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EARLY BASIN AND RANGE DEVELOPMENT IN TRANS-PECOS TEXAS AND ADJACENT CHIHUAHUA: MAGMATISM AND ORIENTATION, TIMING, AND STYLE OF EXTENSION

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Abstract. Magmatism during early Basin and Range extension in Trans-Pecos Texas consisted of widespread but volumetrically minor alkali basalts (24-17 Ma), an alkalic mafic to intermediate composition stratovolcano (28-27 Ma), and a dominantly rhyolitic, possibly bimodal, caldera complex in adjacent Chihuahua (31-28 Ma). This magmatism contrasted sharply with the much more voluminous and compositionally more diverse Eocene-Oligocene magmatism. The age and orientation of dikes emplaced during this magmatic episode have been used to determine the orientation of least principal stress, σ_3. An ENE orientation of σ_3, similar to early extension throughout the Basin and Range province, can be well documented by 28 Ma and possibly as early as 31 Ma. Faulting, consisting almost exclusively of movement along high-angle normal faults, was underway by 23 Ma. Some initial extension was taken up along preexisting WNW trending structures, oblique to ENE oriented σ_3. The least principal stress probably changed to WNW as it did elsewhere in the Basin and Range province, but the timing of this change is not well constrained in Texas. ENE and NE striking silver-copper-lead veins in Precambrian and Cretaceous red beds may have formed during the later Basin and Range extension. The present Basin and Range topography of this region is the result of movement along high-angle and dominantly NNW trending faults established early under σ_3 oriented ENE and reactivated after σ_3 changed to WNW.

Introduction

Trans-Pecos Texas encompasses the southeasternmost part of the Basin and Range province and may be a southern continuation of the Rio Grande rift (Figure 1). This report considers the characteristics of magmatism and extension during Basin and Range development in Texas for several reasons. Comparison of events in Texas and the rift indicates how they are related. Determining the orientation of maximum tension or least principal compressional stress, σ_3, as a function of time is crucial to understanding the cause of extension in the Rio Grande rift and in the rest of the Basin and Range province. Was σ_3 oriented the same throughout the province? Did σ_3 change with time? Did extension begin everywhere at the same time? Answers to such questions will help test various hypotheses of the origin of Basin and Range extension [Ingersoll, 1982]. We emphasize that although we refer to both the Basin and Range province and Rio Grande rift, we consider the Rio Grande rift to be a part of the broader Basin and Range province. Part of this report will attempt to show that there exist both major similarities and considerable variations across the province.

Dikes commonly are injected preferentially in planes perpendicular to σ_3. Rehrig and Heidrick [1976], Zoback and Thompson [1978], Zoback et al. [1981], Lipman [1981], and Laughlin et al. [1983] have used this principle to present evidence that early (30-10 Ma) tension throughout the Basin and Range province was oriented ENE. Data from the Rio Grande rift in New Mexico were included in these studies, but until recently, few data were available from Texas.

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Dasch et al. [1969], in the only previous study to address this question, dated WNW striking and NNW striking Rim Rock dikes in the Texas portion of the Basin and Range province (Figure 1). They suggested that σ_3 was NNE at about 23 Ma and ENE at about 19 Ma. (All ages in this study are recalculated according to the decay constants of Steiger and Jager [1977].) This conclusion differs from the above cited findings from other regions and sparked our interest.

This study characterizes magmatism and provides new isotopic ages and interpretations on dike orientations for the early stage of Basin and Range extension in the Trans-Pecos region. Price and Henry [1984] presented structural evidence that extension in the region did not begin before 32 Ma. Although the bulk of the Tertiary igneous activity in Texas occurred before 30-32 Ma [Henry and Price, 1984], scattered post-32 Ma igneous rocks are known [McDowell, 1979], and some can be used to infer orientations of σ_3 with time.

New K-Ar ages and chemical analyses are presented on the Rim Rock dike swarm and on similar alkali basalts in the Bofecillos Mountains and Black Gap areas (Figure 1). In addition, results of earlier mapping studies in the Sierra Rica caldera complex in Chihuahua [Chuchla, 1981; Immitt, 1981], the Bofecillos volcano [McKnight, 1970], and the Solitario fault area [Moon, 1953] are combined with isotopic dating [McDowell, 1979; Gregory, 1981] to interpret regional stress orientations.

Magmatism During Early Basin and Range Extension and Implications for Orientation of σ_3

Magmatism during early Basin and Range extension in Trans-Pecos Texas consists of three temporally and chemically distinct groups. (1) Widespread but volumetrically minor, 24-17 Ma alkalic basalts occur in the Cox Mountain, Rim Rock, Bofecillos Mountains, Solitario, Big Bend, and Black Gap areas (Figure 1). (2) A 28-27 Ma alkalic, mafic to intermediate stratovolcano formed in the Bofecillos Mountains. (3) The Sierra Rica caldera complex in adjacent Chihuahua erupted dominantly rhyolitic, but possibly bimodal, volcanic rocks at 31-28 Ma (Figure 1).

Rim Rock Dike Swarm

The Rim Rock dikes are an 18-24 Ma swarm of alkalic basalts (hawaiites) in the western part of Trans-Pecos Texas (Figures 1 and 2 [Dasch, 1959; Dasch et al., 1969]). More than 100 dikes up to 4 km long and a few meters wide cut Upper Cretaceous shales and marly limestones and upper Eocene-lower Oligocene volcaniclastic sediments in a 150 km^2 area adjacent to the Rim Rock fault. A few related sills are also present.

