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Stratigraphy and geochemistry of volcanic rocks in the Lava Mountains, California: Implications for the Miocene development of the Garlock fault

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ABSTRACT

Volcanism in the Lava Mountains occurred between 11.7 and 5.8 Ma and was contemporaneous with sinistral motion on the Garlock fault. Volcanic rocks, equivalent in age and chemistry to those in the Lava Mountains, crop out 40 km to the southwest in the El Paso Mountains across the Garlock fault. Three chemical groups of volcanic rocks erupted in the Lava Mountains over a period of 5 m.y. These are (1) andesite of Summit Diggings, Almond Mountain volcanic section, and Lava Mountains Andesite, (2) basalt of Teagle Wash, and (3) tuffs in the northeastern Lava Mountains and dacite in the Summit Range. Volcanic rocks of each group have distinctive chemical signatures useful for correlation of units across the Garlock fault. Our work demonstrated that tuffs in the Almond Mountain volcanic section may be equivalent to a tuff in member 5 of the Miocene Dove Spring Formation, El Paso Mountains. The basalt of Teagle Wash probably correlates with basalt flows in member 4, and tuffs in the northeast Lava Mountains may be equivalent to tuff of member 2. Correlation of these units across the Garlock fault implies that the Lava Mountains were situated south of the El Paso Mountains between 10.3 and 11.6 Ma and that 32–40 km of offset occurred on the Garlock fault in ~10.4 m.y., resulting in a displacement rate of 3.1 to 3.8 mm/yr. Projecting this rate to the total offset of 64 km on the Garlock suggests that left-lateral slip began at ca. 16.4 Ma.

INTRODUCTION

The Lava Mountains lie just south of the active Garlock fault, a major continental strike-slip fault that separates the southwestern Basin and Range to the north from the Mojave block to the south. The fault extends 250 km from the San Andreas fault to the Avawatz Mountains just south of Death Valley (Fig. 1). Total sinistral displacement on the Garlock fault is ~64 km (Smith, 1962; Smith and Ketner, 1970; Davis and Burchfiel, 1973; Monastero et al., 1997). Estimates of the initiation of faulting vary from 10 to 9 Ma (Burbank and Whistler, 1987; Loomis and Burbank, 1988) to after 17 Ma (Monastero et al., 1997). Faulting continued to the present with a minimum of 18 km of displacement occurring across the central Garlock

