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SMALL-SCALE STRUCTURES IN THE GUADALUPE MOUNTAINS REGION: IMPLICATION FOR LARAMIDE STRESS TRENDS IN THE PERMIAN BASIN

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Abstract Numerous small-scale structures exist in the Guadalupe Mountains region that can be interpreted as Laramide in age. These structures, observed in the Bell Canyon Formation, include tectonic stylolites and associated veins, slickensided thrust and strike-slip faults, and local folding. Within the Guadalupe Mountains, northeast-southwest compression is identified by tectonic stylolite teeth and thrust fault slickensides in Pine Spring Canyon at N28°E and N31°E, respectively. Northward in the McKittrick Canyon region, tectonic stylolite teeth change in trend to N38°E. Eastward in the Delaware Basin a further change in stress field trend is identified from slickensides trending N42°E on a thrust fault. This evidence for northeast-southwest compression is consistent with the trend of Laramide compression found elsewhere in Trans-Pecos Texas.

INTRODUCTION

Research has been conducted within the Guadalupe Mountains region since the first such undertakings by Lieutenant F. T. Bryan in the summer of 1849 (Bryan, 1850). Because of numerous investigations since then, the Guadalupe Mountains are probably one of the most thoroughly studied plots of ground in the world. Though Permian stratigraphy in the Guadalupe Mountains region has been well studied, knowledge of structural styles and tectonic deformation in this area is sparsely documented. Laramide deformation has dramatically influenced much of the Trans-Pecos south of the Guadalupe Mountains, but most geologists believe that this area was generally unscathed by Laramide tectonism. The purpose of this paper is to introduce recent field evidence suggesting Laramide deformation within the Guadalupe Mountains region.

PREVIOUS STUDIES

Previous structural studies in the Guadalupe Mountains region are few, and little direct evidence for Laramide deformation has been presented. King (1948) suggested probable Laramide deformation in the Guadalupe Mountains because of their proximity to Laramide structures in Trans-Pecos Texas, but that tectonic disturbances were small in magnitude because effects due to Laramide compression were not clearly evident.

Hayes (1964) described the Huapache monocline (Fig. 1) as a southwest-dipping reverse or thrust fault originating in at least Pennsylvanian time. Hayes suspected Tertiary movement because the monocline affects rocks of late Guadalupe age, but did not state when in the Tertiary this movement occurred. Hayes (1964) also suggested that broad epeirogenic uplift and northeast tilting of this entire region began during Late Cretaceous or very early Tertiary time. He interpreted major northeast-flowing streams such as Black River, those in Last Chance and Dark Canyons, and Rocky Arroyo that display dendritic drainage patterns and meanders (Fig. 2) as being inherited from ancestral drainage systems established after this uplift. King (1948) had previously observed this distinctive meandering of certain streams and interpreted them as consequent streams flowing east, north and northwest from the crest of a broad arch located near the present summits of the southern Guadalupe Mountains.

Anderson and Kirkland (1970, 1988) gave a detailed analysis of microfolding within the Castile Formation along U.S. 62/180 at a large roadcut near the Texas—New Mexico state line. They suggested that layer-parallel compression was responsible for microfold formation, and that this compression was probably tectonic in origin. Anderson and Kirkland (1988) speculated an early Cenozoic age for this deformation.

Kelley and Thompson (1964), Thompson (1966) and Kelley (1971) suggested that various structures in the Sacramento Mountains region are of early Tertiary age. Thompson (1966) interpreted the Sierra Blanca Basin and the Mescalero arch, which borders this basin, as late Laramide features. Kelley (1971) suggested that the Dunken uplift (Fig. 1) may be Laramide but was unclear as to whether the long, northeast-trending Serrano, Border, Six Mile, and Y-0 faults (Fig. I) that border the Dunken uplift displayed Laramide movement. Yuras (1991) described the folds of the Dunken uplift and Tinnie fold belt as exhibiting near-vertical axial planes, but with some folds displaying westward vergence and westward asymmetry. Yuras suggested westward tectonic transport during late Laramide time (Eocene?) as the responsible agent for these fold trends.

TECTONIC STYLOLITES

Most of my field work within the southern Guadalupe Mountains has focused on identifying tectonic stylolites for determining effects of horizontal compression. Tectonic stylolites are pressure solution surfaces identical to bedding plane stylolites except that tectonic stylolites cut across bedding. The stylolites observed in this study are three-dimensional surfaces with a tooth-in-socket structure. Each "side" of the solution surface has cone-shaped projections that fit into a corresponding socket on the other half of the surface, producing a perfect interlocking system. The stylolite teeth measured in this study range from 1 to 15 mm in amplitude. Tectonic stylolites can be thought of as compression cracks (anticrack of Fletcher and Pollard, 1981) and represent the antithesis of tensile cracks. The same mechanical models used to quantitatively model tensile cracks can be used to model compression cracks, with only a change in the direction of loading (Fletcher and Pollard, 1981).

