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D. F. Reaser and James R. Underwood Jr.
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TECTONIC STYLE AND DEFORMATIONAL ENVIRONMENT IN THE EAGLE-SOUTHERN QUITMAN MOUNTAINS, WESTERN TRANS-PECOS TEXAS*

D. F. REASER
The University of Texas at Arlington
and
JAMES R. UNDERWOOD, JR.
Kansas State University
Manhattan, Kansas

INTRODUCTION

In the exposed rocks in the Eagle–southern Quitman Mountains region there is evidence of several major tectonic episodes:

1. Geosynclinal subsidence, deposition and metamorphism within the old Texas Craton late in the Precambrian (Flawn, 1956).
2. Development of the Marathon geosyncline, the sediments in which were deformed by late Paleozoic orogeny that ended early in the Permian Period. This orogeny uplifted and tilted the foreland area, created the Van Horn uplift as well as the larger Diablo Platform, and erected the present structural framework of Texas, indeed of the central United States (King, 1942).
3. Geosynclinal subsidence of, and deposition in, the Chihuahua Trough and episodic advance northward and eastward onto the Diablo Platform of the Mexican sea during the Jurassic and Cretaceous Periods. The alternating advance and retreat of the Mexican sea resulted in the deposition of couplets of calciclastic and siliciclastic rocks. The geosynclinal cycle culminated in the late Mesozoic-early Cenozoic orogeny (Laramide), which produced open to nearly recumbent folds and created thrust blocks, most of which moved northeastward.
4. Intrusion and widespread extrusion of alkaline igneous rocks in late Eocene–early Oligocene times (Jones and Reaser, 1970).
5. Development of the gross outline of present-day ranges in the region by late Tertiary normal faulting that created a series of debris-filled grabens (bolsons) and eroded horsts (mountain masses).

In rocks exposed in the Eagle Mountains–Indio Mountains–Devil Ridge complex there is evidence of all five of the episodes; in the Quitman Mountains, there is evidence only of the last three.

The Eagle–southern Quitman Mountains region lies, therefore, within and near the margins of two superimposed structural provinces: near the eastern margin of the Basin and Range Province and near the northeastern margin of the Chihuahua Tectonic Belt (fig. 1).

REGIONAL TECTONIC FRAMEWORK

The major Mesozoic negative structural element in western Trans–Pecos Texas and adjacent northeastern Chihuahua was the northwest-trending Chihuahua Trough; the major positive structural element was the Diablo Platform. The Chihuahua Trough, more than 160 km long (DeFord, 1969, fig. 2, p. 63), was bounded on the southwest by the Aldama Platform and on the northeast by the Diablo Platform. The trough abuts the Coahuila Platform on the southeast (DeFord, 1969); southward, the narrow trough probably connected with the main part of the Mexican sea during most of Cretaceous time. According to Haenggi and Gries (1970), all these features "had their inception during Carboniferous time." During Late Jurassic and Cretaceous time an estimated 6,000 m of sediment, including extensive basal evaporites, accumulated in the eastern part of the trough. The thick sedimentary sequence deposited in the trough was intensely deformed during the Laramide orogeny to produce the folded and faulted mountains of the Chihuahua Tectonic Belt. DeFord (1969) remarked that these folded mountains "were eroded almost as fast as they rose out of the trough."

According to DeFord and Twiss (1961), the Diablo Platform "is the central feature of the Trans-Pecos tectonic framework." This stable area, as well as the Coahuila Platform to the south, probably acted as buttresses during Laramide deformation. Overthrusting, overturning, and asymmetry of folds in the eastern part of the Chihuahua Tectonic Belt are mostly northeastward toward the Diablo Platform, a late Paleozoic positive feature. The eastern and northeastern limit of thrust faulting in the Chihuahua Tectonic Belt closely approximates the southwestern edge of the Diablo Platform; the Eagle–Quitman mountains are in the eastern part of the belt within three miles of the approximate limit of Laramide thrust-faulting (Deford, 1953, p. 20 and fig. 10, p. 21). Fold intensity increases westward and southwestward from the edge of the platform.

