JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. B8, PAGES 13,545–13,560, JULY 30, 1991

Mid-Cenozoic Stress Evolution and Magmatism in the Southern Cordillera, Texas and Mexico: Transition from Continental Arc to Intraplate Extension

CHRISTOPHER D. HENRY, JONATHAN G. PRICE,[1] AND ERIC W. JAMES

Bureau of Economic Geology, The University of Texas at Austin

Orientations of dikes, veins, faults, and slickenlines reveal the evolution of stress during Eocene to Miocene magmatism in the southern Cordillera. Where most thoroughly studied by us in Trans-Pecos Texas, magmatism began at about 48 Ma shortly after the cessation of Laramide folding. Dikes and veins that formed from then until about 32 Ma strike dominantly east-northeast. This indicates that the least principal stress (σ_3) was north-northwest; additional data suggest that the maximum principal stress (σ_1) was east-northeast. The stress field changed to σ_1 vertical and σ_3 east-northeast (i.e., east-northeast extension) at least by 28 Ma and probably by 31 Ma. Dikes and veins that formed between 31 and 17 Ma, when all magmatism ceased in Texas, strike north-northwest. This change marks the beginning of regional, Basin and Range extension; however, major normal faulting, exclusively of high-angle type, did not begin until about 24 Ma. A similar stress change, marked by a similar change in dike and vein orientations, occurred throughout the southwestern United States and northern Mexico. The time of change is not well constrained in Texas, but available information allows it to have occurred at the same time thoughout the southern Cordillera. We suggest the earlier stress field is related to east-northeast convergence between the Farallon and North American plates. The change in stress is approximately coincident with collision of the East Pacific Rise and paleotrench. Extension may be related to the change from a convergent to a transform margin along the western edge of North America. The changes in the stress field are accompanied by changes in the sources and compositions of magmas erupted in Texas. Contemporaneity of the changes in stress and magmatism indicates that they are related. Combined with regional age patterns, paleostress and geochemical data indicate that pre-31 Ma magmatism in the southern Cordillera occurred in a subduction-related, continental volcanic arc. Subsequent magmatism occurred in an environment of intraplate extension of the Basin and Range province.

INTRODUCTION

Cenozoic magmatism in western North America spanned the change from a convergent plate margin to the current transform margin along much of the west coast. Magmatism during convergence is largely assigned to a continental volcanic arc [*Lipman et al.*, 1971; *Coney and Reynolds*, 1977; *Damon et al.*, 1981]; later magmatism occurred in a setting of regional (Basin and Range) extension. However, the timing and influence on magmatism and continental tectonics of the change in plate margin are complex and poorly understood, particularly in the southern Cordillera [*Severinghaus and Atwater*, 1990]. The timing and style of regional extension have been especially controversial [*Zoback et al.*, 1981; *Lipman*, 1981; *Elston*, 1984; *Best*, 1988; *Gans et al.*, 1989].

Texas is a critical area for understanding the tectonic and magmatic evolution of western North America. Magmatism in Texas represents the easternmost expression of Cordilleran activity (Figure 1) and occurred nearly continuously from 48 to 17 Ma, spanning the change in plate margin. The origin of magmatism in Texas has itself been controversial, in part because it is not close to any plate margin. *Barker* [1977] originally drew an analogy to the East African rift on the basis of similarity in magma compositions and in recognition of the pervasive late Cenozoic normal faults. However, faulting postdates most igneous activity [*Henry and Price*, 1986]. We now interpret magmatism up to 32 Ma to have occurred in a continental volcanic arc. Magmatism after that time occurred during regional extension. The arc either extinguished or began to extinguish at about 32 Ma, and by 24 Ma, magmatism was clearly related to intraplate extension. This paper and its companion [*James and Henry*, this issue] use data on paleostress, regional age patterns, and composition of magmatism to establish the overall evolution and tectonic setting of magmatism in Texas.

CENOZOIC MAGMATISM IN TRANS-PECOS TEXAS

Regional Setting

Magmatism in Trans-Pecos Texas is the easternmost part of a broad belt of late Mesozoic and Cenozoic activity in the southern Cordillera, much of which is clearly related to subduction (Figures 1 and 2). The paleotrench for this activity lay along the western edge of North America. At about 100 Ma, magmatism was concentrated along the Pacific coast. From there, it swept generally eastward, reaching as much as 1000 km inland [*Lindgren*, 1915; *Anderson and Silver*, 1974; *Henry*, 1975; *Coney and Reynolds*, 1977; *Keith*, 1978; *Damon et al.*, 1981]. The pattern of magmatism has generally been interpreted to reflect progressive shallowing with time of the subducting Farallon plate. The Cretaceous batholiths of western Mexico and southwestern United States are universally agreed to be related to subduction and to a continental arc [*Anderson and Silver*, 1974; *Damon et al.*, 1981; *Gastil et al.*, 1981]. The position of magmatism in Texas at the eastern end of this continuum is one part of the evidence that it also constitutes a continental volcanic arc, despite being 1000 km east of the plate margin.

After about 30 Ma, magmatism either swept rapidly back toward the coast or occurred nearly simultaneously (the ignimbrite flareup) from Texas across northwestern Mexico. This marks the beginning of the end of arc activity, and magmatism after this time occurred during regional, intraplate extension.

[1]Now at Nevada Bureau of Mines and Geology, University of Nevada, Reno.

Paper number 91JB00202.
0148-0227/91/91JB-00202$05.00

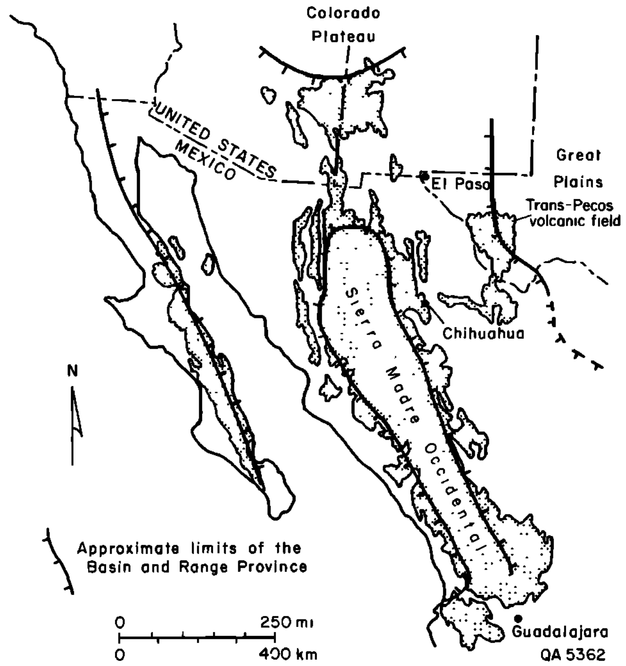

Fig. 1. Location of the Trans-Pecos volcanic field, generalized distribution of Tertiary volcanic rocks, and area of late Cenozoic extension in the southern Cordillera.

Activity in Texas

Magmatism in Trans-Pecos Texas (Figure 3) occurred nearly continuously between 48 and 17 Ma but varied considerably in location, style, composition, volume, and tectonic setting [*Henry and Price*, 1984; *Henry and McDowell*, 1986; *Price et al.*, 1987]. The data of this report and of *James and Henry* [this issue] indicate that magmatism occurred in two distinct tectonic settings: a continental volcanic arc through about 32 Ma and regional (Basin and Range) extension thereafter. All Trans-Pecos magmatism is alkalic, regardless of age, location, or tectonic setting, although the degree of alkalinity varies.

The timing of events is critical to the conclusions of this report and, except where noted, is well constrained. Geochronological constraints are provided by approximately 350 K-Ar ages on more than 200 volcanic and intrusive units, dominantly on separates of alkali feldspar, plagioclase, biotite, or hornblende [*Henry et al.*, 1986, 1989; *Henry and McDowell*, 1986]. *Henry et al.* [1986] compiled K-Ar data as of that date. Precision of the conventional K-Ar ages for mid-Tertiary rocks is always better than 1 m.y. New $^{40}Ar/^{39}Ar$ data are providing much greater precision in several areas [*Kunk and Henry*, 1990]. The isotopic data are supported by and correlated with detailed mapping and stratigraphic studies throughout Trans-Pecos Texas [e.g., *Cepeda and Henry*, 1983; *Henry et al.*, 1989].

Magmatism began about 47-48 Ma with emplacement of small, mafic to intermediate intrusions in the northwestern and southeastern (the Big Bend area) parts of the province (Figure 3a; [*Hoover et al.*, 1988; *Henry and McDowell*, 1986]). At the same time the extensive Alamo Creek Basalt erupted in the southeast. Magmatism continued in the southeast between 44 and 40 Ma with emplacement of abundant, small, silicic to mafic intrusions [*Henry et al.*, 1989] and formation of a small caldera complex, the earliest in Texas, in the Christmas Mountains [*Henry and Price*, 1989].

The greatest volume of magma was emplaced between 38 and 32 Ma in two north-northwest striking geochemical belts: a western, alkali-calcic and an eastern, alkalic belt (Figure 3b) [*Barker, 1977; Henry and Price*, 1984]. This magmatism was

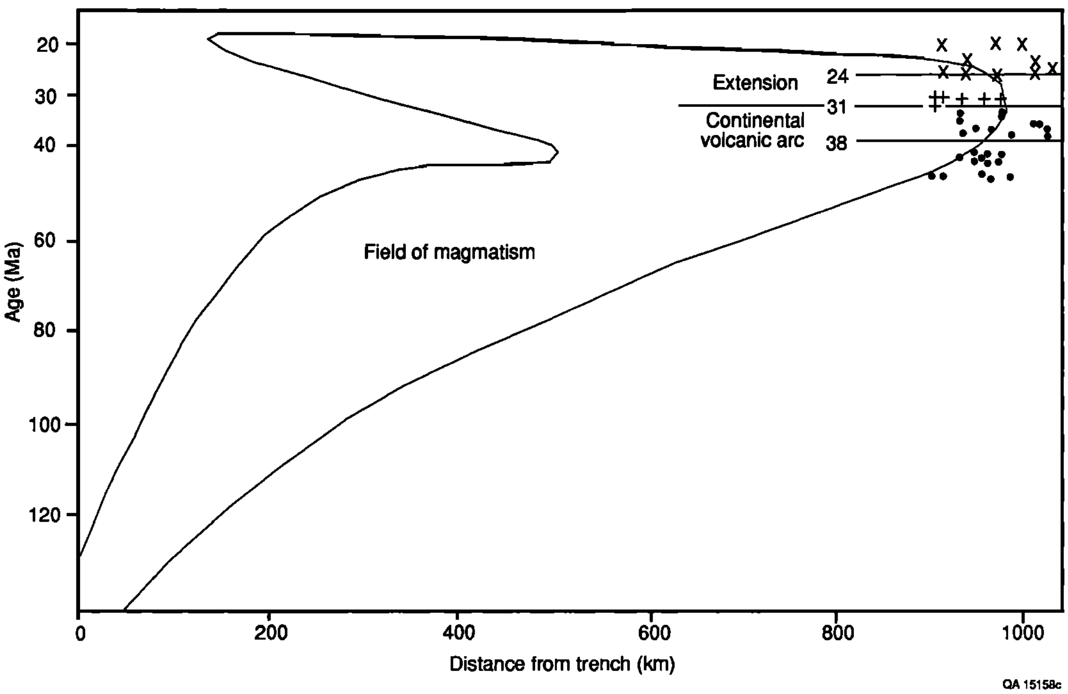

Fig. 2. Timing and location of magmatism in Trans-Pecos Texas in relation to the paleotrench that lay off west coast of North America. Outlined area encompasses ages of magmatism and distances from the paleotrench across northern Mexico compiled by *Damon et al.* [1981]. Activity in Texas constitutes the easternmost magmatism in the southern Cordillera and defines the eastern limit of the magmatic sweep. Crosses, basalts associated with Basin and Range faulting; pluses, volcanic and intrusive rocks emplaced during initial extension between 31 and 27 Ma; circles, volcanic and intrusive rocks emplaced during continental arc activity.

