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1981, pp. 105-112. https://doi.org/10.56577/FFC-32.105

in:

Western Slope (Western Colorado), Epis, R. C.; Callender, J. F.; [eds.], New Mexico Geological Society 32 nd Annual Fall Field Conference Guidebook, 337 p. https://doi.org/10.56577/FFC-32

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TECTONIC EVOLUTION OF WESTERN COLORADO AND EASTERN UTAH

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INTRODUCTION

The boundary between the Colorado Plateau and Southern Rocky Mountain provinces lies somewhere within the western Colorado-eastern Utah region, and is arbitrary in the geological sense, because the stratigraphy and tectonic relationships remain relatively constant throughout the area.

The area of this report lies astride the Uncompahgre Uplift segment of the Ancestral Rockies orogenic system (see fig. 2). To the west of the ancient Uncompahgre fault block lies the northwest-trending Paradox basin and to the east is the strikingly similar Eagle evaporite basin, both of late Paleozoic age. Bounding the region on the east are the marginal Gore and Mosquito faults of the Front Range segment of the Ancestral Rockies. Within this vast area the early Paleozoic stratigraphy is similar and essentially uniform within the paleotectonic basins, suggesting that the two downwarps were not so distinctly separated until after Mississippian time. However, in Pennsylvanian time the main uplift of fault blocks of the Ancestral Rockies abruptly separated and accentuated the Paradox and Eagle evaporite basins, although the stratigraphy of the two depressions remained remarkably similar. Both the Uncompahgre and Front Range uplifts became high topographic features and shed untold cubic kilometers of coarse, arkosic sediments into the eastern reaches of the structural basins. Whether the two salt basins were interconnected in a common sea is still a matter of personal interpretation.

The margins of the Paradox basin usually are defined by the geographic extent of salt deposited during Middle Pennsylvanian time in the Paradox Formation. Consequently, there is little or no reflection of the buried basin at the surface, except for the salt diapirs in the "Paradox fold and fault belt." The basin is bounded on the northeast and east by the Uncompahgre Uplift and is surrounded elsewhere by paleotectonically controlled shallow-water shoals. The ovate basin has a northwesterly orientation, extending from Durango, Colorado and Farmington, New Mexico on the southeast to Green River, Utah on the northwest.

The Uncompahgre Uplift, which is best known for its exposures on the Uncompahgre Plateau and Black Canyon of the Gunnison River, extends for some 700 km northwestward from near Santa Fe, New Mexico almost to Provo, Utah. It is complexly fault-bounded on its southwestern margin and tilts gently eastward into the Eagle basin. Where exposed, the crest of the tilted fault block is Precambrian metamorphic and igneous rocks, overlain by various Mesozoic formations. Although it has a complex growth history, the Uncompahgre Uplift was a dominant feature throughout most of Permo-Pennsylvanian time.

The Eagle evaporite basin lies generally between the tilted eastern margin of the Uncompahgre Uplift and the fault-bounded Front Range Uplift on the east. The generally northwest-trending structural depression is a diminutive copy of the Paradox basin. The Eagle Valley Evaporites in the central part of the basin include gypsum and halite interbedded with drab-colored clastic rocks (Lovering and Mallory, 1962) that interfinger eastward with shelf carbonates and clastics of the Minturn Formation and arkose of the Maroon Formation. As in the Paradox basin, salt diapirs are present at a reduced scale near Glenwood Springs and Eagle, Colorado (see also Campbell, this guidebook).

BASEMENT FRAMEWORK

Although much has been said about the Laramide deformation of the Colorado Plateau and Southern Rocky Mountain provinces, the fact is that the structural fabric of the region was fixed by Late Precambrian time and repeated rejuvenations of the basement structure, including the Ancestral Rockies and Laramide episodes, only modified the original framework.

It was sometime around the summer of 1,700 m.y.b.p. that activity got underway on two major shear systems that transect the Paradox basin and Uncompahgre Uplift as we know them today (fig. 1). One, the dominant northwest-trending swarm of faults that passes through the San Juan Mountains of southwestern Colorado and on into the subsurface of the eastern Paradox basin, may extend as far to the northwest as Vancouver Island, B.C. and toward the southeast into Oklahoma's Wichita aulacogen (Baars, 1976). The subordinate northeasterly swarm of faults forming the conjugate set of fractures extends from Grand Canyon, Arizona through the Colorado Mineral Belt to Lake Superior (Warner, 1978). The northwest-trending set, called the Olympic-Wichita lineament by Baars (1976), appears to have had right-lateral strike-slip displacement; movement took place between 1,720 m.y. and 1,460 m.y. in the San Juan Mountains. The northeast-trending Colorado lineament, dated at 1,700 m.y. by Warner (1978), displaced the basement rocks in a left-lateral sense. The two continental-scale shear systems form a conjugate set that intersect in the vicinity of Moab, Utah.

The basic fracture pattern outlined above could be formed when compressive forces were directed from the north (or south) in Precambrian time. Perhaps a more reasonable solution would be a right-lateral wrenching stress imposed on the western United States that Wise (1963) proposed as his "outrageous hypothesis." Whether the underlying mechanism is the "outrageous hypothesis" of Wise or north-south compression as proposed by Moody and Hill (1956) is irrelevant for this discussion. Recognition of the basic tectonic fabric provides a basis for understanding the "peculiar" structural features of the Colorado Plateau and Southern Rockies.