Viewed today, the Indio Mountains, Eagle Mountains, and Devil Ridge are part of a mountain range that begins just west of Ojinaga near La Mula, Chihuahua, and extends northwestward about 240 km to Sierra Blanca. This range is the easternmost and largest in a belt of folded ranges that emerge from Cenozoic cover in east-central Chihuahua, just east of the Rio Conchos, and extend north-northwestward to the international boundary. These ranges roughly parallel the course of the Rio Grande, but two of them cross the river into Texas. In Texas the eastern element includes the Indio Mountains, the Eagle Mountains, and Devil Ridge; the western, the Quitman Mountains.

The pattern of elongate, en echelon northwest-trending folded mountain ranges in the tectonic belt suggests a system of tectonically related folds. These folds are generally parallel to the margin of the Chihuahua Trough; the general trend of the folds changes from north-northwest to northwest along the Rio Grande between Ojinaga and Juárez. According to Sipperly (1967), this change in trend "probably reflects a bend along the west edge of the Diablo Platform against which this rock was folded."

The marked difference in thickness of the prism of Mesozoic sedimentary rocks, from 6,000 m in the Chihuahua Trough to 600 m north and eastward on the Diablo Platform, doubtless exerted great influence on the character of deformation.

*Revised from Reaser and Underwood (1975).