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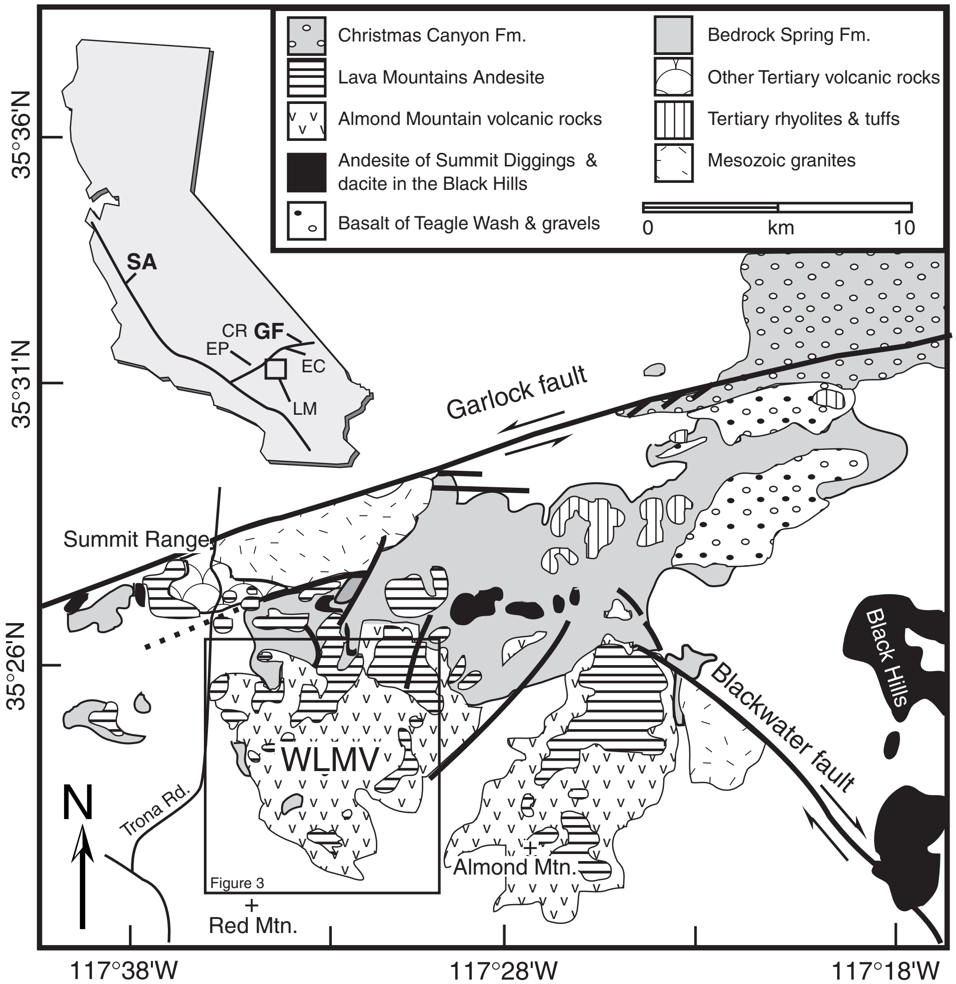

Figure 1. Geologic map of the Lava Mountains and neighboring Summit Range and Black Hills modified from Smith (1964), Dibblee (1967), and Keenan (2000). WLMV—Western Lava Mountains Volcano. Inset map of California shows the following locations: GF—Garlock fault, SA—San Andreas fault, LM—Lava Mountains, EC—Eagle Crags volcanic field, EP—El Paso Mountains, and CR—Coso Range. Box indicates area covered by Figure 3.

fault since the Pleistocene (Carter, 1980). Volcanism in the Lava Mountains began at ca. 11.7 Ma, ended at 6.4 Ma, and is unique in that it represents a period of major volcanic activity astride the Garlock fault that occurred during lateral displacement. The Lava Mountains, originally described by Smith (1964) and Dibblee (1967), were remapped in part to clarify stratigraphic relationships, to determine the petrogenesis of the volcanic rocks, and to calculate offset on the Garlock fault. Smith (1964) established the basic stratigraphic framework for the Lava Mountains and generally located source areas for the Almond Mountain volcanic section and the Lava Mountains Andesite in both the western and eastern Lava Mountains.

The close proximity of volcanic centers in the Lava Mountains to the Garlock fault and the potential for locating units that either flowed or were transported across the fault provide the opportunity to more fully understand the development of the Garlock fault during Tertiary time. Units coeval and geochemically identical to those in the Lava Mountains occur north of the Garlock fault in the El Paso Mountains in the Miocene Dove Spring Formation (Loomis and Burbank, 1988). Furthermore, lithologies characteristic of the El Paso Mountains occur as conglomerate clasts in the eastern Lava Mountains (Carter, 1982, 1987, 1994).

This paper presents the results of new stratigraphic, geochronologic, and geochemical investigations of the Miocene volcanic rocks of the Lava and El Paso Mountains and relies on earlier studies by Smith (1964) and Carter (1980, 1982, 1987, 1994). The principal objective is the correlation of volcanic units between the Lava and El Paso Mountains across the Garlock fault with the purpose of estimating slip rate on the fault. Field studies described a volcanic center in the western Lava Mountains, the source of a significant volume of andesite and dacite lava and pyroclastic material.