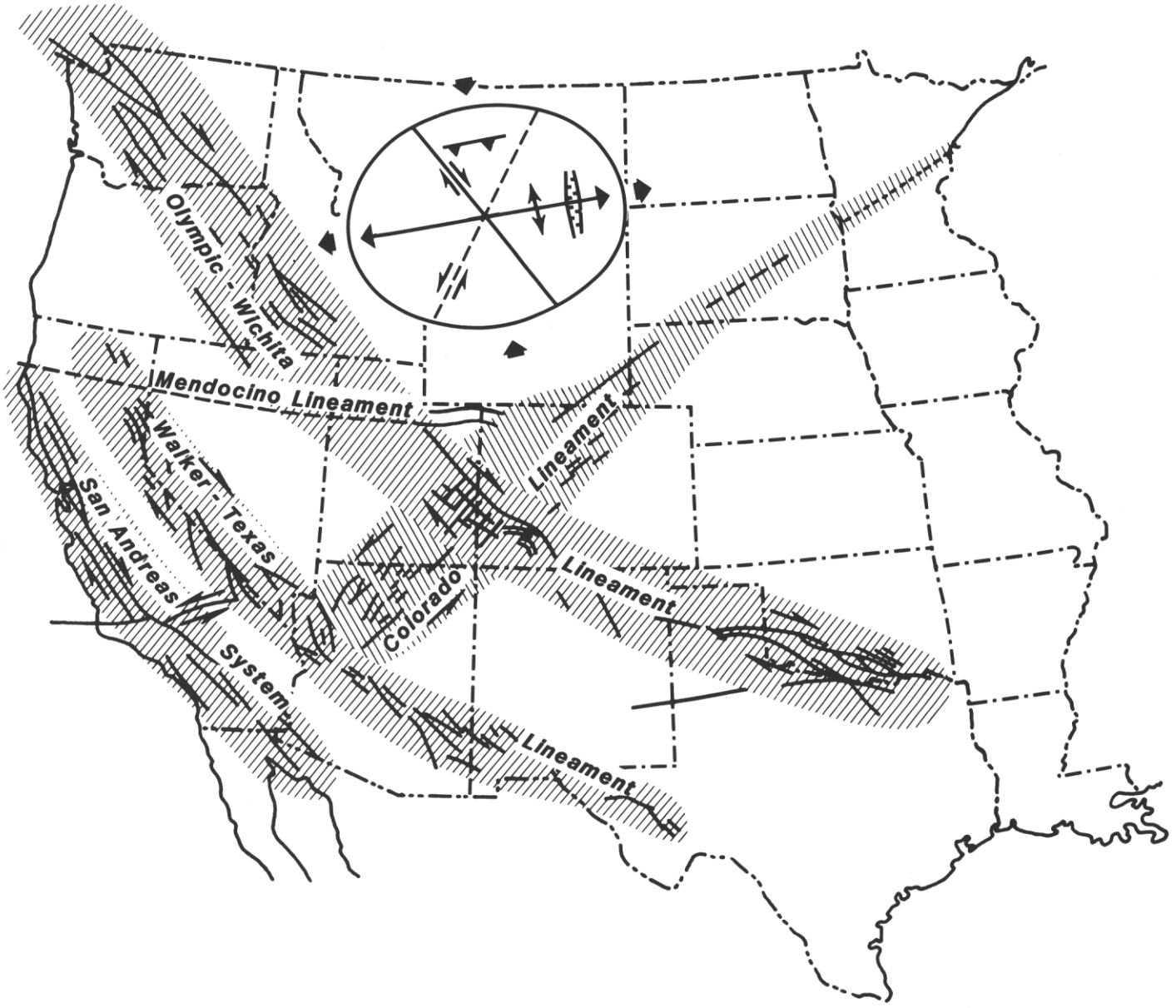

Figure 1. Location of major basement lineaments of the western United States. The sense of strike-slip offset is shown by arrows; northwesterly lineaments are right lateral, northeasterly lineaments are left lateral. The stress-strain ellipsoid is oriented such that maximum compressive stress is directed from the north.

A review of the strain ellipsoid oriented to properly represent the conjugate fractures described above (fig. 2) indicates that northerly-trending normal faults (east-west extension) should occur in conjunction with the wrench faults. It has been well established that the large monoclinal folds of the Colorado Plateau are drape structures over normal basement faults of Precambrian age; thus the monoclines originated as third-order features of the stress field. Furthermore, the large bounding faults of the Colorado Rockies (the Gore and Mosquito faults along the Front Range Uplift and the Cotopaxi fault that bounds the Wet Mountains Uplift farther south) are north-northwest normal faults that originated in Precambrian time (Tweto, 1980a, 1980b) and appear to have resulted from the same basic mechanism. Baars (1972, 1975) demonstrated early Paleozoic rejuvenation of these features. We should also expect to have easterly-trending folding and thrusting (north-south compression) which readily explains the "maverick" east-west trending thrusted anticlines of the Uinta Mountains. At least the very large Uinta Mountain arch had a Precambrian origin and fits the stress field described. Thus, the tectonic stage was set long before the Ancestral Rockies and Laramide orogenies, and most likely by about 1,700 m.y.b.p.

