish hatchery	Fish hatchery on East Rifle Creek.	Garfield	23-4S-92W	1	Mallory, this report.
Johnston	English Oil Co. Johnston-Govt. 1.	Rio Blanco	28-3N-88W	2	AmStrat log 888.
Jones	Pan American Jones 1	Routt	13-7N-87W	2	AmStrat log D-2085.
Juniper Mtn	Cross Mtn.-Juniper Mtn	Moffat	18-6N-94W	1	Wilson (1957).
Kagie	O. D. Robinson Kagie 1	Routt	29-4N-87W	2	AmStrat log 587.
King Mountain	Texaco King Mtn. Unit-Govt.1.	do	2-1S-85W	2	AmStrat log D-1812.
Kritsas	Kern County Land Co. Kritsas 1.	Rio Blanco	8-1N-93W	2	AmStrat log 2089.
Lewin	Continental Oil Co. Lewin 1.	Moffat	17-3N-91W	2	AmStrat log 329.
Madison	Stanolind Oil & Gas Co. Madison Unit 1.	do	22-4N-92W	2	AmStrat log 211.
McCoy	McCoy-Burns	Eagle	6-2S-83W	1	Chronic (1957).
Miller Creek	Miller Creek	Rio Blanco	7-2S-92W	1	Upper part, Mallory, this report: lower part, Murray and Chronic (1965).
Minturn	Minturn	Eagle	25-5S-81W	1	T. S. Lovering (written commun., 1965).
North Elk Creek.	North Elk Creek	Rio Blanco	25-1S-92W	1	Mallory, this report.
O'Brien	Miami Oil Producing Co. O'Brien 1.	Moffat	14-4N-90W	1	AmStrat log D-2479.
Pastorius	Daubes Oil Co. Pastorius 1.	Routt	23-3N-85W	2	Petroleum Inf. Corp.
Patterson	Roaring Fork Oil Co. Patterson 1.	Garfield	36-7S-88W	2	AmStrat log D-2429.
Poose Creek	Phillips Petroleum Co. Unit 1.	Rio Blanco	10-2N-88W	2	AmStrat log 28.
Quiett	Miracle and Wooster Quiett 1.	do	26-1S-92W	2	AmStrat log D-1637.
Ruedi	Core hole M-1-63 at Ruedi dam.	Eagle	17-8S-84W	2	Bureau of Reclamation.
Rose	Shannon Oil Co. Rose 1	Garfield	12-7S-89W	2	AmStrat log D-1467.
Steele	Siegel-Animonetto Steele 1.	Rio Blanco	25-1N-91W	2	AmStrat log 193.
Treleaven	Texaco Treleaven 7	Moffat	31-5N-95W	2	AmStrat log D-1661.
Tully	Pan American Tully 1	Eagle	30-6S-85W	2	AmStrat log D-1819.
20-Unit	Texas Co.-California Co. Unit 20.	Rio Blanco	34-3N-94W	2	AmStrat log 314.
Woods Lake	Woods Lake	Eagle	21-7S-83W	1	Mallory.
Yellowjacket	Phillips Petroleum Co. Unit 1.	Rio Blanco	1-1N-92W	2	AmStrat log W-49.

Care was mandatory in selecting surface and subsurface sections of the evaporite and its enclosing strata. The typical outcrop of the Eagle Valley Evaporite is a contorted mass of gypsum and gypsiferous mudstone and siltstone having little apparent continuity and therefore little value in correlation. The base of the section is commonly obscured by alluvium, and the top is commonly truncated by erosion. These relations are especially troublesome in areas where the evaporite is thick and relatively free from clastic components. Measurable surface sections are limited to those areas where internal structure of the evaporitic rocks is not complex. Most of these areas are peripheral to the central part of the evaporite basin. Five sections were measured for this investigation—Cattle Creek, Dotsero, North Elk Creek, fish hatchery, and Miller Creek.

The structural simplicity of the thick surface section on the west side of the Roaring Fork River near Cattle Creek Station (pl. 3) is fortunately anomalous. Although the base of the formation is not exposed, 2,000 feet of relatively undistorted vertical to near-vertical beds on the west limb of a diapiric anticline (Mallory, 1966) is readily accessible for study. An additional 3,000 ft of Eagle Valley has been penetrated by the adjacent Rose well, but the degree of structural distortion and solution in the well at depth and the relation of the section in the well to the surface section are unkown.

For the area southeast of the Colorado River and around the periphery of the White River Plateau, nearly all the known measurable sections and wells drilled are included in this study. Farther northwest, in eastern Rio Blanco County and southeastern Moffat County, a larger number of wells have been drilled. Most wells, however, do not penetrate the Pennsylvanian System. Those for which good sample logs are available and which are so located as to form a satisfactorily spaced control grid were selected. Hence, this study considers virtually all the significant surface and subsurface data which are available.

ACKNOWLEDGMENTS

Keith F. Oles contributed skilled assistance in the field during the summer of 1963 in the measurement of sections and the collection of fossils. John K. Snobble pointed out the anomalous slope of river terraces in the Carbondale area. Thomas S. Lovering, while mapping the northwest part of the Minturn quadrangle in 1961, joined in establishing stratigraphic relations of the Eagle Valley Evaporite in the type locality. The author thanks Frank M. Tully, consulting geologist, for a map of the Red Table Mountain area and John W. Vanderwilt, consulting geologist, for information on a well core at Climax.

STRATIGRAPHY

NOMENCLATURE

Nomenclature in the upper Paleozoic rocks of the Eagle basin has changed from time to time because of complex stratigraphic relations and the introduction of new names by different authors. In 1944 Brill (p. 623, 624, 632) reviewed the nomenclature of upper Paleozoic rocks in northwest Colorado, and in 1952 he discussed (p. 811) names proposed in the intervening period. In 1954 Langenheim (fig. 2) tabulated the development of nomenclature to that date. Nomenclatural developments to date are shown in figure 2 of the present paper.

The significant steps in the development of the nomenclature of the evaporite have been made since 1950. Benson and Bass (1955) referred to the gypsum-bearing strata in the valley of the Eagle River as the Paradox Formation because of their similarity in age and lithology to the extensive evaporite beds of the Paradox Member of the Hermosa Formation in the Paradox basin of southwest Colorado. Opposition to this name was based on the distance that separated the two bodies of evaporite rocks. In 1958 Bass (p. 91) again used the name Paradox Formation. Also in 1958 Murray (p. 52) used the name Eagle Evaporite Member of the Minturn Formation, and Katich, as well as Bissell and Childs, used the term Eagle Evaporites. Their terminology reflected the nearly universal application of the name Eagle to these rocks by subsurface geologists. In 1962 Lovering and Mallory formally introduced the name Eagle Valley Evaporite—Eagle was preempted—for gypsum and gypsiferous clastic strata which intertongue with the Minturn and Maroon Formations near Avon. Their purpose was to recognize the most common usage and to avoid confusing these rocks with the Paradox Formation, a separate body of rocks in a different basin.

At present six generally accepted names (fig. 3) identify the major lithologic units which correlate with or enclose the Eagle Valley Evaporite in the Eagle basin. These are, in ascending order, (1) Belden Shale, (2) Minturn Formation, (3) Maroon Formation, (4) Gothic Formation of Langenheim (1952), (5) Morgan Formation, and (6) Weber Sandstone. The Jacque Mountain Limestone Member at the top of the Minturn Formation is an important marker bed.

1. The Belden Shale was originally named by Brill (1942, p. 1385) as the basal member of his Battle Mountain Formation (now Belden, Minturn, and Maroon Formations) to replace the archaic name "Weber shale" in northwestern Colorado. In 1944 Brill raised it to formation rank.