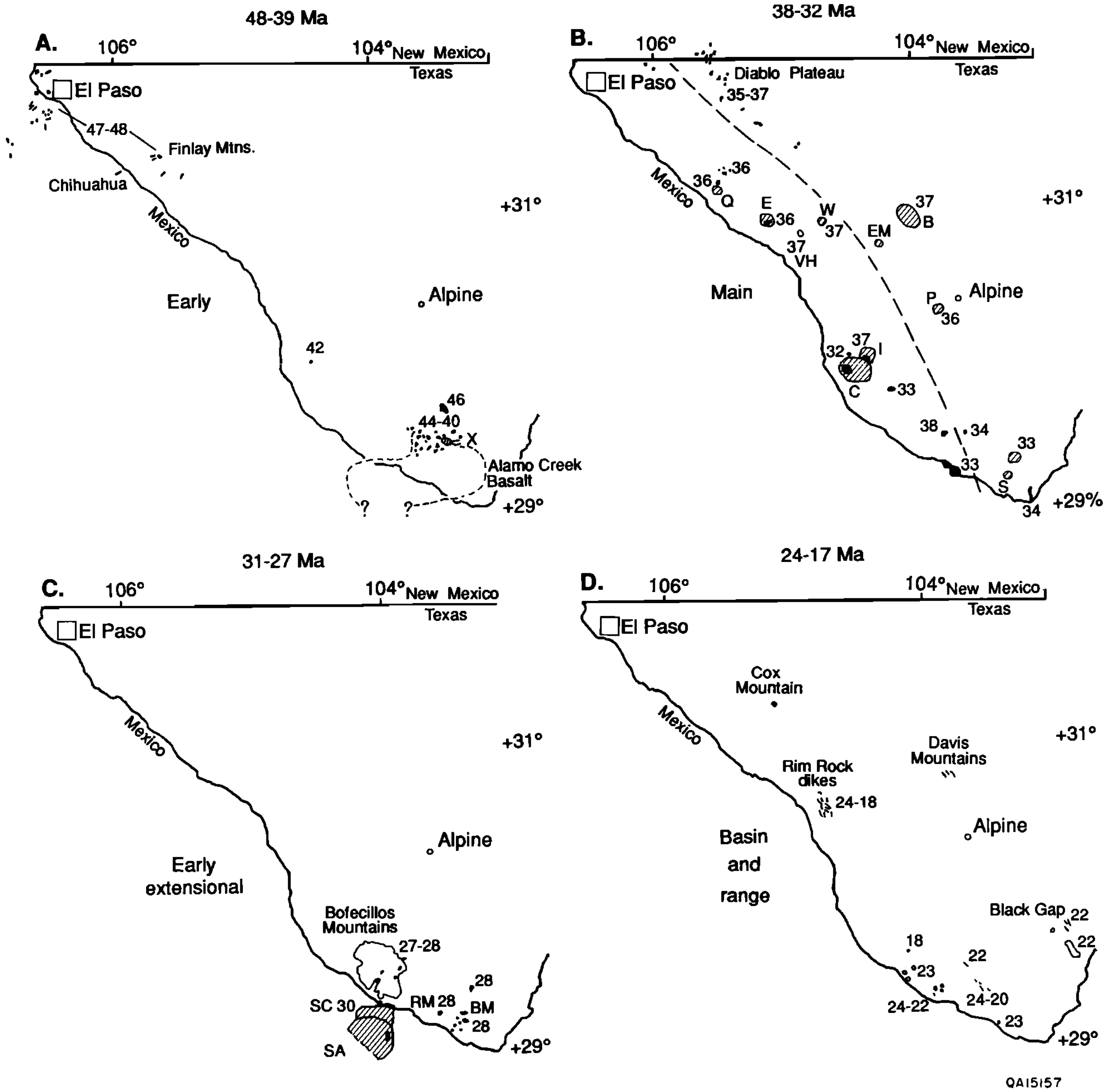

Fig. 3. Distribution of magmatism through time in Trans-Pecos Texas. Numbers indicate times of major activity of individual centers or areas of magmatism. Ruled areas are calderas and solid areas are major intrusions. (a) Initial encroachment of volcanic arc (48–39 Ma). Moderate volumes of magma were emplaced in northern and southern Trans-Pecos Texas. (b) Main continental arc phase (38 to 32 Ma). Large volumes of magma were emplaced, mostly from caldera complexes, throughout Trans-Pecos. AC and A denote western alkalicalcic and eastern alkalic belts. (c) Initial extensional phase (31–27 Ma). Moderate volumes of magma were emplaced exclusively in southern Trans-Pecos Texas and Chihuahua, contemporaneous with initial east-northeast extension. (d) Main Basin and Range phase (24–17 Ma). Small volumes of magma were emplaced throughout Trans-Pecos Texas contemporaneous with major Basin and Range faulting. EP, El Paso. Letters next to calderas: X, Christmas Mountains caldera complex; Q, Quitman Mountains caldera; E, Eagle Mountains caldera; VH, Van Horn Mountains caldera; W, Wylie Mountains caldera; B, Buckhorn caldera; EM, El Muerto caldera; P, Paisano volcano; I, Infiernito caldera; C, Chinati Mountains caldera; PC, Pine Canyon caldera; S, Sierra Quemada caldera; SC, San Carlos caldera; Sa, Santana caldera.

dominated by eruptions from calderas, occurred throughout Trans-Pecos Texas, but shifted with time, and was most voluminous in the central and southern parts of the region. Contemporaneous noncaldera magmatism consisted of numerous small intrusions and lavas scattered throughout the province. A northwest trending belt of silica-undersaturated intrusions was also emplaced at this time, most notably in the Diablo Plateau of northern Trans-Pecos (Figure 3b) [*Barker*, 1977]. At about 35 Ma, volcanism shifted from the northern and central parts of the region to the southern part, in the Chinati Mountains and Big Bend area.

Magmatism between about 31 and 27 Ma was restricted to southern Trans-Pecos Texas and adjacent Chihuahua (Figure 3c). Caldera-related volcanism continued, as two large calderas (San Carlos and Santana calderas) formed at 30 and 28 Ma in Chihuahua, just across the Rio Grande. In Texas, the Bofecillos volcanic center erupted mafic to intermediate lava flows. Intrusions of peralkaline rhyolite and nepheline-normative hawaiite were emplaced in the Bofecillos Mountains and Big Bend area.

After a several million year hiatus, rocks exclusively of basaltic composition were emplaced throughout much of Trans-Pecos Texas as dikes, small stocks, and some lavas (Figure 3d). The beginning of this volcanism at 24 Ma coincided with the beginning of significant Basin and Range faulting.

Volumes of erupted rocks varied tremendously through time. By far the largest volumes erupted between 38 and 32 Ma. Subordinate, but still major, volumes of magmas were emplaced between 48 and 39 Ma and between 31 and 28 Ma. Although widespread, the 24-17 Ma magmatism accompanying Basin and Range faulting was volumetrically minuscule.

Stress Analysis from Dike and Vein Orientations

This paper uses dike and vein orientations to infer stress orientations during their emplacement; the paleostress data are then used to interpret the tectonic setting and evolution of the region. A similar approach has been widely used [*Rehrig and Heidrick*, 1976; *Price and Henry*, 1984; *Aldrich et al.*, 1986; *Best*, 1988]. More indirectly, *Nakamura* [1977] used alignment of flank eruptions around a volcano to infer dike orientations and paleostress. The basic assumption in all these approaches is that a dike or vein is emplaced perpendicular to the minimum principal stress (σ_3). This assumption only holds if the dike occupies a mode 1 fracture (a fracture that opens only perpendicular to its plane [*Pollard and Aydin*, 1988]) that formed in response to the contemporaneous stress field, and the dike has not subsequently been rotated. A wide variety of factors can influence the proper interpretation of stress orientations from dike or vein orientations.

1. A dike or vein may be emplaced into preexisting fractures formed in a stress field unrelated to that during dike emplacement. *Delaney et al.* [1986] demonstrated that dikes can occupy preexisting fractures at various angles oblique to the stress field if the magma driving pressure exceeds a function of the two principal horizontal stresses. In the extreme case, a dike can intrude a joint of any orientation if magma pressure exceeds the maximum principal horizontal stress.

Additionally, dike orientation even in a rock without preexisting fractures may be determined by structures in underlying rocks. For example, dikes that rose through jointed basement rock would, in many circumstances, follow the joints. As the dikes propagated upward into unjointed rocks, they would begin to reorient to the prevailing stress field. Whether or not they succeeded is a function of several factors including dike propagation rate, magma viscosity, and distance traversed [*Emerman and Marrett*, 1990]. Although commonly rapid [*Emerman and Marrett*, 1990], reorientation may not occur if the jointed rocks are shallow. Because dikes are always emplaced into existing rocks and through basement rocks that are commonly complexly deformed, host anisotropy is always a potential uncertainty.

2. Dikes or veins may be emplaced into non-mode 1 fractures. For example, dikes emplaced into or along active strike-slip faults could be substantially oblique to the minimum principal stress [*Best*, 1988].

3. Local stress fields may differ markedly from regional stress fields. Most critically, dikes emplaced around a circular intrusive center can be strongly affected by magma pressure in the center. For example, dikes related to Spanish Peaks, Colorado, show a radial pattern near the central intrusive bodies but curve to a more uniform east-northeast orientation away from the centers [*Muller and Pollard*, 1977]. This pattern reflects the influence of a pressurized circular conduit (the central intrusion) on a regional stress field [*Muller and Pollard*, 1977].

4. Interpretation of complex dike swarms requires nearly complete knowledge of dike distribution and orientation. The Spanish Peaks dikes show quite regular orientations in each segment of arc around the intrusive center [*Muller and Pollard*, 1977], but none of these orientations reflects the regional stress field. This problem applies particularly to areas in the Basin and Range province or areas of recurring magmatism where much of a dike swarm may be buried beneath basin fill or covered by later volcanism.

5. Even if the dikes or veins were emplaced perpendicular to the minimum principal stress, uncertainty in their age may lead to assignment of a stress field to an incorrect period. Age uncertainty is particularly a problem in areas of recurrent magmatism, where reheating or hydrothermal alteration of dikes may reset or alter their apparent ages.

6. Subsequent rotation can produce dike swarms whose orientation does not correspond to the orientation during emplacement. Vertical axis rotation during Laramide or Basin and Range deformation has been suggested for many areas in southwestern North America [*Nelson and Jones*, 1987; *Hagstrum and Sawyer*, 1989].

For cases 1 (preexisting fractures) and 3 (local stress fields), the difference between the horizontal stresses is particularly important. Where the stress difference is small, dikes can more easily intrude preexisting joints of any orientation [*Delaney et al.*, 1986]. Where the stress difference is large, only preexisting joints close in orientation to the minimum principal stress can be occupied. Delaney et al. call regions of small stress difference tectonically inactive and regions of large difference tectonically active. Even in active regions, horizontal stresses generally differ by no more than 50% [*McGarr*, 1982; *Delaney et al.*, 1986].

Given these uncertainties, it is clear that interpretation of paleostress from dike and vein systems must be based on a thorough understanding of their geology. Both theoretical considerations and our own data suggest that hydrothermal veins within contemporaneous resurgent intrusions of calderas are the most consistent and reliable indicators of the stress field. Accurate assessment of the paleostress field can be determined from thoroughly understood dike swarms even in older rocks, however.

1. Resurgent intrusions are most likely to be isotropic, that is, to contain no fractures formed in a previous stress field. Obviously, this applies only to veins and dikes formed essentially contemporaneously with the host intrusion. In contrast, hydrothermal activity in areas of locally recurring magmatism, for example, the San Juan volcanic field of Colorado, is in many cases much younger than that of the host caldera [*Lipman et al.*, 1976]. Additionally, because they are deep-seated bodies, resurgent intrusions are least likely to be affected by structures in underlying rocks.

2. In Trans-Pecos Texas veins commonly show more consistent orientations than dikes, possibly for several reasons. If fluid pressure in hydrothermal veins is less than magma pressure in dikes, the veins will be less likely to occupy preexisting fractures that are not perpendicular to the least principal stress [*Delaney et al.*, 1986]. Also, because hydrothermal fluids are much less viscous than any magmas, they are more likely to reorient to prevailing stresses [*Emerman and Marrett*, 1990].

Finally, veins clearly form in brittle rock: dikes may be emplaced while the host intrusion is still partly liquid and less able to transmit regional stresses.

Some uncertainties remain even for resurgent intrusions. Magma pressure within the intrusion could induce a local stress field, analogous to that of the Spanish Peaks. Magma pressure would not affect veins formed after solidification of the intrusion, however. Also, the caldera block uplifted by the resurgent intrusion may be in part floating on the intrusion and therefore decoupled from the regional stress field. This possibility may explain the random orientation of dikes within the Questa caldera, New Mexico, and distinct northwest strike of contemporaneous dikes outside the caldera [*Lipman*, 1983].

DIKE AND VEIN ORIENTATIONS DURING CENOZOIC MAGMATISM, TRANS-PECOS TEXAS

Dikes and Veins Before 32 Ma

Dikes and veins intruded between 48 and 32 Ma in Trans-Pecos Texas dominantly strike east-northeast to east (Figure 4). These data are representative of the major igneous centers of the region, most of which are calderas, include examples from both the western alkali-calcic and the eastern alkalic belts, and span nearly the entire time of pre-32 Ma activity. The 32 Ma Chinati Mountains caldera [*Cepeda and Henry*, 1983], in the western belt, is the youngest center represented. The Organ Mountains caldera [*Seager*, 1981], in southern New Mexico, is geographically and chemically part of the western belt (Figure 4).

Ages assigned in Figure 4 are based on direct determinations on dikes in the Chinati Mountains and Pine Canyon calderas, the Paisano volcano, and the Christmas Mountains intrusive area [*Henry et al.*, 1986, 1989]. Additionally, dikes and veins are inferred to have the same age as the host caldera throughout the region, with the possible exception of the Organ Mountains caldera as discussed below. Detailed geologic and geochronological study demonstrates that calderas and other volcanic centers of Trans-Pecos Texas were isolated from each other, were active briefly, and were not affected by younger thermal events [*Henry and Price*, 1984; *Henry and McDowell*, 1986; *Henry et al.*, 1989]. Undated dikes are tied to the overall caldera magmatism on the basis of field relationships, petrography, and composition. Veins are hosted by resurgent intrusions of the calderas and are typical of open-space-filling hydrothermal veins related to intrusions. Therefore, both dikes and veins must have formed during caldera magmatism or during primary cooling.