FAULT REJUVENATIONS

The Colorado Plateau and Southern Rockies were relatively quiescent during early Paleozoic time; however, Baars (1966) and Baars and See (1968) presented evidence that minor rejuvenations along the Olympic-Wichita lineament in the Paradox basin occurred during Cambrian, Devonian and Mississippian times. Baars (1972, 1975) described similar rejuvenations of tectonic activity along major structures in the vicinity of the Eagle basin and Front Range and Wet Mountains uplifts. Although early Paleozoic displacement on the faults was minor, sufficient vertical movement

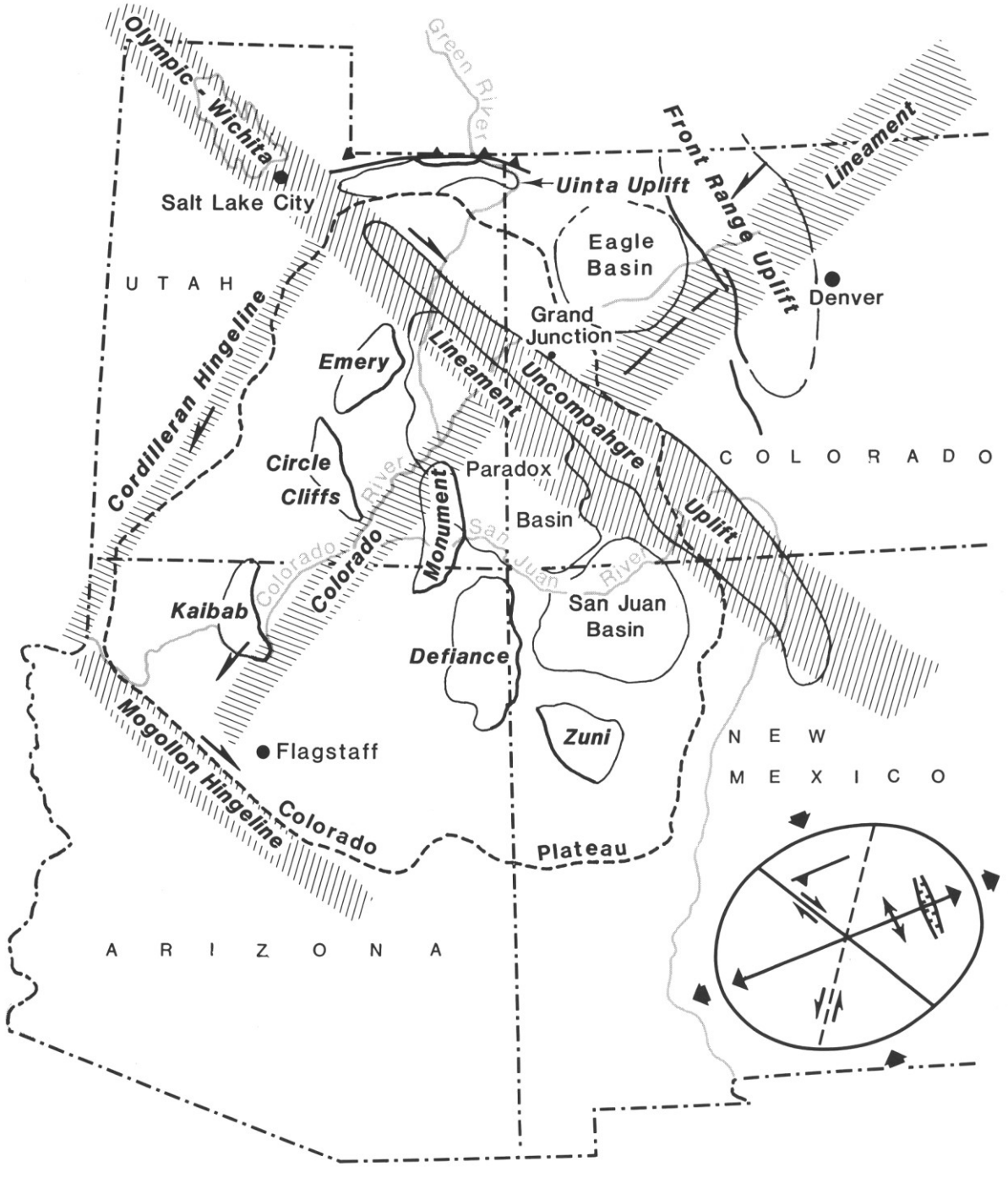

Figure 2. Location of Colorado Plateau and relationship to major orthogonal set of basement lineaments. Northwesterly lineaments are right lateral, northeasterly lineaments are left lateral. Stress-strain ellipsoid oriented such that maximum compressive stress is directed from the north.

occurred to create local shoaling conditions and alter sedimentary facies on a local scale. This structural activity was responsible for isolating local reservoir facies in Late Devonian and Early Mississippian rocks of the central Paradox basin. Similar potential reservoir facies in Mississippian strata of the southern Eagle basin have been reported by Nadeau (1972) in close proximity to basement structures. It appears that repeated paleotectonic rejuvenation on a minor scale is favorable to the development of petroleum reservoirs prior to Pennsylvanian time.