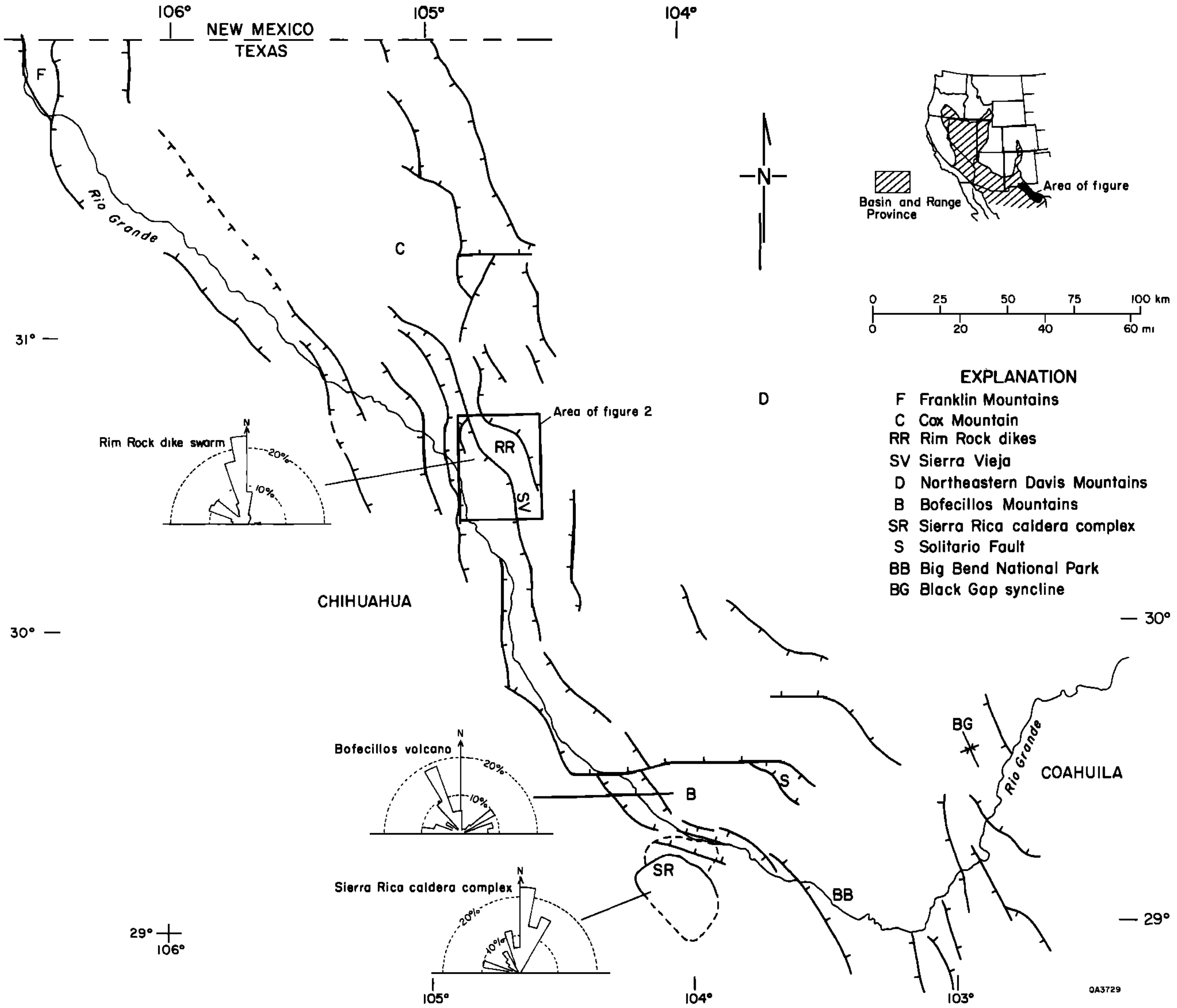

Fig. 1. Basin and Range province of Trans-Pecos Texas, showing major faults active during Basin and Range extension and the location of areas discussed in the text. Strike rosettes of dikes from three areas of magmatism contemporaneous with extension are shown. Strike bars are constructed for 10° intervals. Lengths of bars are proportional to total strike length: 70 km in the Rim Rock dike swarm (data from Dasch [1959]), 32 km in the Bofecillos volcano (data from McKnight [1970]), and 21 km in the Sierra Rica caldera complex (data from Chuchla [1981] and Immitt [1981]).

The dikes are notable for their abundant megacrysts of plagioclase, anorthoclase, biotite, kaersutite, apatite, and magnetite. Dasch et al. [1969] report plagioclase megacrysts up to 25 cm long. A few of the dikes follow actual faults, and a vent area lies along the Rim Rock fault. Several related lava flows are interbedded with conglomerates that are the earliest basin fill deposits in the area (Figure 2). Thus the age of the basalts approximates the time of initial faulting in the area.

The Rim Rock fault is a major Basin and Range normal fault that trends dominantly slightly west of north but makes a bend to a more westerly trend in the vicinity of the dikes (Figure 2). Several other structures, including the basin-bounding normal fault to the east and a Laramide age thrust fault to the north, make similar westerly bends. The density of faults northeast of the northwest trending segment of the Rim Rock fault may be comparable to that to the southwest, but the soft Upper Cretaceous deposits neither crop out nor show structures well.

A rose diagram of orientations and lengths of the dikes shows that a NNW trend dominates over a WNW trend (Figure 1). An east trend is relatively minor. Individual trends are better developed in different areas. The more northerly trend is most widely distributed; it occurs on both the upthrown and downthrown sides of the Rim Rock fault but mostly on the eastern part of the upthrown side. Almost all WNW trending dikes occur on the upthrown side near where the fault returns to a more northerly trend. Several dikes that trend slightly east of north (but appear as part of the NNW group on Figure 1) occur only on the southwest, downthrown side of the fault. Quaternary gravel cover may obscure some dikes, especially in the northeast.

Field, petrographic, and chemical data (Table 1) indicate that the dikes are compositionally fairly uniform. They are hawaiites by the classification of Barker [1979]; all are highly undersaturated with abundant normative nepheline and olivine, and the normative plagioclase compositions are andesine. Ground-

