Structural zones transecting the southern Rio Grande Rift - Preliminary observations

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STRUCTURAL ZONES TRANSECTING THE SOUTHERN RIO GRANDE RIFT— PRELIMINARY OBSERVATIONS

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Tectonic theorizing is a heady wine which, especially if it is spiked with some well-chosen numbers, tends to be habit-forming; the addict prefers to have both his feet off the ground and never permits discordant facts to limit the sweep of his generalizations (Mackin, 1965).

INTRODUCTION

At least thirteen east-west trending zones that transect the Trans-Pecos portion of the Rio Grande rift between 29° and 31°30′ north latitude (fig. 1) have been loci, in whole or in part, for repeated disruption of varying types during the last 1500 m.y. Evidence for these pervasive weak zones includes fold and fault patterns, aligned volcanic centers and intrusions, trends of evaporite diapirism and mineralization, gravity and magnetic anomalies, heat flow patterns and thermal springs, and physiography. They have responded differently to the varying stress regimes applied across the region through time, and it is proposed here that since late Miocene time at least one of the zones may have served as an intracontinental transform crossing the Rio Grande rift.

As Muehlberger discusses the tectonic history of the region elsewhere in this guidebook, I will review only the principal deformational periods and styles, emphasizing effects observable along the east-west structural zones designated in Figure 2.

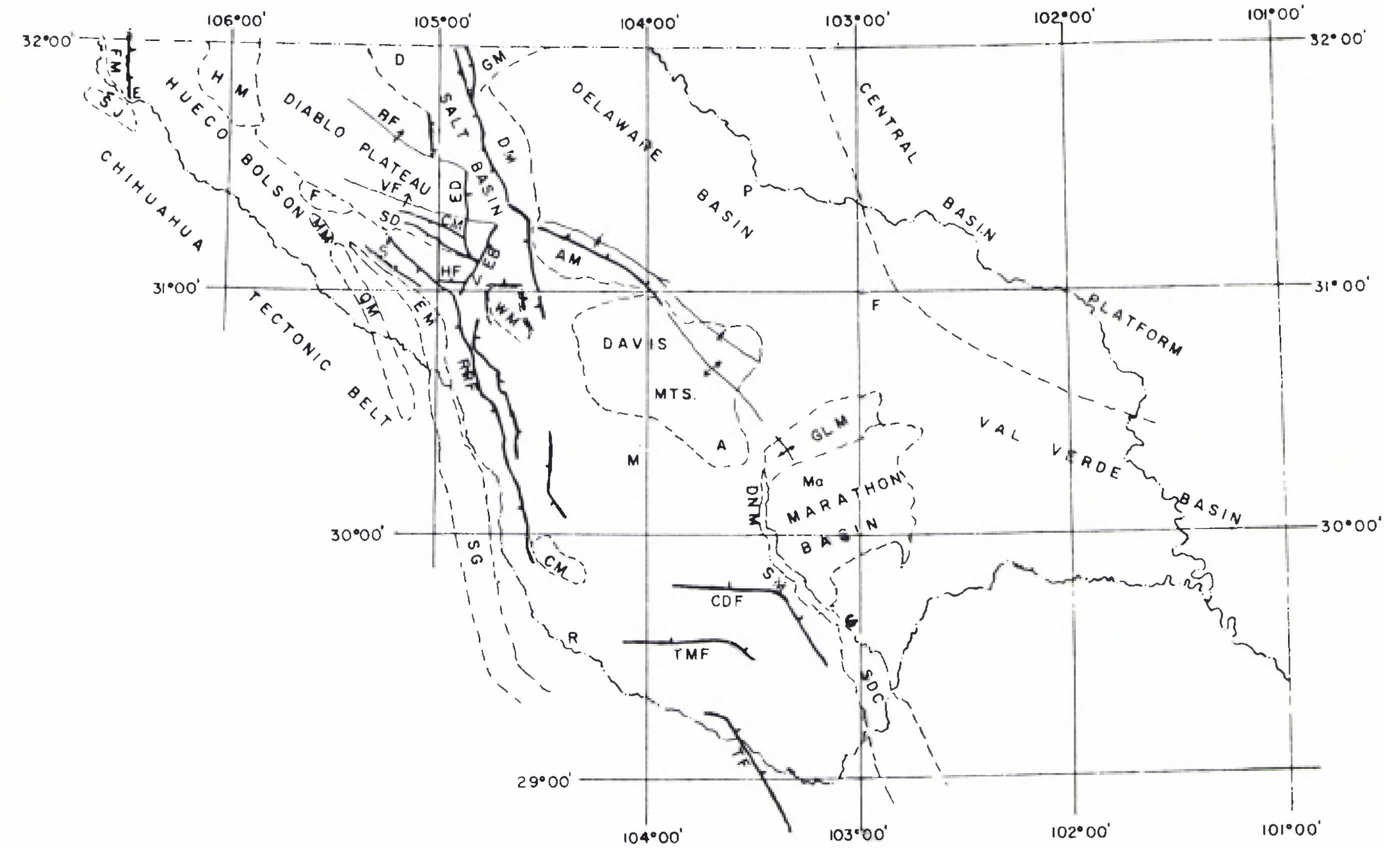

Figure 1. Principal physiographic and tectonic features of Trans-Pecos Texas. Pecos River forms eastern boundary and the Rio Grande the western and southern boundaries of the area. Adjacent parts of Mexico, New Mexico and West Texas are also included. Towns: E-El Paso, S-Sierra Blanca, V-Van Horn, D-Dell City, M-Marfa, A-Alpine, Ma-Marathon, P-Pecos, R-Presidio, F-Ft. Stockton. Mountain ranges: FM-Franklin, HM-Hueco, F-Finlay, MM-Malone, QM-Quitman, EM-Eagle, WM-Wylie, AM-Apache, DM-Delaware, GM-Guadalupe, CM-Chinati, GLM-Glass, DNM-Del Norte, SM-Santiago, SDC-Sierra del Carmen, SG-Sierra Grande, SJ-Sierra Juarez. Flexures (monoclines): BF-Babb, VF-Victorio, G-Persimmon Gap. Faults, ticks on downthrown side: ED-East Diablo, CM-Cox Mountain, SD-South Diablo, HF-Hillside, EB-East Baylor, RRF-Rim Rock, CDF-Chalk Draw, TMF-Tascotal Mesa, TF-Terlingua. Modified from Wiley, 1970 and Muehlberger, this guidebook.