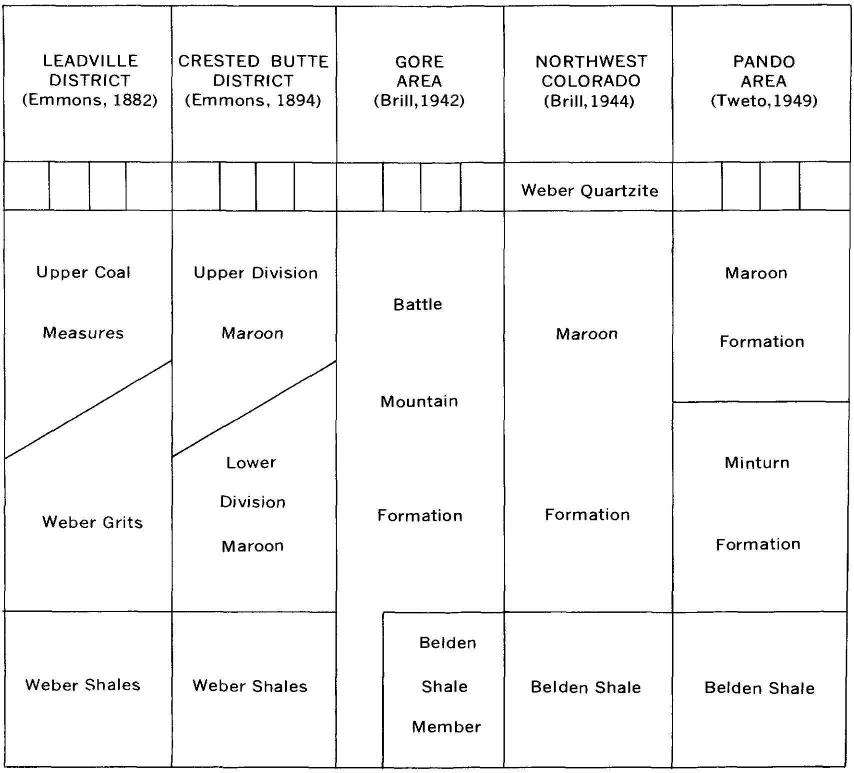
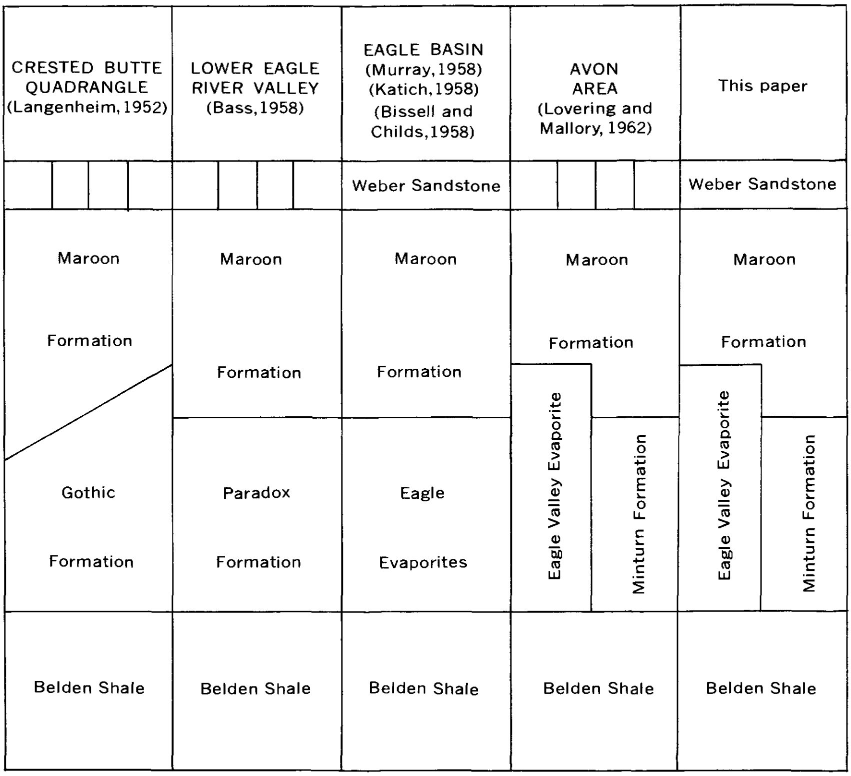


FIGURE 2.—Development of nomenclature for

2. The name Minturn Formation was given by Tweto (1949, p. 194–198) to some 6,000 ft of coarse clastic rocks between the Belden Shale and the Maroon Formation. The name Jacque Mountain Limestone Member was first used by Emmons (1898); this limestone has since been designated the uppermost member of the Minturn Formation (Tweto, 1949, p. 204).
3. The name Maroon Formation was introduced by Emmons (1898). It has been used in several ways by many authors since then. In this paper the name is used with two connotations. In the Minturn quadrangle where the Jacque Mountain Limestone Member is present, the Maroon Formation is restricted to red beds overlying the Jacque Mountain, thus following the usage by Tweto (1949). Wherever the Jacque Mountain is absent, all red beds equivalent to and directly overlying the Eagle Valley Evaporite are referred to the Maroon Formation.



upper Paleozoic rocks in northwestern Colorado.

4. The name Gothic Formation of Langenheim (1952, p. 561–563) is used for nonred clastic rocks and included thin limestone beds on the southwest margin of the basin which are similar in age and stratigraphic position to the Minturn Formation on the northeast side. The name Maroon Formation is used for red beds above the Gothic.
5. The name Morgan Formation was first used by Blackwelder (1910, p. 519) for a sequence of red sandstone and shale with intercalated limestone beds which separates rocks of Mississippian age from the Weber Quartzite. The type section is near the town of Morgan, Utah. The name has been extended into northwestern Colorado, where it is used for intercalated red beds, light-colored sandstone beds, and limestone which occupy the same stratigraphic position. Locally in Colorado the Morgan is subdivided by various authors into two lithic units and elsewhere into three; these units are commonly designated either lower and upper or lower, middle, and upper. No consensus, however, on its proper subdivision throughout the basin is evident.

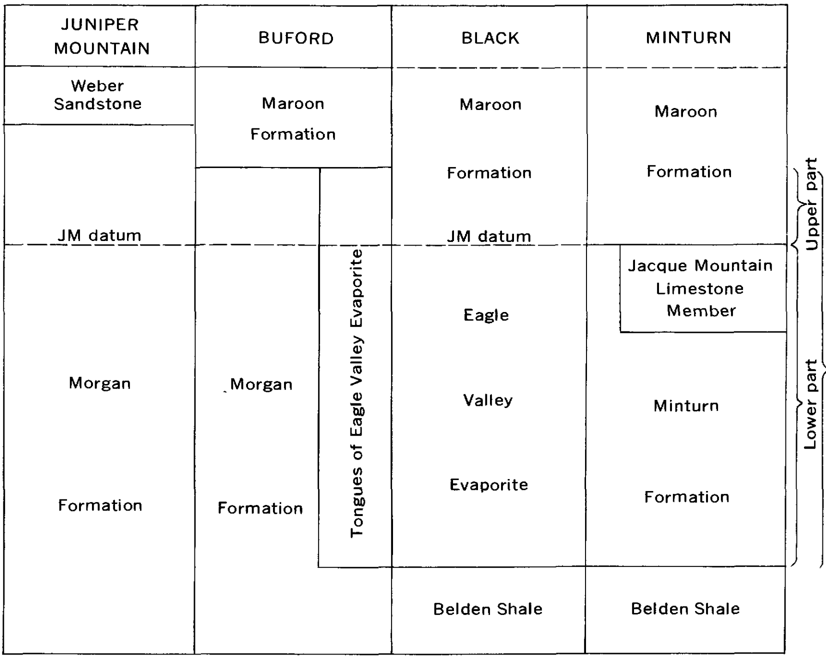


FIGURE 3.—Correlation table of formations included in or related to the evaporite interval at four section localities.

6. The name Weber Sandstone, as used by Kinney (1955, p. 45–48), refers to massive uniform light-colored quartzose sandstone of Pennsylvanian and locally Permian age exposed on the south flank of the Uinta Mountains.

DEFINITION OF THE EAGLE VALLEY EVAPORITE, THE EVAPORITE INTERVAL, AND THE JM DATUM

Eagle Valley Evaporite.—In places where the Eagle Valley Evaporite is unusually thick and contains only minor amounts of clastic rock, it is readily identified. In these areas, however, the base is usually hidden by valley alluvium, and the top is eroded. Near the periphery of the basin the top and base of the formation commonly are exposed, but evaporite beds complexly intertongue with other formations.

Evaporite interval.—Because the Eagle Valley Evaporite is a lithologic unit, or formation, which intertongues laterally with formations of other composition, it is convenient to refer to these intertonguing formations as the "evaporite interval." This interval is here defined as those rocks in the Eagle basin which contain evaporite beds assigned to this formation and adjacent beds of other formations which are laterally equivalent. On sections *A–A′* and *B–B′* (pl. 2) the base and top of this interval are indicated.

JM datum.—The Jacque Mountain Limestone Member is a significant marker bed within the evaporite interval because it separates the Maroon and Minturn Formations (Tweto, 1949, p. 204) and because it is widespread within the belt of coarse clastic rocks on the northeast margin of the Eagle basin (pl. 2, section *A–A′*). It can be traced on the surface with fair confidence from the vicinity of Kokomo northwest to King Mountain (pl. 3) and in the subsurface into the wells which appear on section *B–B′* (pl. 2). Southwestward it terminates at the periphery of the Evaporite; northwestward it merges with the Morgan Formation. The horizon represented by the top of this member of the Minturn Formation has been traced north and west and in this paper is referred to informally as the JM datum (pls. 2, 3*D*). The part of the evaporite interval below the JM datum is referred to as the lower part; the part above, as the upper.

PERIPHERAL AND UNRELATED EVAPORITE BEDS

At the margins of the main part of the Eagle Valley Evaporite, thick sections of the Maroon Formation locally contain isolated lenses of gypsum. Identification of these small deposits as part of the Eagle Valley is questionable. In those places where approximate continuity with the main evaporite body can be assumed or where proximity makes correlation seem reasonable, the beds have been assigned to the Eagle Valley. Examples of such assignments are as follows:

1. Isolated outcrops of gypsum on North Elk Creek and east of Buford in the valley of the North Fork of the White River seem to occupy the same stratigraphic position as anhydrite beds in the nearby Steele and Buford wells (pls. 1 and 2, section *A–A′*).
2. Between Woody Creek and Aspen, outcrops of gypsum and gypsiferous siltstone are associated with a fault zone. Proximity to the evaporite section at Ruedi suggests that these occurrences may be (or may have been before possible flowage) part of the Eagle Valley Evaporite.
3. A small gypsum plug in the valley of Thompson Creek (pl. 1, T. 8 S., R. 88 W., northwest of Mount Sopris) and a group of isolated gypsum outcrops in the walls of the Crystal River valley near Redstone are shown on plates 1, 3*B*, and 3*C* as Eagle Valley because of general alinement with the thick section of halite and sulfates farther north.