Rigby (1953) was apparently the first to identify tectonic stylolites in the Guadalupe Mountains (Pine Spring, McKittrick and Big Canyons), but their importance with respect to regional tectonic forces was seemingly not understood at that time. Stylolite teeth point in a direction parallel with the applied pressure direction (Blake and Roy, 1949; Fletcher and Pollard, 1981; and many others) and also indicate the direction of shortening across the stylolite surface (Bayly, 1985). Thus the tooth orientation corresponds to the principal stress orientation responsible for solution surface formation. To date my own work has resampled two of Rigby's original sites and identified a third new location.

Pine Spring Canyon

The greatest number (101) of tectonic stylolites recorded were found in Pine Spring Canyon (Fig. 2) within the Hegler Limestone (King, 1948) of the Bell Canyon Formation (Fig. 3). Most of these stylolites were identified at a place called the "pothole" (Rigby, 1953, p. 265) along the canyon floor immediately upstream from a fall developed in the Hegler called the "Roman Stairs" (Rigby, 1953, p. 265). A few tectonic stylolites were also found immediately below and above this location. The limestone dips 16° or less, probably a combination of both tectonic deformation due to regional uplift and primary structural features such as bed thickness variations. The stylolite seams form

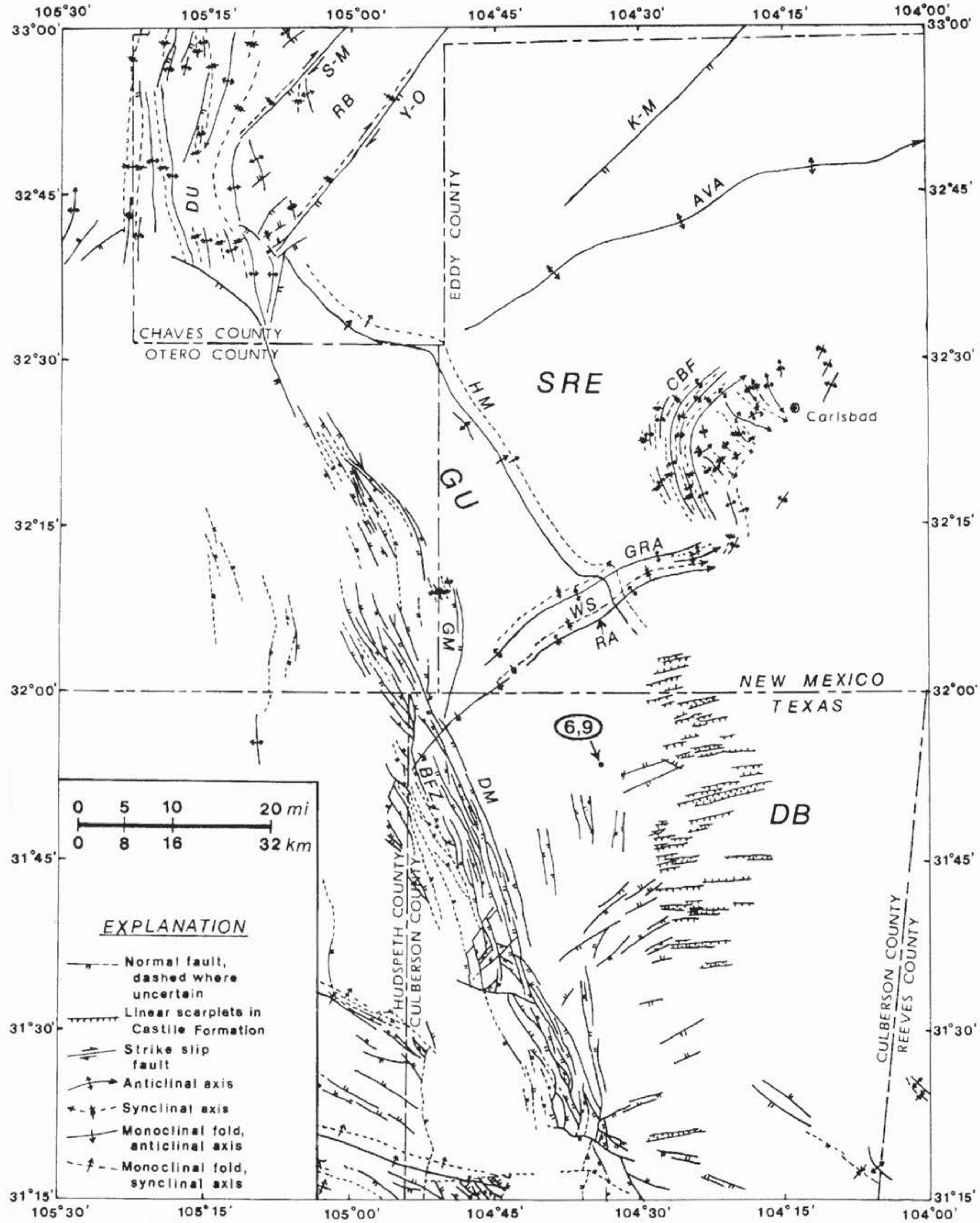