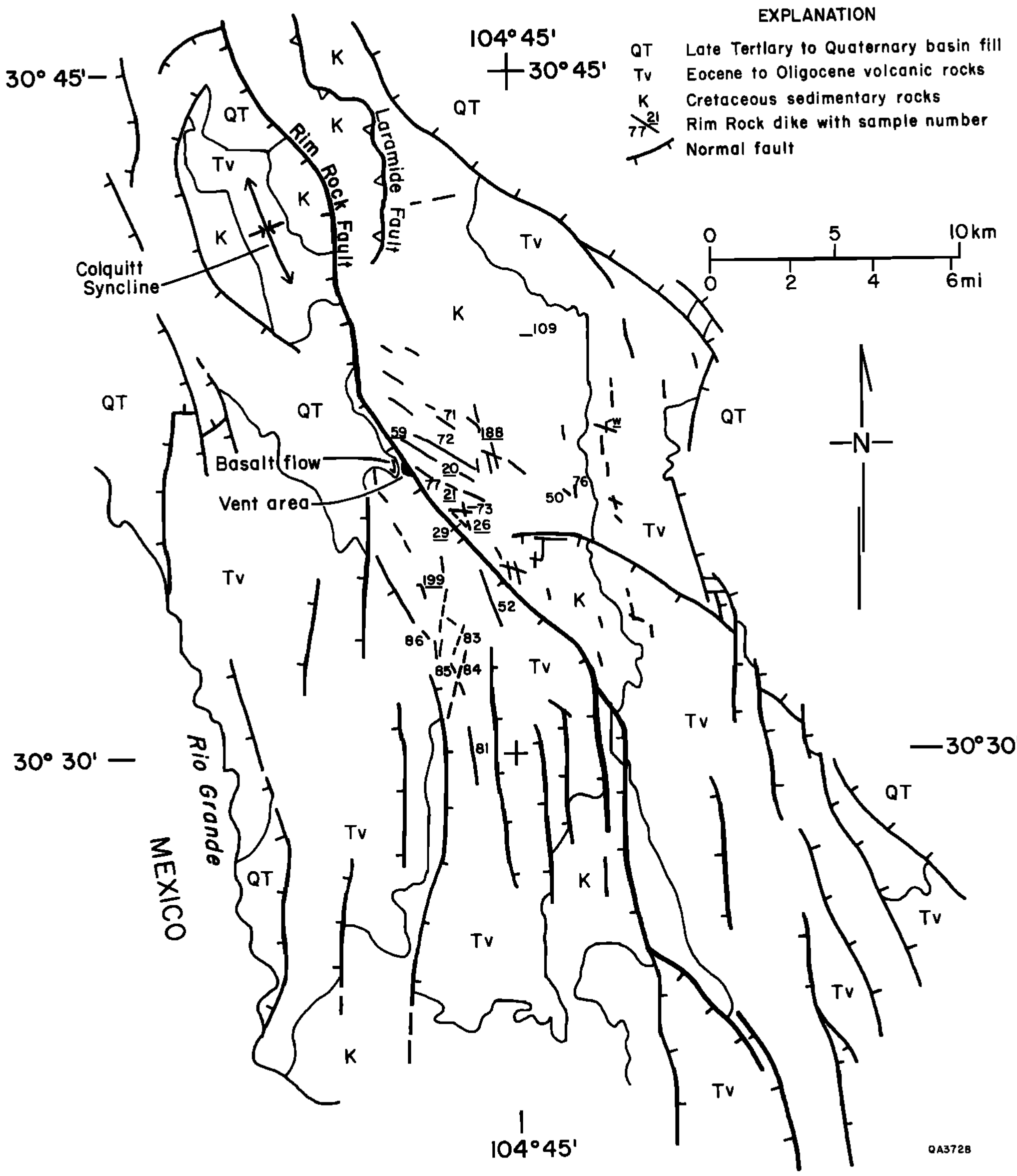

Fig. 2. Geologic map in vicinity of Rim Rock dike swarm showing dated and chemically analyzed samples. Italicized sample numbers are from Dasch et al. [1969]. Location of this figure is shown on Figure 1.

mass phases are plagioclase, highly magnesian olivine, titanaugite, and magnetite. Analcime occurs both as amygdule fillings and interstitial, possibly primary, grains. Most of the dikes are too altered for good analysis, containing abundant secondary calcite, zeolites, or oxidation products. (Analyses reported in Table 1 are only of relatively unaltered samples.) However, analyses of several altered samples show that they are compositionally similar to the unaltered rocks. Dasch et al. [1969], using petrographic data, suggested a wider compositional range: from alkalic basalt to phonolite and lamprophyre; they also indicated that the NNW trending set is compositionally more diverse than the WNW set. Our limited data do not support this contention. The only variation we can see is in the abundance of megacrysts. They are sparse in the WNW set; they can constitute as much as 15% of the rock in some of the NNW trending dikes. Nevertheless, some megacrysts can be found in all dikes.

Our new K-Ar data on the Rim Rock dikes, exclusively on separates of biotite, feldspar, and amphibole megacrysts, are presented in Table 2. They largely support the ages of Dasch et al. [1969], which were part on mineral separates and part on whole rock or matrix samples. Part of our rationale for reexamining these dikes was doubt about the accuracy of the whole rock analyses. Dasch et al. [1969] recognized and described the common groundmass alteration, which has destroyed much of the primary mineralogy of these rocks. Nevertheless, of eight whole rock or matrix ages, only two have demonstrably lost argon, and these have lost no more than 10%. Others give ages identical to ones we obtained on mineral separates of the same or nearby, parallel dikes. Apparently, deuteric alteration occurred during initial emplacement and cooling of the dikes, and all significant potassium-bearing phases remaining after alteration are relatively retentive of argon.

Mineral-mineral or mineral-whole rock pairs for five newly collected samples and two samples studied by Dasch et al. [1969] were analyzed. Two biotite-amphibole age pairs agree very closely (Table 1).

TABLE 1. Chemical Analyses of Basin and Range Age Basalts

	Rim Rock Dikes						Bofecillos Mountains	
	H82-76	H82-81	H82-83	H82-86	H82-85	H84-52	MGD-566	MGD-567
	N6W	N10W	N21E	N40W	N28W	N21W	--	--
SiO_2	45.22	48.30	46.64	48.85	48.06	47.96	47.60	48.26
TiO_2	2.28	2.07	2.37	2.04	2.28	2.27	2.37	2.34
Al_2O_3	15.79	16.99	16.51	17.04	17.03	16.93	16.62	16.75
Fe_2O_3	4.43	3.35	3.46	2.87	3.68	2.38	4.84	4.87
FeO	6.23	6.16	7.29	7.63	6.84	7.58	5.39	5.33
MnO	0.13	0.17	0.16	0.17	0.17	0.17	0.16	0.16
MgO	5.65	5.12	6.63	6.04	5.47	5.57	6.46	6.67
CaO	7.97	6.33	7.55	6.87	6.66	6.89	7.83	7.61
Na_2O	4.41	5.05	4.41	5.23	5.03	4.78	4.14	3.69
K_2O	2.81	3.33	2.34	2.38	3.08	2.81	1.52	2.16
P_2O_5	1.13	1.65	1.12	0.69	1.65	1.22	0.77	0.75
CO_2	0.90	0.10	0.20	0.20	0.10	0.01	0.10	0.30
H_2O^+	2.93	1.60	1.76	1.55	1.22	1.10	1.38	1.11
Total	99.88	100.22	100.44	101.64	101.27	99.67	99.18	100.00
				Norm, wt %				
OR	16.60	19.67	13.83	14.06	18.20	16.60	8.98	12.76
AB	23.00	27.79	24.62	26.72	27.18	25.31	33.31	31.22
AN	14.99	13.86	18.35	15.99	14.80	16.44	22.28	22.76
NE	7.75	8.09	6.88	9.50	8.33	8.20	0.93	0(0.75)
DI	9.18	4.94	8.48	10.01	5.51	7.91	8.61	6.46
HY	0	0	0	0	0	0	0	1.96(0)
OL	10.00	11.42	13.96	13.64	12.31	13.50	10.16	9.79
MT	6.42	4.86	5.02	4.16	5.34	3.45	7.02	7.06
IL	4.33	3.93	4.50	3.87	4.33	4.31	4.50	4.44
AP	2.47	3.61	2.45	1.51	3.61	2.67	1.68	1.64
CC	2.05	0.23	0.45	0.45	0.23	0.02	0.23	0.68

Values in parentheses for sample MGD-567 are from recalculation using Irvine and Baragar [1971] correction for oxidation of Fe.

Among five biotite-feldspar pairs, four have higher biotite ages and one has a higher feldspar age; none are outside 2σ analytical uncertainties. Nevertheless, geologic relations suggest that the biotite age is more realistic for sample H82-85. In contrast, because the apparent feldspar age of sample H82-72 agrees well with ages on adjacent and similar trending dikes, it seems more realistic than the biotite age. Incorporation of excess argon during crystallization does not seem a likely problem for any of these samples because it would have led to more scatter in the apparent ages. Because excess argon is unlikely, we have generally assumed that the older of two ages is more correct and have used the older age in Figure 3.

Combined with the data of Dasch et al. [1969], the new ages show a nearly continuous span of activity from 24 to 18 Ma (Figure 3). Ages show some tendency to cluster geographically. The WNW trending dikes in the northwestern part of Figure 2 are 24 Ma. Many dikes, including all but one dated dike southwest of the Rim Rock fault, sample 188 of Dasch et al. [1969], and several others north of the fault, have ages in the range 21-23 Ma. Our sample H82-76, a NNW trending dike, is younger at 18 Ma. The similar trending dikes C199 and W of Dasch et al. [1969] may be that young as well. A gap may exist between 21 and 18 Ma; its existence is dependent upon one's interpretation of the ages of samples 188 and W.