VOLCANIC STRATIGRAPHY

On the basis of detailed and reconnaissance mapping, Smith (1964) developed a stratigraphy for the Lava Mountains composed of six volcanic units and basin-fill gravels and sandstones. Although he lacked isotopic dates, volcanic units were assigned ages varying from pre–middle Pliocene to Quaternary on the basis of paleontological and stratigraphic observations.

Our work based on geochemistry, geochronology, and field studies required the revision of this stratigraphy and demonstrated that volcanic activity in the Lava Mountains occurred in three episodes spanning about 5 m.y. in the middle Miocene to late Miocene (Fig. 2).

Rocks of the first episode were mapped by Smith (1964) as volcanic units older than the Bedrock Spring Formation. These units are shown herein to range in age from 11.7 to 10.7 Ma, are lithologically diverse, and include (1) dacite (11.7 Ma; Table 1) with large (2 cm) phenocrysts of plagioclase, herein termed "the dacite of Summit Range"; (2) dacite containing quartz, hornblende, biotite, and plagioclase dated at 10.73 Ma (Table 1); and (3) volcaniclastic rocks. A vent area for dacite is marked by a volcanic dome in the Summit Range (Fig. 3). Also included in episode 1 are pyroclastic flows mapped by Smith (1964) in the northeastern part of the Lava Mountains as "other upper Pliocene (?) volcanics (Tt)." The age of this unit is unclear. Smith (1964) indicated that it may overlie the Bedrock Spring Formation, but field relationships are obscure. Geochemical similarities between these pyroclastic units and tuffs of member 2 of the Dove Spring Formation (15.1 to 11.8 Ma; Loomis and Burbank, 1988) support assignment of the flows to episode 1. These pyroclastic units either erupted from nearby domes of rhyolite (mapped as felsite [Tf] by Smith, 1964) or from an unidentified source to the south of the Lava Mountains.

Rocks of the second episode (10.4 to 9.54 Ma; Table 1) are volumetrically the most important and are separated from volcanic rocks of the first episode by the sandstones of the Bedrock Spring Formation (Fig. 2). The following units were produced during the second episode: (1) volcanic rocks in the uppermost part of the Bedrock Spring Formation, (2) the Almond Mountain volcanic section, (3) "Quaternary" andesite (Smith, 1964) herein termed "the andesite of Summit Diggings," and (4) the "Quaternary" basalt (Smith, 1964) herein termed "the basalt of Teagle Wash."

The Almond Mountain volcanic section erupted from the 9-km-diameter western Lava Mountains volcano. This volcanic center was originally recognized by Smith (1964) and briefly described by Carter (1994), but detailed mapping, volcanology, and geochemistry were done by Keenan (2000). The western Lava Mountains volcano (Fig. 3) was active between 10.29 Ma and ca. 9.54 Ma. Coalescing andesite and dacite domes and subvolcanic intrusive rocks make up the central vent area. Domes are surrounded by a thick section of inward-dipping andesite breccia, flows, and lapilli tuff. The dacite breccia contains block-and-ash, rock-avalanche, sandstone and conglomerate, and debris-flow deposits that represent explosive and passive destruction of volcanic domes in the central-vent area. Breccia commonly contains bombs and blocks of andesite up to 3 m in size.