FIGURE 1. Tectonic map of the Guadalupe and Delaware Mountains region of Texas and New Mexico. AVA—Artesia Vacuum arch; BFZ—Border fault zone; CBF—Carlsbad folds; DB—Delaware Basin; DM—Delaware Mountains; DU—Dunken uplift; GM—Guadalupe Mountains; GRA—Guadalupe Ridge anticline; GU—Guadalupe uplift; HM—Huapache monocline; K-M—K-M fault; RA—Reef anticline; RB—Roswell block; S-M—Six-Mile buckle; SRE—Seven Rivers embayment; WS-Walnut syncline; Y-O—Y-O buckle; 6—slickensided thrust in Lamar on Highway 1108; 9—calcite veins in Lamar on Highway 1108. Adapted from Hayes (1964) and Kelley (1971).

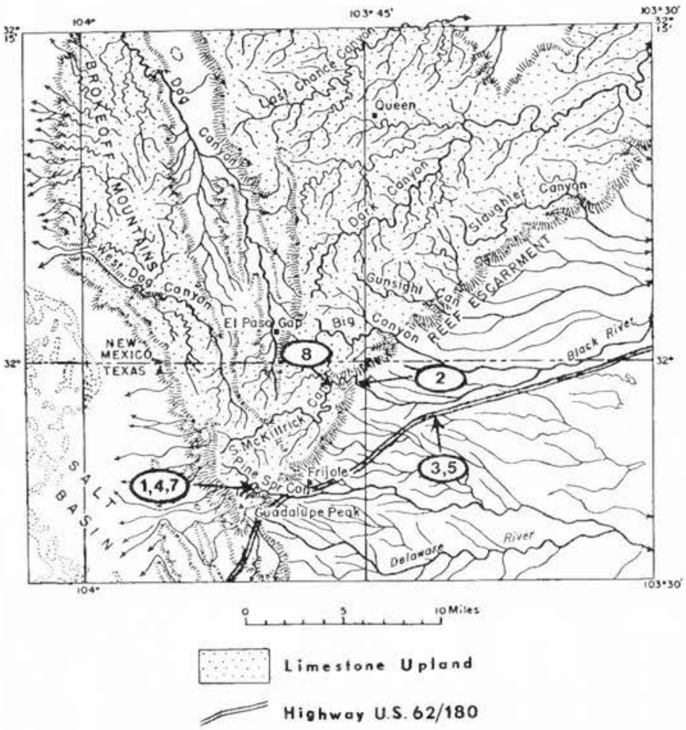

FIGURE 2. Map of the Guadalupe Mountains showing stream patterns and their relation to the limestone uplands. 1—tectonic stylolites in Hegler Limestone of Pine Spring Canyon; 2—tectonic stylolites in limestone outcrops of McKittrick Canyon; 3—tectonic stylolites in Lamar Limestone of roadcut, U.S. 62/180; 4—slickensided thrust fault in Hegler Limestone of Pine Spring Canyon; 5—thrust fault in Lamar Limestone of roadcut, U.S. 62/180; 7—calcite veins in Hegler Limestone of Pine Spring Canyon; 8—slickensides strike-slip faults in Hegler Limestone of McKittrick Canyon. Adapted from King (1948).

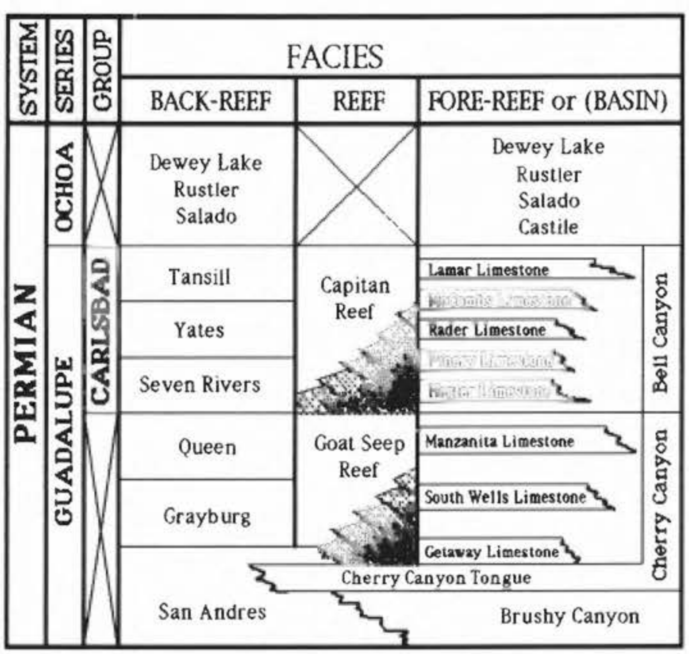

FIGURE 3. Stratigraphic column displaying the position of the Bell Canyon Formation with respect to correlative reef and back-reef facies. Rock units above and below the Bell Canyon are also displayed.

angles of 75° to 90° with bedding in the few places where the complete solution surface was visible. In most cases only the trend of the solution surface and the teeth could be measured. The largest amplitude teeth (15 mm) were observed in Pine Spring Canyon.