Several isolated pods of evaporite are present southeast of the main mass of the Eagle Valley Evaporite (pls. 3*B*, 3*C*). For example, (1) at the north end of Chalk Mountain near Climax, a 40-ft section of anhydrite was recovered in a drill core from the Maroon Formation (J. W. Vanderwilt, oral commun., 1963), and (2) in

South Park near Antero Reservoir (southeast corner of map, pl. 3*C*), an apparently isolated body of evaporite rocks is present in the Maroon Formation. Outcrops of gypsum in buttes west and south of the reservoir in the valley of Salt Creek (pl. 3*B*) show that evaporite rocks have been largely eroded from an area of at least 20 square miles. A salt spring in this area, at the SE. cor. sec. 26, T. 12 S., R. 77 W., indicates the presence of halite (Stark and others, 1949, p. 44–45). These strata occur in the Chubb Siltstone Member of the Maroon Formation, considered by Brill (1952, p. 836) to be the age equivalent of the Minturn Formation; they are therefore correlative with the Eagle Valley.

The regional relations of these pockets of evaporite rocks are unknown; these beds may have been continuous at one time with the main body of the Eagle Valley deposits, or they may have accumulated in separate depressions.

Several minor occurrences of gypsum and anhydrite in the Elk Mountains (Aspen-Marble-Gothic area) have been reported by Bruce Bryant (oral commun., 1965). Complexly disturbed sections containing gypsum in the Highland and Hope mining tunnels in the Castle Creek area are in the Belden Shale and are not related to the Eagle Valley Evaporite. Gypsum and anhydrite in the Maroon and Gothic Formations occur on the west side of the valley of Castle Creek, near Electric Pass, in Monument Gulch near Ashcroft, at Trail Riders Pass, and elsewhere. (These localities are identified on the U.S. Geological Survey topographic maps of the Highland Peak, Maroon Bells, and Snowmass Mountain quadrangles.) All or some of these may be local playa-type evaporites unrelated to the Eagle Valley Evaporite of marine origin. Because these lenses are isolated and have uncertain equivalence to or continuity with the main body of the Eagle Valley, they are not named in this report.

THICKNESS OF THE EVAPORITE INTERVAL AND THE EAGLE VALLEY EVAPORITE

The thickness pattern of the evaporite interval is that of a simple depositional trough with two subtroughs of exceptionally thick deposits (pl. 3*A*).The major subtrough is centered near Eagle townsite and is elongate northwest, as is the main trough. The lesser subtrough is centered at the Cattle Creek anticline, a salt diapir (Mallory, 1966) southeast of Glenwood Springs. It is possible that this subtrough had greater areal extent at one time and that subsequent flowage associated with the formation of the diapir concentrated the plastic evaporite salts into a smaller area.

The evaporite interval thins abruptly northeast and southwest, but more gradually northwest. The areas of exceptionally thick rocks in the evaporite interval (greater than 3,000 ft) lie almost entirely southeast of the Colorado River. In areas peripheral to the White River Plateau, the interval ranges from zero to at least 2,500 feet. If the rocks of the interval were restored over the plateau, from which they have been eroded, they would probably be 2,000–2,500 feet thick.

Thickness and extent of the Eagle Valley Evaporite are shown on plate 3*B*. This map was drawn by computing the composite total of evaporite and evaporitic rocks at each surface or subsurface section. The thickest evaporitic rocks occur in the same areas as the evaporite interval. The largest is an irregular area (the Alkali subbasin) centering around the towns of Eagle and Gypsum. Rocks composing the main axis of thick evaporite in this area are exposed on the west side of the valley of the Colorado River at Range Station, a location on the gravel road between McCoy and Dotsero. The smaller area of thick evaporite is the Cattle Creek anticline southeast of Glenwood Springs. Northwest of the Colorado River several tongues of evaporitic rock range in total thickness from zero on the basin margins to 740 feet in the Steele well (pl. 2).

LITHOLOGY OF THE EAGLE VALLEY EVAPORITE

The type locality of the Eagle Valley Evaporite was designated by Lovering and Mallory (1962, p. D47) at the interfluve west of Nottingham Creek near Avon (pl. 2, section *A–A′*) on the north side of the Eagle River. This locality, like most other exposures of the evaporite, leaves much to be desired for stratigraphic clarity. The top of the evaporite is brush covered and the base is concealed by alluvium. Nevertheless, the locality is of value because it is the only one where the relation of the Eagle Valley Evaporite to an important marker bed, the Jacque Mountain Limestone Member of the Minturn Formation, can be seen. Other surface sections are thicker and better exposed or contain more abundant quantities of pure sulfates and chlorides, but in these other sections the stratigraphic relation to rocks in the rest of the formation is obscure.

The Eagle Valley Evaporite varies in lithology from place to place. In the vicinity of the type locality, it is mainly a light-colored gypsiferous mudstone and siltstone which contains some bedded gypsum, a few cherty dark-gray limestone beds about 1 ft thick, and a few beds of reddish shale and siltstone. On the south side of the Eagle River, about 1 mile from the type locality, the evaporite is composed of massive-bedded gypsum in bluffs displaying chaotic internal structure.

In the subsurface at the town of Eagle (the Black well), the Eagle Valley is shaly anhydrite, black and gray shale, dark siltstone, halitiferous shale, siltstone, and probable halite.

On the surface west of Cattle Creek Station, the Eagle Valley Evaporite is massive, coarse- to fine-grained, white to gray gypsum having black sooty streaks and widely separated beds of calcareous sandstone and dark platy to fissile shale. In the subsurface near Cattle Creek Station (the Rose well), the evaporite is gray to brown anhydrite interbedded with light-colored siltstone and sandstone and a few dark shale beds to a depth of 2,125 feet. Below this level halite is the principal rock. No halite is present at the surface anywhere in the area.

In the Benton well about 10 miles northwest of Eagle, the evaporite is present only as tongues of anhydrite 10 to about 100 feet thick in the Maroon Formation. These tongues are separated by much thicker arkosic sandstone and shale.

Northwest of the Colorado River the Eagle Valley is thin and less varied. One of the thickest sections on the northwestern flank of the White River Plateau is penetrated by the Buford well (common to sections *A–A′* and *B–B′*, pl. 2). There the Eagle Valley is composed of anhydrite interbedded with shale, siltstone, sandstone, arkosic sandstone, and beds of carbonate rock.

At the fish-hatchery section on East Rifle Creek, the Eagle Valley is present at the base of the Maroon Formation as two tongues of gypsum totaling 180 feet, the lower tongue being of unusual purity.

LITHOLOGY, EXTENT, AND STRATIGRAPHIC RELATIONS OF THE EVAPORITE INTERVAL

LOWER PART

The dominant lithology of the lower part of the evaporite interval is shown on plate 3*C*. This map is objective in that it is based on data from surface and subsurface sections, but interpretation between control points was necessary to develop the patterns shown.

Lithologic variety characterizes the lower part of the evaporite interval. The interval itself contains mixtures of halite, anhydrite, gypsum, mudstone, and siltstone, and the equivalent rocks into which it tongues also contain assorted lithologies. Northeastward the evaporite interval assemblage tongues into dark shale, light-colored sandstone, both red and gray arkosic grit, red sandstone, shale, and conglomerate of the Minturn Formation. The transition from one formation to the other is commonly abrupt, taking place in many areas in the space of a mile or two. This transition is well exposed about a mile west of the intersection of U.S. Highways 6 and 24 at Dowds (Lovering and Mallory, 1962). Numerous small reefs are common in the Minturn Formation in or near the band of facies change. They are well exposed in the valley of Two Elk Creek at Minturn.

The Morgan Formation in Rio Blanco County contains abundant light-colored and some reddish sandstone beds, seen in cuttings from the Steele and Quiett wells (pl. 2). Tan and pinkish sandstone associated with gypsum beds forms the base of the Morgan Formation near the fish hatchery on East Rifle Creek. Northwestward the lower part of the evaporite tongues into limestone and minor shale beds in the lower part of the Morgan Formation.

Pink, maroon, and red sandstone and shale beds in the Bowen well (north of Rifle) are assigned to the Gothic Formation. The top of a limestone at a depth of 2,995 feet in the Bowen well is probably correlative with the JM datum, but the limestone cannot be identified with confidence as an exact equivalent of the Jaque Mountain Member of the Minturn Formation. The presence westward and presumably southwestward of red beds in this unit reflects the presence of the Uncompahgre uplift on the southwest side of the Eagle basin.

The recent (mid-1968) drilling of a dry hole (Gary and Grizzle No. 11–5 Aspegren) to Precambrian basement at a location (SW¼NW¼ sec. 11, T. 1 S., R. 85 W.) about a mile southwest of Texaco's King Mountain well adds new information on the lower part of the evaporite interval. The well penetrated 440 ft. of Triassic red beds and then 527 ft. of the red Maroon Formation. Below the Maroon the drill penetrated 1,418 ft. of limestone reported to contain crinoid fragments and fusulinids and to be interbedded with sandstone. This limestone-and-sandstone is probably the Minturn Formation, but its lithology is anomalous in an area where conglomeratic arkosic sandstone is expected. The presence of reefs is a possible explanation, but the aggregate thickness of limestone seems excessive.

Algal reefs interbedded with coarse clastic rocks of the Minturn Formation are present in the upper part of Piney Creek. (T. S. Lovering, oral commun., 1967) and at Two Elk Creek, east of Minturn (pl. 3*C*). These two occurrences and that in the Aspegren well are alined northwest and may define an environmental belt. A northwest-trending belt of reefs may also be present in the Jacque Mountain Member in this area (pl. 3*D*).