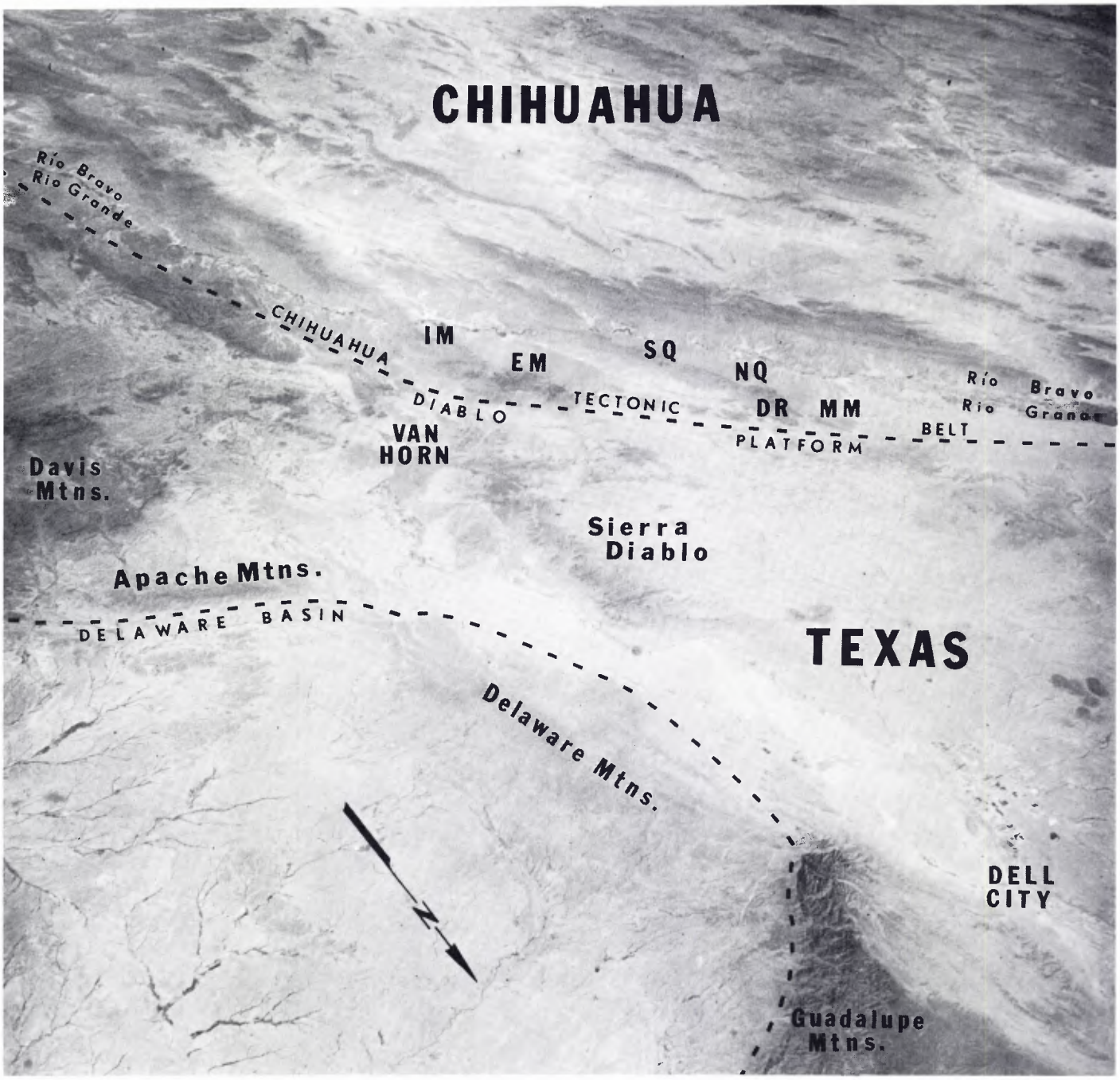


Figure 1. Oblique, southward view of mountain ranges in Texas and Mexico relative to the major tectonic framework. Photograph taken by White and McDivot with a hand-held Hasselblad camera on flight of Gemini-4, June 1965. Altitude is more than 160 km. Photograph courtesy of NASA.

Key to Ranges

DR–Devil Ridge
EM–Eagle Mountains
IM–Indio Mountains
MM–Malone Mountains
NQ–Northern Quitman Mountains
SQ–Southern Quitman Mountains

EAGLE MOUNTAINS, INDIO MOUNTAINS, DEVIL RIDGE

Although parts of a continuous range, the Eagle Mountains, Indio Mountains, and Devil Ridge display different structural styles. In both the Devil Ridge and Indio Mountains areas, earlier workers (Smith, 1940; Allday, 1953; Adams, 1953; Bostwick, 1953) identified northwest-trending major early Laramide folds several kilometers wide, now largely masked by later Laramide and Basin and Range deformation.

In the eastern part of the Indio Mountains there are well exposed the remnants of several folded thrust blocks resting on sparsely exposed overridden blocks. West of the Indio fault, the imbricate thrust sheet is well preserved on the downthrown block. Immediately east of the Indio fault the thrust sheet has been eroded from the high part of the mountain but is preserved in topographically low areas along the east margin of the mountains (Underwood, 1963, pl. 1).

Many of the relatively small imbricate thrust slices in the Indio Mountains appear to have moved southwestward as counter-thrusts. This should not be surprising. A homogeneous mass undergoing northeast-southwest compression might be expected to fail equally along southwest dipping or northeast dipping fractures (DeFord, 1958). That most of the faults originally dipped southwest may be the result of inhomogeneities in the rocks, irregularities in the underlying basement, and/or marked thinning of the late Paleozoic and Mesozoic rocks from southwest to northeast. Because of later folding, dips of the fault planes are now northeast to east-northeast.

Folds, for the most part, are open and symmetrical (Horse Peak anticline and Lost Valley syncline), but the vertical- to near-vertical rocks in Bramblett Ridge are the strikingly exposed steep southwest limb of a north-northwest-trending syncline (fig. 2).

Thus, the Indios are characterized by complex thrust faults and mostly open, symmetrical folds. Imprinted on these are major normal faults: the Indio fault along the axis of the mountains and the unnamed bounding fault along the west margin of the Indio Mountains (fig. 3).

The Mesozoic rocks of the Eagle Mountains are largely covered by a thick sequence of volcanic rock which masks many of the details of folds and thrust faults of Laramide age. The Devil Ridge thrust fault, for example, cannot be traced with certainty through the Eagles, although a number of thrust faults have been mapped therein (Underwood, 1963). The main part of the mountains appears to be resting in the trough of a large syncline (Gillerman, 1953), which may be the result of subsidence following extrusion of a vast quantity of volcanic rock.

The east- to east-northeast-striking faults are significant structural features of the Eagle Mountains (Underwood, 1963). These faults may well have developed during the period of Laramide compression as one of a possible set of conjugate shear fractures, with dominant strike-slip motion. Reorientation of the stress field produced vertical movement during the late Tertiary episode of Basin and Range block faulting when some of the early to mid-Tertiary igneous rocks were offset. A similar history of movement is recognized along the Red Bull fault zone in the southern Quitman Mountains (Jones and Reaser, 1970).

The Speck Ridge–Black Butte area (fig. 4), on the northwest flank of the Eagles, is a complexly folded and faulted area from which once-covering volcanic rocks have been eroded. The folds are



Figure 2. Northern Indio Mountains; northwestward view of Bramblett Ridge, composed of near-vertical beds of Bluff Limestone; Eagle Bluffs, Upper Rhyolite, in background.