Rigby (1953) suggested that these stylolites developed along previous northwest-trending joints; however, reanalysis of the stylolites suggest their formation independent of joints. The stylolites often form left- or right-stepping en echelon zones (Fig. 4). Where individual stylolites overlap near their ends there is a tendency for these surfaces to bend toward each other. This stylolite overlap and subsequent change in trend is common when cracks (tensile or compression) form and propagate laterally toward each other (Kranz, 1979).

Another reason for suggesting stylolite formation independent of joints is the orientation of tooth trend with the overall trend of the stylolite surface. In cases where previous joint formation is suspected, the tooth trend often makes an angle of 75° to 50° or less to the solution surface (Ramsay and Huber, 1987; Erdlac, 1988) and is evidence that the stylolite has formed along a previous joint surface. However, the teeth trends measured in Pine Spring Canyon have angles between 80° to 90° with the solution surface, providing additional evidence for independent formation of these stylolite surfaces.

Calcite veins are often associated with tectonic stylolite formation (Fletcher and Pollard, 1981). In Pine Spring Canyon calcite veins were found nearly perpendicular to the trend of stylolites, suggestive of contemporaneous formation of both features under identical loading conditions (Fig. 5). By their nature, stylolites represent surfaces where calcite has been removed by going into solution, whereas the local formation of tensile cracks in the principal compressive loading direction represent sinks where this dissolved calcite is precipitated. This is especially true at this location, where some of the calcite veins die out away from stylolite surfaces (Fig. 5). The association of stylolites and calcite veins in this way defines pure shear with simultaneous shortening in one direction and elongation at right angles to the shortening direction.

Rigby (1953) discussed the trend of stylolite surfaces, but of far greater importance is the trend of stylolite teeth because the teeth indicate the principal stress loading direction that existed locally at the time of stylolite formation. A histogram plotting tooth trend versus tooth frequency (Fig. 6) shows that all but one tooth measurements trend in a northeast direction. The stylolite tooth frequency shows a normal distribution slightly skewed to the east. The mean of these teeth trends strongly suggests a local trend of about N28°E for compressive stress (Table 1). This orientation of stress is consistent with a northeast trend of Laramide age compression. The single stylolite surface with northwest-trending teeth may or may not have formed contemporaneously with the northeast-trending stylolite teeth. Several interpretations are possible but are beyond the scope of this paper.

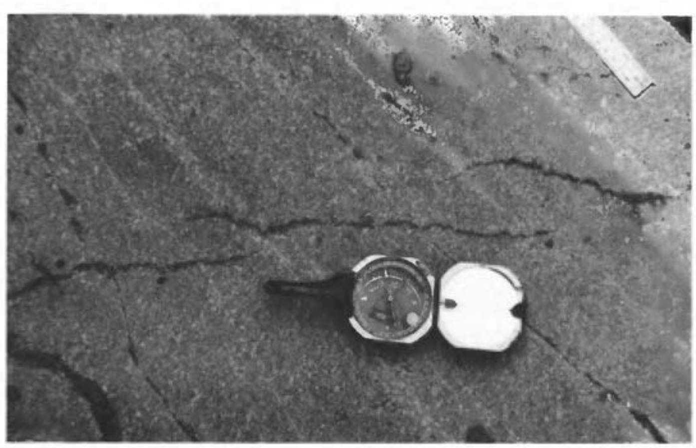

FIGURE 4. Tectonic stylolites in the Hegler Limestone near the "Roman Stairs" in Pine Spring Canyon. Note the en echelon nature of these stylolites and the curving of the stylolites toward each other where they overlap. Brunton is oriented northwest.