Dasch et al. [1969] originally concluded that the WNW trending set was older than the NNW trending set and that this pattern indicated a change in regional stress orientations. Field data on relative ages are unclear because most dikes do not intersect; in some that do, extensive alteration has made interpretation impossible. The new isotopic data bear out the difference in ages with some exceptions and additions (Figure 3). First, the new data, which were collected purposefully on dikes with widely different orientations, indicate that at any given time, strike of dikes may be scattered by as much as 80°. Second, a large group of

TABLE 2. K-Ar isotopic data on Basin and Range age basalts

Sample	Orientation	Material	K, %		^{40}Ar* x 10^{-6} scm^3/g	^{40}Ar*, %	Age, Ma ± 1σ
Rim Rock dikes							
J82-109	N89W	F	1.05 1.06		1.01 0.983	35 41	24.1 ± 0.7
H82-71	N57W	F	1.09 1.10		1.13 1.05	34 38	25.4 ± 0.8
H82-72	N49W	F	1.10 1.10	1.06	1.03 1.06	40 36	24.6 ± 0.6
		B	6.49 6.46		5.77 5.73	65 67	22.7 ± 0.4
H82-73	N7W	B	6.58 6.54	6.57	5.19 5.50	53 59	20.8 ± 0.3
H82-76	N6W	A	1.40 1.49	1.37	0.997 0.991	63 77	17.9 ± 0.4
		B	6.51 6.48		4.56 4.54	55 56	17.9 ± 0.3
H82-77	N65W	F	1.13 1.08	1.09	1.04 1.06	29 27	24.4 ± 0.6
H82-81	N10W	A	1.16 1.15		0.967 0.964	61 69	21.4 ± 0.4
H82-84	N16E	F	2.63 2.60	2.58	2.11 1.99	78 65	20.2 ± 0.4
		B	6.35 6.34		5.27 5.38	52 53	21.5 ± 0.3
H82-85	N28W	F	2.84 2.90		2.20 2.24	70 59	19.8 ± 0.4
		B	6.42 6.32	6.34	5.28 5.23	59 65	21.1 ± 0.3
H82-86	N40W	F	1.70 1.66		1.50 1.55	44 44	23.2 ± 0.6
H84-50	N65W	F	1.44 1.42		1.23 1.23	77 53	22.0 ± 0.5
H84-52	N21W	F	2.22 2.18		1.81 1.81	85 57	21.1 ± 0.4
		B	5.69 5.74		5.07 4.60	65 59	21.6 ± 0.4
North of Black Gap							
SI-8369-1	N18W	F	3.02 3.01		2.63	66	22.3 ± 0.5
Bofecillos Mountains							
MGD-566	Lava flow	WR	1.30 1.30		1.00 1.03	59 60	20.0 ± 0.4
MGD-567	Lava flow	WR	1.79 1.71	1.74	1.56 1.62	71 63	23.3 ± 0.5
Recalculated Rim Rock dikes†							
59	N58W	WR	1.32		1.21 1.24	15 16	23.7 + 1.0
C20	N65W	WR	1.70		1.43 1.48	18 19	21.9 + 1.0
C21	N64W	WR	1.17		1.05 1.14	20 19	23.9 + 1.0
C29	N44W	WR	1.08		0.931 0.908	16 19	21.8 + 1.0
188	N10W-N50W	M	2.15		1.68 1.63	21 28	19.7 + 0.6
		F	2.10		1.62	41	19.7 + 0.5
		B	6.51		5.28	68	20.8 + 0.4
		A	1.10		0.90	40	20.9 + 0.5
W	N7E	M	1.72		1.28 1.33	26 43	19.4 + 0.5
		F	3.03		2.19 2.08	57 61	18.0 + 0.5
C26	N18W	WR	2.41		2.02 1.86	28 27	21.4 + 0.9
C199	N6W	WR	2.83		2.23 1.95	29 19	18.2 + 1.0

Samples 59 and C20 from same dike; sample C21 same dike as H82-77; sample C26 same dike as H82-73
$\lambda_\beta = 4.963 \times 10^{-10}$ yr^{-1}; $\lambda_{\varepsilon+\varepsilon'} = 0.581 \times 10^{-10}$ yr^{-1}; ^{40}K/K = 1.167×10^{-7}. F, feldspar; B, biotite; A, amphibole; WR, whole rock, M, matrix.

*Radiogenic.

†From Dasch et al. [1969] using new decay constants.

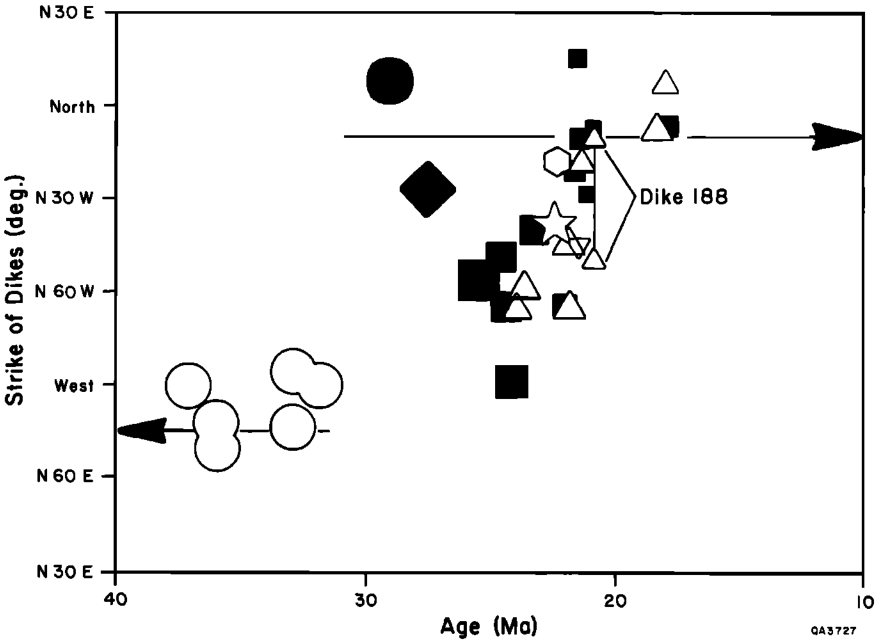

Fig. 3. Strikes of dikes and veins versus time in the Trans-Pecos region. The size of symbols indicates the analytical uncertainty in the age. Solid squares, Rim Rock dikes from this study; triangles, Rim Rock dikes from Dasch et al. [1969]; open circles, mean orientations of dikes and veins in early Oligocene calderas in Texas and in the Organ Mountains caldera in southern New Mexico [from Price and Henry, 1984]; solid circle, mean orientation of dikes and veins in and near the Sierra Rica caldera complex in Chihuahua; diamond, mean orientation of dikes radiating from the Bofecillos volcano [from McKnight, 1970; McDowell, 1979]; star, basalt dike 14 km south of the Bofecillos volcano, dated by McDowell [1979]; inverted triangle, basalt related to Solitario fault [from Moon, 1953; McDowell, 1979]; hexagon, basalt dike near Black Gap, described by Dahl and Lambert [1984] and dated in this study. Arrow at lower left indicates the mean orientation of late Eocene to early Oligocene dikes and veins in the Trans-Pecos region. Arrow at upper right indicates the primary orientation of Rim Rock dikes.