Figure 3. Southern Indio Mountains; northwestward view along western boundary fault; Red Light bolson fill, left; Yucca Formation, right; Red Mountain, right skyline; Eagle Mountains, left and distant skyline.

open and symmetrical but are offset along transverse strike-slip faults or along normal faults parallel to the fold axes.

In Devil Ridge the principal deformation was the northeastward movement of two imbricate thrust blocks, the Red Hills and the Devil Ridge blocks. With the exception of the anticline overturned to the northeast that forms much of Back Ridge, folds there mostly are open and symmetrical.

Love Hogback (fig. 5) is part of the Devil Ridge thrust block; there the oldest exposed Cretaceous rock in the immediate area, the Yucca Formation, rests on the youngest exposed Cretaceous rock, the Chispa Summit. Stratigraphic separation is about 2,400 m; estimated horizontal movement along both the Red Hills and Devil Ridge thrust faults totals 5,800 m (Underwood, 1963).

In the Devil Ridge area, the orientation of the greatest principal stress during the Laramide orogeny was northeast-southwest. The more easterly orientation of the greatest principal stress in the Indio Mountains was the result of local irregularities in the stress field. These, in turn, reflected the influence of such diverse factors as the configuration of the basement, size and shape of the body



Figure 4. Aerial view northward of Black Butte, right center, capped by dark-colored Trachyte Porphyry. In near foreground, Finlay Limestone and Cox Sandstone in southeastern part of Speck Ridge. Left background, southeast-plunging anticline of Finlay Limestone; right background, Roof Garden.



Figure 5. View southward from summit of Love Hogback (Bluff Limestone in foreground) of northwest flank of Eagle Mountains. Left skyline, dark-colored Trachyte Porphyry overlying light-colored Lower Rhyolite; middle, Black Butte with sharp syncline in Espy Limestone visible beneath capping Trachyte Porphyry; in front, southeast-plunging anticline of Finlay Limestone, with vertical- to near-vertical Finlay Limestone in Speck Ridge, right.

of rock being deformed (which was controlled by the configuration of the Chihuahua Trough and the adjacent Diablo Platform), and inhomogeneities of the rock being deformed.

In summary, the dominant structural characteristics of the different blocks of the Eagle Mountains–Indio Mountains–Devil Ridge complex are:

1. Eagle Mountains—major east- to east-northeast-trending faults; open folds broken by younger faults.
2. Indio Mountains—complex system of thrust faults;open folds.
3. Devil Ridge—less complex thrust faults; minor folds.

SOUTHERN QUITMAN MOUNTAINS

The Quitman Mountains are part of a nearly continuous, 105-km range that extends from Puerto Alto in Chihuahua northwestward to the Southern Pacific–Texas and Pacific railroad tracks at the north end of the Malone Mountains in Texas. The range may continue another 115 km to Cuchillo Parado, Chihuahua. Haenggi (1966) observed that the evaporite core of the Cuchillo Parado anticline is on trend with the evaporite core of a large breached anticline that is inferred to underlie Bolson El Cuervo (Haenggi, 1966, p. 209 and Fig. 35, p. 304). Gries and Haenggi (1970) pointed out that the Cuchillo Parado anticline, Bolson El Cuervo, and the Sierra del Alambre–Quitman anticline are all along the same structural-geographic trend. Because of the alignment of these features, the Cuchillo Parado–Malone trend, from 200 to 240 km long, is interpreted to be another north-northwest-trending structural element of the eastern Chihuahua Tectonic Belt, similar to and parallel with La Mula–Sierra Blanca Range to the east.

Structurally, the Quitman Mountains are part of a large-scale, northwest-trending, nearly recumbent anticline. The normal west limb of the fold has been eroded and faulted. A large part of the inverted, eastern limb of the fold is exposed along the Rio Grande but has been reduced by erosion to a series of narrow, resistant limestone ridges separated by equally narrow strike valleys formed from less resistant nodular limestone, sandstone, siltstone, and shale (fig. 6). Many of the beds are overturned from 45° to 60° northeastward, but locally some beds have been rotated nearly 180°.

In the northern part of the range the rocks are broken by the Quitman thrust fault along which east-northeastward movement was estimated to be about 1,500 m (Jones and Reaser, 1970). This thrust block is the third in a northeast to southwest sequence: Devil Ridge, Red Hills, and Quitman.