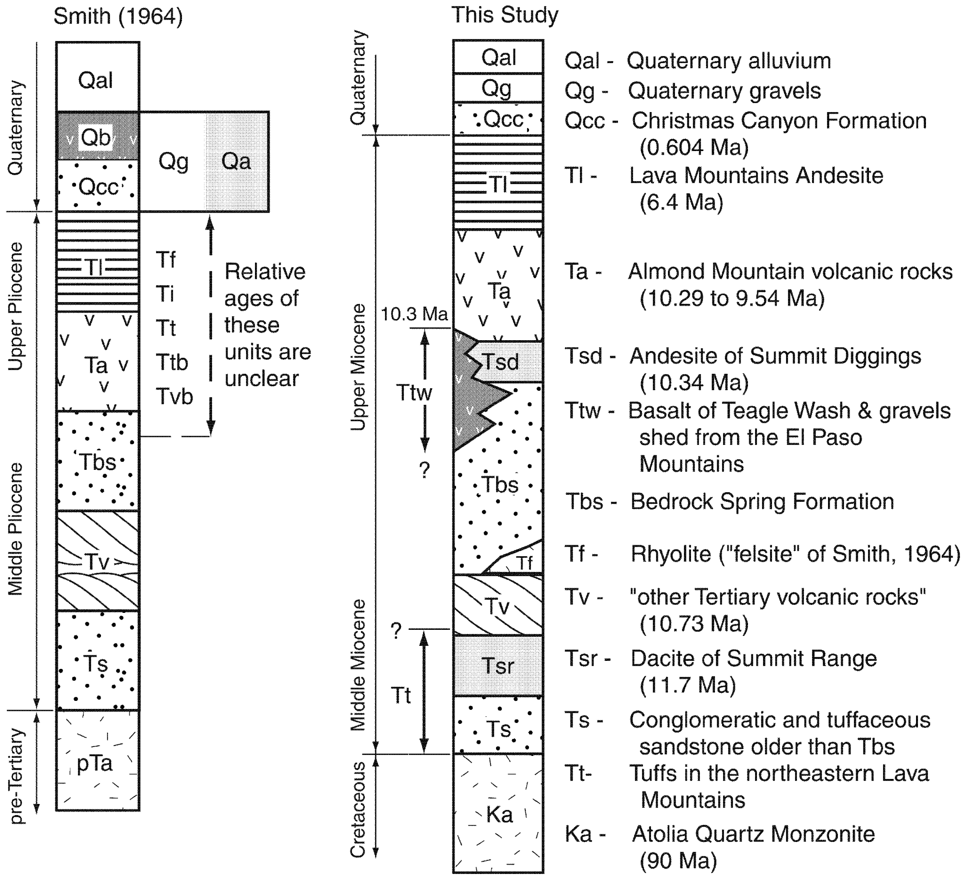

Figure 2. Comparison of the volcanic stratigraphy of Smith (1964) with the revised stratigraphy of this paper. Note that Qb and Qa in Smith's (1964) stratigraphy are equivalent to Ttw and Tsd, respectively, in the revised stratigraphy.

TABLE 1. DATES BY ^{40}Ar/^{39}Ar INCREMENTAL-HEATING TECHNIQUE OF SAMPLES FROM THE LAVA MOUNTAINS

Sample	Unit	Date (Ma)	Uncertainty (2σ) (± m.y.)	Date type	MSWD	Mineral
LM96-2	Tsd	10.34	0.69	plateau (inc. 3–9)		hornblende
LM96-2	Tsd	7.81	0.14	plateau (inc. 5–9)		biotite
LM96-15	Tv	10.73	0.10	plateau (inc. 7–11)		biotite
LM96-16	Ta	9.54	1.14	plateau (inc. 10–11)		hornblende
LM96-16	Ta	7.82	0.21	plateau (inc. 7–9)		biotite
LM96-17	Tat	10.29	0.78	plateau (inc. 10–11)		hornblende
LM96-17	Tat	8.73	1.58	isochron (inc. 3–11)	1.73	hornblende
LM1132	Tl	6.4	0.1	isochron (inc. 3–9)	0.9	biotite
GFZ-85	Tsr	11.7	0.2	isochron (inc. 4–10)	2.0	sanidine

Note: ^{40}Ar/^{39}Ar dates by the the Cambridge Laboratory for Argon Isotopic Research (CLAIR), Massachusetts Institute of Technology. Tsd—dacite of Summit Diggings, Tv—other Tertiary volcanic rocks, Ta—Almond Mountain andesite, Tat—Almond Mountain tuff, Tl—Lava Mountains andesite, Tsr—dacite of Summit Range. Inc. = Increments of the Ar spectrum used to calculate either the isochron or plateau age. MSWD = mean square of weighted deviates for isochron dates.