The stratigraphic section near Woods Lake contains red sandstone of undetermined age assigned to the Maroon Formation. In poor exposures the sandstone rests on dark shale and thin limestone beds of the Belden Shale. This relation indicates (1) that the evaporite is absent by nondeposition, or (2) that red beds replace the Eagle Valley in this area. Absence of evaporite in rocks assignable to the evaporite interval in the Tully well south of Gypsum is noteworthy because gypsum crops out a few miles east and west (pl. 3*C*).

JACQUE MOUNTAIN LIMESTONE MEMBER OF THE MINTURN FORMATION AND THE JM DATUM

Plate 3*D* is an interpretation, based on available data, of the areal geology of the upper surface of the Jacque Mountain Limestone Member and the lithology at the horizon shown on sections *A–A′* and *B–B′* (pl. 2) as the JM datum. It therefore portrays an instant in geologic time.

The Jacque Mountain Limestone Member of the Minturn Formation is a narrow band paralleling the southwest edge of the Front-range uplift (pl. 3*D*). It is exposed in several localities within or near the area investigated—in the valley of Gore Creek near Minturn, in the valley of Piney River, in the vicinity of McCoy, and at King Mountain, where it is remarkably similar in appearance and lithology to the Jacque Mountain at the type locality. Eastward it tongues into coarse clastic rocks of the Minturn Formation or is faulted against Precambrian rocks of the Gore Range. Westward it tongues into gypsum of the Eagle Valley; the intertonguing is exposed near Avon (Lovering and Mallory, 1962, fig. 132.1). At the terminus of each limestone tongue in the Avon area is a small algal reef; this fact suggests that, in all or most places where the Jacque Mountain grades into the gypsum, a more or less continuous band of small algal reefs is present. In the subsurface in at least one well (Steele) near the belt of apparent facies change from carbonate to sulfate rock (pl. 2, section *A–A′*), the rock at the JM datum (at 1,510 ft) is described as abundantly fossiliferous. In the surface section on North Elk Creek and beneath a gypsum bed 300 feet thick, the top of a limestone identified by the author as the JM datum is clearly an algal reef. At Miller Creek there are several algal reefs in rocks probably correlative with the Minturn Formation (fig. 4).

In southeastern Moffat County and adjacent areas the JM datum is identified as limestone or dolomite in the Morgan and Minturn Formations (pls. 2, 3*D*).

UPPER PART

The upper part of the evaporite interval (above the JM datum) is composed mainly of red coarsely clastic rock in contrast to the lower part, which contains a broad central belt of limestone and evaporite (pls. 2, 3*E*). Evaporite in the upper part is limited to relatively thin beds of gypsum and anhydrite intercalated with red beds of the Maroon Formation and the upper part of the Morgan Formation. Most of the evaporite in the upper part of the interval occurs in the subsurface in eastern Rio Blanco and Moffat Counties (pl. 3*E*). Local lenses also are present on the north side of the Eagle River and in the vicinity of the Benton well.

FIGURE 4.—Algal reef, with prominent vertical jointing, in rocks correlative with the Minturn Formation at Miller Creek, southeast of Meeker.

Limestone is scarce except in the Dougherty well, in which most of the upper part of the interval is unusually fossiliferous limestone. Perhaps this area was the site of a relatively permanent Pennsylvanian reef. Tongues of limestone are intercalated with sandstone at Juniper Mountain.

Coarse conglomerate is abundant along the southwest margin of the Frontrange uplift and is well exposed on U.S. Highway 6 at Vail Pass about 14 miles southeast of Minturn. Conglomerate is also abundant on the northeast margin of the Uncompahgre uplift in the valley of the Crystal River. It can be seen along Colorado Highway 133 between Redstone and the Elk Mountains thrust (near the Gunnison County line), which juxtaposes the Maroon and Mesaverde Formations.

Interbedding of light-colored and red sandstone in the upper part of the Morgan Formation is well exposed in the valley of the White River near Buford.

AGE OF THE EAGLE VALLEY EVAPORITE

Paleontological information for dating the Eagle Valley Evaporite is abundant. Bass and Northrop (1963, p. J36, J43–J46) stated that in the Glenwood Springs quadrangle, in the center of the study area, 42 fossil collections had been taken from the evaporite. The Pennsylvanian fossils in their report were identified by Lloyd G. Henbest, Thomas G. Roberts, Helen Duncan, J. Brookes Knight, I. G. Sohn, Arthur L. Bowsher, and David H. Dunkle. Bass and Northrop concluded that the formation now called Eagle Valley Evaporite in the Glenwood Springs quadrangle is of late Atoka and early Des Moines age.

The evaporite interval is equivalent to the upper 5,300 ft of the Minturn Formation as measured by T. S. Lovering (written commun., 1966) at Minturn, or about the upper four-fifths of the formation (pl. 2, section *A–A′*). Tweto (1949, p. 205) stated that at least the lower five-sixths of the Minturn is of Des Moines age and the remainder of the formation is inferentially of Pennsylvanian age. Hence, that part of the Eagle Valley Evaporite which intertongues with the lower five-sixths of the Minturn Formation is of Des Moines age.

T. S. Lovering and Ogden Tweto collected fossils from the Minturn Formation; regarding these fossils, Mackenzie Gordon, Jr., and E. L. Yochelson (written commun., 1966) stated:

> * * * the Minturn Formation is regarded as Middle Pennsylvanian in age, and includes beds of Atoka and Des Moines age. The Robinson and White Quail Members are dated as Des Moines in age by their megafossil content. The Hornsilver Dolomite and Robinson Limestone Members are dated as early Des Moines in age by fusulinids. The presence of *Fusulinella* in a collection of unknown horizon dates at least some of the lower part of the Minturn Formation as late Atoka in age.

K. F. Oles and W. W. Mallory collected Foraminifera from three measured sections. In a small ravine near Cattle Creek Station 7 miles south of Glenwood Springs, Oles and Mallory measured 2,000 feet of vertically dipping gypsum beds with a few intercalated sandstones overlain by several thousand feet of Maroon Formation. Foraminifera were collected from a shaly siltstone in the Maroon 350 feet above the top of the gypsum. Near the fish hatchery on East Rifle Creek, two beds of gypsum, 50 and 130 feet thick, are separated by a tongue of Maroon Formation 60 feet thick. Foraminifera were collected from a calcareous siltstone in the middle of the Maroon tongue. At Miller Creek (pl. 2, section *B–B′*), 350 feet above the algal bioherm zone visible on the valley sides, Foraminifera were collected from a dove-gray limestone 2 feet thick intercalated between siltstone and sandstone of the Morgan Formation. These forms were identified and dated by L. G. Henbest (written commun., 1964). The location of each section and the forms identified by Henbest are listed below.

Garfield County, west side of Roaring Fork valley near Cattle Creek, Station, sec. 1, T. 7 S., R. 89 W.

Osagia sp.
Tuberitina sp.
Ammovertella sp.
Minammodytid
Calcivertella sp.
Trepeilopsis sp.
Cornuspirinae (sedentary tubiform genera with smooth shells)
Tetrataxis millsapensis Cushman and Waters
Spiroplectammina sp.
Climacammina? sp.
Bradyina sp.
Endothyranella sp.
Millerellid?
Eoschubertella? sp. or juvenarium of a higher genus of Fusulinellinae

Garfield County, fish hatchery, sec. 23, T. 4 S., R. 92 W.

Marine algae
Cuneiphycus? sp. (Algae)
Tuberitina sp.
Minammodytid
Sedentary aggulutinate foraminifers
Trepeilopsis sp.
Cornuspirinea (sedentary forms with smooth shells)
Calcivertella sp.
Hyperammina? sp.
Spiroplectammina sp.
Tetrataxis millsapensis Cushman and Waters
Polytaxis sp.
Polytaxis sp. or trochamminid
Globivalvulina sp.
Bradyina sp.

Millerella sp. (rare)
Paramillerella or *Millerella* sp. (rare)
Eoschubertella sp. or possibly juvenaria of a fusulinellid

Rio Blanco County, Miller Creek, sec. 7, T. 2 S., R. 92 W.
Tuberitina sp.
Tolypamminidae
Cornuspirinae (tubiform genera with smooth shells)
Calcivertella sp.
Trepeilopsis sp.
Spiroplectammina sp.
Tetrataxis millsapensis Cushman and Waters
Globivalvulina sp.
Millerella or *Paramillerella* sp. (very rare)

Concerning the age of these forms, Henbest stated:

Early Middle Pennsylvanian is suggested and Middle Pennsylvanian is indicated with fair assurance. Morrow age seems very unlikely. Late Pennsylvanian age is possible but seems unlikely. The fusulinids are very scarce. Although they seem to be early Middle Pennsylvanian species, it could hardly be proved that these primitive forms are not juvenile individuals of advanced, later species. All the rather vague or ambiguous evidence agrees in indicating Middle Pennsylvanian age, and a part, in indicating the earlier part of the epoch. It is recognized, of course, that in sum total vague or ambiguous evidences that agree do not necessarily add to a solid truth * * *.

No fossils indicative of Late Pennsylvanian or of Permian age were recognized in these three samples.