Numerous, well exposed, superimposed folds probably reflect the general geometry, mechanics of folding, and deformational environment of the major fold. The geometric form of the folds in cross-section ranges from sharp, chevronlike, Z-shaped folds to rounded, S-shaped and broad "horseshoe" folds. The most characteristic form is a combination of the "S" and "Z" folds that is similar in cross-section to the Arabic numeral "2." Looking north from the second gorge of the Rio Grande an observer sees a rounded, nearly recumbent anticline on the west and a sharp, nearly recumbent syncline on the east; looking south the observer sees the outline of the folds as a reversed "2" as shown in Figure 7.

Most of the congruent minor folds and drag folds superimposed on the major folds are concentric (parallel) folds that are probably transitional to disharmonic folds. The large folds are also concentric folds. According to de Cserna (1969), the geometry of folds exposed in north-central Chihuahua indicates that they are concentric (parallel) folds.

Some of the minor folds in the souther Quitmans appear to be disharmonic folds that die out at relatively shallow depths. Their amplitudes range from less than 10 m to more than 150 m; their individual widths generally are from a few tens of meters to a few hundred meters. The wave lengths of successive folds range from a hundred meters to more than 300 meters. These folds are remarkably similar in appearance to disharmonic folds exposed in the foothills of the Rocky Mountains in northeastern British Columbia, Canada (Fitzgerald and Braun, 1965, figs. 6 and 7, p. 427, fig. 12, p. 431).

Minor folds in the southern Quitmans are probably best displayed in the bounding limestone ridges along the 5.6-km length of Goat Canyon in Texas, both in the upper part of the Finlay on the west and in the lower member of the Espy on the east. There near-horizontal beds adjacent to steeply-dipping beds reflect sharp Z-type folds at most places. These folds, modified by erosion and small-scale faulting, are well shown in cross-section along northeast-trending drainage courses that cut across the Espy and Finlay outcrops (Fig. 8). Short, vertical and east-dipping limbs of some tight folds form sharp declivities along the limestone floor of the arroyos. Folds rounded in topographic profile appear "squared off" along arroyos that cut through the crowded cores of the folds. Small-scale thrust faults, dipping both southwestward and northeastward at low angles, have dismembered some of the folds; indeed at places the observer is confronted by a confusing complex of severed parts from multiple folds, and one must look "down structure" from a high vantage point in order to interpret the structural relations. Many of the smaller folds are clearly disharmonic folds; at some places erosion has reduced the fold to an isolated anticlinal core or synclinal trough superjacent to less deformed strata. Some fold remnants on the steep west side of the Espy ridge in Texas are incipient slide blocks.

DEFORMATIONAL ENVIRONMENT

The type and style of folding in an area can be indicative of the deformational environment. Sharp, angular bends and the uniform thickness of individual beds within a fold indicate that most folds exposed in the region are flexural, including both flexural slip and flexural flow as defined by Donath and Parker (1964, table 1, p. 49). The prominent type is flexural slip. According to Donath and



Figure 6. Oblique aerial photograph of southern Quitman Mountains in Texas and adjacent Sierra Cieneguilla in Chihuahua. Annotations Koj, Kb, Kem, Kue, Kle, Kbe, and Kf, refer to exposed Cretaceous formations as follows: Ojinaga, Buda, Eagle Mountains, upper member of Espy, lower member of Espy, Benevides, and Finlay. Kb, Kle, and Kf are ridge-formers. View southward into Mexico from head of Calvert Canyon. Photograph by Pavlovic, 1962.



Figure 7. Minor folds in upper member of Quitman Formation along second gorge of the Rio Grande below Indian Hot Springs. Nearly recumbent anticline and syncline, upper center and left center of photograph, resemble reversed Arabic numeral "2." Core of anticline has been crushed and broken by small-scale faults. Notice the intense fracturing of beds. View southward into Mexico. Photograph by D. H. Campbell.