The ages of veins in the Shafter silver district and the Terlingua mercury district, which are outside of calderas, are inferred to be about 32 and 34 Ma, respectively. The Shafter district is along the southern margin of the 32 Ma Chinati Mountains caldera; mineralization there is probably related to caldera igneous activity. The origin of the Terlingua mercury deposits is uncertain, but they are most likely related to local igneous activity [*Yates and Thompson*, 1959]. K-Ar ages of intrusions in the area are mostly about 34 Ma [*Henry et al.*, 1986].

All data sets show the dominant east-northeast orientation (Figure 4), but clearly other orientations occur and are prominent in a few centers. Most scatter around a distinct east-northeast peak; others (e.g., the Quitman Mountains and Organ Mountains) are clearly bimodal with a north or northwest trend in addition to a prominent east trend. Examination of representative examples suggests the origin of the scatter and the caution necessary in interpreting these data.

Christmas Mountains dike swarm. A 40–44 Ma dike swarm in the Christmas Mountains is one of the earliest clear paleostress indicators associated with igneous activity and a good example of scatter around an east-northeast peak (Figures 4 and 5). The dikes are related to a small caldera complex centered in the Christmas Mountains and to a nepheline-normative gabbro that preceded caldera activity; both are approximately 42 Ma [*Henry et al.*, 1989; *Henry and Price*, 1989]. Dike compositions range from basalt, petrographically similar and probably related to the gabbro, to rhyolite, probably part of the caldera system.

Ages of seven dikes, representing most of the petrographic variation, range from 40.3 to 47.2 Ma [*Henry et al.*, 1989; *Laughlin et al.*, 1982]. The 47 Ma dike is likely a feeder to the extensive Alamo Creek Basalt and may not be part of the Christmas Mountains swarm [*Henry et al.*, 1989].

The dikes, only a fraction of which are shown on Figure 5, exhibit a wide range of orientations. However, both the map and the rose diagram demonstrate the dominant east to east-northeast orientation (Figures 4 and 5). The complete dike swarm is exposed because younger cover is negligible. The small but distinct northerly and northwesterly peaks on the rose diagram almost entirely reflect the two long dikes south and southeast of the Christmas Mountains.

The dike orientations indicate that the minimum principal stress (σ_3) was north to north-northwest and that the maximum horizontal stress was east-northeast, parallel to the preferred dike orientation. For reasons discussed more fully below, we interpret the maximum horizontal stress to be σ_1. Although the variation in dike orientations could reflect all the uncertainties cited above, host anisotropy is probably most important. The dikes were emplaced into Cretaceous sedimentary rocks that are not significantly deformed here but are intensely folded and faulted in north-northwest trends just 20 km to the southwest [*Erdlac*, 1990]. Additionally, complexly deformed Paleozoic rocks of the Ouachita-Marathon foldbelt occur at depths less than 1 km [*Henry et al.*, 1989]. A local stress field resulting from intrusion of the gabbro or the silicic caldera magma body was probably not a factor, because dikes maintain their dominant east to east-northeast orientation within the intrusive area.

The variation in dike orientations around the Christmas Mountains illustrates the need to know the complete distribution of a dike swarm. Examination of only a few dikes could easily give a false impression of stress orientations during their emplacement. Indeed, *Laughlin et al.* [1982], who dated the two long dikes south and southeast of the Christmas Mountains, interpreted them to indicate major changes in stress orientations at the time.

Quitman Mountains caldera. Dikes in the Quitman Mountains show a bimodal distribution (Figure 4). Dikes that cut ring fracture intrusions and caldera fill volcanic rocks strike east-northeast or approximately north [*Albritton and Smith*, 1965]. Epithermal veins in the intrusions strike east-northeast. By our criteria, the east-northeast trend is most likely perpendicular to the least principal stress, which would be north-northwest. The significance of the north trend is uncertain, but it may be related to preexisting structures in Cretaceous rocks folded during Laramide deformation. The north striking dikes are petrographically similar to other intrusive rocks of the Quitman Mountains caldera; therefore, they are unlikely to be much younger.

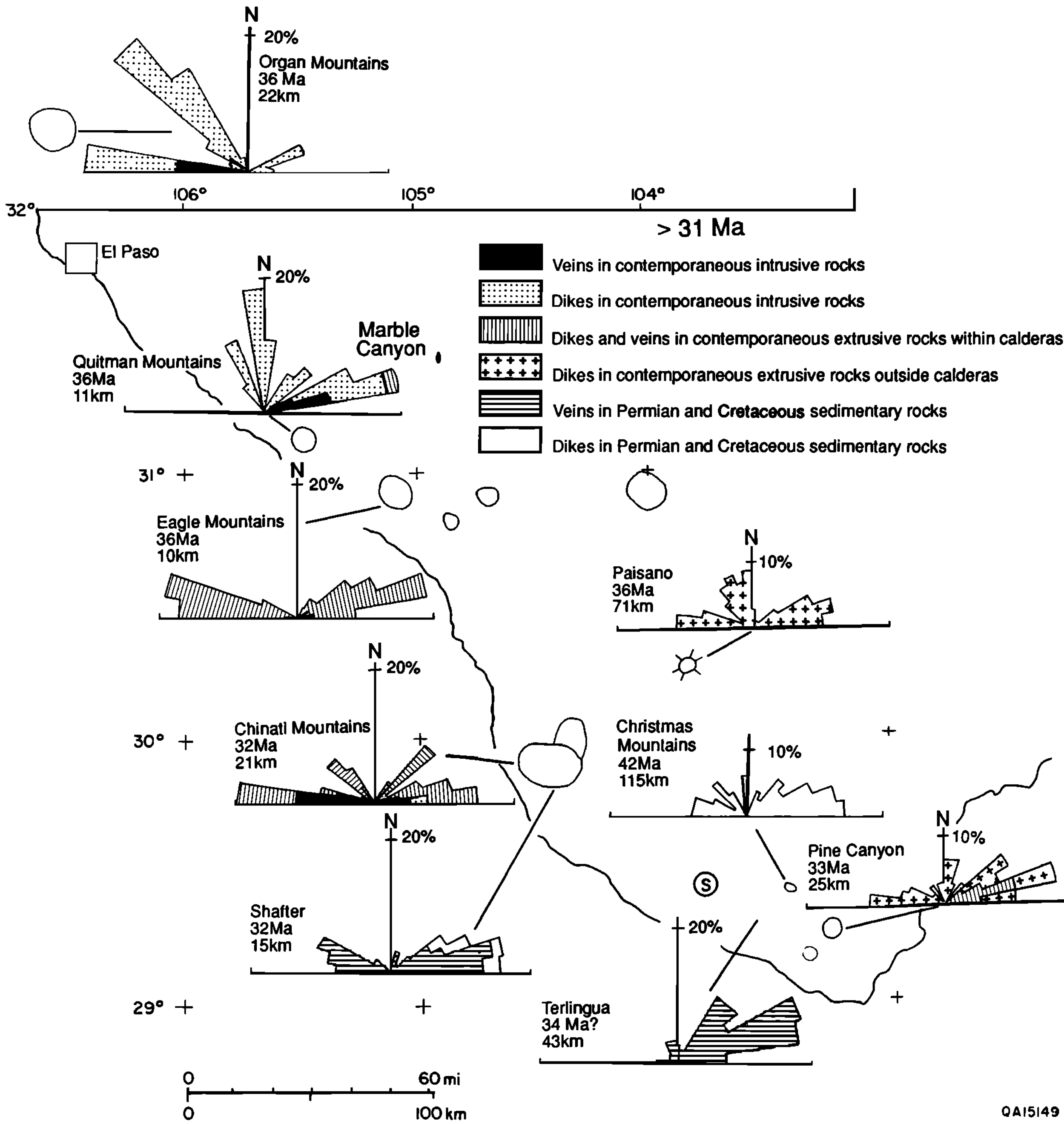

Fig. 4. Strike rosettes for dikes and veins, with age and total strike length, during magmatism between 48 and 32 Ma in Trans-Pecos Texas. Most dike and vein systems are within or adjacent to calderas. Strike bars are constructed for 10° intervals; lengths of bars are proportional to percentages of total strike length. Dominant east to east-northeast strike of dikes indicates that the least principal stress (s_3) was north to north-northwest. Maximum principal stress (s_1) was interpreted to be east-northeast (see text).

Additional examples and one exception. Other, smaller or incompletely studied dike and vein systems in Trans-Pecos Texas show dominant east-northeast trends. Dikes associated with 47 Ma syenitic intrusions in and southeast of El Paso strike northeast (Figure 3a) [*Albritton and Smith*, 1965; *Hoover et al.*, 1988). The dikes have not been mapped in detail, however, and areas of outcrop are surrounded by upper Tertiary basin fill that may cover many dikes. Syenitic, aplitic, and pegmatitic dikes in the 37 Ma Marble Canyon (Figure 4) intrusion of the eastern belt strike east-northeast [*Price et al.*, 1986], as do dikes and epithermal veins in the Solitario (Figure 4), a 38 Ma laccolith and caldera.

A possible exception to the consistency of north-northwest least principal stress occurred at approximately 37 Ma. A group of extensive, large-volume, silicic lavas, the Bracks Rhyolite, Star Mountain Formation, and Crossen Trachyte, were emplaced at this time, apparently from north-northwest striking fissures [*Henry et al.*, 1990]. These could represent a brief episode of east-northeast extension, but such an event would clearly be atypical of the stress field in Texas at the time.

Postemplacement rotation of the dikes around vertical axes is not a problem in Texas. The only significant deformation to have affected dikes is Basin and Range extension. In Texas, total extension was less than 10% as shown by the geometry

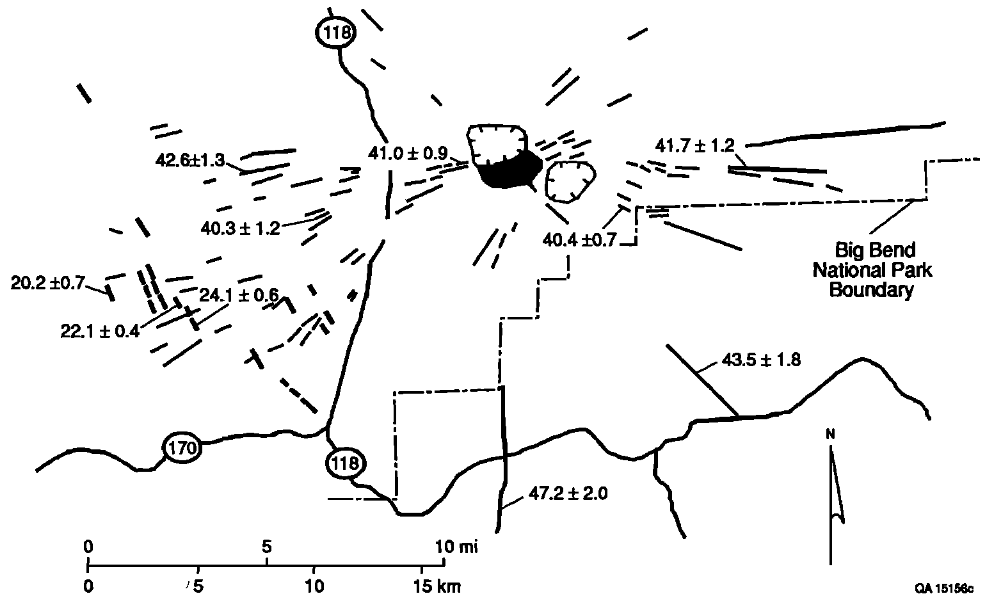

Fig. 5. Dikes in the Christmas Mountains area, southern Trans-Pecos Texas. Lighter lines denote Eocene dikes related to the Christmas Mountains gabbro (shaded) and Christmas Mountains caldera complex (hachured). Only a representative fraction of the 211 measured dikes are shown. Heavy lines denote Miocene dikes related to east-northeast extension. Older dikes show a range of orientations with a maximum at east-northeast. Younger dikes strike uniformly north-northwest. Location and rose diagrams of dike orientations are shown in Figures 4 and 7. Ages from *Henry et al.* [1989] and *Laughlin et al.* [1982].

of extended rocks within both horsts and grabens [*Henry and Price*, 1986]. Strike-slip displacement that could generate significant vertical axis rotation occurred along structures oblique to the east-northeast extension [*Muehlberger*, 1980]; however, the total amount of such displacement was far too small to have rotated significant areas.

Interpretation of east-northeast orientation of σ_1. The preferred east-northeast orientation of dikes and veins in Trans-Pecos Texas indicates that the minimum principal stress (σ_3) was north-northwest and that the maximum principal stress (σ_1) was in the plane of the dikes and veins. However, σ_1 could range from east-northeast to vertical. The former stress field is commonly considered a strike-slip environment, whereas the latter is that of north-northwest extension. Because faulting accompanying magmatism was negligible, interpretation of the true environment is equivocal. As discussed below, we interpret σ_1 to be east-northeast because of (1) evidence for minor, contemporaneous strike-slip faulting, (2) by comparison with the stress field during Laramide folding that immediately preceded magmatism, and (3) by analogy with stress orientations in Arizona and New Mexico.