UPRISING OF ANCESTRAL ROCKIES

The relatively mild nature of the early Paleozoic tectonic activity took a dramatic change by the beginning of Middle Pennsylvanian (Atokan) time. Vertical displacement along the basement faults of the Paradox basin and Southern Rockies began slowly, but picked up momentum as Middle Pennsylvania (Desmoines) time progressed. The major uplifts of the Ancestral Rockies developed during this time as tilted fault blocks rising from Precambrian wrench faults and major normal faults became major source areas for coarse, arkosic clastic sediments. The Uncompahgre, Front Range and Wet Mountains uplifts arose to considerable heights, shedding hundreds of cubic kilometers of coarse clastics to the adjacent basins. More than a thousand meters of arkosic debris accumulated along the eastern flanks of the Paradox and Eagle (Maroon) basins in Permo-Pennsylvanian time. Although vertical displacement definitely dominated the earlier wrenching stress field, the structural fabric of the basement remained essentially unchanged, and east-west extension of the crust was greatly enhanced. Kluth and Coney (1981) have postulated that the increased tectonic activity resulted from the collision of the North American and South American-African plates at this time. However, the basic fabric remained essentially unchanged from the Precambrian pattern.

Uplifts

Uncompahgre-San Luis Uplift

The Uncompahgre Uplift had a complex history that is not completely understood because of poor exposures and limited subsurface data. Major uplift of the faulted highland began in Atokan time in a southern segment that extends from just east of Santa Fe, New Mexico northwestward to Ouray, Colorado. Relatively thick Atokan clastics in north-central New Mexico and southwestern Colorado attest to the early growth. This segment, the San Luis Uplift of early workers, continued its relatively modest rate of uplift well into Permian time, supplying clastic sediments to the Sangre de Cristo, Hermosa and Abo formations along the adjacent lowlands.

A pronounced westerly arc, or flex, occurs in the highland just east of Ouray, paralleling a similar westward flex in the adjacent Sneffels and Grenadier grabens of the San Juan Mountains (Baars and See, 1968). This arcuate bend in the basement faults is interpreted to be a left-lateral drag fold of enormous proportion caused by the Colorado lineament. It also appears to occur at the northwestern termination of the San Luis (Atokan) positive feature. From Ouray northwestward to the northwestern plunge of the surface Uncompahgre Plateau near Cisco, Utah, the middle (or Uncompahgre) segment of the uplift did not begin shedding massive amounts of arkose until Desmoinesian (Middle Pennsylvanian) time, but continued its positive tendencies well into Permian time. This northwesterly termination of the Uncompahgre Plateau also marks the emergence of the Colorado lineament into the Paradox basin. In other words, the Uncompahgre Uplift appears to have been segmented by the coupling of the Colorado and Olympic-Wichita lineaments.

The northwestern element of the Uncompahgre Uplift, perhaps best termed the Book Cliffs segment, extends from about Cisco to the overthrust belt in the Wasatch Mountains east of Provo, Utah in the subsurface. Its existence is known from geophysical and subsurface data underlying the southern flank of the Uinta Basin beneath the Book Cliffs. Thus, the rigid basement block provides a sill over which the structural basin sagged, creating the peculiar triangular shape of the basin. It did not shed significant amounts of arkosic debris until Early Permian time.

Front Range- Wet Mountains Uplifts

The complex growth history of the numerous individual segments of the Front Range-Wet Mountains uplifts of the Ancestral Rockies has been thoroughly documented and summarized by De Voto (1972). It will suffice here to reiterate that the history of the tectonic activity east of the Uncompahgre Uplift is similarly segmented and variably dated as that described for the Uncompahgre Uplift (see De Voto, 1972).

Complimentary Basins

Paradox Basin

The Paradox basin formed adjacent to the southwestern bounding faults of the Uncompahgre Uplift as a complimentary faulted depression (fig. 3). The deepest part of the basin lies immediately adjacent to the uplift, having stepped down structurally in a series of half-grabens from the western and southwestern shelves, or hingeline (fig. 4). Restricted marine circulation resulted in evaporite sedimentation throughout most of Desmoinesian (Middle Pennsylvanian) time. Salt deposition began in early Desmoinesian time in the deeper faulted troughs (Hite, 1960) and slowly filled the basin, burying the basement faults by the close of the epoch. Simultaneously, the Uncompahgre Uplift was supplying ever increasing amounts of arkosic sediments to the northeastern margin of the basin. The highland was continuously, or episodically, rising throughout the remainder of Pennsylvanian time, as the basin sank along the continuously active basement faults.

Most, if not all, of the smaller structural features of the Paradox basin were in place and growing during Paradox time. These folds exist at the surface today, having been enhanced by Laramide compression, but they were sufficiently prominent in Middle Pennsylvanian time to significantly impede open circulation of marine waters and to control salt thickness. Figure 3 shows the generalized surface structure of the region from Kelley (1955) overlain with Paradox salt isoliths. It is clear that the modern surface structures were actively developing around the periphery of the salt basin during the deposition of the salt and were actively affecting salt depositional patterns, as well as restricting marine circulation. These are all basement-related structures, and pre-date the Laramide orogeny.