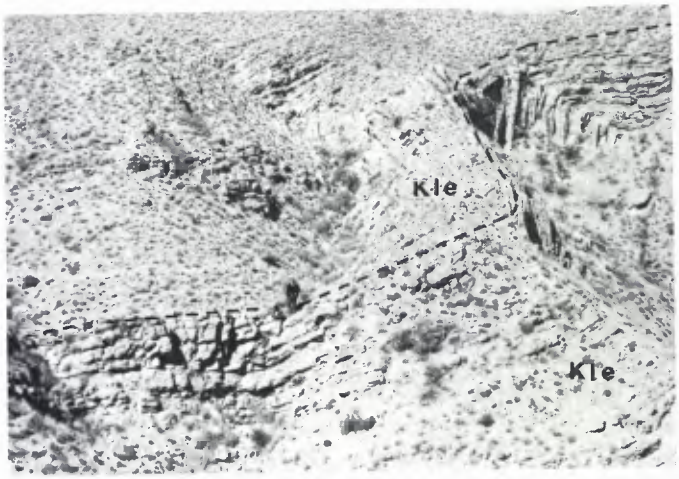


Figure 8. Large Z-fold in the lower member of Espy Limestone (Kle) displayed in section along northeast-trending drainage course about a mile north of the Rio Grande. Dashed line shows trace of fold along steep slope. Geologists in lower center of photograph provide scale. View northwestward.

Parker (p. 60), "Flexural mechanisms depend on the presence of mechanical anisotropy and operate most commonly in deformational environments characterized by low to moderate pressures and low temperature."

They pointed out (Fig. 3, p. 50-51) that under near-surface conditions a sequence of limestone or of limestone and shale could fold by flexural slip.

Gries and Haenggi (Haenggi, 1966; Gries and Haenggi, 1969; Gries, 1970; Haenggi and Gries, 1970; Gries and Haenggi, 1970) after studying a large part of northeastern Chihuahua, concluded that Cretaceous rocks in the Chihuahua Trough were intensely deformed along a décollement zone during the Laramide orogeny. They elaborated on the structural development of these rocks in northeastern Chihuahua and remarked (Gries and Haenggi, 1969) that Laramide overfolds and eastward-displaced thrust blocks of Cretaceous rocks in the eastern Chihuahua Tectonic Belt resulted from décollement on Jurassic(?) evaporites.

The lack of significant thickening and thinning of folded beds suggests that they were deformed by flexural slip folding. The intensity of fractures, moreover, suggests that deformation occurred in a relatively low-temperature low-pressure environment where brittle deformation, rather than plastic deformation, was dominant.

Fold geometry and other characteristics coupled with the intensity and shallow depth of folding in the southern Quitmans suggest deformation of a stratal "carpet" as might be expected in the plis de couverture of a décollement or in the upper plate of a large bedding thrust fault.

SUMMARY

The north-northwest to northwest trend of folds and thrust faults formed during the Laramide orogeny indicate that the directions of maximum compressive stress were oriented generally east-northeast and northeast to south-southwest and southwest. Well-developed conjugate shear patterns on the flanks of some folds support this conclusion. The intermediate stress was horizontal, parallel to the trend of major folds, and normal to the direction of maximum stress; locally, during strike-slip faulting, this was also the direction of minimum stress. The minimum stress during folding and development of thrust faults was vertical.

Large northwest- to north-northwest-trending normal faults in the region, such as the Caballo and Schroeder faults along the west side of the Quitman Mountains (Jones and Reaser, 1970), the Indio fault along the axis of the Indio Mountains, and the unnamed fault along the west side of the Indio Mountains (Underwood, 1963) indicate a reorientation of stresses in mid- to late Tertiary time. During faulting the maximum stress axis was vertical, the intermediate stress axis was horizontal and in the plane of the fault, the minimum stress axis was oriented northeast-southwest.

Asymmetrical folds occur throughout the Eagle–southern Quitman Mountains; such folds are more common in the southern Quitmans. Most, but not all, of the folds are asymmetrical to the east or northeast. DeSitter (1956, p. 239-246) has suggested that asymmetry of folds arises mainly 1) from differences in thickness of the folded strata along a basin margin, and 2) from an original difference in elevation between the limbs of a fold.

The thinning of the strata of the Chihuahua Trough toward the Diablo Platform is well documented. Because the radius of curvature of a fold is directly proportional to the thickness of the strata involved in the folding, the limb of the fold nearest the platform will have a shorter radius and thus a steeper dip.

Asymmetric folds also form where an original difference in elevation exists between flanks of a fold. Where an area bordering a trough is uplifted while folding commences, the steep limb of the resulting asymmetrical fold will be toward the trough. If, however, the strata of the trough were uplifted relative to the marginal area, the asymmetry of the folds would be toward the marginal area. Undoubtedly, such factors as these, plus irregularities of the basement, pre-existing folds in older strata, competence and incompetence of strata, and others, interrelate in a complex way to control the direction and degree of asymmetry.