Two sets of dikes at Glenn Draw in Big Bend National Park illustrate the evidence for strike-slip faulting (Figure 6) [*Price and Henry*, 1988]. At this location, one dike set strikes approximately northeast. The other set forms a west-northwest trending en echelon pattern in which individual dike segments strike east-northeast. We interpret these dikes to fill mode 1 fractures along a left-lateral shear zone. En echelon dikes along complementary northeast trending right-lateral shears occur at two locations within 8 km of the area depicted in Figure 6. The ages of the dikes at Glenn Draw are not well established. The basalt is compositionally like the 48–32 Ma rocks and distinctly unlike the more primitive basalts emplaced after 31 Ma [*Price and Henry*, 1988; *James and Henry*, this issue.] An apparent K-Ar age of 57 Ma (±5.6 Ma) probably reflects excess argon as no Cenozoic igneous rocks are that old in Trans-Pecos Texas

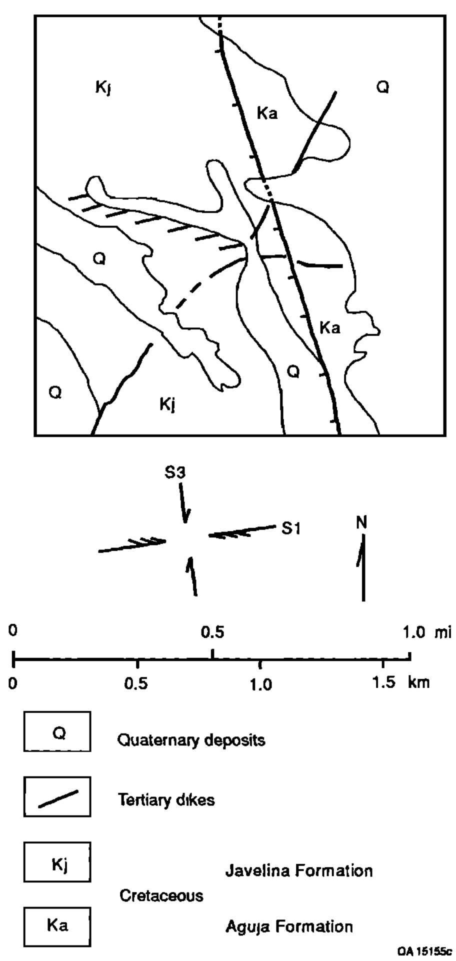

Fig. 6. Geologic map of dikes in Glenn Draw area, Big Bend National Park, modified from *Maxwell et al.* [1967]. Individual dikes in west-northwest striking, en echelon system strike east-northeast, parallel to probable maximum principal stress.

[*Henry et al.*, 1986]; excess argon has been found unequivocally in similar basalts in the Big Bend area [*Harlan et al.*, 1986]. Reliable dates on chemically and petrographically similar rocks in the Big Bend area are mostly around 34 Ma [*Henry and McDowell*, 1986].

Orientations of folds, thrust faults, slickenlines, stylolites, calcite twin lamellae, and other kinematic indicators demonstrate that σ_1 was east-northeast and σ_3 vertical during Laramide folding that preceded magmatism in Texas [*Berge*, 1982; *Moustafa*, 1988; *Erdlac*, 1990]. The similarity in orientation of maximum horizontal stress and the lack of a significant time gap between folding and magmatism suggest that the east-northeast direction continued to be σ_1, although the minimum principal stress (σ_3) rotated from vertical to north-northwest.

The analogy to stress orientations in Arizona and southwestern New Mexico is less direct, but the data are more definitive in those areas. *Heidrick and Titley* [1982] also found east-northeast preferred orientation of dikes and veins. Additionally, they found conjugate shears arranged symmetrically around the dikes and veins that demonstrated that σ_1 was horizontal and approximately N70°E.

Although a stress field with σ_1 and σ_3 horizontal is commonly considered a strike-slip environment, we do not refer to it in this way. Strike-slip faulting, in fact, faulting of any kind, was negligible during magmatism between 48 and 32 Ma in Texas. The only faulting was related to igneous doming and caldera collapse. In contrast, strike-slip faulting was relatively common both during preceding Laramide compression (σ_1 east-northeast and σ_3 vertical) and during subsequent Basin and Range extension (σ_1 vertical and σ_3 east-northeast) as a result of reactivation of west-northwest basement structures under those stress fields [*Muehlberger*, 1980].

Relative stress magnitudes. The considerable scatter of dike and vein orientations around the east-northeast peak suggests that the difference in magnitude between the two horizontal stresses was small. *Delaney et al.* [1986] consider this characteristic of tectonically inactive regions, which seems consistent with the lack of faulting in Trans-Pecos Texas between 48 and 32 Ma. Nevertheless, despite its relative inactivity, the area still had a distinct stress pattern that governed dike and vein orientations.

Amount of northerly extension. The total amount of northerly extension represented by the dikes and veins is small throughout Texas. Both dikes and veins are relatively thin and only locally abundant. Dikes range up to about 10 m thick but probably average about 2 m. Veins are uniformly less than a few meters thick. Even where dikes are most abundant, for example, west of the Christmas Mountains, total extension was no more than a few percent. Areas between dike swarms may have undergone no extension.

Dikes and Veins After 32 Ma

Dike orientations and fault kinematic data indicate a change to σ_3 east-northeast and σ_1 vertical, probably by 31 Ma and definitely by 28 Ma. This change marks the beginning of east-northeast extension, which characterized early extension throughout the Basin and Range province [*Zoback et al.*, 1981].

Sierra Azul, Chihuahua. The earliest evidence for the change occurs in the Sierra Azul of northern Chihuahua, which is part of the San Carlos caldera (Figures 3 and 7) [*Chuchla*, 1981; *Gregory*, 1981]. Dikes in a granitic intrusion there strike dominantly north-northwest (Figures 7 and 8), which indicates that σ_3 was east-northeast. The dikes are accompanied by a series of small-displacement normal faults (Figure 8). Dikes and faults were probably broadly contemporaneous. Faults mostly cut dikes, but a few dikes appear to have intruded along faults. Paleostress analysis from fault and slickenline orientations of 31 faults using the method of *Angelier* [1979] indicates that σ_3 plunged gently S63°W and that σ_1 was nearly vertical (Table 1).

The age of the dikes and therefore of initial east-northeast extension is based largely on a single K-Ar age of 31.4 ± 0.7 Ma on biotite of the host granite [*Gregory*, 1981]. The dikes are fine-grained, porphyritic varieties of the granite and clearly the same age. Dates of 30.2 ± 0.7 and 30.6 ± 0.7 Ma on alkali feldspar phenocrysts from the ash flow tuff derived from the San Carlos caldera lend some support to 31 Ma age. However, field relations do not constrain the relative ages of the granite and ash flow tuff. Additional dating of the granite and particularly the dikes is warranted to constrain the age of the stress change.

Bofecillos Mountains. East-northeast extension was unequivocally established by 28 Ma based on the north-northwest strike of dikes associated with the 28 Ma Bofecillos Mountains volcano (Figure 7). The subsidiary northeast to east peaks may reflect dikes whose orientations were controlled by structures in underlying rocks. The 28 Ma volcanic rocks in the Bofecillos Mountains are underlain by 32 Ma and older volcanic rocks that likely have east-northeast striking joints. Therefore, the 28 Ma east striking dikes may reflect the influence of basement structures, rather than of preexisting joints in the exposed host rocks, as discussed above.

Basin and Range basalts. The youngest igneous activity in Texas consisted of widespread but volumetrically minor alkali basalts and hawaiites emplaced between 24 and 17 Ma (Figures 3d and 7). The rocks are preserved mostly as dikes, but lavas fed by the dikes occur in a few areas. Throughout the region, the dikes dominantly strike north-northwest, indicating continued east-northeast extension. Lengths and orientations of all known dikes were determined at two locations: the Rim Rock dike swarm near the Rio Grande and dikes near Terlingua west of Big Bend National Park (Figure 7).

The Rim Rock dike swarm consists of at least 480 dikes totaling 70 km in length and ranging in age from 24 to 17 Ma [*Dasch et al.*, 1969; *Henry and Price*, 1986]. The dikes are generally vertical and intrude Cretaceous sedimentary rocks and 38–32 Ma Tertiary volcanic and volcaniclastic rocks. The subsidiary west-northwest trend includes many of the oldest dikes of the swarm and parallels a major Precambrian basement trend [*Muehlberger*, 1980]. Dike emplacement along this trend probably reflects initial opening of the basement structure under east-northeast extension [*Henry and Price*, 1986]. As extension continued, the north-northwest trend opened and became dominant. The west-northwest structure is otherwise not apparent in the Cretaceous or Tertiary host rocks; therefore, dike emplacement may have been controlled by the basement structure rather than by preexisting joints in the exposed host. North-northwest striking Basin and Range faults throughout Texas commonly step over along short west-northwest segments that reflect the basement structure.

A smaller swarm, consisting of 35 dikes totalling 5 km long, occurs southwest of the Christmas Mountains (Figures 7 and 5). Three dikes have been dated between 24 and 20 Ma [*Henry et al.*, 1986]. The consistent north-northwest orientation of these dikes contrasts with the generally east-northeast but more

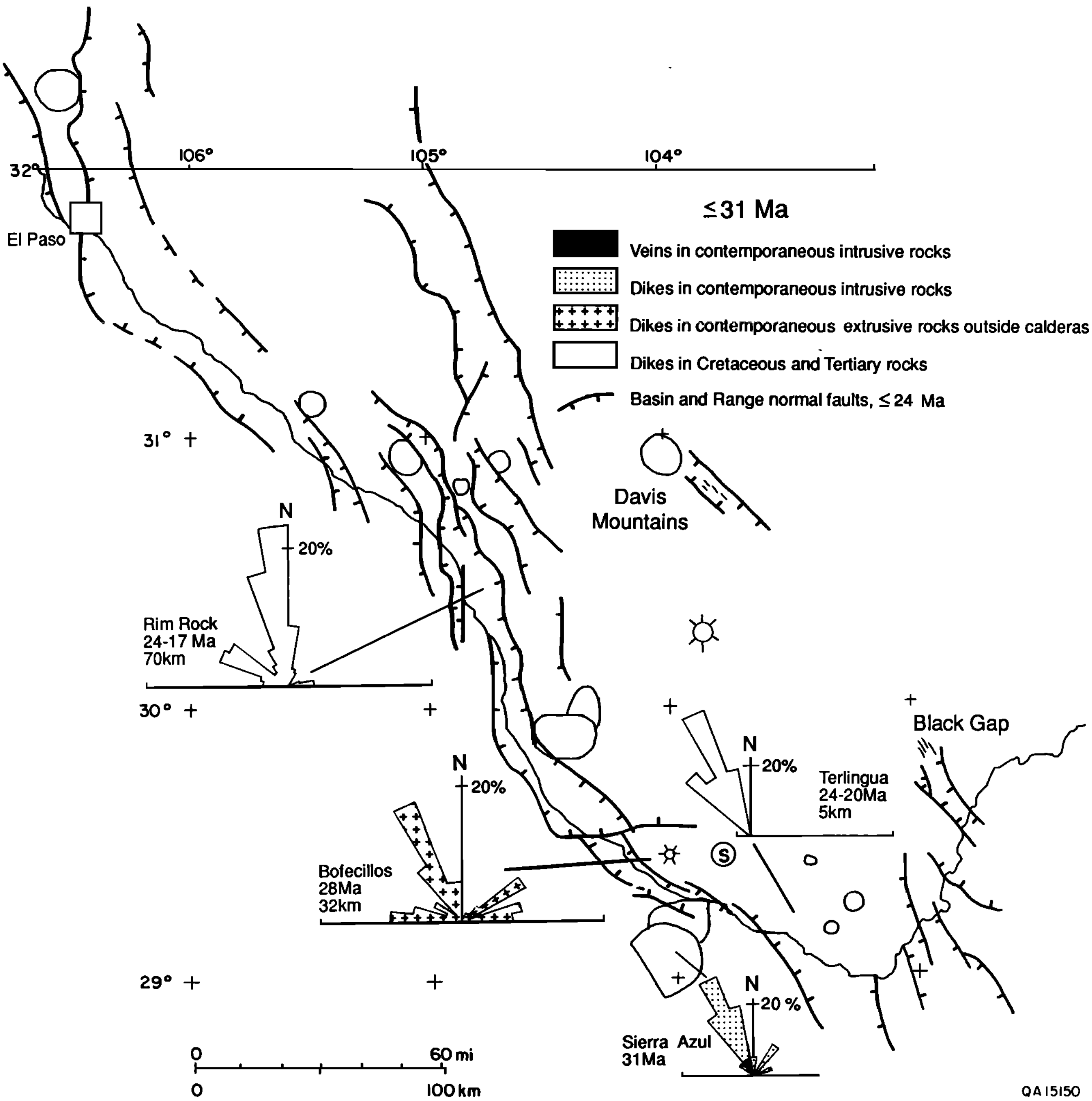

Fig. 7. Dikes, veins, and faults related to post-31 Ma magmatism in Trans-Pecos Texas. Four rose diagrams, constructed from percentages of total strike length as in Figure 4, show orientations of major dike swarms. All features, including 24 Ma dikes in Black Gap and the Davis Mountains strike dominantly north-northwest, indicating that least principal stress was east-northeast. Subsidiary west-northwest and east-northeast peaks reflect reactivation of older structures (see text). Calderas dominantly predate extension but are rarely cut by major Basin and Range faults.

variable orientation of the 42 Ma dike swarm. A few Basin and Range dikes cut dikes of the older swarm.