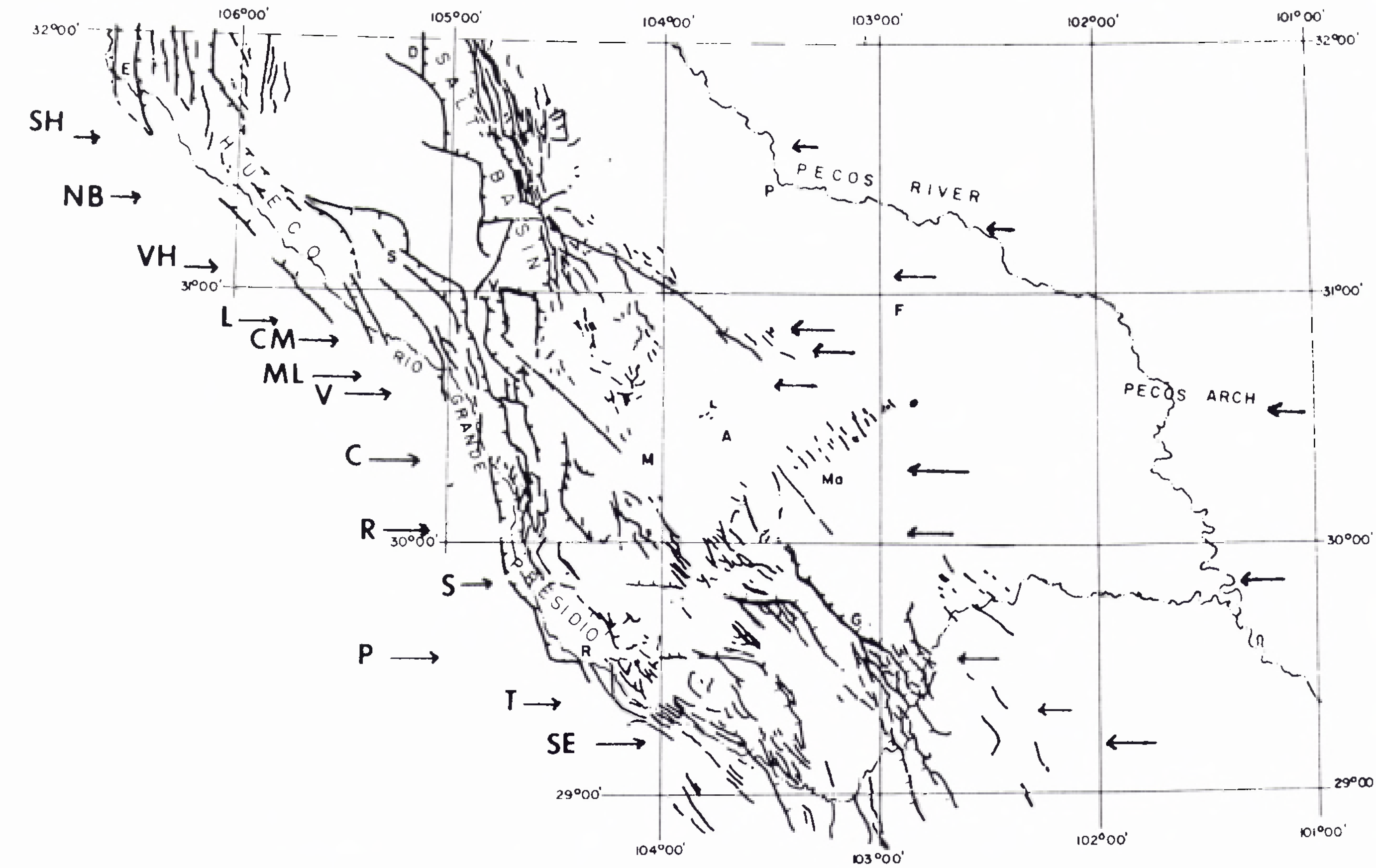

Figure 2. Major east-west structural zones described in this paper and known late Cenozoic faults. Tick marks on principal graben-bounding faults. Arrow between Chispa Mountain and Mount Locke zones points to the Valentine fault, the fault interpreted to have moved during August 16, 1931, Valentine earthquake (Dumas and others, 1980). Zones: SH–South Hueco, NB–North Baylor, VH–Van Horn, L–Lobo, CM–Chispa Mountain, ML–Mount Locke, V–Valentine, C–Candelaria, R–Ruidosa, S–Shafter, P–Presidio, T–Terlingua, SE–Santa Elena. Arrows mark approximate end points for Trans-Pecos portions of zones.

DEFORMATIONAL PERIODS

1,500 m.y.b.p. If the hypothesis of Sears and Price (1978; their fig. 1) is correct, that the North American and Siberian cratons rifted apart approximately 1,500 m.y. ago, then that event may be recorded in this area by deposition of the Precambrian Carrizo Mountain Group, and the Allamoore, Hazel, Castner and Llanoria Formations. Along the cratonic margins of the southwestern United States, middle Proterozoic platform sediments with arkosic and quartzose sandstone and conglomerates, stromatolitic dolomites and shales overlie deeply weathered crystalline basement rocks. The section in the Trans-Pecos region also includes volcanic rocks, and in the Franklin Mountains section, unmetamorphosed rhyolite is exposed. From this association of lithologies and the locations of aulacogens in Figure 2 of Sears and Price (1978), one could propose that the Precambrian sedimentary units of this area, too, were deposited in an aulacogen that extended slightly south of east, beginning at the southwestern corner of the post-rifting North American craton.