dikes gives ages between the two extremes; this group includes several WNW trending dikes (samples H82-86, H84-50, and C29). Finally, many dikes change orientation along strike. Dike 188, a younger dike of Dasch et al. [1969] best demonstrates this change (Figure 4). The dike lies within a cluster of dikes that generally trend N10°W. It bends from N10°W at its southern end to N50°W at its northern end. A nonporphyritic dike parallels 188 only along its northwest trending segment. The northwest trend is the same as the 24 Ma dikes: the nonporphyritic dike is probably also 24 Ma. The age of 188 could be indicative of either the WNW or NNW group (Figure 3). Thus dikes of a variety of orientations were emplaced at the same time, and the same orientations were repeated throughout the time of intrusion.

We suggest the following alternative hypothesis to the conclusion of Dasch et al. [1969] that stress orientation changed with time. The area was experiencing tension, and σ_3 was oriented ENE throughout the time of dike emplacement. The earliest, 24 Ma dikes were emplaced before significant extension, i.e., before a throughgoing set of normal faults had developed. These dikes followed preexisting WNW and NW trending structures, developed initially at least as long ago as Laramide time and probably considerably earlier. These structures opened before NNW trends because they were major existing zones of weakness; it was easier to dilate older zones of weakness, even oblique ones, than to establish totally new ones. Later, as a throughgoing NNW set of normal faults developed, dikes were emplaced along that trend. This latter set dominates the overall dike pattern (Figure 1) and probably better reflects the regional stress pattern. Nevertheless, some younger dikes were still emplaced along other trends, including WNW, and some (188) even curved to follow both trends. Dasch [1959] suggested a similar possibility.

The data in Figure 3 could be interpreted to indicate a progressive rotation of σ_3 from 24 to 20 Ma. We doubt this interpretation for three reasons: (1) Considerable scatter in orientation exists at any one time, (2) dikes do curve to follow more than one orientation, and (3) dike orientations, discussed below, determined from other parts of Trans-Pecos Texas support a single σ_3.

Our interpretation implies the following. First, there would be no need to postulate a change in stress orientation in early Basin and Range time. It would always have been oriented with σ_3 ENE. Second, significant faulting must have begun between 24 and 18 Ma, probably about 22 or 23 Ma, because dikes this old follow the dominant N10°W trend. An age on the flows interbedded with basin fill just west of the vent would be a useful check of this conclusion. Unfortunately, we were unable to collect samples of the flows suitable for dating.

Regional considerations support the importance of preexisting structures. As noted above, the Rim Rock dikes lie along a part of the Rim Rock fault that shows a significant westward divergence from its dominant slightly west of north trend. Several other major and minor structural features show similar bends. They suggest a major underlying WNW trending structure that has influenced all of the Basin and Range age

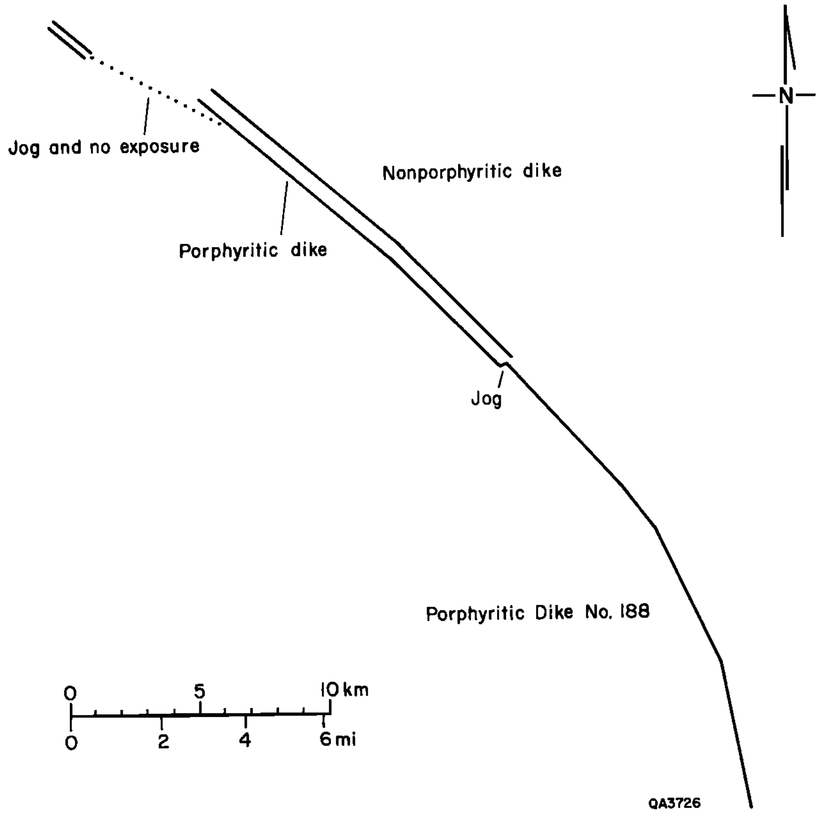

Fig. 4. Brunton and pace map of dike 188 [Dasch et al., 1969]. Dike trend changes from N10°W at south end to N50°W at north end. Nonporphyritic dike parallels dike 188 only along northwest trending segment.

features. Muehlberger [1980] has shown how the WNW trending Texas lineament and other preexisting trends have influenced the fault pattern in Trans-Pecos Texas. Because the Laramide thrust fault at the top of Figure 2 shows a similar bend, the northwest trend is probably as old or older than Laramide. Muehlberger suggests that it was established at least by the late Paleozoic. The Rim Rock dikes may be restricted to this area because they were intruded along a major crustal flaw, even though their generation was certainly in the mantle [Dasch, 1969].

Muehlberger [1980] indicates that a preexisting NNW trend may also underlie the Rim Rock area. This trend consists of a hypothesized series of normal faults related to formation of the Jurassic age Chihuahua Trough; these faults are not exposed but may roughly follow the present day Rio Grande in the subsurface. It could be argued that the NNW trend of some dikes is also inherited. However, an older NNW trend along the Rio Grande cannot account for the development of NNW trends throughout Trans-Pecos Texas. Also, NNW trending Rim Rock dikes are clearly dominant over other trends (Figure 1). If a similar basement structure were important, it probably would have opened first during extension. Age and orientation data from other areas in the Trans-Pecos region (Figure 3) support our hypothesis that σ_3 was ENE throughout the time of Rim Rock dike emplacement.

Bofecillos Mountains

The Rawls Formation of the Bofecillos Mountains consists of a sequence of alkalic mafic to intermediate flows and minor intrusions [McKnight, 1970]. They include some of the youngest volcanic rocks of Trans-Pecos Texas. K-Ar ages [McDowell, 1979] (Table 2) and field relationships reveal two distinct groups. The vast majority of rocks are from 28-27 Ma [McDowell, 1979, and unpublished data, 1982] and consist of flows and intrusions related to a large stratovolcano. Several basalts in the upper part of the formation are 24-18 Ma [McDowell, 1979] (Table 2).