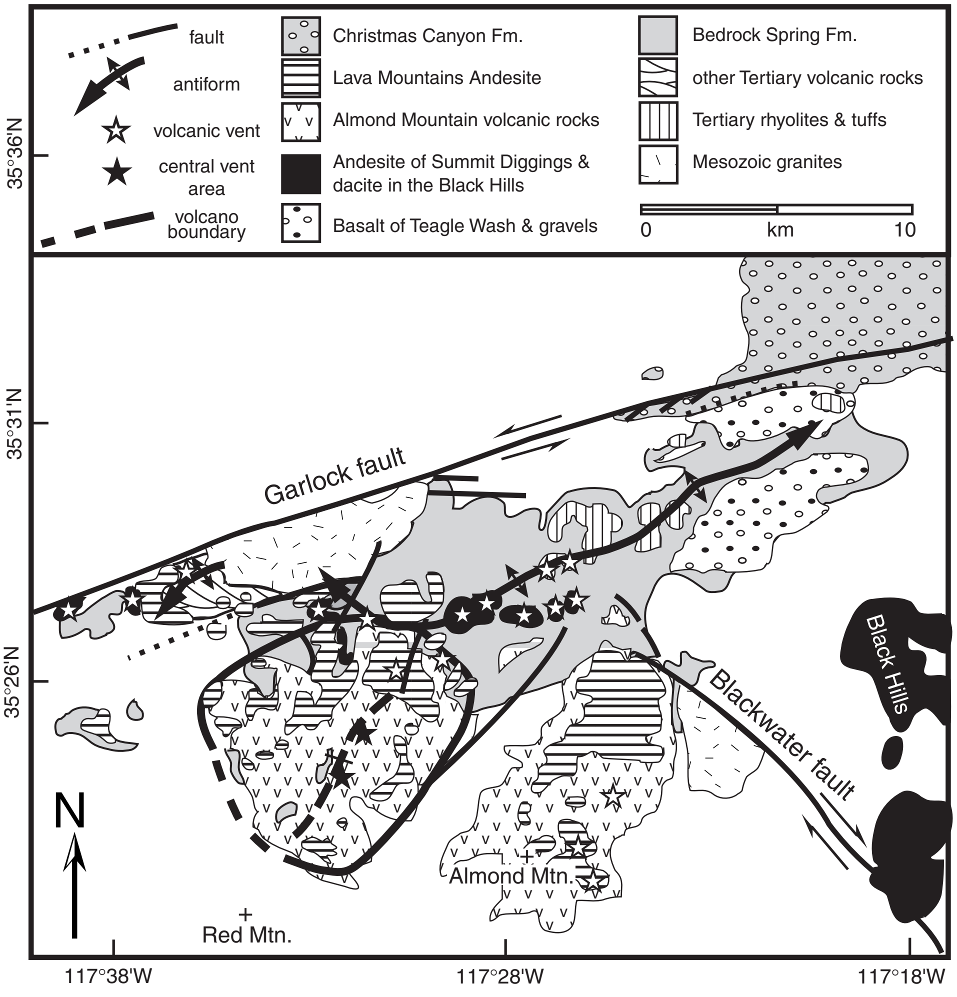

Figure 3. Geologic map showing the locations of volcanic centers and major fold axes in the Lava Mountains and adjacent areas. Geology modified from Smith (1964), Dibblee (1967), and Keenan (2000). Note that many of the vent areas lie on the axes or flanks of major folds. The area of the western Lava Mountains volcano includes the central-vent area and moat composed of inward-dipping block-and-ash and debris-flow deposits, and pyroclastic and lava flows. The domes of the central-vent area intruded tilted, topographically and structurally high beds of Bedrock Spring Formation.

Placing the andesite of Summit Diggings, the basalt of Teagle Wash, and volcanic rocks of the Bedrock Spring Formation into the same time frame as the Almond Mountain volcanic section represents a major revision of Smith's (1964) stratigraphy. Detailed justification for assigning these units to the second episode of volcanism follow.