1,000 m.y.b.p. The Carrizo Mountains and adjacent areas experienced igneous activity and thrust-faulting at about 1,000 m.y.b.p. Basalts, volcanic conglomerates and siliceous units are present in the Allamoore Formation; thrusting was from south to north. Farther east at this time, the Llano orogeny (Muehlberger and others, 1967) was taking place; the projection of the South Hueco zone of this paper marks the approximate northern boundary of the Llano Uplift. The Llano granitic terrane (1,100 m.y.b.p. and younger) constitutes crystalline basement in the Pecos Arch and has also been described and radiometrically dated in well samples from the Val Verde Basin floor (Nicholas and Rozendal, 1975). Following the thrust-faulting in the Van Horn region, the Van Horn Sandstone was deposited (ca. 850 m.y.b.p.) in an east-west trough lying north of the deformed zone. The sediments were derived from granite and rhyolite porphyry exposed farther north and deposited as fans and fan deltas in the trough (McGowen and Groat, 1971).

Post-Precambrian/Pre-Late Cambrian. Evidence for this episode includes uplift, tilting, block faulting and beveling of Van Horn Sandstone prior to deposition of the Bliss Sandstone (Late Cambrian to Early Ordovician). In the southern Franklin Mountains, a 500-m.y.-long unconformity separates the Bliss Sandstone and Riphean-aged granitic basement rocks. Isotopic dates in this range are recorded from volcanic and metasedimentary rocks in the Devils River Uplift block (Nicholas and Rozendal, 1975).

The fault boundary between the Val Verde Basin and Devils River Uplift (on the Shafter zone of this paper) also separates Llano-terrane basement material (1,100-1,000 m.y. old) flooring the basin from 500-m.y.-old material on the uplift.

Ordovician (Taconic?). Ellenburger (Cambrian–Ordovician) rocks are erosionally truncated in the Diablo Plateau area (Muehlberger, this guidebook), and there are unconformities both between the El Paso (Early Ordovician) and the Montoya (Late Ordovician) Groups and at the top of the Montoya in the Franklin Mountains (LeMone, 1969). Nicholas and Rozendal (1975) suggest possible Ordovician tectonism, based on radiometric age dates in the Devils River Uplift area.

Devonian (Acadian?). Metamorphosed granitic fragments in the Haymond Formation of the Marathon area yield isotopic dates indicating a Devonian age; the source area for the fragments is thought to be south of the Devils River Uplift (Denison and others, 1971). An episode of cooling following structural deformation in Devonian time is interpreted from potassium-argon dates on the Devils River block (Nicholas and Rozendal, 1975).

Late Paleozoic. In *Mississippian* time the Central Basin Platform of the Permian Basin began to be uplifted; the platform underwent episodic uplift throughout the late Paleozoic (Galley, 1959). The Midland Basin began forming in Late Mississippian time, evidenced by deposition of the Woodford and Barnett Shales.

Among the more visible products of *Pennsylvanian* tectonism is the Marathon fold belt, in which strata as young as Desmoinesian—the Gaptank Formation—were folded and thrust-faulted in response either to compression from southeast to northwest or to gravity sliding and crumpling off an emerging area to the southeast. (Sole markings at the base of the Marathon allochthonous block may include *Hecho en Mexico.*) Muehlberger (this guidebook) discusses the latter possibility in somewhat greater detail, as well as evidence for right-lateral wrenching across the region during the late Paleozoic.

Interpretation of gravity (fig. 3), sedimentologic and subsurface data (Woollard and others, 1969; Pearson, 1978; Nicholas and Rozendal, 1975; Flawn, 1959; Wall and others, 1961) by this author supports gravity transport in response to basement block movement. The observed features here, as well as farther north, may have formed by right-lateral wrenching; I would propose that convergent wrenching produced the upthrusts along the northern edge of Devils River Uplift that are shown by Nicholas and Rozendal (their fig. 23). Convergence may reflect local conditions or it may characterize late Paleozoic deformation along the Shafter zone, as thrusting also occurred along the Chalk Draw fault in Green Valley (Pearson, 1978). Potassium-argon dates from the Devils River Uplift area indicate a cooling episode following Ouachita–Marathon tectonism (Nicholas and Rozendal, 1975).

Features elsewhere in the area attributable to late Paleozoic wrenching probably include the Babb and Victorio Flexures (related to the South Hueco and North Baylor zones), north-side-down monoclines that formed in post-Early Pennsylvanian/pre-Hueco Limestone (Wolfcampian) time. Their orientation suggests extension where it would be expected within a simple shear couple, although the low angle of the faults relative to the bounding shears may indicate divergence. Both were reactivated in Leonardian time. If the Victorio Flexure continued southeastward, along the present trend of the Apache Mountains, there may have been a late Paleozoic monocline at that locale; it would have provided a shelf break where the later Leonardian and Guadalupian (now exposed in Apaches) reef facies could develop. The southern margin of the Sierra Diablo has a similar trend.

The exact time of deformation is still a matter of conjecture in some areas. There is evidence, though, for a distinct *Wolfcampian*