Perhaps the most obvious and certainly the most interesting structural features of the Paradox basin are the large salt diapirs of east-central Utah and west-central Colorado (fig. 3). This broad region, termed the "Paradox fold and fault belt" by Kelley (1955), overlies the deeper structural depression of the Paradox basin where depositional salt thickness may have reached 1500 to 2400 m. The oldest and thickest salt deposits lie in the basement-controlled half grabens described above, but massive salt flowage has totally obscured other depositional characteristics.

The salt anticlines are strongly elongated northwesterly, paralleling the Uncompahgre frontal faults and overlying deep-seated basement faults (Cater and Elston, 1963; Joesting and Byerly, 1958;

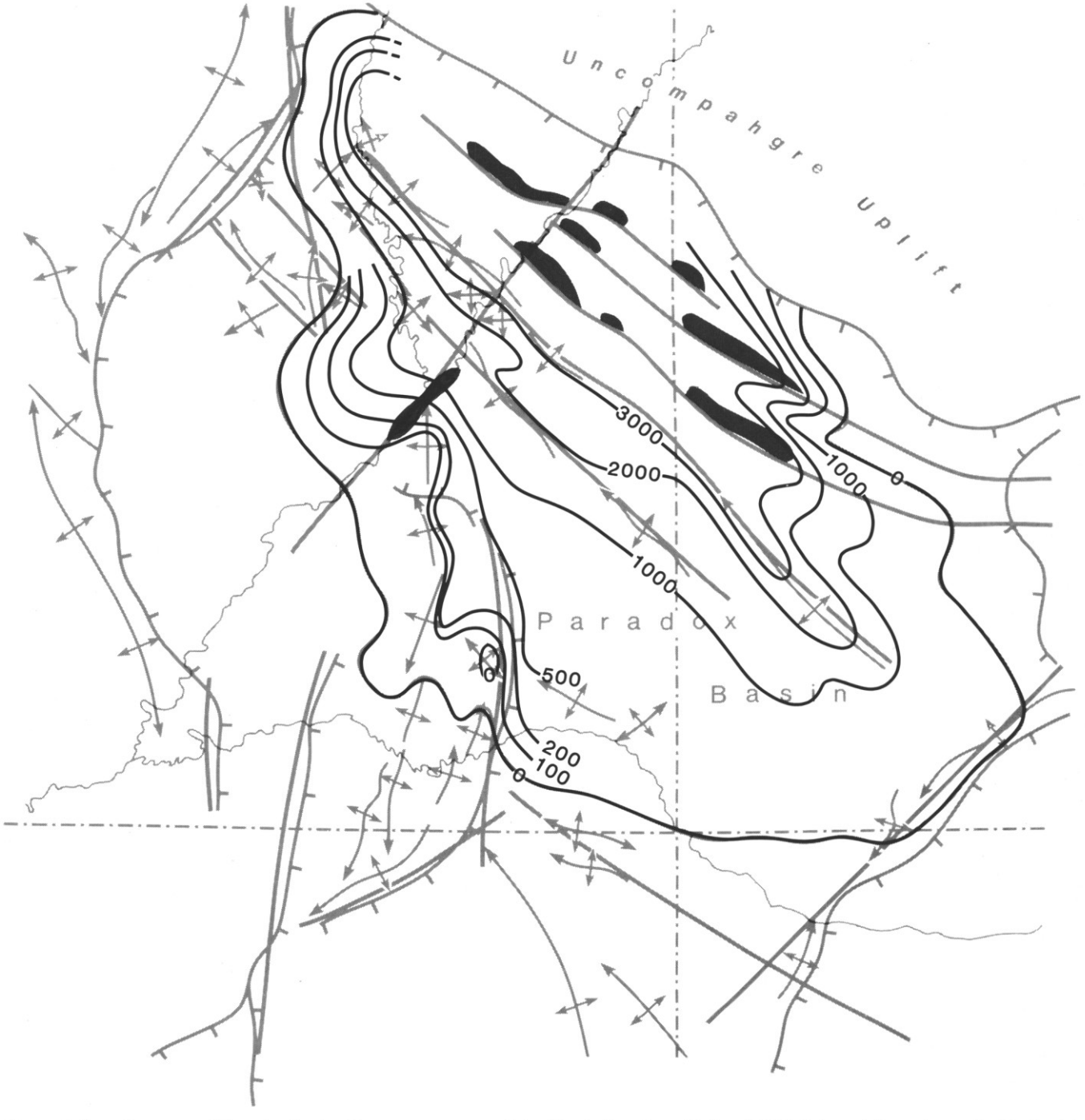

Figure 3. Location map of Paradox basin. Contours are net salt isoliths in feet from Kelley (1955). Salt anticlines shown in black with related northwest-trending basement faults (from Baars, 1966). Salt diapir on right is Paradox Valley; structure at left is Lisbon Valley.