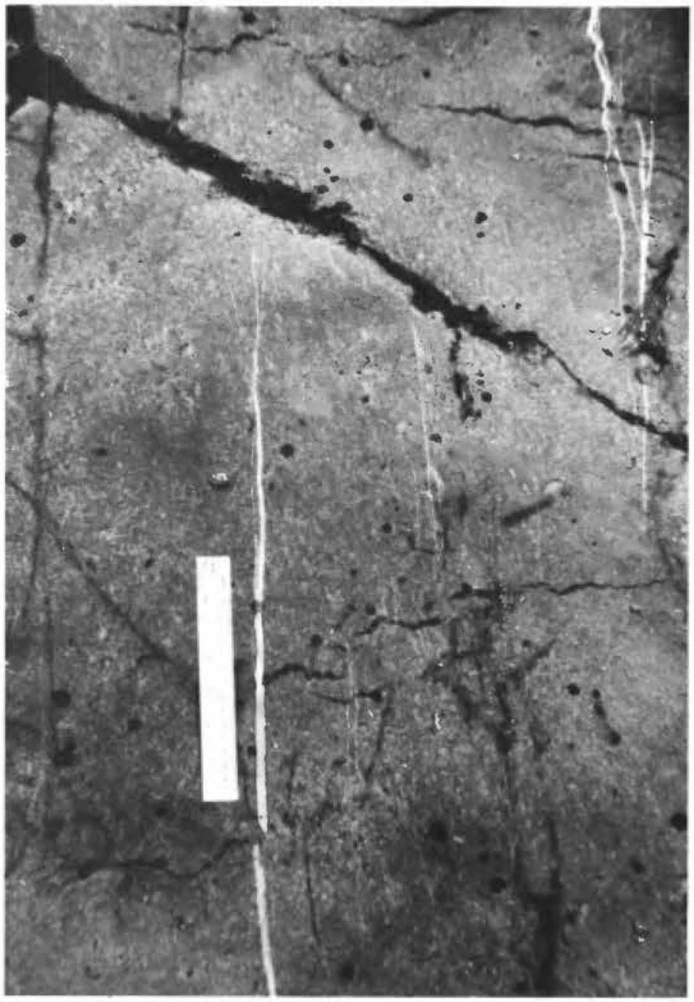

FIGURE 5. These calcite veins trend in the same direction as the teeth of the tectonic stylolite surfaces that the veins cross. The veins narrow and die out away from the stylolite surfaces, suggesting that both formed contemporaneously. The lower left corner of the photograph shows a part of a calcite vein offset across a stylolite due to dissolution of the vein along the stylolite surface. By comparing the tooth trend (N12°E), the vein trend at the stylolite surface (N25°E), and the amount of right-stepping displacement of the vein across the stylolite (14 mm), the amount of dissolved rock was estimated at 6 cm.

TABLE 1. Statistical analysis of tectonic stylolite teeth measured in the Guadalupe Mountains region. These statistics were determined from the data displayed in the text (Figs. 6–8).

Location	Mean	Variance	Standard Deviation
Pine Spring Canyon	N28.24°E	110.47	10.51°
McKittrick Canyon	N38.08°E	235.84	15.36°
Lamar Ls. Road Cut	N37.83°E	115.56	10.75°

McKittrick Canyon

A total of 33 tectonic stylolites were measured in McKittrick Canyon, within outcrops of the McCombs, Rader and Hegler limestones of the Bell Canyon Formation, and in the Capitan Limestone (Fig. 3). According to King (1948, pl. 3) the McCombs Limestone crops out in the canyon floor near the entrance to McKittrick Canyon (Fig. 2), where the present McKittrick Canyon trail crosses the stream bed. Numerous stylolites were found at this location with calcite veins nearly perpendicular to stylolite surfaces. Although most of the stylolite teeth trend northeast, two measurements were made on solution surfaces with teeth trending northwest. This was the most prolific location for tectonic stylolites in the canyon, with 16 solution surfaces being identified.

Other outcrops in the canyon where tectonic stylolites were found are 300 m upstream in McKittrick Canyon from the McCombs Limestone site where the Rader Limestone crops out in the canyon floor; in the Capitan Limestone 700 m upstream from the Rader Limestone site; in the area near the Pratt Lodge where the Hegler Limestone crops out (King, 1948, pl. 3); and south of the "Grotto" (trail location) in the Hegler Limestone where the stream forms a sharp S-shaped valley west of hill 6933. *(Note:* Field mapping in McKittrick Canyon should not be attempted off-trail unless the Park Service has been informed in advance.) Rigby (1953, p. 267) also identified tectonic stylolites in the south wall of McKittrick Canyon "about a hundred yards below the junction of North and South McKittrick Canyons, near the valley floor." Although tectonic stylolites were observed along this south canyon wall, the vertical nature of the wall made it impossible to accurately measure the trend of the stylolite surfaces or the teeth. The exact location described by Rigby was not located and may now be covered.

All stylolite teeth measured in McKittrick Canyon are plotted in a histogram (Fig. 7) to compare their frequency distribution with stylolite teeth measured in Pine Spring Canyon. A normal distribution also describes the stylolite teeth in McKittrick Canyon, but the mean northeast trend of data is greater at about N38°E (Table 1) and the normal distribution is broader in its range as signified by the larger standard