At Miller Creek, Murray and Chronic (1965, p. 594–596) collected conodonts which they consider to be of middle or late Des Moines age from a limestone that this author considers approximately correlative with the Jacque Mountain Limestone Member of the Minturn Formation (pl. 2, section *B–B′*).

EFFECTS OF DEFORMATION

Since its deposition, the Eagle Valley has been subjected to at least four types of stress: (1) Load metamorphism, (2) Laramide orogenic movement, (3) growth of diapiric anticlines, and (4) local contortion due to flowage and hydration of anhydrite. Probably every example of deformation of the evaporite interval in the basin has been subjected to all these forces in varying degrees.

LOAD METAMORPHISM

Almost without exception in the Eagle basin, calcium sulfate beds at a depth of more than several hundred feet are present as anhydrite. Inasmuch as the salt was originally deposited as gypsum (the hydrous form), metamorphism by elimination of water was probably effected by burial. Heard and Rubey (1966, p. 741) stated that the calculated gypsum$\leftrightharpoons$anhydrite$+H_2O$ reaction takes place at a depth of 2,500–

6,000 feet. Because the Eagle Valley Evaporite was covered by a much greater thickness of upper Paleozoic and Mesozoic strata, the gypsum was probably dehydrated throughout the basin at one time.

EFFECTS OF LARAMIDE OROGENIC MOVEMENT

A high angle of dip in the Eagle Valley Evaporite and older rocks occurs in the Grand Hogback near Newcastle and also south of Avon and Edwards on the north flank of the Sawatch Range. Both features exemplify hogbacks flanking major uplifts of Laramide origin, where gypsiferous strata are involved only incidentally with other rocks in the stratigraphic section.

DIAPIRIC ANTICLINES

Near Cattle Creek Station in the valley of the Roaring Fork between Glenwood Springs and Carbondale, a vertical dip in gypsum strata on the west side of the Roaring Fork River and a gentle east dip on the east side define the Cattle Creek diapiric anticline. The Rose well, drilled on or near the crest of this structure, penetrated gypsiferous and anhydritic shale and siltstone to a depth of 640 feet. From this depth to 2,125 feet, the section contains siltstone and anhydrite. Below 2,125 feet to the total depth of 3,060 feet, the section is mainly halite. The vertical dip on the west side of the structure is attributed to vertical movement of the diapir and high confining pressure (Mallory, 1966).

The Eagle River anticline is clearly developed along the valley of the Eagle River for a distance of about 3½ miles above Dotsero. Benson and Bass (1955, p. 103) compared this structure with the Meander anticline in the Paradox basin of Utah and ascribed the arching to upwelling of evaporitic rocks at depth along the course of the Eagle River, the upwelling being caused by the load of overlying rocks on both sides of the valley. Other anticlines or plugs that can be classified as diapirs or that may have been subjected to some diapiric buckling may also be present in the Eagle basin.

LOCAL CONTORTION DUE TO HYDRATION AND FLOWAGE

Nearly everywhere at depth in the basin, calcium sulfate salts are in the form of anhydrite, but in outcrop the salt is principally gypsum, and anhydrite is rare. There is little doubt that the gypsum at the surface resulted from hydration of anhydrite by meteoric waters. The typically chaotic structure in gypsum outcrops is attributed to expansion and accompanying internal pressure due to hydration of anhydrite to gypsum and flowage valleyward caused by the weight of overburden on the valley sides. The amount of expansion which accompanies hydration is not accurately known but seems to range from 30 to 58 percent of the original rock. The pressure exerted has been estimated at 300 to 10,000 pounds per square inch (Brune, 1965, p. 30).

GEOMORPHIC EXPRESSION AND RECENT TECTONIC ACTIVITY

Most outcrops of the Eagle Valley Evaporite are in the valleys of the major streams which drain the Eagle basin area. The valley of the Eagle River in the vicinity of Eagle and Gypsum is typical. Here the river flows in a channel incised into broad, level Pleistocene terraces. On either side of the alluvial valley floor, bluffs of gypsum rise abruptly to form bold, gnarly masses (fig. 5), which contrast oddly with more conventional landforms. A typical local expression applied to such a form is the "partial dome," because it looks like an upwelled cupola with the side facing the stream truncated or collapsed. The question arises as to why so friable and soluble a rock in a well-watered environment forms bold topography. Ordinarily a soft, easily weathered rock, overlain by thousands of feet of Maroon Formation and younger rocks, would be concealed by slide and slump blocks, talus, and colluvium, and good exposures would be rare.

An explanation for this apparent paradox may lie in a review of Pleistocene and Holocene history in the area.

Unroofing of the Eagle Valley Evaporite by stream erosion in Tertiary time caused upwelling of the salts in valleys because of the weight of overburden on interfluves and because of attendant crumpling due to hydration of anhydrite by meteoric water. During Pleistocene time, pluvial climate and glacial melt waters from the Gore and Sawatch Ranges intensified hydration and the accompanying expansion of sulfate salts. Concomitantly, glacial melt-water streams cut broad flood plains in the central parts of the valleys; these plains are now expressed as cobble- and gravel-covered terraces. The result is a series of level-floored alluvial valleys flanked by bluffs of gypsum. Post-Pleistocene weathering and solution could be expected to have subdued the topographic expression of gypsum outcrops. The fact of their present prominence, however, seems to demand that upwelling and expansion are still proceeding at a rate commensurate with or locally exceeding solution and erosion. The unusual appearance, therefore, of the Eagle Valley Evaporite where it is typically expressed is the result of two major processes acting at roughly equal rates: (1) upwelling, expansion by hydration, and flowage due to unequal weight of overburden, and (2) erosion and solution.

In the vicinity of Carbondale on the flanks of the southern end of the Cattle Creek anticline, surfaces of low relief which seem to be old river terraces slope gently away from the Roaring Fork River rather than toward it, this fact indicating post-terrace arching in the central part of the valley. This circumstance supports the concept that salt tectonism still continues in the Eagle basin.

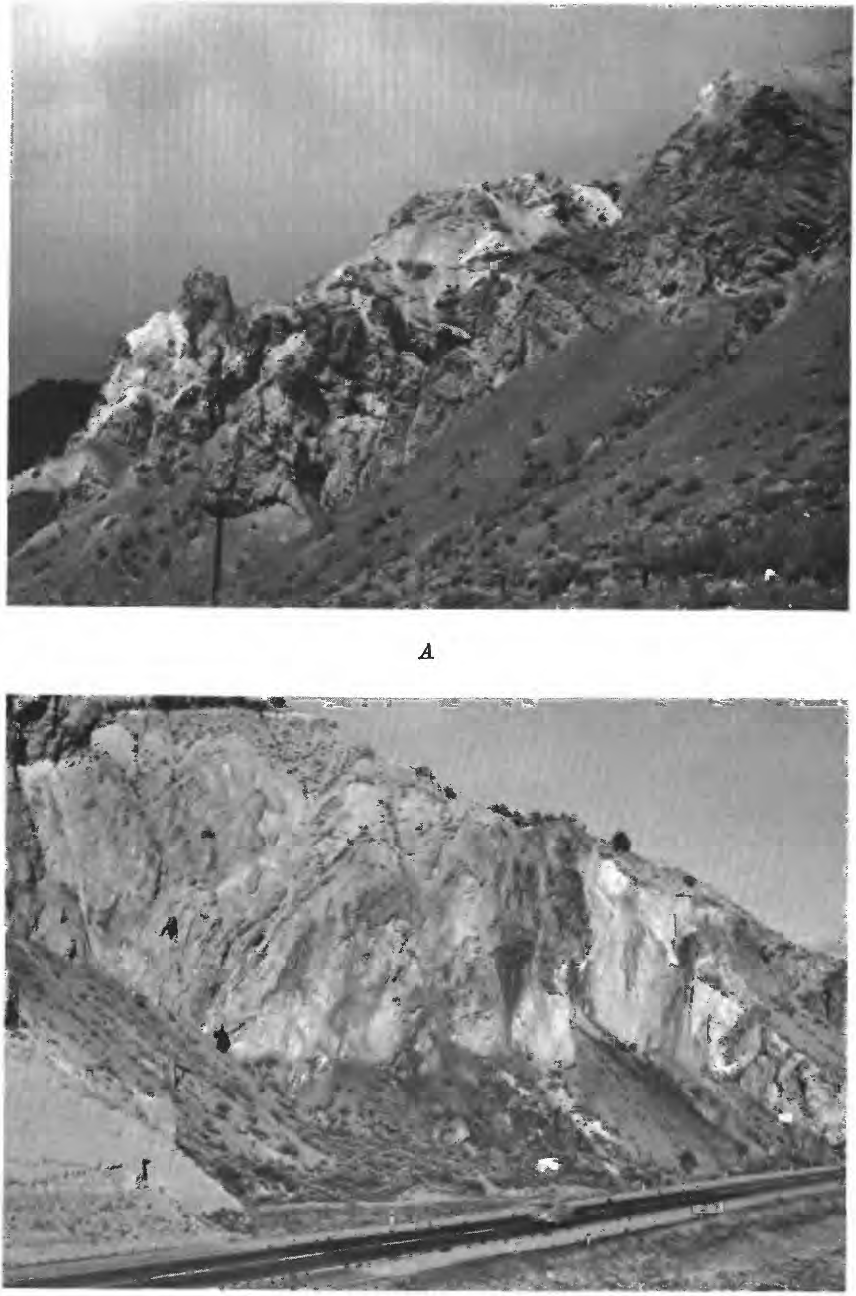
Gyp Hill is a dissected cone of gypsum 800 feet high in the valley of the Fryingpan River at Ruedi. On its west side are a series of alined solution sinks, one of which collapsed in 1961. The west flank of Gyp Hill is a scarp steep enough that large blocks of gypsum fall from time to time into the sink area; in 1967 a small slide partly filled the 1961 sink. In spite of active slumping and sliding, however, the scarp maintains topographic expression. The mechanism of replenishment is probably upwelling of sulfates and possibly halite at depth. This combination of active tectonic and solution processes in a small area is not commonly observable in the Eagle basin.