Smith (1964, p. 44) based the Quaternary age of the andesite of Summit Diggings on one contact where "andesite rests on the upper part of a surface that was elsewhere covered by older gravels of early Quaternary age." A new ^{40}Ar/^{39}Ar date of 10.34 Ma (Table 1) brings this field-based interpretation into question and places the andesite of Summit Diggings stratigraphically below the Almond Mountain volcanic section. New field observations also support this age assignment. A dome and several flows of the andesite of Summit Diggings intrude and overlie the Bedrock Spring Formation. Resting on the flows are the lapilli tuff and breccia of the Almond Mountain volcanic section and flows of Lava Mountains Andesite (Fig. 2).

Assignment of the basalt of Teagle Wash to this episode is based mainly on field relationships. Smith (1964) assigned a Quaternary age to the basalt because he mapped it lying on and intruding the conglomerate facies of the Quaternary Christmas Canyon Formation. We do not question the age assignment of the Christmas Canyon Formation, which appears to be firmly based on fossil evidence and a 602 ka ^{40}Ar/^{39}Ar date from an interbedded tuff (Gansecki et al., 1998). However, we question the assignment of the conglomerate beneath the basalt to this formation. The conglomerate described by Carter (1982, 1987, 1994) contains clasts of spotted Mesquite Schist, carbonate clasts of the Paleocene Goler Formation, weakly lineated hornblende quartz diorite, and vesicular basalt that is chemically identical to basalt flows in member 4 of the Dove Spring Formation (see Geochemistry and Implications section). These clasts only could have been derived from the El Paso Mountains north of the Garlock fault (Carter 1982, 1987, 1994). The conglomerate probably represents part of a fanglomerate sheet that extended from drainages in the El Paso Mountains south into the Lava Mountains and then was cut and displaced by movement along the Garlock fault (Carter, 1982). If we assume that the conglomerate belongs to the Christmas Canyon Formation and is Quaternary in age as mapped by Smith (1964), at least 30 km of displacement must have occurred along the Garlock fault in ~620 k.y. This interpretation results in a displacement rate as high as 5 cm/yr, a value that is one order of magnitude higher than the estimated average long-term slip rate of 7 mm/yr (Carter, 1987, 1994). A slip rate of 5 cm/yr is unreasonable for the Garlock fault; we suggest, therefore, that the conglomerate and overlying basalt are Tertiary in age. Furthermore, this age assignment is strengthened by the geochemical correlation of 11.6 to 10.4 Ma basalt in the Dove Spring Formation with both the basalt boulders in the conglomerate and the basalt of Teagle Wash (see Geochemistry and Implications section).

Volcanic units in the uppermost part of the Bedrock Spring Formation contain block-and-ash deposits and pyroclastic flows. The block-and-ash deposits resemble those of the Almond Mountain section in that they contain lithologically identical clasts. Clasts are similar in three important ways. First, they commonly show radial fractures and fine-grained mantles that contain micro–columnar joints, features that indicate eruption while still hot. Clasts similar to these are otherwise only found in breccias of the Almond Mountain volcanic section. Second, clasts are mineralogically identical to Almond Mountain dacite in that they contain phenocrysts of plagioclase, hornblende, and biotite. Finally, they are chemically identical to clasts within block-and-ash deposits of the Almond Mountain section (Table DR1).[1] From these observations, we suggest that the volcanic units within the Bedrock Spring Formation represent the initial stages of Almond Mountain activity.

After a hiatus of 2–3 m.y., activity continued with the eruption of the Lava Mountains Andesite (6.4–5.8 Ma, Table 1) forming the volcanic rocks of the third episode.