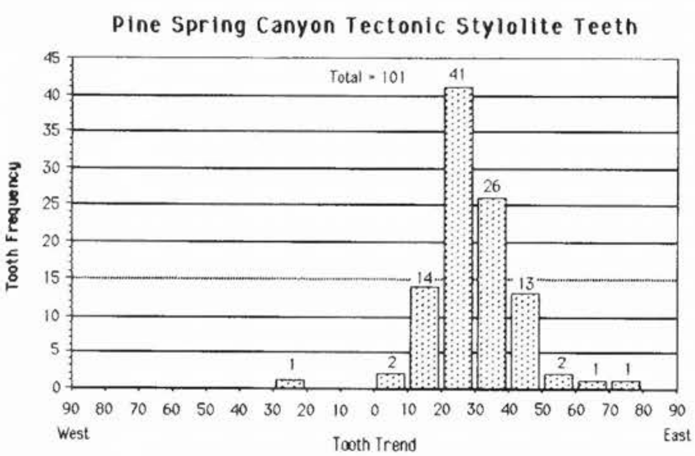

FIGURE 6. Histogram of tectonic stylolite teeth in Pine Spring Canyon, displaying tooth trend versus tooth frequency. A mean of N28°E is calculated for this distribution.

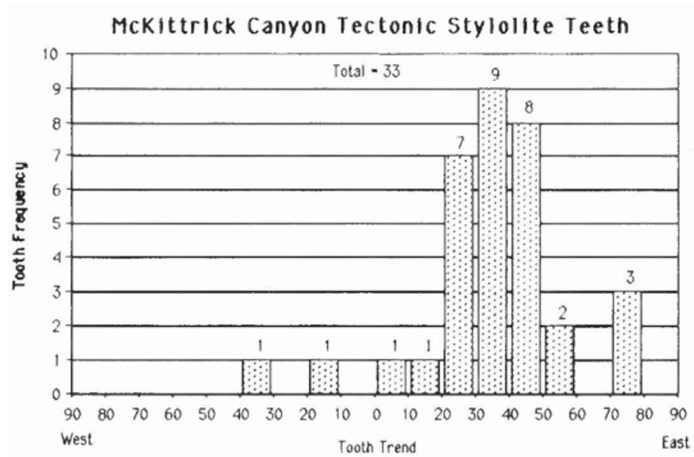

FIGURE 7. Histogram of tectonic stylolite teeth in McKittrick Canyon, displaying tooth trend versus tooth frequency. A mean of N38°E is calculated for this distribution.

deviation in McKittrick Canyon compared to Pine Spring Canyon. This larger standard deviation may result from fewer stylolites measured in McKittrick Canyon. The mean trend for stylolite teeth is again consistent with a northeast-directed Laramide compressive event.

Lamar Limestone roadcut

A third site of tectonic stylolites, not identified by Rigby, is located about 1.5 km northeast of the entrance to McKittrick Canyon along U.S. 62/180 (Fig. 2). This outcrop exposes the thin-bedded, black Lamar Limestone of the Bell Canyon Formation. Fifteen stylolites were identified and measured, although many more exist that could not be properly measured. Stylolite teeth are on the order of 1 mm or less in amplitude and thus are small and difficult to find.

A histogram of these teeth measurements (Fig. 8) displays a normal distribution with a standard deviation similar to that found in Pine Spring Canyon (Table **I**). The mean tooth trend, however, is about N38°E, and thus is statistically identical to the mean trend of teeth in McKittrick Canyon. The change in mean tooth trend from Pine Spring Canyon to the area covered in McKittrick Canyon and the Lamar roadcut is interpreted as local variations in the regional stress field responsible for stylolite formation. Stress field variations of this type are probably common and have been observed elsewhere in the Big Bend region of Texas (Erdlac, 1988, 1990). I contend that the majority of tectonic stylolites observed at these three locations are the result of regional northeast-oriented Laramide compression.

THRUST FAULTS

Much of the faulting presented by King (1948) is related to late Tertiary Basin and Range extension. However there are faults in the Guadalupe Mountains region not easily accounted for by this deformation period. My own field work in the southern Guadalupe Mountains has identified thrust faults not previously mapped by King (1948). These faults are small in extent and magnitude of offset, but still important in determining the structural styles expressed in this region.

Pine Spring Canyon

In the Pine Spring Canyon arroyo south of Devils Hall and north of the "Roman Stairs" (Rigby, 1953, p. 265) a small thrust fault was found in the Hegler Limestone (Fig. 9). This fault is oriented at N52°W, 28°SW with slickensides trending N3 I°E, nearly perpendicular to the strike of the fault plane. This thrust requires northeast-southwest compression to account for the slickenside trend. The amount of offset across this fault is uncertain, but the lack of any breccia development precludes any large offset. I would estimate this offset at 1 m or less.