In areas where the Eagle Valley Evaporite is composed of gypsiferous mudstone (as on the north side of the Eagle Valley near Avon), its topographic expression is subdued. It forms rounded slopes and the rock is commonly covered by slopewash and colluvium. Here gypsum tectonics apparently are only mildly active and conventional geomorphic processes dominate.

STACKS

Stacks, or chimneys of rock which protrude vertically from gypsum outcrops, are a curious topographic form found in several places. They are composed of poorly compacted rubble, commonly containing angular blocks of yellow calcareous sandstone varying widely in size. Some are accompanied by yellow crusty limestone. The matrix is commonly of silt- and clay-size material apparently of the same composition as the larger pieces. They are usually some tens of feet tall and 5 to 20 ft in diameter. Some are isolated; others are roughly alined and may be connected at the base. They are present on the upper reaches of Gypsum Creek, in the vicinity of Carbondale, and at Miller Creek (fig. 6).

The origin of these features is not clear, but two possibilities can be mentioned. They may be remnants of calcareous sandstone lenses deposited by turbidity currents or slump masses which were later mangled and crushed by contortion incident to flowage accompanying the change from anhydrite to gypsum; subsequent weathering may have caused the chimneylike form. Alternatively, they may be the remains of solution sinks formed rather recently and filled by collapse of overlying local lenses of calcareous sandstone.



A

B

FIGURE 5.—Geomorphic expression of the Eagle Valley Evaporite. *A* and *B*, Scarp of gypsum on U.S. Highway 6, 1 mile west of Gypsum, illustrating topographic

C

D

prominence and contorted bedding. *C* and *D*, Bluffs of gypsum on the east side of the Roaring Fork River near Cattle Creek Station. Note contorted bedding.

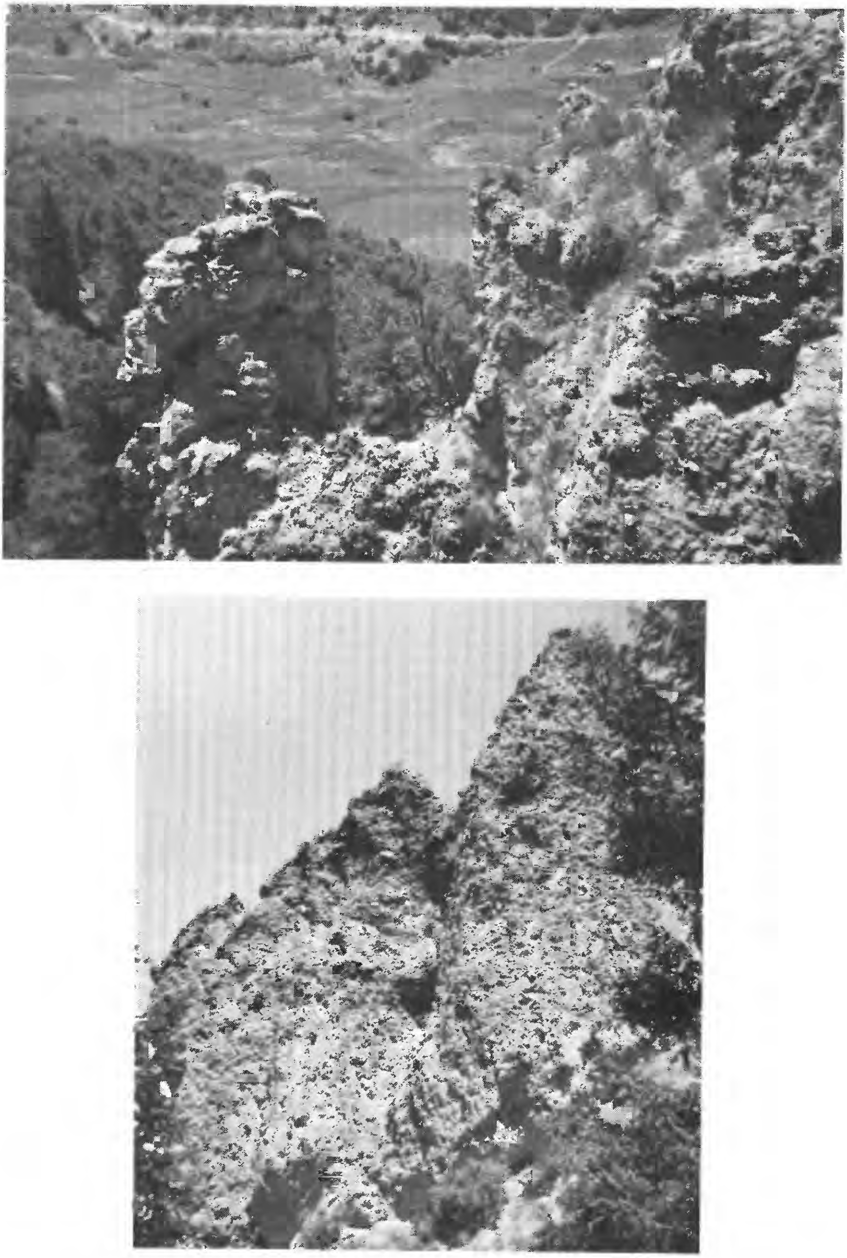


FIGURE 6.—Stacks at Miller Creek, southeast of Meeker.

GEOLOGIC HISTORY IN PENNSYLVANIAN TIME

DEVELOPMENT OF THE EAGLE BASIN AND ITS BORDERING HIGHLANDS

Rocks of Mississippian age in western Colorado and eastern Utah make up a simple wedge of limestone which thickens uniformly westward to central Utah; they provide a record of widespread uniform subsidence. Pennsylvanian tectonic patterns, however, are markedly different. The oldest formation of Pennsylvanian age in the Eagle basin is the Belden Shale, in which fossils of Morrow and early Atoka age have been identified (Bass and Northrop, 1963, p. J46). Land areas bordering the basin at that time (fig. 7) were broad lowlands supplying moderate quantities of mud and silt. In late Atoka and Des Moines time the trough widened and subsided more rapidly. The Frontrange and Uncompahgre uplifts (fig. 8) attained maximum elevation and shed large quantities of coarse detritus (Minturn and Gothic Formations), which was deposited on the margins of the basin while the

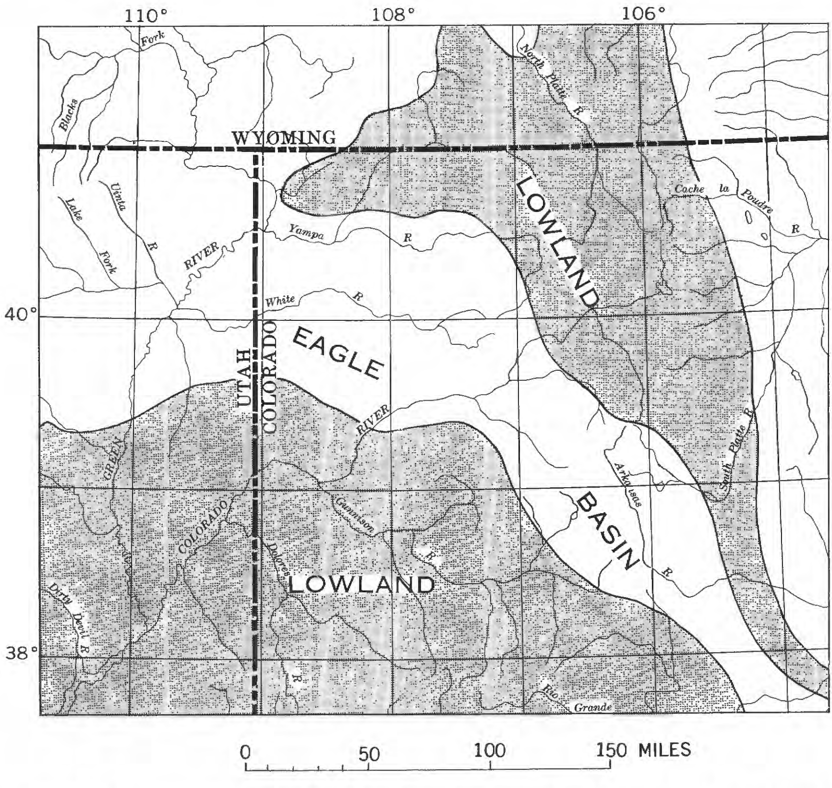


FIGURE 7.—Paleogeography of the Eagle basin region in Morrow and early Atoka time.