Relative stress magnitudes. Dikes emplaced after 31 Ma show a much narrower range of orientations than do dikes emplaced before then. This consistency suggests that the two horizontal stresses have considerably different magnitudes. The value of f (0.768 where $f = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$; Table 1) calculated from fault and slickenline data from the Sierra Azul also indicates that σ_2 and σ_3 were significantly different. *Delaney et al.* [1986] characterize this situation as being tectonically active, which, in turn, seems consistent with emplacement of the dikes during active extension.

Timing of Basin and Range faulting. Basin and Range faulting, which was exclusively high-angle, began slightly before 24 Ma. Volcanic rocks of the 28–Ma Santana caldera and Bofecillos volcano show no change in thickness across Basin and Range faults [*Henry and Price*, 1986]. Basalt lavas of the 24 Ma suite are interbedded with lower parts of basin fill in several grabens but are never at the base or below basin fill. Thus faulting must have started sufficiently before 24 Ma

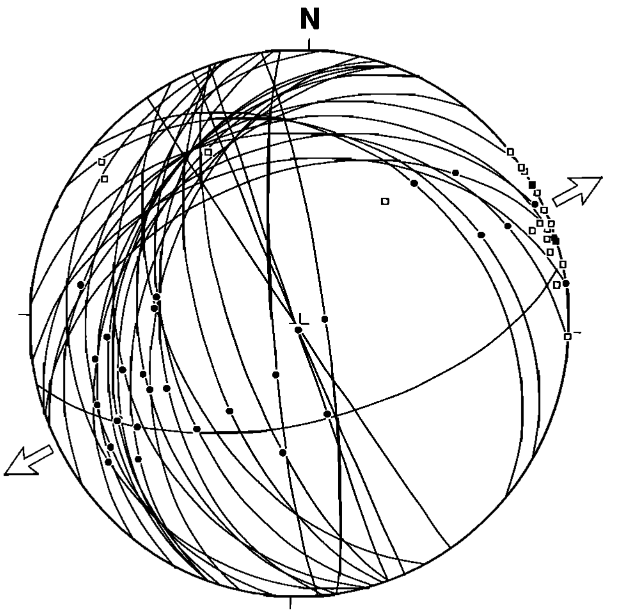

Fig. 8. Stereonet plot of small-displacement faults and slickenlines (curves and solid circles) and poles to dikes (open squares) and veins (solid squares) within the Sierra Azul granite of the San Carlos caldera, Chihuahua. Faults were contemporaneous with dikes of the granite, which is 31 Ma [*Gregory*, 1981; *Chuchla*, 1981]. Quantitative analysis of the fault data indicates that least principal stress (σ_3) was S63°W and the maximum principal stress (σ_1) was approximately vertical (Table 1). Similarly, dike and vein orientations indicate that the least principal stress was east-northeast (see also Figure 7).

for basins to form and accumulate a few tens of meters of coarse sediment. The beginning of significant faulting may have lagged the stress change, which we consider the more fundamental event, by as much as 7 m.y. Nevertheless, both faults and dike orientations indicate east-northeast extension.

STRESS ORIENTATIONS IN THE SOUTHWESTERN UNITED STATES AND NORTHERN MEXICO

A preliminary look at the evidence for paleostress in adjacent areas of the southern Cordillera to compare with the stress evolution in Texas is worthwhile. Comprehensive analyses have been done in southwestern New Mexico and Arizona [*Rehrig and Heidrick*, 1976; *Heidrick and Titley*, 1982], in the Rio Grande rift [*Aldrich et al.*, 1986], and more broadly in the southwestern United States [*Best*, 1988]. Additionally, sparse data are available for northwestern Mexico.

TABLE 1. Stress Orientations Calculated From Slickenline Data, Sierra Azul, Chihuahua (31 Ma) for 31 Faults

	Orientation
σ_1	N7°W 77°
σ_2	S28°E 12°
σ_3	S63°W 5°
$\phi = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$	0.768

New Mexico

Dike and vein orientations in the Organ Mountains caldera of southern New Mexico (Figure 4) illustrate the complexity that can occur. Veins dominantly strike approximately east [*Dunham*, 1935; *Seager*, 1981]; we consider these to be the most reliable indicator of paleostress and therefore indicate σ_3 to be north. Many dikes also strike east, but most dikes strike northwest [*Seager*, 1981]. Conventional K-Ar ages of volcanic and intrusive rocks of the caldera, including one northwest striking dike, are 32 to 33 Ma [*Loring and Loring*, 1980; *Seager*, 1981]. New Ar^{40}/Ar^{39} ages on ash flow tuffs of the Organ caldera, including units previously dated as 33 Ma, are 35.6 and 36.1 Ma [*McIntosh*, 1989]. The Organ batholith, the resurgent intrusion of the caldera that hosts the veins, has not been redated. However, given the brief period of activity of most calderas, the batholith and the veins are most likely 36 Ma.

Newcomer et al. [1983] interpreted the northwest dikes to indicate northeasterly extension, beginning by 32.5 Ma, the K-Ar age of one of the dikes [*Loring and Loring*, 1980]. However, the dikes have not been redated, and the new Ar^{40}/Ar^{39} data suggest that they may be older. A 32.5 Ma age is within analytical uncertainty of the beginning of extension in Texas, whereas 36 Ma is distinctly older. More critically, the dikes do not occupy mode 1 fractures; they are reported to have been emplaced within northwest-striking shear zones [*Seager*, 1981]. Therefore they do not indicate northeasterly extension regardless of their age.

East-northeast extension clearly did begin in the Rio Grande rift in New Mexico at about 31 Ma (Figure 9b) based on dike orientations and domino-style faulting [*Laughlin et al.*, 1983; *Chamberlin*, 1983; *Aldrich et al.*, 1986]. Also, substantial east-northeast extension occurred at 26 Ma in the Latir volcanic field in northern New Mexico [*Lipman*, 1983]. We find no evidence for east-northeast extension as early as 40 Ma as proposed by *Elston* [1984] for the Mogollon-Datil volcanic field.

Arizona and Southwestern New Mexico Laramide

Rehrig and Heidrick [1976] and *Heidrick and Titley* [1982] examined in great detail the orientations of dikes and veins associated with Laramide plutons (75–50 Ma) of Arizona and southwestern New Mexico. They found a dominant east-northeast orientation to purely dilatant joints throughout this region (Figure 9a). Additionally, they found two sets of fractures, N60°E and N80°E, with horizontal slickensides that represent conjugate shear. From all these data, *Heidrick and Titley* [1982] concluded that the maximum principal stress was N72°E and the least principal stress perpendicular to that; this stress field persisted to at least 56 Ma and possibly to 50 Ma. Furthermore, they attributed this stress pattern to similarly oriented Farallon-North America plate convergence, an interpretation with which we agree.

Rehrig and Heidrick additionally determined that upper Tertiary (<30 Ma) epithermal veins in Arizona dominantly strike north-northwest (Figure 9b). They interpreted this to indicate east-northeast extension. Although the paucity of magmatism between about 50 and 30 Ma in Arizona precludes determining the exact time of change, the stress evolution there appears to be identical to that in Texas.

Southwestern United States

Best [1988] interpreted a more complex evolution of stress from dike orientations in part of the southwestern United States

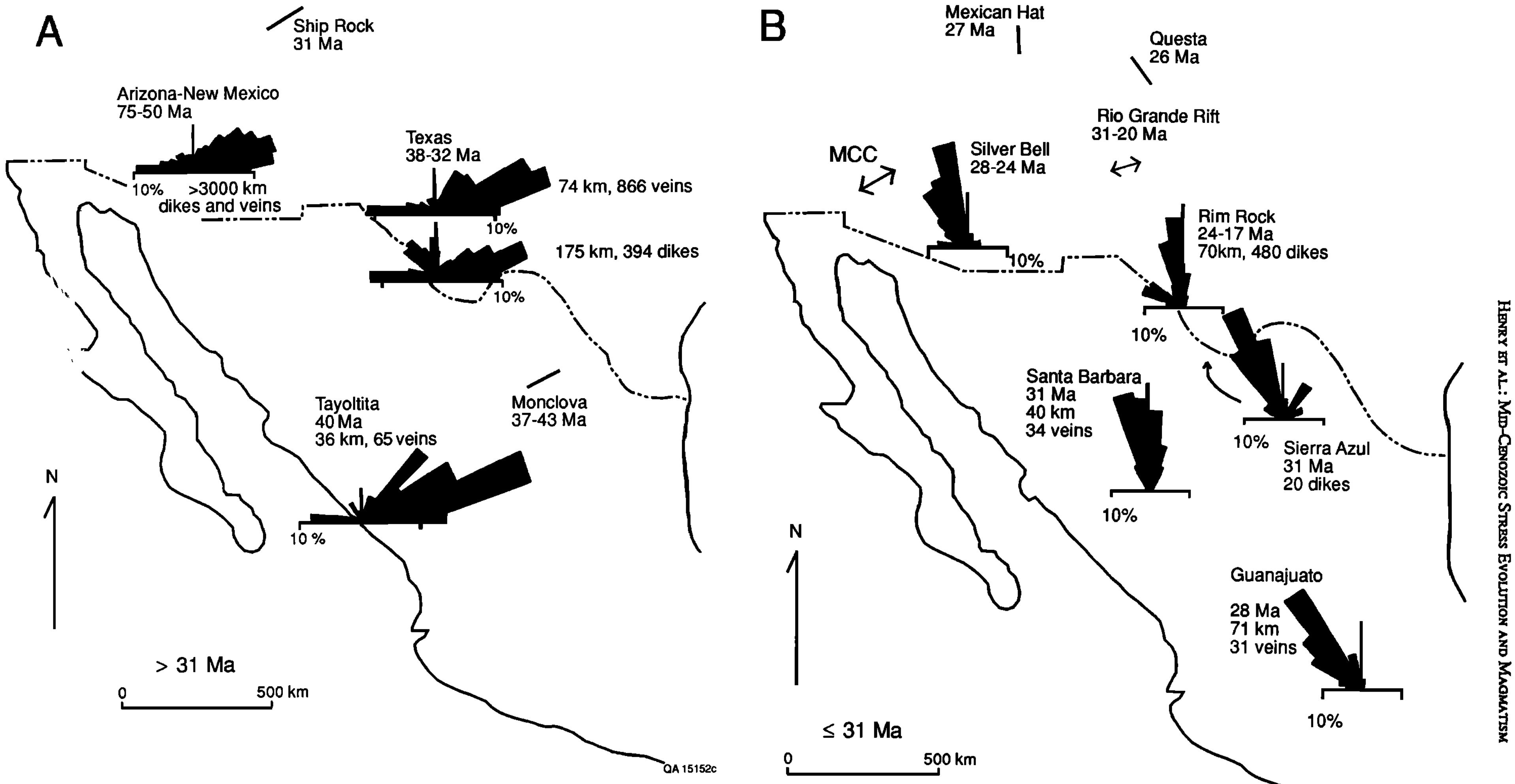

Fig. 9. Summary of paleostress indicators in the southern Cordillera. (a) Pre-31 Ma dikes and veins dominantly strike east-northeast. Data from *Heidrick and Titley* [1982] for Arizona and New Mexico, *Smith et al.* [1982] for Tayoltita, Durango, and this study for Texas. Line at Ship Rock indicates orientation of dike that was definitely emplaced perpendicular to the least principal stress (s_3) [*Delaney et al.*, 1986]. Line at Monclova represents orientation of dikes and intrusive belts [*Sewell*, 1968; R. E. Denison, personal communication, 1989]. (b) Post-31 Ma dikes and veins dominantly strike north-northwest. Data sources: Silver Bell, Arizona [*Rehrig and Heidrick*, 1976], representative of post-30 Ma orientations in Arizona; Mexican Hat, Utah (line indicates dike emplaced perpendicular to least principal stress [*Delaney et al.*, 1986]); Questa, New Mexico (line indicates general dike orientations from *Lipman* [1983]); Rim Rock and Sierra Azul, this study; Santa Barbara (vein orientations from Santa Barbara G13A57 geologic map, Detenal; age on vein adularia from *Grant and Ruiz* [1988]); and Guanajuato (orientation and age from *Gross* [1975]). Also, lines with arrows indicate direction of least principal stress (σ_3) determined from detachment faults and metamorphic core complexes in southern California and Arizona (MCC [*Wust*, 1986]) and from dikes and domino-style faults in the central Rio Grande rift [*Laughlin et al.*, 1983; *Chamberlin*, 1983; *Aldrich et al.*, 1986].

from Nevada to Texas. He interpreted the change in least principal stress from more northerly to easterly to have occurred diachronously, from as old as 31 Ma in Texas (based on our data) to 26 Ma or even 18 Ma farther north and west. However, Best noted that dike orientations seemed to indicate continued northerly least principal stress whereas extension in contemporaneous metamorphic core complexes in southern California, Arizona, and Sonora was uniformly east-northeast (Figure 9b) [*Wust*, 1986]. Also, *Delaney et al.* [1986] analyzed the orientations of dikes and related joints to indicate a change in least principal stress from N34°W to N80°–90°E between approximately 31 and 27 Ma in southern Utah and northern New Mexico (Figure 9a, Ship Rock, and Figure 9b, Mexican Hat). This area is within the Colorado Plateau so its application to the Basin and Range province is uncertain. Nevertheless, some of Best's data were also from the plateau immediately adjacent to the area examined by Delaney et al.