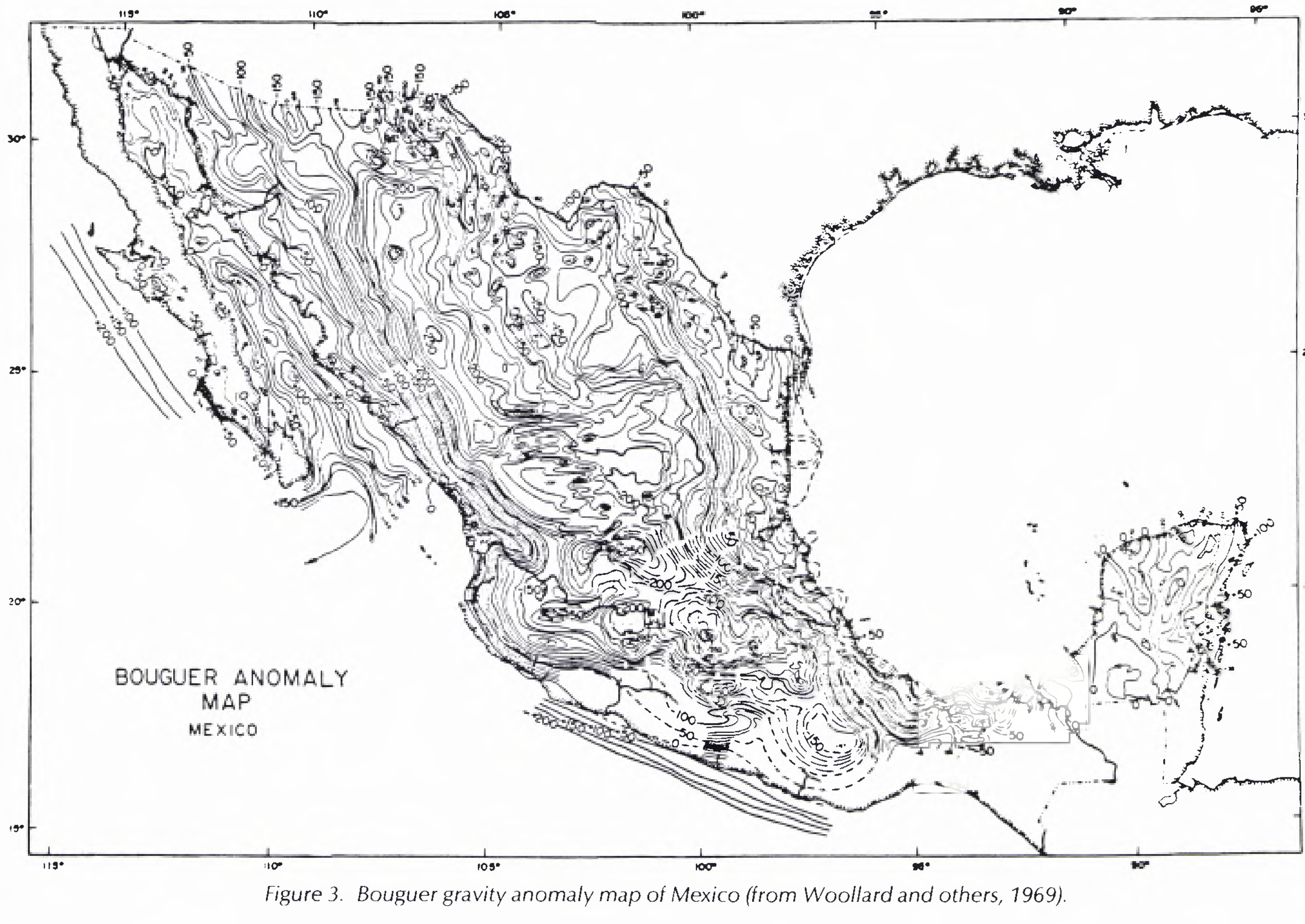

Figure 3. Bouguer gravity anomaly map of Mexico (from Woollard and others, 1969).

episode of convergent wrenching near the present Chalk Draw fault (Shafter zone, this paper) in Green Valley (Pearson, 1978). Wells on opposite sides of the fault, a zone of thrusting in Wolfcampian time, record absence of Permian strata south of the fault and presence of about 2,000 m of Permian north of the fault. The area north of the fault may have been part of a graben, as proposed by Pearson; the basin may also have been offset during right-lateral wrenching and differential uplift on the south. Sediments in the graben or basin contain green chert clasts sourced from the folded area to the south; Cretaceous strata unconformably overlie the Permian to the north and the Mississippian–Pennsylvanian Tesnus Formation to the south.

Permian deformation is recorded on the Central Basin Platform as another episode of uplift (Galley, 1959) and on the Devils River Uplift, where strontium-rubidium dates indicating Permian tectonism were interpreted to indicate cooling after a late pulse of Ouachita deformation (Nicholas and Rozendal, 1975); however, they could as easily represent a separate shearing episode.

Laramide. The dominant deformational style during this episode was left-lateral convergent wrenching. This tectonic fabric is best displayed in the Carta Valley fault zone (in Shafter zone of this paper), an area affected by at least three periods of deformation prior to the Laramide. Between the Presidio and Terlingua zones and the Terlingua and Santa Elena zones the convergent character of the wrenching is well expressed.

With convergent wrenching along shear zones, thrust-faulted segments may result, particularly if there is shale or salt in the stratigraphic section, as in the Chihuahua Tectonic Belt. The Chihuahua thrust front is not an unbroken line of uniform strike, and distances of thrust transport are not great. Thrust segments are separated by east-west faults coincident with several of the zones described in this paper, and evaporite diapirism is commonly associated with the tear faults (Gries and Haenggi, 1971, fig. 1). East-west evaporite diapiric areas can be seen along the Cuatralbo fault and in Sierra Lágrima north of La Bamba on the Candelaria zone, and in Cañon de Navarrete opposite Pinto Canyon of the Ruidosa zone. These features could easily have been formed during Laramide left-lateral convergent wrenching across the area, obviating the necessity for transmitting compressive stresses across the widest expanse of Mexico, in response to plate collision and subduction in the Gulf of California (Reaser and Underwood, this guidebook).

Thrust-faulting in the Santiago Mountains is of a different style (upthrusting) and direction of transport (westward). A possible reason for the comparatively simple structural array on the east side of the Sunken Block in the Big Bend may be the northward projection of a possible basement ridge through the area (see gravity map, fig. 3). The structural grain of this area is almost north-south, and the large continuous ranges south of the Santiagos (Sierra del Carmen, Sierra San Vicente) suggest basement involvement along a band very nearly coincident with the ridge expressed in the gravity data. During Laramide time the Marathon block was elevated and the Sierra del Carmen experienced an episode of uplift along that trend. The upthrusts in the Santiagos may have formed as the interpreted ridge was uplifted. They were probably not produced in response to shearing on bounding zones, as the direction of transport and orientations are inappropriate to either Laramide or Basin and Range wrenching. The Ruidosa, Shafter and Presidio zones do offset the Santiagos, however, and the Presidio zone marks the southern limit of thrust-faulting in that range.