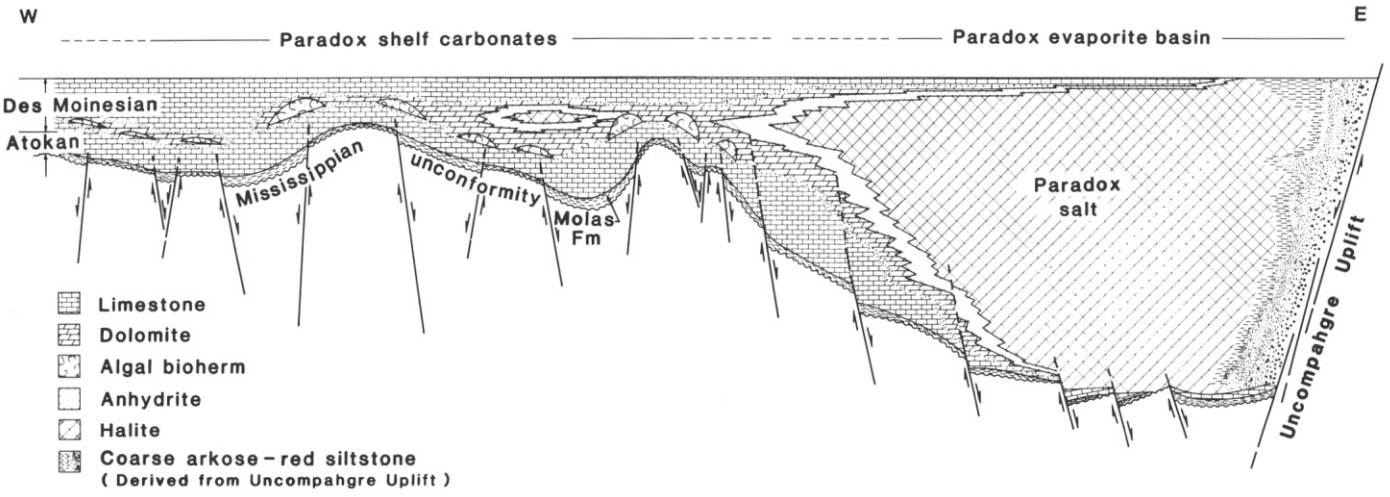

Figure 4. Schematic cross-section across Paradox basin at late Middle Pennsylvanian time, showing relationship of shelf carbonate to evaporite facies. Algal bioherms are shown in general relationships to basement structures. Salt diapirs are not shown.

Baars, 1966). As salt thickness reached about a thousand meters over the half-grabens, thick wedges of arkose were being deposited along the transition between the Uncompahgre highlands and the low-lying evaporite basin. The directional nature of the clastic overburden was a large factor in the initiation of salt flowage toward the southwest and the large basement faults, which are known to have vertical displacements of over 1800 m in Paradox Valley (fig. 5). Thus, the deep-seated faults were major buttresses to lateral salt movement. As the mobilized salt encountered the fault "scarps," flowage was directed upward and diapirism was initiated. Continued deposition of clastic overburden to the northeast caused salt to flow continuously or episodically until the supply was depleted in Late Jurassic time, as shown by repeated angular unconformities and pinchouts along the flanks of the structures. The source of the ever-thickening clastic overburden on the Uncompahgre Uplift was buried by Late Triassic and Jurassic sedimentation as the supply of salt diminished, marking the close of the diapiric activity.

Eagle Evaporite Basin

The poorly known Eagle evaporite basin, lying between the Uncompahgre and Front Range uplifts, has a similar history of subsidence and sedimentation as the Paradox basin. A paucity of subsurface data and limited exposures of Middle Pennsylvanian deposits provide only limited data, and interpretations are therefore highly generalized.

As previously outlined, basement faulting with a history of repeated rejuvenation is similar, if not identical, to the Paradox basin. Coarse clastic deposits were derived from the Front Range Uplift, and perhaps others, to the east and southeast, and interfingered with marine clastics and carbonates of the Minturn Formation of the Central Colorado Trough and the Eagle Valley Evapo-