The resolution to this discrepancy may lie in the data used by *Best* [1988]. To minimize the influence of preexisting joints formed in older stress fields, he used dikes emplaced into host rocks that were only slightly older than the dikes. However, nearly half of the resultant 27 occurrences consisted of only one to three dikes. Without knowing the details of each occurrence and noting all the uncertainties listed above, we suggest that the small number of dikes measured in some areas may not allow a reliable determination of paleostress. Instead, the sum of data mentioned here is consistent with a change in least principal stress from north-northwest to east-northeast about 30 Ma throughout the southwestern United States.

Northern Mexico

Our preliminary data on the evolution of stress in northern Mexico indicate a similar stress evolution to that in the southwestern United States [*Price, et al.*, 1988; *Drier, 1984*]. Epithermal veins at the major mining district of Tayoltita, Durango, west of the Sierra Madre Occidental, strike dominantly east-northeast (Figure 9a) [*Smith et al.*, 1982]. Dating of host rocks and vein adularia indicates that vein formation occurred at 40 Ma (C. D. Henry and F. W. McDowell, unpublished data, 1990). A belt of 37-43 Ma intrusions near Monclova, Coahuila, also indicates east-northeast s_1 (Figure 9a). The belt itself strikes east-northeast, and dikes related to the intrusions strike east-northeast [*Sewell*, 1968; R. E. Denison, unpublished data, 1990].

Examples of east-northeast extension in northern Mexico are widespread both east and west of the Sierra Madre Occidental, a relatively unextended block [*Henry*, 1989]. In general, northern Mexico is a little recognized continuation of the Basin and Range province characterized by north-northwest striking basins and ranges [*Stewart*, 1978; *Henry*, 1989]. Several major mining districts, including Santa Barbara-Parral [*Grant and Ruiz*, 1988] and Guanajuato [*Gross*, 1975], are characterized by generally northwest-north striking vein systems and are reliably dated at between 31 and 28 Ma (Figure 9b). At Guanajuato, the veins occupy contemporaneously active northwest-striking faults [*Gross*, 1975] that indicate substantial northeast extension.

Other evidence for east-northeast extension includes a 28 Ma north-northwest striking dike swarm in Sinaloa, west of the Sierra Madre Occidental [*Henry and Fredrikson*, 1987; *Henry*, 1989]. Near Nazas, east of the Sierra Madre, *Aguirre-Diaz and McDowell* [1988] found 23 Ma alkali basalts related to north-northwest striking grabens. The rocks are chemically similar to the Basin and Range basalts of similar age in Texas, occupy identical structural positions, and indicate a similar tectonic-magmatic setting.

The available data in northern Mexico thus indicate east-northeast σ_1 at least to about 37 Ma and east-northeast σ_3 beginning by about 31 Ma. The abundance of evidence for east-northeast extension between 31 and 28 Ma suggests that it may have begun then. At the least, the data allow a similar stress history as found to the north. Clearly, more thorough study is needed to understand stress evolution in northern Mexico.

CENOZOIC STRESS EVOLUTION IN THE SOUTHERN CORDILLERA

During Laramide Deformation

The comparison of data from the southwestern United States and northern Mexico suggests a similar stress history throughout this region. Laramide folding occurred at different times in Arizona and Texas but largely preceded magmatism in both areas [*Drewes*, 1978; *Henry and McDowell*, 1986]. The so-called Laramide plutons of Arizona mostly postdate major folding, although minor, later folding may have occurred locally [*Drewes*, 1978]; thus Laramide deformation there occurred largely before 70 Ma. In Texas, Laramide folding occurred in the early Eocene [*Wilson*, 1971], ended at about 50 Ma, and preceded all magmatism. The 47–48 Ma intrusive rocks in the El Paso area crosscut Laramide folds and are themselves undeformed [*Hoover et al.*, 1988]. Basalt lavas of the same age in Big Bend unconformably overlie folded Cretaceous rocks. Possibly magmas, if present, could not penetrate the crust in a strongly compressional environment.

Despite the difference in timing of Laramide folding, stress orientations during folding in Texas and Arizona were similar. Transport directions, orientations of folds, thrust faults, slickenlines, stylolites, calcite twin lamellae, and other kinematic indicators demonstrate that σ_1 was east-northeast and σ_3 vertical [*Drewes*, 1978; *Berge*, 1982; *Moustafa*, 1988; *Erdlac*, 1990].

During Mid-Cenozoic Magmatism

Stress orientations during magmatism immediately following Laramide folding appear to be similar throughout a transect from southern Arizona to Texas and likely in northern Mexico. The maximum principal stress was east-northeast, as it was during folding, but the minimum principal stress rotated from vertical to north-northwest. Note, however, that because Laramide folding occurred much later in Texas than in Arizona, σ_3 was north-northwest in Arizona at the same time that it was vertical in Texas. Nevertheless, throughout this region before about 31 Ma, the maximum principal stress appears to have been east-northeast. In Texas before 31 Ma, both the western, alkali-calcic and the eastern, alkalic belt show similar east-northeast dike and vein orientations, indicating that both belts were experiencing the same stress field.

A distinct change in the stress field, to σ_3 east-northeast and σ_1 vertical or east-northeast extension, occurred throughout the region. Where best dated in Trans-Pecos Texas, this change occurred at least by 28 Ma and possibly abruptly at 31 Ma. The time of change is less constrained in other parts of the southwestern United States and in northern Mexico, but the data allow the change to have occurred at 31 Ma also.

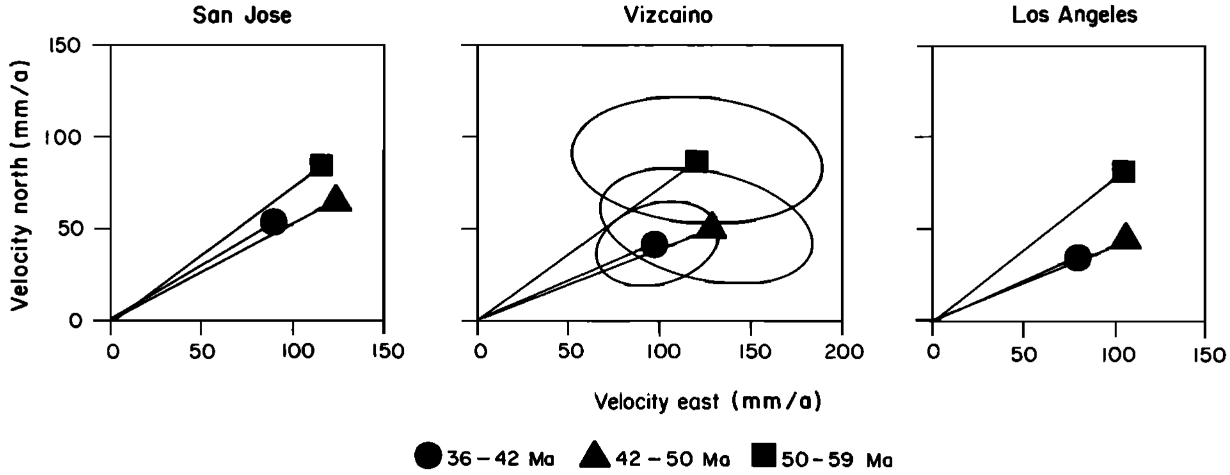

Fig. 10. Farallon-North American plate convergence directions and rates [*Stock and Molnar*, 1988]. Locations, which span the southern Cordillera, are San Jose, mouth of Gulf of California; Vizcaino, Vizcaino Peninsula, Baja California; Los Angeles, Los Angeles, California. Ages span time of most activity discussed here. Ellipses for Vizcaino plot indicate uncertainties determined by Stock and Molnar.

ORIGIN OF THE STRESS PATTERNS

The similarity in stress patterns throughout such a wide area requires a regional cause, which we suggest is related to plate interactions. In particular, the east-northeast maximum principal stress is parallel to Farallon-North American plate convergence at the time (Figure 10) [*Stock and Molnar*, 1988]. The data in Figure 10 span the southern Cordillera from about the Trans-Mexican volcanic belt to the southern United States and most of the time of earlier magmatism discussed here. Note that the dike and vein orientations and inferred maximum principal stress are parallel to the convergence direction.

Similar fracture patterns and stress fields (i.e., perpendicular to the continental margin and parallel to convergence) are common in convergent margins [*Nakamura and Uyeda*, 1980; *Hancock and Bevan*, 1987; *Feraud et al.*, 1987]. Additionally, maximum horizontal stress is commonly parallel to absolute plate motions [*Zoback et al.*, 1989]. Although the origin of broad-scale stress fields is beyond the scope of this paper, proposed mechanisms that seem likely include shear traction at the base of the lithosphere that is driving or resisting plate motion [*Zoback et al.*, 1989] or shear between the subducting and overriding plates [*McKenzie*, 1969; *Nakamura and Uyeda*, 1980].

The only unusual aspect of the stress field in Texas before 31 Ma is its existence so far inboard from the continental margin. We suggest that this reflects the commonly cited shallow subduction at the time [e.g., *Lipman et al.*, 1971; *Coney and Reynolds*, 1977]. The stress field in Texas before 31 Ma corresponds to a variation of case 1 of *Nakamura and Uyeda* [1980], in which the maximum horizontal stress remains parallel to convergence from arc to back arc regions but changes from σ_1 to σ_2. Nakamura and Uyeda suggested that this reflects gradual landward diminution of compressive stress. The maximum horizontal stress may have remained σ_1 over a wide zone perpendicular to the continental margin in the southern Cordillera because the zone of coupling between the shallowly subducting slab and the overriding North American plate was so broad.

The data of *Stock and Molnar* [1988] also bear on the timing, origin, and style of Laramide deformation. They found that convergence slowed most significantly between 56 and 50 Ma and that the convergence direction rotated clockwise, from northeast to east-northeast. They noted that the 50 Ma slowdown does not correspond to the commonly cited 40 Ma end of the Laramide orogeny [*Coney*, 1972] and that clockwise rotation was opposite to the suggested counterclockwise rotation of the orientation of crustal shortening [*Chapin and Cather*, 1983]. Both observations of *Stock and Molnar* [1988] coincide exceptionally well with the timing and orientation of Laramide deformation in Texas, however. Paleontologic data [*Wilson*, 1971] and the ages of undeformed igneous rocks that immediately follow folding indicate that Laramide deformation ended by approximately 50 Ma. Additionally, orientations of folds, faults, stylolites, and calcite twin lamellae indicate that σ_1 rotated from northeast to east-northeast during Laramide folding [*Berge*, 1982; *Price et al.*, 1985]. *Dickinson et al.* [1988] interpreted a diachronous end to Laramide deformation as late as 35 Ma in New Mexico. However, their data are inconsistent with its unequivocal end at 50 Ma in Texas immediately south of New Mexico. Thus, on the basis of Stock and Molnar's data, we find a good correlation between timing and orientation of Laramide deformation and rate and direction of plate convergence. Furthermore, we suggest that the stress field between 50 and about 30 Ma continued to reflect convergence but that the slower convergence resulted in a lower stress magnitude insufficient for significant deformation to continue.

Our data also provide some constraints on current models of the origin of mid to late Cenozoic extension in western North America. These models emphasize either plate interactions [*Atwater*, 1970; *Glazner and Bartley*, 1984; *Engebretson et al.*, 1984] or gravitational collapse of overthickened crust [*Wernicke et al.*, 1987]. Extension may have begun contemporaneously throughout the southern Cordillera and at nearly the same time as collision of the East Pacific Rise and paleotrench about 29 Ma [*Stock and Molnar*, 1988]. This collision marked the beginning of the end of convergence over much of the western margin of the North American plate. Additionally, the area of extension in Trans-Pecos Texas does not coincide with areas of likely crustal thickening. Laramide folding was limited to the western margin of Texas, along the Rio Grande, and the volume of preextensional magmatism seems too small to have induced much crustal thickening. Thus the data seem more supportive of a mechanism of extension related to the end of convergence and the change in type of plate margin than to collapse of overthickened crust. The possibility that extension began nearly contemporaneously over such a broad area also suggests that it is not solely related to triple junction migration along the continental margin [*Ingersoll*, 1982; *Glazner and Bartley*, 1984].