Eocene–Oligocene. The dominant expression of this deformational period is extension, accompanied by widespread volcanism, by intrusive activity, and probably by renewed evaporite diapirism where salts were present, principally in the Chihuahua Tectonic Belt. Evidence for shear or vertical tectonics is lacking; extension along old weak zones may have occurred in response to regional upwarping over diapiric welts in the upper mantle (Barker, 1977) prior to faulting in the Rio Grande rift which began in Miocene time.

Intrusions and volcanic centers in the region fall along faults and fractures of several trends, to the extent that isotopic age dating is required to work out the igneous history of large parts of the area. Some, however, are related to major east-west cross-faults, similar to those described by Fairhead (1980) in the East African rift. The Eagle Mountains intrusion, for example, is elongated east to west and lies along the Lobo zone; the Rosillos Mountains are along the Presidio zone; portions of the intrusive mass of the Chinati Mountains lie along the Ruidosa and Shafter zones. The larger part of the Chinati intrusion, though, abuts one of the Presidio Bolson-bounding faults.

Basin and Range. The Rio Grande rift began forming in Miocene time, characterized by extension accompanied by right-lateral divergent wrenching. With the reversal in shear direction, bands of en echelon folds that formed during Laramide left-lateral convergent wrenching were reactivated as extensional faults during the later episode. What had been the Laramide fold trend became the synthetic shear trend in Basin and Range time, exemplified by the northwest-trending dip-slip faults between the Presidio, Terlingua and Santa Elena zones. The more northward component of the motion of Mexico relative to Texas indicated by Muehlberger (this guidebook, fig. 5) may reflect bias toward the direction of transform faulting through the Gulf of California; that segment of Mexico, however, appears to have acted as part of a separate basement segment, more influenced by the San Andreas stress regime (fig. 3).

The northwest dip-slip faults in the Beach and Baylor Mountains and in Sierra Diablo probably formed during late Paleozoic right-lateral wrenching and were reactivated in late Tertiary time, accompanied by divergence.

The dip-slip faults of the Glass Mountains formed along the synthetic shears produced during right-lateral wrenching. Faults of similar style and orientation cut late Eocene to Miocene volcanic deposits between the Ruidosa and Shafter zones; as no folds appear to be associated, they were probably formed during the late Tertiary episode, without Laramide precursor structures.

Salt Basin and Lobo Valley are currently active parts of the Rio Grande rift (Muehlberger and others, 1978; Dumas and Goetz, both this guidebook). In extensional environments, dog-leg offsets along rift-margin faults are not at all uncommon; however, in this region the bights in the basin margins coincide with east-west zones of disruption, as is well shown in potential fields data. The South Hueco (30°30′) and North Baylor (31°15′) zones are easily seen on Figures 3, 4, of Veldhuis and Keller and on Figures 5, 6 of Keller, Hills and Djeddi (both this guidebook).

The right-lateral Valentine fault (Dumas, this guidebook; Dumas and others, 1980) is one of the youngest features in this tectonic complex. Its strike (N 50° W) and axis of maximum extension (S 74° W) suggest that it is a synthetic fault, which lies between the Chispa Mountain and Mount Locke (possibly extending to the Candelaria) zones, and which has formed in response to ongoing Basin and Range right-lateral divergent wrenching.

STRUCTURAL ZONES

Thirteen east-west structural zones, and possibly more, cross the Trans-Pecos region between 29° and 31°30′ N. The following catalog is by no means exhaustive, but it does demonstrate the variety of geological/geophysical expressions and range in age of component features within the zones (described from west to east in each case). The use of *zone* rather than *line* is intentional and is more indicative of variations in width from one to the next. Each is named for a prominent geologic or recognizable cultural feature and not necessarily for either end point. The zone just north of 31°N has been named for Van Horn, in order to avoid confusion with Texas Lineament, Streeruwitz thrust, or Hillside fault terminology and genetic implications. Also evident in this list is the author's comparative lack of information on Mexican geology; principal sources for features in Mexico have been McAnulty (map, this guidebook) and Henry and Bockoven (1979). The V Horn–El Paso, Marfa and Emory Peak–Presidio sheets of the Geologic Atlas of Texas (Barnes and others, 1975; 1979 a, b) and the tectonic map of Henry and Bockoven (1979) provided much of the information for this compilation.

South Hueco Mountains Zone (SH). Southern boundary of Sierra Juárez (Sierra Juarez probably produced during Laramide left-lateral convergent wrenching between SH and zone to north); south end of Hueco Mountains; east-west-elongate dune field and windblown sand between Granite Mountain and Tepee Butte, natural tanks along same line (Barnes and others, 1975); Sierra Prieta (Barker, this guidebook); Babb Flexure and Bitterwell Break (King, 1942; Goetz, this guidebook); gravity and magnetic anomalies across Salt Basin, Delaware Basin (Veldhuis and Keller; Keller Hills, and Djeddi, both this guidebook); Cottonwood Creek drainage; constriction in Delaware Basin, waist in Central Basin Platform, fault boundary at south end of Midland Basin (King, 1969); east-west-flowing segment of Pecos River; approximate northern margin of Llano Uplift.

North Baylor Mountain Zone (NB). North end of Sierra Samalayuca; igneous intrusions and normal faults of Finlay Mountains; Malone Mountains appear to be product of Laramide left-lateral convergent wrenching between NB and VH zones; intrusive core of Quitman Mountains (Cordell and others, 1978) between NB and VH zones may have been emplaced along early Tertiary antithetic fault between shears (gravity expression includes both Quitmans and Sierra Blanca Peaks as suggested by Barker, this guidebook); Movie Mountain; Cox Mountain–youngest Tertiary isotopic date in region on basalt at Cox Mountain, 16 m.y. (Barker, this guidebook); Cox Mountain fault separating Permian Hueco Limestone overlying Precambrian on south from Permian Hueco overlying Paleozoic rocks on north; northern boundary fault of Baylor Mountains; Seven Heart Gap; alluvial basin north of Apache Mountains; gravity and magnetic anomalies in Salt Basin and Delaware Basin (same source as for SH discussion).