Do the thrust faults penetrate to the Precambrian? This question cannot be answered certainly with present data, but no thrust fault in the Eagle–southern Quitman Mountains region brings Precambrian rocks to the surface. Probably the major thrust faults, and almost certainly the minor ones, flatten at depth and become bedding-plane faults within the lower part of the Cretaceous section or within the Jurassic section.

In the southern Quitmans, the crustal shortening of the Laramide orogeny was accommodated by intense folding, whereas in the Eagle Mountains, Indio Mountains, Devil Ridge complex shortening was achieved primarily by thrust faulting and more open folding. This may have resulted from the rocks in the southern Quitman Mountains having been deformed along a zone of décollement. Because the Jurassic(?) evaporite sequence of the Chihuahua Trough presumably does not underlie the Eagle Mountains–Indio Mountains–Devil Ridge area (DeFord and Haenggi, 1970, Fig. 4, p. 181), deformation there was characterized by intense fracturing rather than by folding.

PLATE TECTONIC IMPLICATIONS

Muehlberger (this guidebook) gives an excellent summary of tectonic events in the region from Precambrian time to the present. The tectonic history of the Eagle–Quitman mountain area is complex and a complete tectonic analysis of the area awaits further study; however, regional geology allows a few speculations concerning Mesozoic and early Cenozoic plate activity to be made. This part of our paper is intended to be a "pot boiler" and should generate heated discussion on the outcrop.

The area of investigation lies along a proposed southward extension of the Overthrust Belt of western North America (Drewes, 1978). Therefore, the general plate tectonic origin of the region, with local modifications, can probably be fitted into the overall pattern of the Mesozoic Cordilleran orogenic belt. Drewes (1978) suggested that the orogenic belt resulted from convergence of two active plates during Jurassic and Cretaceous time. These tectonic elements were the northeastward-moving, oceanic Farallon plate on the west and the westward-moving, cratonic Americas plate on the east. According to Drewes, "the oceanic plate was subducted beneath the western margin of the continental plate . . . " The continental plate consisted of a cratonic core with a flanking wedge of miogeosynclinal deposits. In the study area, the flanking sedimentary prism would include deposits in the Chihuahua Trough. It should be noted that Muehlberger (this Guidebook) relates development of the Chihuahua Trough to opening of the Gulf of Mexico in mid-Mesozoic. The western continental plate margin is not clearly defined but was probably near the eastern edge of the north-northwest-trending ancestral Baja California Trough of de Cserna (1970, fig. 5, p. 106) during Late Jurassic time. Dickinson and Yarbrough (1979, fig. 22-A) show a subduction (trench) complex during middle Cretaceous time along Baja California and the Gulf of California (fig. 9). Although remote relative to the subduction zone, strata deposited in the Chihuahua Trough were affected by the compressional stresses generated by