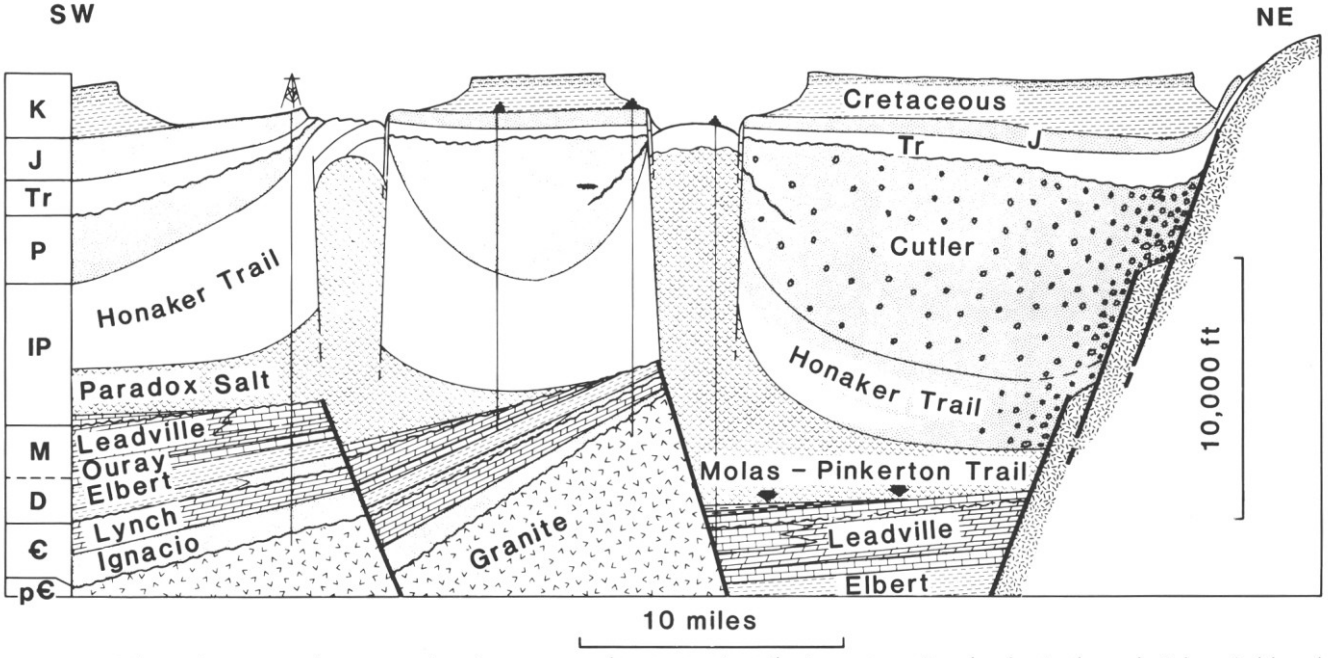

Figure 5. Schematic structural cross-section drawn normal to tectonic strike in eastern Paradox basin through Lisbon field and Wray Mesa region, showing relation between pre-salt faults and flowage structures (from Baars, 1966).

rites in the northwestern Trough (Lovering and Mallory, 1962). As in the Paradox basin, algal bioherms of Middle Pennsylvanian age grew along the margins of the evaporite basin (Walker, 1972). The extent and thickness of salt deposits in the restricted basin are only poorly known, and the nature of sub-salt structure is unknown due to the limited number of deep wells.

Two northwesterly trends of Eagle evaporite exposures in the vicinity of Glenwood Springs and the Eagle-Gypsum area have the characteristics of salt diapirs similar to the Paradox structures. Drilling indicates that salt is present in the structures, but their size and growth histories have not been determined. These salt anticlines may be more similar to the Paradox structures than is generally realized, and further deep exploration of the pre-salt section is certainly warranted.

DEMISE OF THE ANCESTRAL ROCKIES

The Ancestral Rockies had probably reached their zenith by Early Permian time; they underwent denudation for about the first half of the period, supplying great quantities of arkosic sediments to the lowlands during their demise. The Permian red beds from the uplifts finally buried many of the long-existing positive features of the region, such as the Zuni, Defiance, Kaibab, and Nacimiento uplifts of the Colorado Plateau. The Monument Upwarp remained sufficiently positive to cause major facies changes along its flanks and crests, while marine Permian deposits buried the Late Pennsylvanian erosional surface on the Emery uplift underlying the San Rafael Swell.

Fine-grained red beds and eolian sandstones dominated the Triassic and Jurassic systems, with little evidence of structural growth having played a significant role. By Late Cretaceous time, the intracratonic seaways shifted eastward, effectively burying the present day Colorado Plateau and Southern Rockies in marine muds and sands.

LARAMIDE DISTURBANCE

The Laramide orogeny is generally considered to have been the wave of compressional tectonism that reshaped the western North American continent from the west toward the east during latest Cretaceous through early Eocene time. During this event, the Colorado Plateau and Southern Rockies, as a whole, resisted the extensive thrust faulting that occurred to the west and south. The Colorado Plateau acted as a semi-rigid "mini-plate," rejecting intensive deformation along its western margin, the Cordilleran hingeline or Wasatch line, and along its southern border at the Texas-Walker Lane lineament. Pre-existing basement-related structures of the Plateau and Southern Rockies invariably pre-date the Laramide in origin, but were somewhat modified by the westerly compressive forces.

The primary effects of the Laramide on the Colorado Plateau and Southern Rockies were the enhancement of pre-existing structures and the overturning of drape folds, generally toward the east. The amplitude of virtually all of the folded structures was increased considerably by westerly compressive stress (cr,), changing minor, low amplitude folds into major structures. Major monoclines formed over the larger north-oriented basement normal faults on the Plateau, and vertical throw was increased on similar faults in the Rockies. The net effect was to overturn the basement faults toward the east, and to create east-facing monoclines. There are a number of west-facing monoclines on the eastern Plateau and White River uplift (Kelley, 1955), but most of these occur as drape folds over the primary basement wrench faults rather than third-order normal faults. In spite of a flurry of extraordinary explana tions of the Laramide origin of the Uinta Mountain arch by various structural geologists in recent years, the easterly trending fold was present in essentially its present configuration prior to Cambrian time, as shown by angular unconformities at that horizon. The Uinta-Piceance basin is a negative fold, draping off the Uinta Mountain arch on the north and the Uncompahgre Uplift under its southwest flank.