TECTONIC SETTING OF TRANS-PECOS MAGMATISM

Synthesis of regional age patterns with paleostress and geochemical data [*James and Henry*, this issue] from Trans-Pecos Texas provides a clear picture of the evolution of magmatism there: from a continental volcanic arc through 32 Ma to regional (Basin and Range) extension afterward.

Briefly, the evidence for a continental arc setting up to 32 Ma includes (1) the regional age pattern, where magmatism in Texas is part of a geographic and temporal continuum with activity along the west coast that is clearly subduction related (Figure 2); (2) the paleostress data, which we interpret to be related to paleoconvergence (Figures 4, 9a, and 10); and (3) geochemical data that indicate a continental arc setting [*James and Henry*, this issue]. The geochemical evidence includes (1) the presence of differentiation suites, more alkalic than, but otherwise similar to those of typical continental volcanic arcs; (2) evolution of the differentiation suites from relatively evolved, mantle-derived mafic rocks by fractionation and variable crustal assimilation; and (3) arc trace element signatures (low Nb and Ta, high large ion lithophile elements). Pre-31 Ma Trans-Pecos magmatism is simply a more alkalic version of a typical continental volcanic arc. These characteristics apply across the province: to the western, alkali-calcic and eastern, alkalic belts, to peralkaline rocks in both belts, and to silica-undersaturated differentiation suites that occur in the eastern belt.

The beginning of regional, east-northeast extension at about 31 Ma is accompanied by a two-stage change in composition of erupted magmas. Initially, between 31 and 28 Ma, erupted rocks were bimodal. Although the rocks display within-plate or rift trace element signatures, they are intermediate in some geochemical measures of arc versus continental rift environment (see discussion by *James and Henry* [this issue]). Contemporaneously, magmatism with a clear arc trace element signature, the southern Cordilleran basaltic andesite suite (SCORBA) of *Cameron et al.* [1989], continued to the west in northern Mexico. Similar to 28 Ma activity in Texas, SCORBA appears to be part of a bimodal suite that includes minor evolved rhyolites. The overall pattern and characteristics of 28 Ma magmatism in the southern Cordillera suggest that regionally, the arc did not extinguish abruptly. Indeed, subduction continued along much of the continental margin to the west, ceasing only when the southern triple junction jumped to near the mouth of the present Gulf of California about 12.5 Ma [*Mammerickx and Klitgord*, 1982]. Nevertheless, the contemporaneity of the stress and compositional changes suggest that they are related, possibly to the encroachment and collision of the East Pacific Rise and paleotrench about 29 Ma [*Stock and Molnar*, 1988].

By 24 Ma, igneous activity in Texas consisted exclusively of alkalic basalts, typical of continental rifts, that accompanied major Basin and Range faulting. The basalts are relatively primitive, as shown by high Mg numbers and Ni contents, and have Nb and Ta highs on spidergrams. These basalts have asthenospheric sources with no suggestion of an arc component [*James and Henry*, this issue].

These data and interpretations may provide some constraints on the history of plate interactions in the southern Cordillera, which is poorly constrained by plate kinematic models [*Severinghaus and Atwater*, 1990]. Severinghaus and Atwater modeled the thermal evolution of the subducting slab beneath North America to determine when it became rheologically incapable of seismicity. The same model also suggests the relative capability of the slab to generate magmatism and transmit stress. By the criteria of Severinghaus and Atwater, arc magmatism probably should not have been occurring in Texas at 35 Ma. The clear presence of arc magmatism in Texas at that time suggests either (1) that arc magmatism can occur even after the slab is seismically inactive or (2) that subduction geometry is insufficiently known for the southern Cordillera, as suggested by Severinghaus and Atwater.

INTERPRETATION OF ANCIENT RECORD

Finally, we note that our data have implications for interpreting older tectonic settings. Pre-31 Ma igneous rocks of Trans-Pecos Texas could be interpreted to be anorogenic, given their lack of significant, coeval deformation and similarity in composition to what have been called anorogenic granites [*Anderson*, 1983]. Nevertheless, the relatively subtle evidence of dike and vein orientations indicate that pre-31 Ma magmatism occurred in a continental volcanic arc related to a distant convergent margin. It is becoming increasingly apparent that alkalic rocks are quite comfortable in plate margin or orogenic settings [*Whalen et al.*, 1987; *Reagan and Gill*, 1989], including strongly compressional ones [*Halliday et al.*, 1987].

On the other hand, magmatism in Texas was preceded and followed, by only a few million years, by major compressional and extensional deformation. Indeed, magmatism was continuous into the episode of extension. In older igneous terranes, resolution of such small time differences could be difficult, and magmatism could be interpreted to be contemporaneous with either of the deformations. As an example, *Barker* [1977] initially suggested an analogy between Trans-Pecos Texas and the East African rift. He did so on the basis of similarity of rock compositions and, without the benefit of recent dating, on the assumption that extension and magmatism in Texas were contemporaneous. Thus interpretation of older igneous settings must recognize that changes can occur rapidly.

Acknowledgments. Research support was provided by the U.S. Bureau of Mines grant G1194148 to the Texas Mining and Mineral Resources Research Institute and by the COGEOMAP program of the U.S. Geological Survey (Cooperative Agreement 14-08-0001-A0408 and 14-08-0001-A0662). We thank C. E. Chapin and A. W. Laughlin for reviews.

REFERENCES

Aguirre-Diaz, G., and F. W. McDowell, Nature and timing of faulting in the southern Basin and Range, central-eastern Durango, Mexico, *Eos Trans AGU*, *69*, 1412–1413, 1988.

Albritton, C. C., and J. F. Smith, Geology of the Sierra Blanca area, Hudspeth County, Texas, *U.S. Geol. Surv. Prof. Pap.*, *479*, 131 pp., 1965.

Aldrich, M. J., Jr., C. E. Chapin, and A. W. Laughlin, Stress history and tectonic development of the Rio Grande rift, New Mexico, *J. Geophys. Res.*, *91*, 6199–6211, 1986.

Anderson, J. L., Proterozoic anorogenic granite plutonism of North America, *Mem. Geol. Soc. Am.*, *161*, 133–154, 1983.

Anderson, T. H., and L. T. Silver, Late Cretaceous plutonism in Sonora, Mexico and its relationship to circum-Pacific magmatism, *Geol. Soc. Am. Abstr. Programs*, *6*, 484, 1974.

Angelier, J., Determination of the mean principal stress for a given fault population, *Tectonophysics*, *56*, 17–26, 1979.

Atwater, T., Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, *Geol. Soc. Am. Bull.*, *81*, 3513–3536, 1970.

Barker, D. S., Northern Trans-Pecos magmatic province: Introduction and comparison with the Kenya Rift, *Geol. Soc. Am. Bull.*, *88*, 1421–1427, 1977.

Berge, T., Structural evolution of the northeastern Chihuahua tectonic belt, in *Geological Studies of the Cordilleran Thrust Belt*, vol. 1, edited by R. B. Powers, pp. 451–457, Rocky Mountain Association of Geologists, Denver, Colo., 1982.

Best, M. G., Early Miocene change in direction of least principal stress, southwestern United States: Conflicting inferences from dikes and metamorphic core-detachment fault terranes, *Tectonics*, *7*, 249–259, 1988.

Cameron, K. L., G. J. Nimz, D. Kuenz, S. Niemeyer, and S. Gunn, Southern Cordilleran basaltic andesite suite, southern Chihuahua, Mexico: A link between Tertiary continental arc and flood basalt magmatism in North America, *J. Geophys. Res.*, *94*, 7817–7840, 1989.

Cepeda, J. C., and C. D. Henry, Oligocene volcanism and multiple caldera formation in the Chinati Mountains, Presidio County, Texas, *Rep. Invest. 135*, 32 pp., Bur. of Econ. Geol., Univ. of Tex. at Austin, 1983.

Chamberlin, R. M., Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico: A summary, *Field Conf. Guideb., N. M. Geol. Soc.*, *34*, 111–118, 1983.

Chapin, C. E., and S. M. Cather, Eocene tectonics and sedimentation in the Colorado Plateau-Rocky Mountain area, in *Rocky Mountain Foreland Basins and Uplifts*, edited by J. D. Lowell, pp. 33–56, Rocky Mountain Association of Geologists, Denver, Colo., 1983.

Chuchla, R. J., Reconnaissance geology of the Sierra Rica area, Chihuahua, Mexico, M.S. thesis, 199 pp., Univ. of Tex. at Austin, 1981.

Coney, P. J., Cordilleran tectonics and North American plate motion, *Am. J. Sci.*, *272*, 603–628, 1972.

Coney, P. J., and S. J. Reynolds, Cordilleran Benioff zones, *Nature*, *270*, 403–406, 1977.

Damon, E., M. Shafiqullah, and K. F. Clark, Age trends of igneous activity in relation to metallogenesis in the southern Cordillera, *Ariz. Geol. Soc. Dig.*, *14*, 137–154, 1981.

Dasch, E. J., R. L. Armstrong, and S. E. Clabaugh, Age of Rim Rock dike swarm, Trans-Pecos Texas, *Geol. Soc. Am. Bull.*, *80*, 1819–1824, 1969.

Delaney, T., D. D. Pollard, J. I. Ziony, and E. H. McKee, Field relations between dikes and joints: Emplacement processes and paleostress analysis, *J. Geophys. Res.*, *91*, 4920–4938, 1986.

Dickinson, W., M. A. Klute, M. J. Hayes, S. U. Janecke, E. R. Lundin, M. A. McKittrick, and M. D. Olivares, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region, *Geol. Soc. Am. Bull.*, *100*, 1023–1039, 1988.

Drewes, H., The Cordilleran orogenic belt between Nevada and Chihuahua, *Geol. Soc. Am. Bull.*, *89*, 641–657, 1978.

Drier, J., Regional tectonic controls of epithermal veins in the western U. S. and Mexico, *Ariz. Geol. Soc. Dig.*, *15*, 28–52, 1984.

Dunham, K. C., The geology of the Organ Mountains, *Bull. N. M. Bur. Mines Miner. Resour.*, *11*, 272 pp., 1935.

Elston, W. E., Subduction of young oceanic lithosphere and extensional orogeny in southwestern North America during mid-Tertiary time, *Tectonics*, *3*, 229–250, 1984.

Emerman, S. H., and R. Marrett, Why dikes?, *Geology*, *18*, 231–233, 1990.

Engebretson, D. C., A. Cox, and G. A. Thompson, Correlation of plate motions with continental tectonics: Laramide to Basin-Range, *Tectonics*, *3*, 115–120, 1984.

Erdlac, R. J., A Laramide-age push-up block: The structures and formation of the Terlingua-Solitario structural block, Big Bend region, Texas, *Geol. Soc. Am. Bull.*, *102*, 1065–1076, 1990.

Feraud, G., G. Giannerini, and R. Campredon, Dyke swarms as paleostress indicators in areas adjacent to continental collision zones: Examples from the European and northwest Arabian plates, in Mafic dyke swarms, *Geol. Assoc. Can. Spec. Pap.*, *34*, 273–278, 1987.

Gans, B., G. A. Mahood, and E. Schermer, Synextensional magmatism in the Basin and Range province; a case study from the eastern Great Basin, *Spec. Pap. Geol. Soc. Am.*, *233*, 53 pp., 1989.

Gastil, R. G., G. J. Morgan, and D. Krummenacher, The tectonic history of peninsular California and adjacent Mexico, in *The Geotectonic Development of California*, edited by W. G. Ernst, pp. 285–306, Prentice-Hall, Englewood Cliffs, N.J., 1981.

Glazner, A. F., and J. M. Bartley, Timing and tectonic setting of Tertiary low-angle normal faulting and associated magmatism in the southwestern United States, *Tectonics*, *3*, 385–396, 1984.

Grant, G. J., and J. Ruiz, The Pb-Zn-Cu-Ag deposits of the Granadena Mine, San Francisco del Oro-Santa Barbara district, Chihuahua, Mexico, *Econ. Geol.*, *83*, 1683–1702, 1988.

Gregory, J. L., Volcanic stratigraphy and K-Ar ages of the Manuel Benavides area, northeastern Chihuahua, Mexico, and correlations with the Trans-Pecos Texas volcanic province, M. S. thesis, 78 pp., Univ. of Tex. at Austin, 1981.

Gross, W. H., New ore discovery and source of silver-gold veins, Guanajuato, Mexico, *Econ. Geol.*, *70*, 1175–1189, 1975.

Hagstrum, J. T., and D. A. Sawyer, Late Cretaceous paleomagnetism and clockwise rotation of the Silver Bell Mountains, south central Arizona, *J. Geophys. Res.*, *94*, 17,847–17,860, 1989.

Halliday, A. N., M. Aftalion, I. Parsons, A. P. Dickin, and M. R. W. Johnson, Syn-orogenic alkaline magmatism and its relationship to the Moine Thrust Zone and the thermal state of the Lithosphere in NW Scotland, *J. Geol. Soc. London*, *144*, 611–617, 1987.