Lamar Limestone roadcut

In the Lamar along U.S. 62/180 (Fig. 2) a thrust fault was observed in conjunction with Lamar folding (Fig. 10). These limestone beds

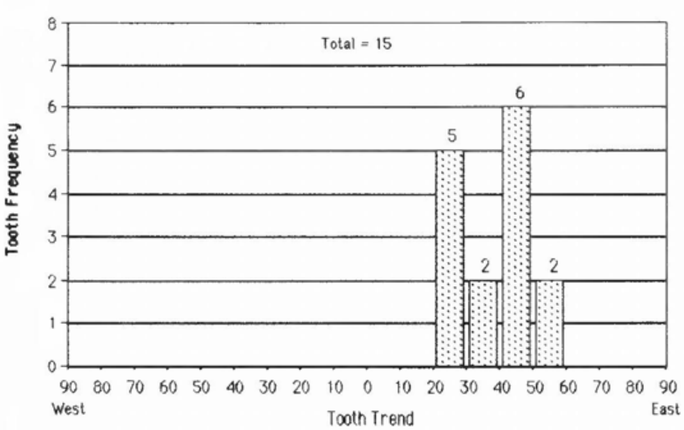

FIGURE 8. Histogram of tectonic stylolite teeth in Lamar Limestone roadcut on U.S. 62/180, displaying tooth trend versus tooth frequency. A mean of about N38°E is suggested for this distribution.

FIGURE 9. Small thrust fault in the Hegler Limestone of the Bell Canyon Formation. Photograph is in the Pine Spring Canyon floor upstream from the "Roman Stairs." Fault is oriented N52°W, 28°SW, with slickensides trending N31°E. The slickenside trend is toward the viewer and can be seen on the calcite surfaces above and below the Brunton compass.

display minor folding throughout the formation, with dips varying from as little as 5°SE to nearly 30°NE, with strike ranging from N57°E to N57°W, respectively. The thrust fault, at the western end of the roadcut, is accompanied by folding of the Lamar to assist in contraction. No well-defined fault plane was measured, but the ruptured beds and associated folds indicate the location of the fault on the north and south sides of the road (Figs. 10A and 10B, respectively). The fault trends about N45°W, with an estimated dip of 45°NE. Although this thrust was previously interpreted as soft-sediment deformation (e.g., Harms and Pray, 1985), the trend of the thrust and fold axis, and fault dip, are not consistent with soft-sediment deformation from gravity sliding or slumping. Joints at this outcrop are longitudinal and fan outward from the fold axis, suggesting their formation during brittle deformation (Ramsay and Huber, 1987). In addition, the recognition of tectonic stylolites at this outcrop demonstrates that tectonic compression oriented northeast-southwest has deformed the Lamar at this outcrop. The amount of offset along this fault is estimated to be 1 m or less.

Delaware Basin thrust fault

In the Delaware Basin along Highway 1108 (Fig. 1) the thin-bedded, black Lamar Limestone crops out as a low ridge, locally oriented N60°E, 3°NW. Where the road crosses this ridge is a small thrust fault oriented N39°W, 22°NE, with slickensides trending N42°E. Several small calcite veins were oriented at N48°E, 87°NW. The trends of the slickensides

A

B

FIGURE 10. Thrust/fold combination located along U.S. 62/180 at an outcrop of the Lamar Limestone in the Bell Canyon Formation. **A.** North side of roadcut. Fault strikes roughly N45°W with fault surface dipping northeast. Note camera lens cap in upper left quarter of photograph for scale. This fault projects across the road to the south side of roadcut. **B.** South side of roadcut. This photograph is a reversed image of the actual roadcut in order to show the relation of the fault and fold on both sides of the road. Note camera lens cap to the left of center for scale.

and calcite veins suggest formation due to northeast-southwest compression.

STRIKE-SLIP FAULTS

In addition to thrust faults, two localities in Pine Spring and McKittrick Canyons display strike-slip faults.

Pine Spring Canyon

In Pine Spring Canyon, at the south end of the narrow Devils Hall (Fig. 2), a series of en echelon calcite veins trends N82°W, with individual calcite veins trending N53°E (Fig. 11). The orientation of the calcite veins requires the maximum principal compressive stress to be northeast-southwest, resulting in sinistral shear across the zone. This stress trend is consistent with regional trends for Laramide compression. The west wall of the canyon displays little to no affect of the shear, but the east canyon wall shows an increase in fracture frequency where the shear zone projects into the wall.

McKittrick Canyon

In McKittrick Canyon strike-slip faults in the Hegler Limestone (near the canyon floor, east of hill 7170 and south of the Pratt Lodge) are oriented at N64°E, 77°NW and at N12°E, 73°SW (Fig. 2). Both fault surfaces are undulatory with varying dip. The N64°E-trending fault displays a single set of slickensides raking 18°NE, whereas the latter fault displays two sets of slickensides raking 13°NE and 5°NE (Fig. 12). An acute angle of 52° between the strike of these two faults suggests that they may be conjugate, with the possible compression direction being the bisector of this angle at N36°E. The near horizontal rake of these slickensides requires a strong component of strike-slip movement on these faults.

SIGNIFICANCE OF STRUCTURES FOR LARAMIDE DEFORMATION

Many different types of structural features are identifiable in the Guadalupe Mountains region. Some of these structures, such as slickensided thrust faults and tectonic stylolites, require a northeast-southwest compressive stress for their origin, consistent with a Laramide origin. A summary of various structures and possible trends of principal compressive stress are listed in Table 2. The orientation for suspected Laramide compression associated with these structures ranges from north-northeast to northeast. The stress trends associated with tectonic stylolites and slickensided thrust faults of all these structures are most consistent with Laramide compression.