The vent of the Bofecillos volcano consists of a central dioritic intrusion, probably the eroded feeder to the flows, and a set of dikes radiating from the intrusion. A rose diagram of the dikes reveals a preferred NNW orientation (Figure 1). The dikes have not been dated, but we assume that they are the same age (28-27 Ma) as the central intrusion and the related flows.

The uppermost unit of the Rawls Formation as mapped by McKnight [1970] consists of several basalt flows. Along the Rio Grande, in an area dropped down by Basin and Range faults, the flows are interbedded with early basin fill sediments; elsewhere they lie at the top of the volcanic section. McDowell [1979] obtained whole rock ages of 23 and 24 Ma on two of the latter flows and 18 Ma on a small plug. Ages on two of the flows interbedded with basin fill sediments are 20 and 23 Ma (Table 2). The two flows are stratigraphically close; the lower age may simply reflect incomplete retention of argon. McDowell [1979] obtained an age of 23 Ma on a dike trending N38°W, presumably a feeder to the flows.

The age and orientation data from the Bofecillos Mountains suggest that σ_3 was oriented east-northeast, that this orientation of tension was established by about 28 Ma, and that it continued to at least 23 Ma. Basin and Range faults in the area trend NNW in the western part of the Bofecillos Mountains, bend to WNW in the southern part, but are NNW farther southeast. As suggested for the Rim Rock dike orientations, major basement structures may have helped localize the Bofecillos magmatism. Basin and Range faulting must have been well established by 23 Ma, because the flows are interbedded with sediments deposited in newly formed grabens.

Analyses of the two interbedded basalts show that they are chemically similar to the Rim Rock dikes (Table 1) but are less silica undersaturated and lack megacrysts. The similarity in age, chemistry, and structural setting indicates a distinct basaltic magmatic event in the early Basin and Range development of Trans-Pecos Texas.

Black Gap Area

A 140-m-thick sequence of basalt flows occurs in the Black Gap syncline (Figure 1) in southeastern Trans-Pecos [St. John, 1965]. Moustafa [1983] has interpreted the syncline as forming by sag into a rhomb graben developed during Basin and Range extension. The NNW trending graben presumably formed in response to regional ENE extension, which caused right-lateral strike slip on NW or WNW basement faults. The NNW trending Colquitt syncline (Figure 2) [Frantzen, 1958; Twiss, 1959], located north of the Rim Rock dike swarm, may have had a similar origin. Whole rock K-Ar ages on three samples of basalt from the Black Gap syncline are 22-23 Ma (F. W. McDowell and D. S. Barker, unpublished data, 1983). A fourth age of 20 Ma may indicate later volcanism or incomplete argon retention. The basalts are alkalic but less so than either the Rim Rock or Bofecillos basalts (D. S. Barker, unpublished data, 1983).

Immediately north of the Black Gap area, basalt dikes possibly related to the flows are emplaced along a N18°W trend [Dahl and Lambert, 1984]. A K-Ar age of 22 Ma (Table 2) on a plagioclase separate (supplied by D. A. Dahl and D. D. Lambert) from megacrysts in one of the dikes, supports a genetic relationship to the basalts in the Black Gap syncline and indicates that σ_3 was oriented ENE.

Sierra Rica, Chihuahua

Two calderas formed at 30 and 28 Ma in the Sierra Rica area of Chihuahua, immediately south of the Bofecillos Mountains [Chuchla, 1981; Henry and Price, 1984]. Dike orientations (Figure 1) include a variety of data but are dominated by (1) a single alkalic basalt dike that trends dominantly north but alternates between slightly west and slightly east of north and (2) a north elongated granitic intrusion in one of the calderas. Two whole rock ages on the dike are 31 Ma, but the age of a plagioclase separate is 34 Ma; the age of the granite is 31 Ma [Gregory, 1981]. Clearly, neither the orientation nor the age data can be interpreted unequivocally; nevertheless the data are consistent with σ_3 oriented approximately east as early as 31 Ma.

Other Basin and Range Basalts

Other areas of young, Basin and Range related basalts are in southern, northern, and northeastern Trans-Pecos Texas (Figure 1). A 22 Ma basalt was erupted from a feeder along a NW trending segment of the Solitario fault [McDowell, 1979; Moon, 1953]. A 23 Ma basalt flow lies at the base of basin fill sediments in Big Bend National Park (J. B. Stevens, personal communication, 1985). The 17 Ma [McDowell, 1979] Cox Mountain basalt is a flow unrelated to any known vent. One of the numerous WNW trending faults in the area [King, 1965] could have been the conduit for the flow. Faults of this trend, which parallel the Texas lineament, experienced repeated displacement during Precambrian, Pennsylvanian-Permian (Ouachita), and mid-Tertiary to Recent (Basin and Range) deformations [King and Flawn, 1953]. Basaltic dikes, trending N15° to 35°W, were emplaced during Basin and Range faulting at one location in the northeastern Davis Mountains [Parker, 1972]. The Cox Mountain basalt is a hawaiite [Barker, 1980] but is less alkalic than either the Rim Rock or Bofecillos basalts. Both the Cox Mountain basalt and the basalt along the Solitario fault were probably injected along preexisting structures in response to the regional ENE tension.

Discussion

Regional Stress Orientations

Dike orientation data from the Trans-Pecos region (Figure 3) support the conclusion of Zoback et al. [1981] that regional σ_3 during early extension (before about 10 Ma) in the Basin and Range province was ENE. The data in Texas allow a range in σ_3 from about N65°E to N90°E. The scatter may reflect interaction of σ_3 with a variety of preexisting structures. The evidence from the Rim Rock dike swarm alone is somewhat ambiguous. Some WNW striking dikes were injected early; Dasch et al. [1969] used this relationship to suggest an early period of extension with σ_3 oriented NNE. We suggest that the WNW striking dikes filled preexisting cracks in response to a regional σ_3 that was oriented ENE throughout early Basin and Range time. When combined with other data from the Trans-Pecos region and from other parts of the Basin and Range province, the latter explanation appears more plausible.

Data from the Bofecillos Mountains and from the Sierra Rica caldera complex (Figure 3) suggest that σ_3 was ENE during the interval from 31 to 23 Ma. We are aware of only few published data for this time. Rehrig and Heidrick [1976] indicated ages of between 24 and 28 Ma for NNW striking dikes at Silver Bell, Arizona. Rehrig and Heidrick also gave age and orientation data for dikes in the Santa Rita Mountains in Arizona. Interpretation is ambiguous because two trends (ENE at 28-26 Ma and WNW at 28-27 Ma) are approximately equal in strike length and nearly perpendicular to the trend at Silver Bell. Lipman [1981] presented evidence of preferred NW strike in the Questa area of New Mexico. Laughlin et al. [1983] reported 28 Ma for NNW striking dikes in west central New Mexico. Elston et al. [1976] had previously included these dikes as part of a radial set centered on part of the Mogollon volcanic field, however. Zoback et al. [1981] summarized additional data for rocks younger than 23 Ma and scattered throughout the Basin and Range province and adjoining areas. Taken together, these data suggest that σ_3 was probably ENE throughout the province during early (30-10 Ma) extension. Our data support the conclusion of Christiansen and Lipman [1972] that extension began early in the southern Basin and Range province.