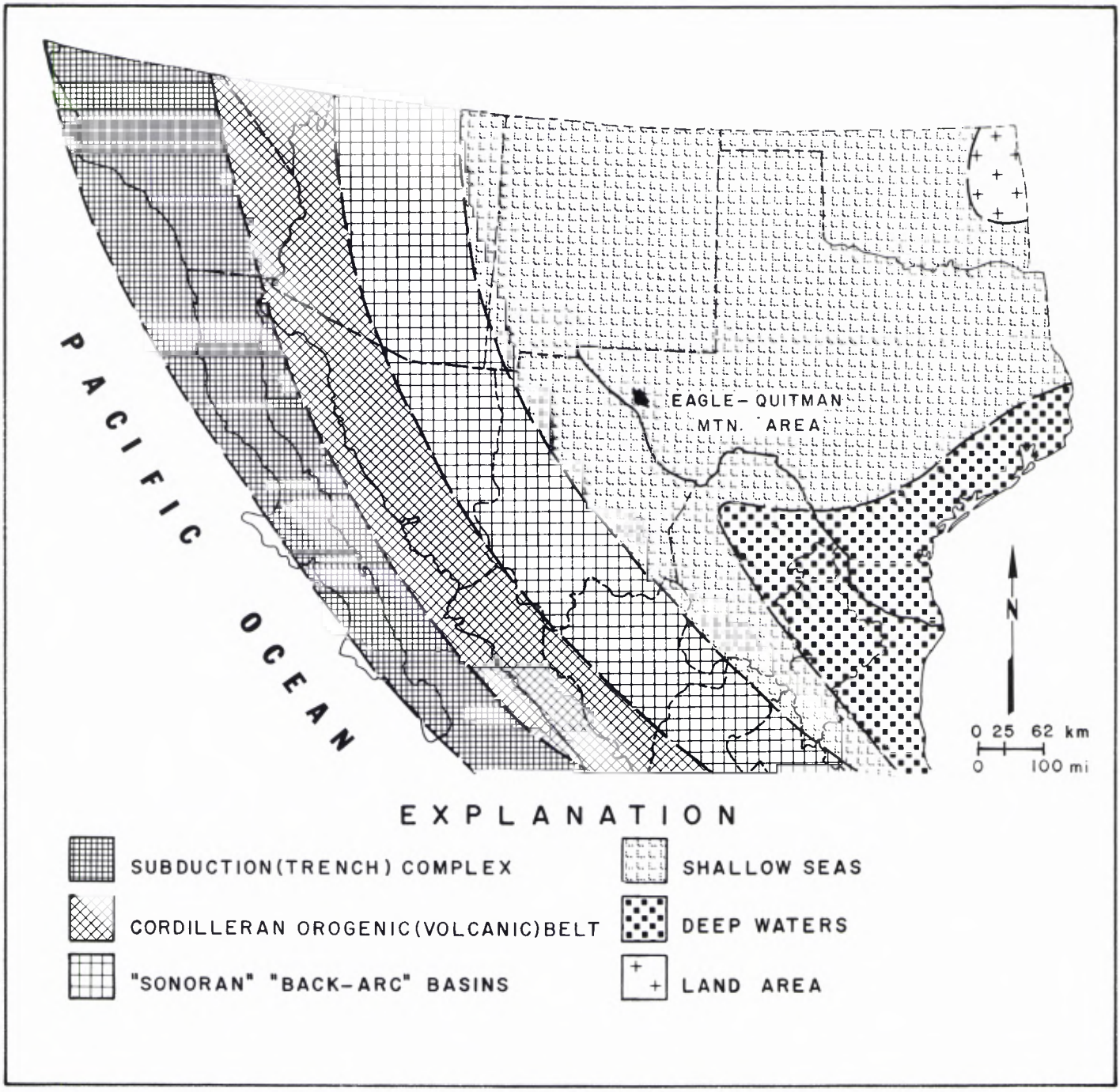


Figure 9. Generalized paleogeographic map showing part of western North America during middle Cretaceous time (100 million years b.p.). Modified from Dickinson and Yarborough (1979, fig. 22-A).

the eastward-moving, subducting slab. Deformation, including northeastward tectonic transport (probably along evaporite zones), proceeded slowly from west to east during Late Cretaceous and early Tertiary times. Subduction apparently ceased during early Tertiary time and gradual absorption of the high-density slab into the mantle resulted in isostatic disequilibrium (Hay, 1976). Some writers (Lipman and others, 1971, fig. 3, p. 824) have suggested that two descending slabs, the easternmost a broken remnant, underlie the Americas plate. Ostensibly, the imbalance related to melting of the oceanic plate led successively to 1) regional uplift, 2) extensive volcanic activity, and 3) Basin-and-Range rifting. Major faulting occurred during early to middle Miocene time, but the deforming forces may still be active at places along the southern Rio Grande rift system in Trans-Pecos Texas near the Texas–New Mexico–Chihuahua border (Muehlberger and others, 1978, p. 337).

Barker (1977, p. 1421) has drawn an analogy between the northern Trans-Pecos magmatic province and the Kenya rift system of East Africa. He pointed out the "similarities in tectonic style, extent and duration of magmatism, and igneous rock compositions" and suggested that deformation in the provinces probably resulted from the formation of diapiric welts in the upper mantle. In con-

trast to the proposed arc-trench system, Barker stated that the two intracontinental areas may be similar in their "independence from a subduction zone." He noted that

> Intracontinental igneous rock provinces do tend to associate with extensional faulting, but the fractures may be an effect of magmatism rather than a cause. Perhaps doming, magmatism, and faulting are all symptoms of mantle diapirism, as suggested by Koide and Bhattacharji (1975).

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