Because these structures are within the Bell Canyon Formation, the only age constraint on their development is that they are post-Guadalupian. The interpretation of Laramide age for these structures is based on the contention that a post-Guadalupian northeast-southwest compression was most likely to result from Laramide tectonism. This compression direction is consistent with trends of similar structures in

FIGURE 11. Calcite-filled fractures in the Hegler Limestone at the south end of Devils Hall. The overall trend of the fractures is N82°W, away from the viewer of this photograph. The individual en echelon calcite veins trend N53°E toward the lower right corner of the photograph. These calcite veins suggest dextral simple shear with the principal compressive stress oriented northeast. Brunton is oriented northwest.

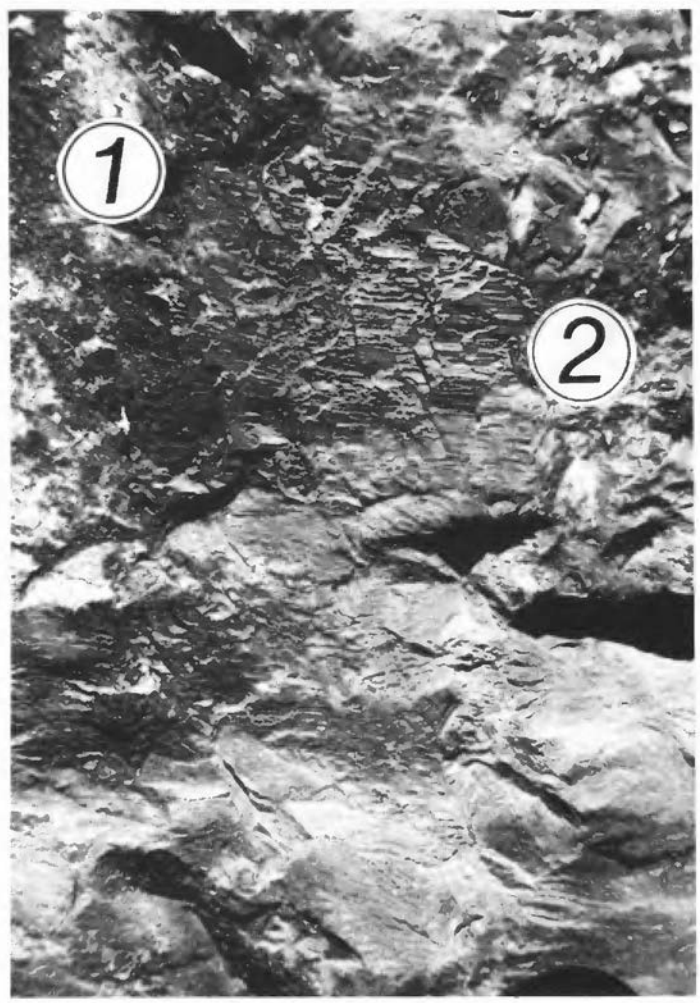

FIGURE 12. Slickensided fault surface in the Hegler Limestone south of the Pratt Lodge in McKittrick Canyon. This fault surface is oriented at N12°E, 73°SW and has two sets of slickensides raking 13°NE and 5°NE. These slickensides are labeled 1 and 2, respectively.

TABLE 2. List of the structures discussed in text, including the inferred trend of the principal compression stress σ_1. Each of the structure types is numbered for correlation with their location (Figs. 1 and 2).

Loc. Num.	Structure Type	Location	Trend	Inferred σ_1
1	stylolite teeth	Hegler; Pine Spring Canyon	N28.24°E mean	N28°E
2	stylolite teeth	McKittrick Canyon	N38.08°E mean	N38°E
3	stylolite teeth	Lamar; U.S. 62/180	N37.83°E mean	N38°E
4	slickensides (thrust)	Hegler; Pine Spring Canyon	N31°E	N31°E
5	thrust	Lamar; U.S. 62/180	~ N45°W	~N45°E ?
6	slickensides (thrust)	Lamar; Hwy. 1108	N42°E	N42°E
7	calcite veins	Hegler; Pine Spring Canyon	N53°E	N53°E
8	conjugate shears (slickensides)	Hegler; McKittrick Canyon	N36°E bisector	N36°E
9	calcite veins	Lamar; Hwy. 1108	N48°E	N48°E

Cretaceous limestones of the Big Bend region, which are interpreted as Laramide age (DeCamp, 1981; Moustafa, 1988; Erdlac, 1990).

This study is not the final analysis of Laramide tectonism in this region but only a beginning. Further detailed structural investigations are needed to determine the extent of Laramide deformation in the Guadalupe Mountains region and to explore the regional extent of Laramide compression.

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