Lava Mountains Andesite crops out about the central-vent area of the western Lava Mountains volcano and in the eastern Lava Mountains and is mineralogically and chemically similar to volcanic rocks formed during the two preceding episodes. Although the Lava Mountains Andesite covers considerable area and is topographically prominent (Fig. 3), it is usually composed of one to three flows that rarely exceed 100 m in thickness.

In summary, volcanism in the Lava Mountains occurred in three episodes. The first episode was separated from the second by deposition of the Bedrock Spring Formation and ~500 k.y. of time. The period between episode 2 and 3 was no longer than 3 m.y. The period of quiescence may have been shorter considering that the younger date for the Almond Mountain volcanic section is from a bomb in the upper-middle part of the section.

GEOCHEMISTRY, GEOCHRONOLOGY, AND STRATIGRAPHY: IMPLICATIONS FOR MIOCENE DEVELOPMENT OF THE GARLOCK FAULT

Geochemical fingerprinting of volcanic rocks is useful for correlation of units between separate localities. Of specific interest is the correlation of volcanic rocks between the Lava and El Paso Mountains to provide markers that can be used to estimate the slip rate on the Garlock fault. Our geochemical database includes 71 new samples from the Lava and El Paso Mountains. All samples were analyzed for major oxides and trace elements by X-ray fluorescence spectrometry on fused disks at the Rock Chemistry Laboratory, University of Nevada, Las Vegas. Concentrations of rare earth elements (REEs) and other selected trace elements were determined for 69 samples at the GeoAnalytical Laboratory at Washington State University

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[1] GSA Data Repository item 2002###, Table DR1, Major Element Oxide, Trace, and Rare Earth Element Analyses, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

by ICP-MS (inductively coupled plasma–mass spectrometry). The Isotope Geochemistry Laboratory at the University of Kansas provided radiogenic isotopic analyses (Sm/Nd, Rb/Sr, and Pb systems) of 41 samples. The Cambridge Laboratory for Argon Isotopic Research (CLAIR), Massachusetts Institute of Technology, dated six samples by using the ^{40}Ar/^{39}Ar incremental-release technique (Tables 1, DR1, and DR2 [see footnote 1]).

On the basis of these new geochemical and geochronologic data and the stratigraphic studies described in the preceding section, we argue that during late Miocene time, the El Paso Mountains lay just to the north of the Lava Mountains across the Garlock fault. Four lines of evidence support this contention: (1) chemical correlation of the basalt of Teagle Wash with basalt in member 4 of the Dove Spring Formation in the El Paso Mountains, (2) chemical correlation of basalt boulders in a conglomerate beneath the basalt of Teagle Wash to both the basalt of Teagle Wash and to basalt in member 4 of the Dove Spring Formation, (3) chemical correlation of tuff in the Almond Mountain section with tuff of member 5 of the Dove Spring Formation, and (4) correlation of clasts in a conglomerate beneath the basalt of Teagle Wash to sources in the El Paso Mountains.

Volcanic rocks in the Lava Mountains are age equivalent to the volcanic section in the upper part of the Dove Spring Formation, El Paso Mountains. The Dove Spring Formation, divided into six members, consists of a section of conglomerate, sandstone, mudrock, chert, tuff, and basalt (Loomis and Burbank, 1988). Although occurring throughout the section, volcanic units are most prevalent in members 2, 4, and 5 (Fig. 4).

Tuffs in member 2 thin to the north and form prominent cliffs in Red Rock Canyon in the western El Paso Mountains. These tuffs may correlate with rhyolitic tuffs (mapped by Smith [1964] as Tt) in the northeastern Lava Mountains (Fig. 4). Member 2 tuff and Tt share low Ba, P, Ti, and Zr contents, high Rb, Th, and U contents, and negative Eu anomalies compared to Almond Mountain tuff (Fig. 5). Tt differs from member 2 tuff in having higher REE abundances. Tuffs in member 2 are too old (fission-track ages of 15.1-11.8 Ma in Loomis and Burbank, 1988) to correlate with tuffs of the Almond Mountain volcanic section.