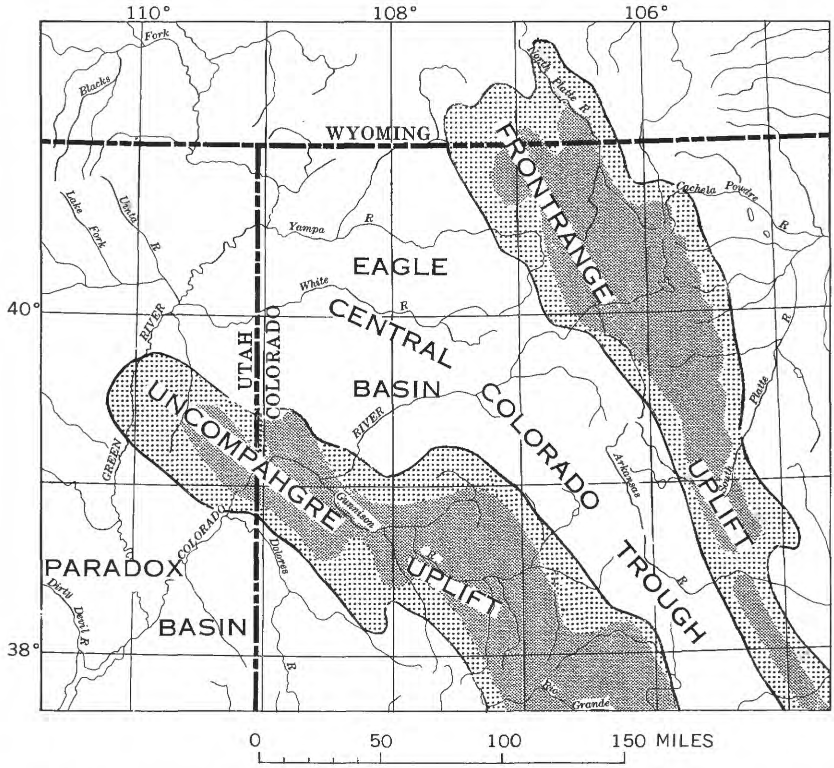


FIGURE 8.—Paleogeography of the Eagle basin region in Des Moines time. Patterned areas show where Pennsylvanian rocks are not present; darker area is extent of major uplift in Des Moines time as inferred from arkose studies (W. W. Mallory, unpub. data).

evaporites of the Eagle Valley were accumulating in the central part (pl. 3*C*). In Late Pennsylvanian time red beds of the Maroon Formation and red and white sandstone of the upper part of the Morgan Formation, interlaminated locally with gypsum (pl. 3*E*), were deposited throughout the basin.

PALEOTECTONIC ACTIVITY AND ORIGINAL EXTENT OF THE EAGLE VALLEY EVAPORITE

The boundaries of the Eagle basin in Des Moines time were formed by the Frontrange and Uncompahgre uplifts, the two major elements of the Ancestral Rocky Mountains. Within the basin five paleotectonic provinces can be delineated for early Eagle Valley time (pl. 3*F*). These are: (1) a marginal belt adjacent to the southwest flank of the Frontrange uplift, where arkosic conglomerate and grit were deposited, (2) a complementary marginal belt on the northwest flank of the Uncompahgre uplift, where red beds were deposited but which is less well known, owing to fewer exposures and absence of deep wells, (3) a shelf area in Moffat and Rio Blanco Counties, where limestone, interbedded limestone and sandstone, and sandstone were deposited (here termed the marine shelf), (4) a southeastern continuation of the shelf in eastern Garfield and Rio Blanco Counties, now mostly occupied by the White River Plateau (here termed the evaporite shelf), and (5) that part of the evaporite basin which lies southeast of the Colorado River (here termed the bittern basin).

Most of the evaporite shelf in the vicinity of the White River Plateau (province 4) is missing owing to Tertiary erosion, but preserved remnants on its northeast flank suggest (pl. 2, section *A–A′*) that the thickness of gypsum and interbedded red rocks was moderate (±2,000 ft) and relatively uniform throughout the province. The boundary between the evaporite shelf (province 4) and the bittern basin (province 5) is at the Colorado River between Dotsero and Glenwood Springs. It may be significant that this boundary coincides with a monocline (here termed the Glenwood monocline) well exposed in Glenwood Canyon; the monocline is an eastward continuation of the Grand Hogback.

The bittern basin has irregular limits (except at the Glenwood monocline) and a pronounced contrast in thickness and composition of the evaporite rocks. There are four distinct tectonic elements within the bittern basin: (1) the Alkali subbasin (named after Alkali Creek, between the towns of Eagle and Gypsum), (2) the Red Table anticline (after Red Table Mountain), (3) the Fryingpan embayment (after the river), and (4) the Crystal embayment (after the river). Thickness of evaporite rocks ranges from 7,500 ft in the Alkali subbasin at the town of Eagle (measured in the Black well) to zero in the adjacent Red Table anticline. The Eagle Valley Evaporite contains gypsum, anhydrite, halite, and potassium salts in the Alkali subbasin. Halite was cored in the Rose well on the Cattle Creek anticline (Mallory, 1966) and is present at the site of Ruedi Reservoir as small inclusions in contorted gypsum in cores from shallow holes drilled by the Bureau of Reclamation.

The Alkali subbasin contains three depositional axes. One trends northwest and crosses the Colorado River between Sweetwater and Range Station; another trends east and passes through the town of Eagle; a third extends southwest from the town of Gypsum. The axis of the Red Table anticline curves from west to northwest. The Fryingpan embayment apparently trends northwest, and the Crystal embayment trends north to northwest.

All the paleotectonic features described seem to have originated in Pennsylvanian time, although one or more of them may have been intensified later during the Laramide orogeny.

A significant aspect of the bittern basin is the fact that the irregular southeastern limit of evaporite rocks is everywhere (with minor local exceptions) a belt of depositional pinchout (pl. 3*B*). The pinchout is most evident in the Minturn-Woods Lake-Red Table area. On Beaver Creek west of Minturn, the evaporite can be seen to tongue into grit and conglomerate of the Minturn Formation. In the Woods Lake-Red Table area small lenses of gypsum and algal limestone mark the southern limit of the Alkali depositional basin. Near Redstone and Mount Sopris small lenses of gypsum high on the valley walls are part of the thin distal end of the Crystal embayment, and similar pods of gypsum between the towns of Snowmass and Woody Creek probably mark the southern limit of the Fryingpan embayment. Abundant gypsum and active extrusion of gypsum in Gyp Hill at Ruedi suggest the presence here of a small but fairly deep evaporite basin. More than 3,000 feet of gypsum, anhydrite, and halite (Mallory, 1966, p. B13) are present in the Cattle Creek anticline and are now the thickest part of the Crystal embayment. This area is the site of a salt diapir, however, where original thickness has been increased an unknown amount by flowage.

Evaporite rocks are absent in the Red Table anticline, as is shown by the pinchouts visible in surface exposures on its north flank and by the lack of evaporite in the Tully well. Although abundant gypsum is present in the inlier of the Eagle Valley near the headwaters of Gypsum Creek (T. 6 S., Rs. 84 and 85 W.), marked southward thinning can be observed even in this small area. The thinning-to-extinction of evaporite on the north flank of the Red Table anticline and the location of the structure near the general pinchout on the southeast flank of the bittern basin support the interpretation that the anticline was active in Des Moines time and that evaporite was not deposited upon it. Flowage may have affected the anticline and adjacent areas somewhat.

In attempting to establish original extent of the Eagle Valley Evaporite, the pinchout on the southeastern margin of the bittern basin and various isolated evaporite deposits (at Climax, Salt Creek, Monument Gulch, Snowmass Mountain, and elsewhere) suggest two interpretations. Either the present site of the Sawatch Range and its vicinity were tectonically neutral in evaporite time and no rocks were deposited, or red beds equivalent in age to the Eagle Valley were deposited as a series of coalescing fans and deltas derived from the bordering highlands. Perhaps a combination of these two circumstances was responsible.

Rocks deposited in the upper part of the evaporite interval are restricted to beds of gypsum and anhydrite interlaminated with sandstone, siltstone, and limestone of the Maroon and Morgan Formations (pls. 2, 3*E*). The original extent of these deposits probably included their present extent and much of the White River Plateau area as well.

MECHANICS OF DEPOSITION OF EVAPORITES

Classic theories of thick evaporite deposition postulate a bar or sill at the open end of a restricted marine basin. In many ancient evaporite basins, however, a bar or sill cannot be demonstrated. A mechanism proposed by Scruton (1953, fig. 4) for deposition of evaporites eliminates the necessity of a sill at the basin mouth. His example is a subsiding arm of the sea, or trough, having restricted access to normal marine water and virtually uniform water depth. According to Scruton's (1953, p. 2498) theory, high evaporation rate at the water surface develops a strong horizontal salinity gradient which produces a surface inflow and lateral segregation of different salts during precipitation. An escaping deep current returns to the sea those salts which have not been precipitated.

The Eagle basin probably differed from Scruton's simple nonsilled basin in two details. First, the access to the open sea was not through a narrow channel, but rather by a broad shelf (pl. 3*F*) where sea water was probably very shallow at all times and perhaps lacking at intervals. Second, water depth in the basin was probably not uniform. Access southeastward to the Raton basin (southeastern end of the Central Colorado trough) was probably blocked by extensive alluvial fans in the narrow center of the trough. That part of section *A–A′* (pl. 2) restored across the White River Plateau between the Steele well and the surface section at Dotsero apparently accumulated beds of gypsum intermittently between deposits of medium- to fine-grained red beds swept in from the Frontrange and Uncompahgre uplifts. Sinking was probably only slightly faster than on the marine shelf farther seaward.