Van Horn Zone (VH), a probable boundary transform. South ends of Sierra de Samalayuca, Sierra del Presidio, Sierra Guadalupe; breaks in faults in Sierra San Martin del Boracho; gravity anomaly extending westward to about 111°W (fig. 3); southern edge of Quitman Mountain igneous core gravity anomaly (Cordell and others, 1978); Smugglers Gap in Quitman Mountains, west-southwest rhyolite dikes (Jones and Reaser, 1970), Bonanza Mine area Ag/Pb/Zn/Cu/Mo mineralization and fluorspar deposits associated with east-west rhyolite porphyry dikes (Murry, this guidebook); Eagle Springs and Hot Wells; fault termination of Love Hogback; north ends of Speck Ridge, Carpenter fault zone and Espy Ridge, the Red Hills, east-west course of Goat Arroyo (Underwood, 1963); fluorspar deposits along east-west faults in Eagle Mountains (road log, day 3, this guidebook); east-west thrust at north end of Devil Ridge (Underwood, 1963); Streeruwitz thrust; Hillside fault and east-west faults through central Beach Mountains (Barnes and others, 1975); Hazel fracture zone and Cu/Ag mineralization (road log, day 2, this guidebook); northern boundary of Wylie Mountains; depositional trough (possible aulacogen?) where Precambrian Carrizo Mountain Group, Allamoore and Hazel sediments were deposited; east-west trough during Van Horn Sandstone deposition (McGowen and Groat, 1971); northwestward bend in north-south Rim Rock fault; gravity and magnetic anomalies crossing Salt Basin and Delaware Basin (same source as for SH, NB discussions); break or strike change in Stocks fault and north side of Apache Mountains; northern ends of Rounsaville syncline, Hovey anticline (probably formed between VH and zones to south during Laramide left-lateral convergent wrenching); deeps in Delaware, Midland Basins (King, 1969); inflection in craton margin near Fort Stockton (fig. 1); east-west course of Pecos River between 102°30′ and 101°50′ W.

Lobo Zone (L). Fault terminations in Sierra San Jose del Prisco; Red Bull Fault zone (Jones and Reaser, 1970); Eagle Mountains–Rhyolite fault/Frenchman Canyon and fluorspar mineralization, east-west elongated Eagle Peak Syenite mass, southward bight in range around intrusion; fault separating igneous rocks of Eagle Mountains from Mesozoic sedimentary rocks of southern Eagles/Indios, southeastward strike change of Indio Mountains faults (Underwood, 1963); headwaters of Green River; water gap at south end of Carrizo Mountains; break in western boundary fault of Eagle Flat; outcrop boundary of Paleozoic rocks in Van Horn Mountains; bight in eastern margin of Lobo Flat; south end of Central Basin Platform and north edge of Sheffield Channel (Wilson, 1975).

Chispa Mountain Zone (CM). Threshold in basin west of Sierra del Pino and fault terminations in basin east of the Sierra (Henry and Bockoven, 1979); narrow neck of Mesozoic outcrops in Sierra de la Cieneguilla; Garren Group (late Eocene–Oligocene) outcrop boundary in Indio Mountains; waist in Van Horn Mountains; eastward bend in east side of Van Horn Mountains and fault strike change; change in drainage direction of Chispa Creek; bend in east side of Lobo Valley at Chispa Mountain; east-west faults in mountains north of Valentine and through Davis Mountains; northern edge of western Davis Mountains intrusive rocks.

Mount Locke Zone (ML). Strike change and fold terminations in Sierra del Pino, faults bounding Mesozoic block between Sierra del Pino and Sierra de la Cieneguilla, east-west faults through narrows of Sierra de la Cieneguilla (Henry and Bockoven, 1979); eastward kink in Rio Grande, constriction in Red Light Bolson, east-west faults and Rio Grande drainage at south end of Indio Mountains, bend in Green River from north-south to east-west to join Rio Grande (Underwood, 1963); south end of Van Horn Mountains; eastward promontory of Sierra Vieja and northwestward strike change; narrowing of Lobo Valley; El Muerto Peak, Sawtooth Mountain and Mount Locke in Davis Mountains; post-Oligocene east-west faults, as near Lonely Lee Peak and between Mount Livermore and Sawtooth Mountain (Barnes and others, 1979a); post-Eocene–Oligocene fault terminations in Barilla Mountains; large embayment in Cretaceous outcrop band near Reeves, Pecos, Jeff Davis county line junction (McAnulty, map this guidebook).

Valentine Zone (VZ). Fold terminations in Sierra de la Cieneguilla and change from syncline to overturned fold (Henry and Bockoven, 1979); northwestward strike change of Sierra Vieja; Vieja Pass; east-west segment of Chispa Creek southwest of Valentine, and threshold between areas of thick and thin basin fill just west of Valentine; fault terminations in vicinity of Highways 166 and 505; south end of Diablo Platform in subsurface; southern edge of Sheffield Channel (Wilson, 1975); Mitre Peak; northern margin of Glass Mountains; Sierra Madera plug; the Pecos Arch lies between the V and L zones, with Permian strata resting on Precambrian, and may indicate Late Pennsylvanian–Early Permian convergence(?).

Candelaria Zone (C). East-west evaporite diapirs north of La Bamba in Sierra Lágrima; Cuatralbo fault zone and evaporite diapirs (Gries and Haenggi, 1971); hot springs east and west of Rio Grande; threshold between shallow and deep basin fill near Candelaria (Henry and Bockoven, 1979); Salt Basin/Alamitos Creek (Rio Grande tributary) drainage divide; southeast end of Valentine fault near Marfa; Cathedral Mountain; Mount Ord; north edge of Marathon fold belt; Spencer Mountain.