Hancock, L., and T. G. Bevan, Brittle modes of foreland extension, in Continental Extensional Tectonics, edited by M. P. Coward, J. F. Dewey, and L. Hancock, *Geol. Soc. Spec. Publ. London*, *28*, pp. 127–137, 1987.

Harlan, S. B., J. W. Geissman, J. G. Price, C. D. Henry, T. C. Onstott, and J. Oldow, Paleomagnetic documentation of the cessation of Chihuahuan fold thrust belt deformation, SW Texas, *Geol. Soc. Am. Abstr. Programs*, *19*, 810, 1987.

Heidrick, T. L., and S. R. Titley, Fracture and dike patterns in Laramide plutons and their structural and tectonic implications, in *Advances in Geology of Porphyry Copper Deposits, Southwestern North America*, edited by S. R. Titley, pp. 73–91, Univ. of Ariz., Tucson, 1982.

Henry, C. D., Geology and geochronology of the granite batholithic complex, Sinaloa, Mexico, Ph.D. dissertation, 144 pp., Univ. of Tex. at Austin, 1975.

Henry, C. D., Late Cenozoic Basin and Range structure in western Mexico adjacent to the Gulf of California, *Geol. Soc. Am. Bull.*, *101*, 1147–1156, 1989.

Henry, C. D., and G. Fredrikson, Geology of a part of southern Sinaloa, Mexico adjacent to the Gulf of California, *Geol. Soc. Am. Map Chart Ser.*, *MCH062*, 1987.

Henry, C. D., and F. W. McDowell, Geochronology of magmatism in the Tertiary volcanic field, Trans-Pecos Texas, *Guideb. 23*, pp. 99–122, Bur. of Econ. Geol., Univ. of Tex. at Austin, 1986.

Henry, C. D., and J. G. Price, Variations in caldera development in the Tertiary volcanic field of Trans-Pecos Texas, *J. Geophys. Res.*, *89*, 8765–8786, 1984.

Henry, C. D., and J. G. Price, Early Basin and Range development in Trans-Pecos Texas and adjacent Chihuahua: Magmatism and orientation, timing, and style of extension, *J. Geophys. Res.*, *89*, 6213–6224, 1986.

Henry, C. D., and J. G. Price, The Christmas Mountains caldera complex, Trans-Pecos Texas: The geology and development of a laccocaldera, *Bull. Volcanol.*, *52*, 97–112, 1989.

Henry, C. D., F. W. McDowell, J. G. Price, and R. C. Smyth, Compilation of potassium-argon ages of Tertiary igneous rocks, Trans-Pecos Texas, *Geol. Circ. 86-2*, 34 pp., Bur. of Econ. Geol., Univ. of Tex. at Austin, 1986.

Henry, C. D., J. G. Price, and D. Miser, Geology and Tertiary igneous activity of the Hen Egg Mountain and Christmas Mountains quadrangles, Trans-Pecos Texas: *Rep. Invest. 183*, 105 pp., Bur. of Econ. Geol., Univ. of Tex. at Austin, 1989.

Henry, C. D., J. G. Price, J. N. Rubin, and S. E. Laubach, Case study of an extensive silicic lava: The Bracks Rhyolite, Trans-Pecos Texas, *J. Volcanol. Geotherm. Res.*, *43*, 113–132, 1990.

Hoover, J. D., S. E. Ensenat, C. G. Barnes, and R. Dyer, Early Trans-Pecos magmatism: Petrology and geochemistry of Eocene intrusive rocks in the El Paso area, *Field Conf. Guideb., N. M. Geol. Soc.*, *39*, 109–118, 1988.

Ingersoll, R. V., Triple-junction instability as cause for late Cenozoic extension and fragmentation of the Western United States, *Geology, 10*, 621–624, 1982.

James, E. W., and C. D. Henry, Compositional changes in Trans-Pecos Texas magmas coincident with Cenozoic stress realignment, *J. Geophys. Res.*, this issue.

Keith, S. B., Paleosubduction geometries inferred from Cretaceous and Tertiary magmatic patterns in southwestern North America, *Geology, 6*, 516–521, 1978.

Kunk, M. J., and C. D. Henry, A detailed chronology of silicic volcanism in the Davis Mountains, Trans-Pecos Texas, *Geol. Soc. Am. Abstr. Programs, 22*, A351, 1990.

Laughlin, A. W., C. Kress, and M. J. Aldrich, K-Ar ages of dike rocks, Big Bend National Park, Texas, *Isochron West, 35*, 17–18, 1982.

Laughlin, A. W., M. J. Aldrich, and D. T. Vaniman, Tectonic implications of mid-Tertiary dikes in west-central New Mexico, *Geology, 11*, 45-48, 1983.

Lindgren, W., The igneous geology of the Cordilleras and its problems, in *Problems of American Geology*, pp. 234–286, Yale University Press, New Haven, Conn., 1915.

Lipman, P. W., Volcano-tectonic setting of Tertiary ore deposits, southern Rocky Mountains, *Ariz. Geol. Soc. Dig., 14*, 199–214, 1981.

Lipman, P. W., The Miocene Questa caldera, northern New Mexico: Relation to batholith emplacement and associated molybdenum mineralization, in *Genesis of Rocky Mountain Ore Deposits, Changes With Time and Tectonics, Proceedings of the Denver Region Exploration Geologists Society Symposium*, pp. 133–148, Denver Region Exploration Geologists Society, Denver, Colo., 1983.

Lipman, P. W., H. J. Prostka, and R. L. Christiansen, Evolving subduction zones in the western United States, as interpreted from igneous rocks, *Science, 148*, 821–825, 1971.

Lipman, P. W., F. S. Fisher, H. H. Mehnert, C. W. Naeser, and T. A. Steven, Multiple ages of mid-Tertiary mineralization and alteration in the western San Juan mountains, Colorado, *Econ. Geol., 71*, 571–588, 1976.

Loring, A. K., and R. B. Loring, K/Ar ages of middle Tertiary igneous rocks from southern New Mexico, *Isochron West, 28*, 17–19, 1980.

Mammerickx, J., and K. D. Klitgord, Northern East Pacific Rise: Evolution from 25 m.y. B.P. to the present, *J. Geophys. Res., 87*, 6751–6759, 1982.

Maxwell, R. A., J. T. Lonsdale, R. T. Hazzard, and J. A. Wilson, Geology of Big Bend National Park, Brewster County, Texas, *Publ. 6711*, 320 pp., Univ. of Tex. at Austin, 1967.

McGarr, A. M., Analysis of stress between provinces of constant stress, *J. Geophys. Res., 87*, 9279–9288, 1982.

McIntosh, W. C., Timing and distribution of ignimbrite volcanism in the Eocene-Miocene Mogollon-Datil volcanic field, *Mem. N. M. Bur. Mines Miner. Resour., 46*, 58–59, 1989.

McKenzie, D. P., Speculations on the consequences and causes of plate motions, *Geophys. J. R. Astron. Soc., 18*, 1–32, 1969.

Moustafa, A., Analysis of Laramide and younger deformation of a segment of the Big Bend region, Texas, *Quad. Map 54*, Bur. of Econ. Geol., Univ. of Tex. at Austin, 1988.

Muehlberger, W. R., Texas Lineament revisited, *Field Conf. Guideb., N. M. Geol. Soc., 31*, 113–121, 1980.

Muller, O. H., and D. D. Pollard, The stress state near Spanish Peaks, Colorado determined from a dike pattern, *Pure Appl. Geophys., 115*, 69–86, 1977.

Nakamura, K., Volcanoes as possible indicators of tectonic stress orientation—principle and proposal, *J. Volcanol. Geotherm. Res., 2*, 1–16, 1977.

Nakamura, K., and S. Uyeda, Stress gradient in arc-back arc regions and plate subduction, *J. Geophys. Res., 85*, 6419–6428, 1980.

Nelson, M. R., and C. H. Jones, Paleomagnetism and crustal rotations along a shear zone, Las Vegas Range, southern Nevada, *Tectonics, 6*, 13–33, 1987.

Newcomer, R., T. H. Giordano, and W. R. Seager, Hydrothermal alteration and mineralization of the Sugarloaf Peak quartz monzonite, Dona Ana Co., N. M., *Geol. Soc. Am. Abstr. Programs, 15*, 276, 1983.

Pollard, D. D., and A. Aydin, Progress in understanding jointing over the past century, *Geol. Soc. Am. Bull., 100*, 1181–1204, 1988.

Price, J. G., and C. D. Henry, Stress orientations during Oligocene volcanism in Trans-Pecos Texas: Timing the transition from Laramide compression to Basin and Range tension, *Geology, 12*, 238–241, 1984.

Price, J. G., and C. D. Henry, Dikes in Big Bend National Park: Petrologic and tectonic significance, centennial field guide, pp. 435–440, *Geol. Soc. Am.*, Boulder, Colo., 1988.

Price, J. G., C. D. Henry, A. R. Standen, J. S. Posey, Origin of silver-copper-lead deposits in red-bed sequences of Trans-Pecos Texas: Tertiary mineralization in Precambrian, Permian, and Cretaceous sandstones, *Rept. Invest. 145*, Bur. of Econ. Geol., Univ. of Tex. at Austin, 1985.

Price, J. G., C. D. Henry, D. S. Barker, and J. N. Rubin, Petrology of the Marble Canyon stock, Culberson County, Texas, *Guideb. 23*, pp. 303–319, Bur. of Econ. Geol., Univ. of Tex. at Austin, 1986.

Price, J. G., C. D. Henry, D. S. Barker, and D. F. Parker, Alkalic rocks of contrasting tectonic settings in Trans-Pecos Texas, *Spec. Pap. Geol. Soc. Amer., 215*, 335–346, 1987.

Price, J. G., S. T. Conlon, and C. D. Henry, Tectonic controls on orientation and size of epithermal veins, in *North American Conference on Tectonic Controls of Ore Deposits and the Vertical and Horizontal Extent of Ore Systems, Proceedings Volume*, pp. 36–46, edited by G. Kisvarsanyi and S. K. Grant, Univ. of Missouri, Rolla, 1988.

Reagan, M. K., and J. B. Gill, Coexisting calcalkaline and high-niobium basalts from Turrialba Volcano, Costa Rica: Implications for residual titanates in arc magma sources, *J. Geophys. Res., 94*, 4619–4633, 1989.

Rehrig, W. A., and T. L. Heidrick, Regional tectonic stress during the Laramide and late Tertiary intrusive periods, Basin and Range province, Arizona, *Ariz. Geol. Soc. Dig., 10*, 205–228, 1976.

Seager, W. R., Geology of Organ Mountains and southern San Andres Mountains, New Mexico, *Mem. N. M. Bur. Mines Miner. Resour., 36*, 97 pp., 1981.

Severinghaus, J., and T. Atwater, Cenozoic geometry and thermal state of subducting slabs beneath western North America, in Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada, edited by B. P. Wernicke, *Mem. Geol. Soc. Am., 176*, 1990.

Sewell, C. R., The Candela and Monclova belts of igneous intrusions—a petrographic province in Nuevo Leon and Coahuila, Mexico, *Spec. Pap. Geol. Soc. Am., 121*, 273, 1968.

Smith, D. M., T. Albinson, and F. J. Sawkins, Geologic and fluid inclusion studies of the Tayoltita silver-gold vein deposit, Durango, Mexico, *Econ. Geol., 77*, 1120–1145, 1982.

Stewart, J. A., Basin-range structure in western North America, a review, in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, edited by R. B. Smith, and G. P. Eaton, *Mem. Geol. Soc. Am., 152*, 1–13, 1978.

Stock, J., and P. Molnar, Uncertainties and implications of the Late Cretaceous and Tertiary positions of North America relative to the Farallon, Kula, and Pacific plates, *Tectonics, 7*, 1339–1384, 1988.

Wernicke, B. P., R. L. Christiansen, P. C. England, and L. J. Sonder, Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera, in Continental Extensional Tectonics, edited by M. P. Coward, J. F. Dewey, and L. Hancock, *Geol. Soc. Spec. Publ. London, 28*, 203–221, 1987.

Whalen, J. B., K. L. Currie, and B. W. Chappell, A-type granites: Geochemical characteristics, discrimination and petrogenesis, *Contrib. Mineral Petrol., 95*, 407–419, 1987.

Wilson, J. A., Vertebrate biostratigraphy of Trans-Pecos Texas, *Publ. 71-59, West Tex. Geol. Soc.*, pp. 157–166, 1971.

Wust, S. L., Regional correlation of extension directions in Cordilleran metamorphic core complexes, *Geology, 14*, 828–830, 1986.

Yates, R. G., and G. A. Thompson, Geology and quicksilver deposits of the Terlingua district, Texas, *U.S. Geol. Surv. Prof. Pap., 312*, 114 pp., 1959.

Zoback, M., R. E. Anderson, and G. A. Thompson, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States, *Philos. Trans. R. Soc. London, Ser. A, 300*, 407–434, 1981.

Zoback, M. L., et al., Global patterns of tectonic stress, *Nature, 341*, 291–298, 1989.

C. D. Henry and E. W. James, Bureau of Economic Geology, University of Texas at Austin, Austin, TX 78713.

J. G. Price, Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557.

(Received July 2, 1990;
revised October 25, 1990;
accepted January 10, 1991.)