The multitude of problems encountered when the structural configuration of the Colorado Plateau and Southern Rockies is interpreted on the basis of Laramide stress fields are essentially eliminated when it is realized that these structures originated in a totally different stress regime in Precambrian time. The basement tectonic fabric of the region was fixed before Phanerozoic time and repeatedly rejuvenated during the various ensuring tectonic events, including the Ancestral Rockies and Laramide episodes. Bodily clockwise rotation of the provinces invoked by many authors to explain the observed relationships is unnecessary and unjustified by field relationships, except along basement shear zones.

AFTERMATH

Tectonic events following the Laramide disturbance have more effect on the geomorphology than anything else. Beginning shortly after the termination of Laramide time (probably during the Eocene) the entire Colorado Plateau Province was gently, but bodily, uplifted and tilted toward the north. A regional vertical doming of central Arizona seems to have been the cause of the tilting. The end result was that surface drainage gained potential energy and surface erosion was accelerated. The early denudation of the Province provided considerable amounts of sediments that were carried northward into a large lake (Lake Uinta) that formed between the structural buttresses of the northwestern Uncompahgre Uplift and the Uinta Mountain arch on the north. The Paradox basin region was merely subjected to surface erosion.

The most prominent topographic features on the Plateau are the so-called laccolithic ranges that stand to elevations exceeding 3,900 m. There are eight in all, and they appear to have been emplaced along basement lineaments (Kelley, 1955) or more likely at intersections of northwest and northeast basement lineaments (Witkind, 1975). Within the individual ranges, intrusive igneous rocks are exposed in the form of stock, dikes, sills, laccoliths and cactoliths. They appear to have been emplaced at two distinct times. One group, including the Ute, Carrizo, La Plata and Rico ranges, have been dated at between 61 and 84 m.y., or about Laramide time. The others, including the Henry (48 m.y.), LaSal (24 m.y.) and Abajo (28 m.y.) ranges were intruded around middle Eocene and early Miocene times (Witkind, 1975). It is interesting that the LaSal Mountains east of Moab were intruded along the basement faults underlying Paradox and Castle Valley salt structures and actually pierced the heart of the salt anticline. The resulting igneous rocks are peculiar aegirine-augite-rich syenite prophyries (soda-enriched) as a result of intrusion through halite. The range was named LaSal (salt) Mountains by the early Spanish explorers, because they found salt water springs in the mountains.

Late in the episode of regional tilting during the intrusion of the younger laccoliths, general elevation of the Plateau and Southern Rockies occurred. Surface and ground water drainage intensity increased and was gradually diverted toward the southwest along the Colorado River system, perhaps by a series of stream piracies along the route. Ground waters began to remove near-surface salt by solution on the larger salt diapirs; consequently, solution collapse of the crests of the anticlines began. Overlying strata of

all ages from Permian to Cretaceous slumped into the weakened crests of the salt anticlines, leaving them with gravity faults along the high flanks and jumbled slump folds depressed into the terminations of the anticlines as we see them today. Superimposed streams cut downward into the structures, sometimes at right angles to the anticlines, creating "paradoxical" river courses that cut across the structures rather than flow along the axial valleys. Thus, the name was derived for Paradox Valley, from which the name was derived for the Paradox Formation and subsequently the Paradox basin.

CONCLUSIONS

The tectonic evolution of the Paradox basin and Southern Rockies may be summarized as follows:

1. A conjugate set of shear zones transected the region at about 1,700 m.y.b.p. The northwesterly shear has been named the Olympic-Wichita Lineament; the northeasterly set the Colorado Lineament. They probably resulted from relative compression from the north.
2. Related basement fractures were northerly oriented normal faults (extension) and easterly oriented folds (compression).
3. Small-scale vertical relief along the fracture system was rejuvenated throughout Cambrian, Devonian and Mississippian time, creating localized reservoir facies on the high, shoaling fault blocks.
4. The Uncompahgre and Front Range Uplifts and the compensatory Paradox and Eagle basins formed along the basement fractures in Pennsylvanian time from extreme east-west extension of the crust.
5. Salt thickened and diapiric structures formed in Pennsylvanian through Jurassic time from clastic overburden on the eastern margins of the basins, causing the salt to flow against and upward along the basement faults.
6. Laramide compressional forces from the west in Late Cretaceous to early Eocene time enhanced the existing structures and overturned them toward the east in most cases. The salt structures were little affected. Monoclines were formed over the northerly oriented normal faults in the basement, and the easterly trending Uinta Mountain arch was enhanced.
7. Regional tilting of the Plateau province toward the north caused surface drainage to fill Lake Uinta with sediments stripped from the south in early Tertiary time.
8. Intrusive igneous laccolithic magmas were implaced during Laramide and middle Tertiary times at intersections of basement lineaments.
9. Major surface structures of the Colorado Plateau and Southern Rockies were not formed in Laramide times, only enhanced from rejuvenation of basement structure. They resulted from a continuum of tectonic activity originating about 1,700 m.y.b.p. and continuing to the present.

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