Numerous workers have observed a shift from early ENE to later WNW extension in the Basin and Range province [Zoback and Thompson, 1978; Lipman, 1981; Zoback et al., 1981; Golombek, 1983; Morgan and Seager, 1983; Lucchita and Suneson, 1983]. In New Mexico and perhaps throughout the province, the shift to WNW extension occurred at about 10 Ma [Golombek, 1983]. Unfortunately, no igneous rocks younger than 17 Ma have been found in Texas. However, a shift in orientation of σ_3 to WNW may be recorded by silver-copper-lead veins found in red bed sequences near Van Horn, Texas [Price et al., 1985]. These veins probably formed when preexisting ENE and NE striking fractures dilated (σ_3 NW) and were mineralized by moderately low temperature (120°-170°C) hydrothermal fluids. Fault displacement data [Price et al., 1985] indicate both ENE and NW extension in the Indio Mountains 25 km northwest of the Rim Rock dike swarm. Because σ_3 during early Basin and Range extension was probably ENE, we infer that the NW extension occurred later.

The Basin and Range province in Texas is currently extending; Quaternary fault scarps are abundant [Muehlberger et al., 1978; Seager, 1980; Henry et al., 1983]. Many Quaternary faults presumably are reactivated earlier Basin and Range faults; therefore strikes of scarps cannot be used to define σ_3 uniquely.

First-motion studies of the 1931 Valentine earthquake, the epicenter of which was 15 km east of the Rim Rock dike swarm, suggest that σ_3 is currently about N74°E [Dumas et al., 1980]. This event resulted from right-lateral strike slip along a WNW striking fault. Another seismic study by Dumas [1981] indicated normal faulting related to a swarm of earthquakes located in Mexico approximately 27 km west of the Rim Rock dikes. For these events, Dumas [1981] indicated that σ_3 was oriented N35°W. Clearly, more seismic events from the Trans-Pecos region need to be analyzed to determine current stress orientations. For the Basin and Range province as a whole, σ_3 is currently WNW [Zoback and Zoback, 1980], in agreement with the shift from ENE σ_3 at about 10 Ma.

Style of Faulting

Zoback et al. [1981] indicated that early extension, which by their definition is not part of Basin and Range extension proper, occurred along closely spaced listric faults to produce highly tilted strata. The extension was shallow, produced little topographic relief, and was contemporaneous with calcalkaline magmatism. Actual Basin and Range extension along high-angle normal faults occurred only after 13 Ma. The high-angle faulting involved little tilting but produced the characteristic topography of the province. The greater penetration of the high-angle faults allowed basalts to leak to the surface so that associated magmatism was all basaltic or bimodal. Chamberlin [1983] interpreted the structural pattern of the Lemitar Mountains in the Rio Grande rift as resulting from nearly continuous extension and tilting along curved normal faults over the last 30 m.y. Early faults were cut and rotated by later faults; shallow dips on these faults were thus a result of later rotation not original listric faulting.

In contrast to this early listric or rotational faulting elsewhere, almost all faulting in Texas has been high angle. Mapped faults are high angle. Our data indicate that Basin and Range faulting began at 23 or 24 Ma and that the present ranges are a product of the cumulative displacement along these same faults. In response to regional ENE σ_3, displacement was normal on newly formed or reactivated NNW striking faults and in part right-lateral oblique slip on faults developed parallel to preexisting WNW and NW striking structures of the Texas lineament. With a change from ENE to WNW σ_3, the NNW, NW, and WNW faults continued to move but presumably with an increased strike slip component. In contrast to the northern Basin and Range province [Zoback et al., 1981], large-displacement NNE striking faults developed only rarely. Those that did may have formed earlier by extension on preexisting NNE trending basement structures, under the influence of ENE σ_3, rather than later, under the influence of a WNW σ_3. The shapes of the major basins and ranges of Texas were determined by the early ENE σ_3.

Range formation is continuing today, as range fronts are sharp and commonly bounded by Quaternary scarps. Fault displacement and range formation may have been continuous since 24 Ma but are difficult to test without concurrent magmatic activity or better stratigraphic data on basin fill. An early and possibly continuous process of Basin and Range development is in contrast to events in both the broader Basin and Range province and the Rio Grande rift. In the latter area, Seager et al. [1984] and Baldridge et al. [1984] indicate two episodes of rifting: an early (to 20? Ma) episode associated with broad basins, and a later (10-3 Ma) episode that gave rise to the distinctive Basin and Range topography.

Horst blocks in Trans-Pecos Texas are generally not significantly tilted. Many are centered on calderas; the underlying batholiths apparently anchored the blocks, preventing them from extending or tilting [Henry and Price, 1984]. The Sierra Vieja, the horst bounded on the west by the Rim Rock Fault (Figures 1 and 2), dips eastward at about 5°-10°. The Sierra Vieja was not a significant source of igneous rocks so is not underlain by a batholith. Nevertheless, it is not clear why it is tilted; rotation on a westerly dipping fault to the east is unlikely, because, for most of its length, the Sierra Vieja is bounded on the east by a basin and an easterly dipping fault (Figures 1 and 2). Only a small part of the southern Sierra Vieja is bounded by a westerly dipping fault. The tilt may simply be sag into the graben to the east. Sagging may explain the dips on the flanks of the Black Gap and Colquitt synclines.

The Franklin Mountains near El Paso offer the only exception to this picture. Paleozoic sedimentary rocks in the range dip 40°-60° to the west; Harbour [1972] mapped several low-angle faults dipping 20° to the northeast or east. Harbour [1972] and Lovejoy [1975] interpreted these faults variously as thrusts or possible landslides. However, all documented movement is normal, and the top plate does not override basin deposits but appears to be truncated by the eastern, high-angle, range-bounding fault. These low-angle faults may be early Basin and Range or Rio Grande rift faults (as suggested by Seager [1981], Kelley and Matheny [1983], and Baldridge et al. [1984]), formerly more steeply dipping, now gently dipping due to rotation of the Franklin Mountains. However, the faults responsible for the rotation have not been identified, and at least some of the tilt of the Paleozoic rocks may have occurred during Laramide compression.

The Trans-Pecos region lies along the eastern edge of the Basin and Range province. The paucity of listric or rotational faulting in the region, with the exception of the Franklin Mountains, may be due to diminished extension along this edge of the province. Zoback et al. [1981] suggested total extension of perhaps 100% or more throughout much of the province, and Chamberlin [1983] found as much as 200% extension in the Rio Grande rift near Socorro. Total extension in Texas was probably no more than 10% and could be at most 30% even if the existing basins are underlain by totally new crust. That the basins are in fact underlain by the same rocks that are exposed in the margins is demonstrated from well data. Unlike areas where high strain rates were accommodated by rotational faulting [Proffett, 1977], strain rates in the Trans-Pecos region were relatively low.