The thickness of evaporite rocks is everywhere greater in the bittern basin than on the shelf (where now preserved), and it is much greater in local basins. The entire area southeast of the Glenwood monocline must have subsided more rapidly than the shelf area. The Glenwood monocline, therefore, may have originated in Middle Pennsylvanian time. Within the bittern basin area, the Alkali subbasin, the Fryingpan embayment, and the Crystal embayment apparently were areas of unusually rapid subsidence. In contrast, the Red Table anticline and the region east of the bittern area (with local exceptions) were tectonically neutral or were uplifted. The thickest section of existing evaporite rocks is in the Alkali subbasin near Eagle, where 5,400 feet of halite, anhydrite, and intercalated shale and siltstone has been logged in the Black well by the American Stratigraphic Co. Another 1,000 feet of gypsum and gypsiferous mudstone is estimated to have been eroded from the valley of the Eagle River at the site of the well, and 1,000 more feet of gypsum and gypsiferous mudstone is estimated to be present on the valley sides. If so, roughly 7,500 feet of evaporite and associated evaporitic rocks was once present along an axis of the Alkali subbasin. Although the Eagle townsite area has not been clearly established as a diapir, flowage of evaporite rocks into the area and consequent postdepositional thickening are possible. The presence of some 3,000 feet of Maroon beds above the Eagle Valley Evaporite and at least 500 feet of Belden Shale below indicates deposition of about 11,000 feet of sediment (including an unknown amount added by flowage) here during Pennsylvanian and somewhat later time.

The Rose well on the Cattle Creek anticline was drilled to a depth of 3,060 feet. The bit was in halite when drilling ceased, so that the actual thickness of the evaporite section in the well is not known. The entire section in the well below 85 feet is evaporite or evaporitic clastic rock, and 2,000 feet of younger gypsum and associated shale was measured on the surface nearby. Therefore, a minimum of nearly 5,000 feet of evaporite and evaporitic rocks is present in the Crystal embayment. Thickness of evaporites in the Fryingpan embayment at Ruedi is unknown, but the currently active tectonic movement in the gypsum (at Gyp Hill) and the probable presence of halite at depth suggest that a generous thickness of evaporites was once deposited. Elsewhere in the bittern basin area, other local basins of subsidence may be present, but their existence is not indicated by surface expression, and deep wells that might provide definitive data are lacking.

In at least three areas, therefore, within the bittern basin (the Alkali subbasin, the Crystal embayment, and the Fryingpan embayment), subsidence during Eagle Valley time was unusually rapid. Unless deposition of evaporite crystals and clastic material occurred so rapidly that these basins of subsidence were full at all times—a contingency which seems unlikely—water depth in them was greater than elsewhere in the bittern basin. These three areas may have formed sumps into which dense, hypersaline waters would be entirely trapped by gravity flow instead of partially escaping seaward as in a simple basin subsiding uniformly. These areas would, therefore, tend to be those in which salts highest in the solubility series would be deposited. The presence of halite in the Black well and of potassium salts 3 miles north of the town of Gypsum (Max A. Krey, written commun., 1967) supports this concept. Because of its size and the great thickness of evaporite, the Alkali subbasin is the area in northwest Colorado most likely to contain salts of economic value.

Deposition of evaporites need not be limited, however, entirely to landlocked areas of the sea. Relatively thin deposits of various salts are present in Holocene intermittent playa lakes of the Great Basin. It is possible that southeast of the main mass of the Eagle Valley Evaporite, in the narrow "waist" of the Central Colorado trough, coalescing alluvial fans of Des Moines age created poorly drained areas in which there accumulated thin playa-type evaporites physically discontinuous from the marine salts in the Eagle basin. Such a circumstance might explain the isolated deposits of evaporite salts at Climax, Salt Creek, Cement Creek, Snowmass Mountain, Monument Gulch, and elsewhere.

CLIMATE IN COLORADO IN MIDDLE PENNSYLVANIAN TIME

An analysis of clay minerals in Pennsylvanian formations on both sides of the Frontrange uplift was published by Raup (1966). His interpretations on climate (p. 260) are as follows:

> The occurrence of trioctahedral chlorite, illite, and mixed-layer illite-montmorillonite in both the nearshore and central basin rocks, and the absence of detrital kaolinite, indicate that the environment of the Ancestral Front Range and the central Colorado (Eagle) basin during Middle and Late Pennsylvanian time was semiarid to arid with the possibility of fairly high temperatures. The Ancestral Front Range probably rose to an elevation of a few thousand feet above sea level, and the top of the range would most likely have been cooler and more moist than the lower elevations. However, the close proximity of a hypersaline sea on the west suggests that the rainfall in the mountains was fairly low.

Field examination of the Eagle Valley Evaporite and interbedded parts of the Minturn and Maroon Formations shows that land-plant remains in these rocks are extremely scarce. Although sooty streaks in the Eagle Valley Evaporite are common, the dominant colors are light—white, pearl gray, yellow, pink. The small amounts of carbonaceous material present may have been derived from organic matter in algal reefs. Both field evidence and laboratory evidence indicate an arid or semiarid climate.

Precipitation may have been seasonal in the Ancestral Rocky Mountain region. Abundant examples of high-angle crossbedding and poor sorting indicate that the pebble and cobble conglomerates in the Minturn, Maroon, and Fountain Formations and other formations were deposited by torrential currents. If scant vegetation protected the slopes of the mountains, infrequent heavy local downpours could have swept along great quantities of rock debris and deposited them in the littoral zone in the attitudes now observed.

By drawing analogies with areas having similar climate today, a regional pattern of climatic cause and effect in Pennsylvanian time can be outlined. The present coast of southern California is a desert whose climate is influenced by the Pacific Ocean. South-flowing coastal currents bring cold water from higher latitudes. The Coriolis force turns surface currents seaward (west) and forces even colder, mineral-laden water at depth to upwell along the shoreline and replace them. Onshore winds chilled at the base by contact with cold waters contain a market temperature inversion which produces atmospheric stability and inhibits precipitation. A similar climatic pattern exists in Peru, where rainfall from coastal air does not occur until the air has been forced up the west flank of the Andes to an altitude of 5,000 ft. At intervals of several years the cool current along the north Peruvian coast is temporarily replaced by a warm current from the north. During these brief periods heavy rains occur (Trewartha, 1943, p. 369–371).

A similar pattern of oceanic currents, prevailing winds, and associated climatic pattern may have existed in Colorado, Texas, and Oklahoma in Middle Pennsylvanian time. Most of the western United States was an epeiric sea; a south-flowing current analogous to the California Current of today may have penetrated eastward as far as the Ancestral Rocky Mountains and turned clockwise on the way in response to earth-rotational forces. Accompanying air was chilled at the base, inhibiting precipitation. Prevailing westerly winds may occasionally have forced this stable air over the Ancestral Rocky Mountains, where it released some moisture. More significantly, however, warm water from the southeast with attendant unstable air may have invaded the area seasonally and given rise to cumulonimbus storms with accompanying torrential rains.

Long periods of aridity would have prevented the growth of vegetation on the mountains, and during heavy rains the unprotected slopes would yield quantities of weathered rock to be carried downward in torrential flow. At such times the water marginal to the uplifts may have been brackish. If a semicontinuous belt of algal reefs rimmed the evaporite pan, such reefs may have prevented intrusions of freshened water. If they did not, deposition of salts may have been interrupted or diminished at such times and a pall of mud may have invaded the basin. The abundance of mudstone in the Eagle Valley indicates the likelihood of such periodic invasion.

MINERAL COMMODITIES OF ECONOMIC VALUE

Gypsum, anhydrite, and halite are the most abundant minerals of possible commercial value in the Eagle basin. All are present in greatest quantity in the Alkali subbasin, but they also occur in the Cattle

Creek anticline; halite is present at least in small quantity at Ruedi. Although contaminated with mud and clay, the thickest and most chemically pure gypsum deposits occur in the vicinity of the towns of Eagle and Gypsum. No commercial development of saline deposits has taken place. The distance from bulk markets and the questionable quality of the Eagle Valley salines place them in a commercial position less favorable than that of established sources.

In 1966, the Pittsburg and Midway Coal Mining Co. drilled two holes north of the town of Gypsum (secs. 23 and 29, T. 4 S., R. 85 W.) (pl. 3*B*) for the Gulf Oil Corp. to test for presence of salts of potassium. In both holes halite is present at a depth of about 1,400 feet, and two beds containing potash, 6 and 7 feet thick, were reported at depths of between 3,600 and 4,000 feet (Max A. Krey, written commun., 1967). No commercial development by the companies concerned is contemplated.

Halite deposits of good quality are known in the Cattle Creek anticline (Rose well) and are probably present in the Alkali subbasin (Black well). Halite is already produced in many parts of the United States, however, from deposits having greater size, higher chemical purity, and easier accessibility to markets.

Oil and gas may be present in carbonate beds of the Morgan Formation in eastern Rio Blanco County where they tongue into red beds and anhydrite. Detailed stratigraphic study may be rewarding in areas where this facies change takes place on northwest-trending anticlines. Oil and gas may also be present in algal reefs or carbonate banks developed at depth on the margins of the evaporite basin. The small size of these features in surface exposures, however, is not encouraging. Oil and gas may occur on the crests or flanks of salt anticlines like the one at Cattle Creek Station, but it must be realized that older strata beneath the evaporite may not be arched to form a fluid trap.

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CONTENTS

[Letters designate the separately published chapters]

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