Ruidosa Zone (R). Gravity anomaly from 111°W, extending eastward through area (fig. 3); Cañon de Navarrete and evaporite diapirs (Gries and Haenggi, 1971); Pinto Canyon; northern margin of Chinati Mountains; strike changes in faults between 104° and 104°05′W; east-west extensional fault zone (Basin and Range) just east of 104°W and 30°N; north end of fault swarm between 103°30′ and 104°W; Elephant Mountain intrusion; Del Norte Gap, strike change in Del Norte Mountain thrust front and in Paleozoic outcrop belt (Eifler, 1943).

Shafter Zone (S), probable boundary transform. Major gravity anomaly (fig. 3) extending westward to 111° or 112°W where interaction with northwest-trending San Andreas transform begins (both S and P zones, or either one, may be represented by the anomaly shown on a map of this scale); Arroyo Ramírez, late Eocene to Miocene intrusion just north of arroyo, hot springs (Henry and Bockoven, 1979); strike of Paleozoic units and intrusive rocks, east-west faults, and mineralization at Shafter (Cepeda, 1978); late Paleozoic east-west thrust fault and graben along Chalk Draw fault in Green Valley, where in well south of fault the Permian section was absent and in well north of fault 2,100 m of Permian was present (Pearson, 1978); Chalk Draw fault zone, southeastward bend in Chalk Draw fault; south end and eastward deflection of Black Peak thrust fault in Santiago Mountains near YE Mesa and Santiago Peak (Eifler, 1943); south edge of Marathon Fold Belt; Devils River Uplift area—boundary between 1,000-m.y.-old Grenville-aged basement and younger (500-m.y.-old) basement along frontal fault of Devils River Uplift, Cambrian–Ordovician boundary between craton-margin carbonate platform deposits and geosynclinal siliceous deposits (Nicholas and Rozendal, 1975), Carta Valley fault zone (Webster, 1980); deflection at Rio Grande of Salado Arch.

Presidio Zone (P), probable ridge transform. Major gravity anomaly (fig. 3) extending westward to 111° or 112°W where interaction with northwest-trending San Andreas transform begins (both S and P zones, or either one, may be represented by the anomaly shown on a map of this scale); Rio Conchos; strike change in fault pattern from north-south to northwest where the Conchos crosses Sierra Grande; from Presidio zone southward, Rio Grande no longer flows from bolson to bolson and its course is in rocks older than middle Miocene; Wilson (this guidebook) proposes different histories for Rio Grande segments north and south of the Presidio zone of this paper, and drainage integration in post-middle Miocene time (possibly a result of transform faulting along the zone); Tascotal Mesa fault—south end of broad Presidio Bolson and thick fill, virtual absence of faults north of Tascotal Mesa fault versus closely spaced faults trending about N 60° W to south of Tascotal Mesa break; Rosillos Mountains; south end of thrust faults of Santiago range; Black Gap, Maravillas Creek valley; possible offset or break in basement ridge interpreted to extend beneath Sierra del Carmen and beneath Devils River Uplift farther east.

Terlingua Zone (T). South end of thick basin fill in Mexican portion of Redford Bolson, major bends in faults of Sierra Mulato (Henry and Bockoven, 1979); fault strike changes north and south of zone between Sierra Mulato and Terlingua Creek; mercury mineralization and hot spring at Terlingua, mineralization at Study Butte; possibly fault terminations in Sierra del Carmen.

Santa Elena Zone (SE). Faults at north end of Sierra de San Carlos; fault terminations in Mesozoic rocks in Mesa de Anguila and Sierra Ponce; Santa Elena Canyon; fault terminations in Mesozoic rocks south of Chisos Mountains core; hot springs at Boquillas; north end of basin with thick Miocene to Holocene fill south of Boquillas; sliver of Paleozoic rocks in fault zone along west flank of Sierra del Carmen; large intrusive body in Sierra del Carmen; the east-west Santa Elena zone may not have been active since late Eocene–Oligocene time, as there is little evidence of east-west disruption of volcaniclastic rocks around the Chisos Mountains; northwest-trending Basin and Range faults are dominant; alternatively, the Santa Elena zone may be a very young feature with little evidence of disruption.

TRANSFORM MECHANISM

Illies' work on the Rhinegraben and its relation to other European, Scandinavian and North African rifts led him to comment that ". . . the rifting process seems to develop independently of the type of crustal superposition. Indeed, morphotectonic inventory and geophysical characteristics of the oceanic rift systems are in surprising agreement with those of the continental grabens" (Illies, 1969). In this context it is instructive to compare the expression of the Rio Grande rift on the geologic map of the United States (King and Beikman, 1974) and the Mid-Atlantic Ridge shown on the physiographic diagram of the Atlantic Ocean floor (National Geographic Society, 1975).

Analogous tectonic styles, timing and extent of magmatism, and igneous rock compositions have been described for the Rio Grande and Kenya rifts by Barker (1977). Based upon analysis of gravity data, faulting, seismicity and geothermal activity for a segment of the Kenya rift, Fairhead (1980) has proposed that the west-southwest to east-northeast chain of Cenozoic volcanic centers crossing northern Tanzania may represent a nascent transform fault.

Transform faulting commonly occurs in conjunction with extension—either intracontinental rifting or sea-floor spreading; in the Trans-Pecos region transform faulting is a Basin and Range-aged to contemporary phenomenon. Laramide deformation in this area was characterized by wrench faulting but not extension; thus, Basin-and-Range-aged transform faults may coincide with Laramide shear zones, but the Laramide shears were not transforms.