Low strain rates are also indicated by the orientation of fracturing and faulting with time. Extension in the Trans-Pecos region began early, at least 28 m.y.

ago and possibly 31 m.y. ago, if the Sierra Rica data are meaningful. However, large-scale faulting did not begin until much later, at about 23 Ma. Early dikes were emplaced along dilated preexisting structures; it was not until 23 Ma that new structures opened perpendicular to σ_3. With the change in orientation of σ_3 to WNW, strain rate probably remained low, because NNE striking faults never developed on a large scale. Instead, essentially all motion was taken up on existing NNW and WNW striking faults.

Magmatism

The widespread 24-17 Ma alkalic basalts and 28-27 Ma alkalic, mafic to intermediate rocks of the Bofecillos Mountains represent distinct magmatic events related to early Basin and Range extension in Trans-Pecos Texas. These rocks contrast sharply with the far more voluminous mid-Tertiary volcanism in the same area. Eocene and lower Oligocene igneous rocks, although similarly alkalic, are compositionally more diverse; most of the rocks are caldera related. They span a range from basalts to high silica and peralkaline rhyolites, and petrologic studies indicate that the rhyolites are differentiates of a mafic, probably basaltic parent [Parker, 1983; Cameron et al., 1982].

The Sierra Rica caldera complex in Chihuahua erupted rhyolitic ash flow tuffs 30 and 28 m.y. ago [Chuchla, 1981; Gregory, 1981; Henry and Price, 1984]. Unlike the older calderas in Texas, these calderas had no associated intermediate rocks [Henry and Price, 1984] and may represent an early stage of bimodal volcanism. They formed near the beginning of extension in the region in contrast to the older calderas, which formed during mild ENE compression [Price and Henry, 1984]. No silicic volcanism younger than about 28 Ma has been found in Texas or adjacent Chihuahua or Coahuila.

The 24-17 Ma basalts vary compositionally. The Rim Rock dikes are most alkalic and are strongly nepheline normative (Table 1). The Bofecillos rocks are only slightly nepheline normative (Table 1 and D. S. Barker, unpublished data, 1983). The Cox Mountain basalt is hypersthene-olivine normative [Barker, 1980] as are the basalts of the Black Gap area (D. S. Barker, unpublished data, 1983). The origin of this compositional range is currently unknown. Degree of alkalinity and silica undersaturation seem to correlate with intensity of Basin and Range extension. The Rim Rock dikes are in an area of abundant, large-displacement normal faults; the few faults in the Cox Mountain area have only minor displacement. Areas of greatest extension may have allowed dikes to have been injected most directly from sources in the mantle. Possibly basalts in areas of lesser extension experienced greater degrees of crustal contamination.

If the observation of Zoback et al. [1981] that basaltic volcanism was largely restricted to the later, high-angle fault style of extension is correct, then the widespread presence of these basalts may be further evidence for early, deeply penetrating, high-angle faults. Zoback et al. [1981] speculated that the greater depth of brittle deformation involved in this style of faulting may have provided conduits to the surface for the basalts. In contrast the ductilely deformed crust associated with listric faulting did not.

Basaltic rocks of similar age have been found elsewhere in the Rio Grande rift [Lipman and Mehnert, 1975; Chapin and Seager, 1975; Baldridge et al., 1980]. Lipman and Mehnert [1975] used the occurrence of 27-18 Ma basalts along the northwestern margin of the rift in Colorado to indicate the timing of initial extension. They recognized a common silicic alkalic basalt type, which is somewhat similar to the basalts of Texas but less alkalic. They are all hypersthene-olivine normative; the compositional differences show up as lower alkalis and TiO_2 and higher CaO and MgO in the Colorado rocks. The less alkalic rocks of the Black Gap area and Cox Mountain are more like these rocks. Baldridge et al. [1980] found 25-19 Ma basalts, including some quartz normative and some strongly undersaturated rocks, in the central Rio Grande rift near Santa Fe.

Basaltic rocks of this age seem rare in the southern part of the rift [Chapin and Seager, 1975; Seager et al., 1984]. A common group of upper Oligocene to lower Miocene basaltic andesites includes rocks having silica concentrations as low as 49%; however, most are more silicic. The 28-27 Ma rocks of the Bofecillos Mountains are similar in age and possibly in composition to this basaltic andesite group. Although we have no chemical data for the Bofecillos rocks, petrographic data of McKnight [1970] indicate that they are trachybasalts and trachyandesites. Thus the silica ranges probably overlap with the basaltic andesites, although the Bofecillos rocks are more alkalic. Elston and Bornhorst [1979] showed that the basaltic andesites were concentrated along the border of the Colorado Plateau and the southern Basin and Range. Although common in the Rio Grande rift, their relationship to it is unclear.

Conclusions

Basin and Range extension began in Trans-Pecos Texas at about 30 or 31 Ma. Faulting, consisting of high-angle normal faults, began at about 23 or 24 Ma. Earliest extension was oriented ENE as it was in the rest of the Basin and Range province. Preexisting zones of weakness oriented WNW, parallel to the Texas lineament, opened first, but probably in response to σ_3 oriented ENE rather than NNE. Shortly thereafter, a throughgoing NNW striking fault system developed. Displacement on these faults was dominantly normal; a strike-slip component probably developed on faults parallel to the preexisting zones of weakness. Low-angle faults, listric faults, and significant rotation of range blocks were not developed except perhaps in the Franklin Mountains of far western Texas. The present topography is a response to continued movement on this fault system. Preexisting structures played a significant role and need to be considered in the analysis of dike and fault orientations and least principal stress. Some evidence suggests that σ_3 shifted to WNW as it did in the rest of the province; the timing of this change is not well constrained in Texas.

Early Basin and Range magmatism in Texas consisted of 30- to 28-m.y.-old rhyolitic rocks in the Sierra Rica area, 28- to 27-m.y.-old alkalic mafic to intermediate rocks in the Bofecillos volcano, and widespread but volumetrically minor, 24- to 17-m.y.-old alkalic basalts. The onset of widespread basaltic dike injection corresponded with the beginning of faulting. The first dikes were injected preferentially along preexisting WNW striking basement fractures that may penetrate the entire crust. By 23 m.y. ago, NNW striking, steeply dipping fractures and faults had developed and began to tap the mantle source of basalts. Magmatism ceased at about 17 Ma, but faulting has continued to the present, largely along the same fractures that were active during the early period of Basin and Range extension.

Zoback et al. [1981] have divided extension in the Basin and Range province into an early, ENE oriented, high strain rate, high total extension, thin skin style (their pre-Basin and Range extension) and a late, WNW oriented, low strain rate, low total extension, high-angle fault style (their Basin and Range extension proper). Extension in the Trans-Pecos region began early, overlapped in time with both, and shared the change in orientation, but had the style only of the latter.

Our data, coupled with regional studies of the entire Basin and Range province, suggest that the timing and orientation of stress were similar across the province. In contrast, style of faulting, amount of extension, and associated magmatism varied widely. Ideas concerning the origin of the Basin and Range province and the Rio Grande rift need to consider both these similarities and differences.

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