There is some evidence for Precambrian transform faulting in the Trans–Pecos, particularly if one subscribes to the Sears and Price (1978) hypothesis regarding rifting between the Siberian and North American cratons. The Texas Lineament has been described by Swan (1975) as a possible Precambrian analog to present oceanic fracture zones; he records a minimum of 6 km of Precambrian left-lateral displacement across the Stockton Pass (Arizona) fault zone and states that the lineament probably originated as a belt of wrench faults and shear foliation. In the terminology of Gilliland and Meyer (1976), it may have been a boundary transform fault.

Several attributes of transform faults are pertinent to this discussion, the first being that "active transform faults bordering blocks of crust follow small circles which are lines of latitude relative to a pole of rotation on the globe" (Menard and Atwater, 1968). Rona and Gray (1980, fig. 3) describe the dependence of the stability of a transform fault upon the length of ridge-ridge offset, the spreading rate, and the thermal conductivity of the lithosphere. According to them, "small offsets are least stable because a short section of thin lithosphere places minimal constraint on the transform fault. The faster the spreading rate and the lower the conductivity, the greater the minimum offset required to maintain stability of a transform fault."

Gilliland and Meyer (1976) set forth two classes of transform faults. Boundary transforms mark edges of major plates and occur along fundamental breaks in the lithosphere; the Van Horn and Shafter zones of this report may be expressions of boundary transforms, possibly during both Precambrian and Basin and Range extension. Ridge transforms result from rift extension and occur within plates between boundary transforms; they develop well after the onset of rifting and offset the spreading axis to varying degrees. Importantly, rifting can and does occur without formation of ridge transforms. There are fewer ridge transforms in areas of thicker, cooler, more rigid crust; for example, north of the Van Horn zone where the South Hueco and North Baylor zones represent possible ridge transforms. South of the Van Horn zone in younger, accreted basement material it should not be surprising to see more of this type of disruption.

Figure 4 displays both transform types well, the Kane Fracture Zone being the boundary transform and the basins marking positions where ridge transforms cross the spreading axis. The area shown in Figure 4 is roughly equal in extent to the Trans–Pecos regions—3° to 4° of latitude and 4° of longitude; relative to the Trans–Pecos province, the diagram illustrates other important features. For example, the spacing of major transforms is similar for the two areas, and bights along the axis of extension are common to both. The disposition of transverse ridges and transverse fracture valleys in the Kane area is interesting (Rona and others, 1976); further work in the Trans–Pecos region may reveal similar features there. The faults that bound the north side of Wylie Mountains cross Lobo Valley and possibly Michigan Draw, and northward groundwater flow is in part blocked by a horst that includes Wylie Mountain (Goetz, this guidebook); the horst, along the Lobo zone of this paper, may be a transverse ridge.

Transform faults lie along the p-shear plane parallel to the principal stress direction in a shear couple. Although the p-shear zone

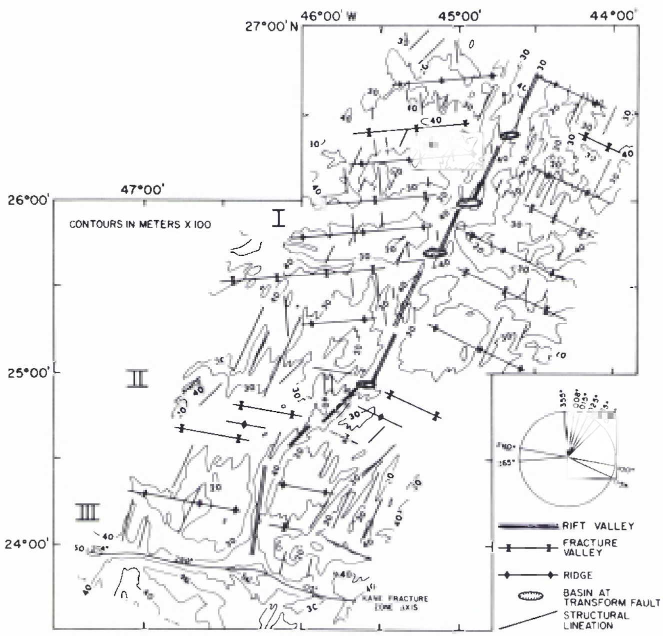

Figure 4. Diagrammatic representation of structural and topographic features in area of Kane Fracture Zone, north Atlantic Ocean. Isobath values in hundreds of meters (from Rona and Gray, 1980).

may comprise myriad very short Riedel shear segments, it does not behave as a synthetic fault. The critical implication for this discussion is that the p-shear direction would be the same for an east-west left-lateral shear couple as it would for an east-west right-lateral shear couple; specifically, the p-shear or transform direction during Basin and Range rifting and right-lateral wrench faulting and during Laramide left-lateral wrench faulting (sans rifting) in the Trans-Pecos region would have been generally the same. The more northward component of the motion of Mexico relative to Texas indicated by Muehlberger (this guidebook, fig. 5) has been discussed in the context of Basin and Range deformation.

With a 180-degree shift of direction of the shear couple, the synthetic faults would obviously not act along the same lines. What had been the direction of folding and reverse faulting during Laramide deformation became the direction of right-lateral synthetic shearing and normal extensional faulting during Basin and Range deformation.

Transform faulting provides a geologically reasonable mechanism for offsetting, bifurcating and creating bights in the Rio Grande rift from Miocene time to the present.

SUMMARY

Between east-west shear zones the normal, extensional faulting direction and right-lateral synthetic shear direction of Basin and Range right-lateral divergent wrench deformation are coincident with fold and reverse-fault directions of Laramide left-lateral convergent wrench deformation. Thus, this structural grain, the N 50° to 60° W Texas Lineament direction of Muehlberger (this guidebook), has been repeatedly reinforced throughout the tectonic history of the region, making it prominent indeed. The principal mechanism producing this array of northwest-aligned features, however, may have been east-west-directed shear, with reversal of relative lateral displacement, rather than regional southwest-northeast Laramide compression followed by regional southwest-northeast Basin and Range extension. With the onset of extension along the Rio Grande rift in Miocene time, one and possibly more of the described east-west structural zones has acted as a transform fault.

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