Basalt in member 4 occurs as two flows (Tdb2 and Tdb3 of Loomis and Burbank, 1988), is fine grained, and vesicular and contains phenocrysts of olivine and plagioclase. Loomis and Burbank (1988) bracketed the age of these flows to between 10.4 and 11.8 Ma by dating tuffs higher and lower in the section (Fig. 4). A new ^{40}Ar/^{39}Ar date of 11.6 Ma on member 4 basalt (unit Tdb2 of Loomis and Burbank, 1988) falls into this age range. Major and trace element abundances and isotopic ratios for member 4 flows are similar to the basalt of Teagle Wash in the Lava Mountains. REEs share a common smooth pattern with 60 to 70 times chondrite enrichment in La and about 10 times chondrite enrichment in Lu (Fig. 6). Samples from the two member 4 flows were analyzed in different laboratories, perhaps explaining the small differences in chemistry between them. Isotopic ratios are also remarkably similar; ^{206}Pb/^{204}Pb varies between 19.2 and 19.3 and ^{887}Sr/^{86}Sr is 0.7054 ± 0.0001. On the basis of these similarities in major and trace element chemistry and isotopic ratios, we suggest that the member 4 basalt in the El Paso Mountains correlates with the basalt of Teagle Wash in the Lava Mountains (Fig. 4).

The source of the fine-grained, vesicular basalt boulders in Quaternary deposits in the Lava Mountains and in the conglomerate beneath the basalt of Teagle Wash is controversial. Smith (1964, 1991) suggested that they originated to the southeast in the Black Hills, and Carter (1980, 1982) thought they might represent Black Mountain basalt from the northern El Paso Mountains (Fig. 7). Geochemical data clearly indicate that neither one of these possibilities is tenable. Dark colored volcanic rock in the Black Hills, thought to be basalt by Smith (1964, 1991), is fine- to medium-grained, flow-banded hornblende dacite with 63.4 to 64.8 wt% SiO_2 and 1.71 to 2.55 wt% MgO; thus it is too felsic to correlate with the basalt boulders in the Lava Mountains. Black Mountain basalt from the El Paso Mountains is too low in SiO_2 (48.3 to 49.1 wt%) and too high in Al_2O_3 (15.5 to 17 wt%) to correlate with the basalt of Teagle Wash (51 wt% and 14.5 wt%, respectively). The chemistry of a basalt boulder in the conglomerate beneath the basalt of Teagle Wash is, however, nearly a perfect match for basalt in member 4 of the Dove Spring Formation (Fig. 8). The basalt boulders, therefore, are Tertiary in age and were derived from basalt flows in member 4 of the Dove Spring Formation in the El Paso Mountains. Many of these boulders were transported to the north during the Quaternary and deposited in the Christmas Canyon Formation. If this history is correct, then the basalt boulders were twice reworked; first transported to the south in Tertiary time and then transported to the north during the Quaternary. These observations reconcile apparent differences between the interpretation of Smith (1964) that the Christmas Canyon Formation and overlying basalt are Quaternary in age and our suggestion that although the Christmas Canyon Formation is Quaternary, the basalt and underlying conglomerate are Tertiary in age.

A thin tuff (10 m thick) in the lower part of member 5 in the Dove Spring Formation (Fig. 4) was dated at 10.4 ± 1.6 Ma (fission-track date, Loomis and Burbank, 1988). In the Lava Mountains, the basal ash flow of the Almond Mountain section is 10.29 ± 0.8 Ma and a lapilli tuff in the lower middle part of the same section is between 10.29 and 9.54 Ma. Both tuffs are potentially candidates for correlation with the member 5 tuff in the Dove Spring Formation, El Paso Mountains. REE plots show that the member 5 tuff is similar in composition to both the basal and lapilli tuffs in the Almond Mountain section (Fig. 9), although member 5 tuff has higher heavy-REE abundances than the Almond Mountain tuffs. On the basis of these observations, we suggest that the member 5 tuff is the distal equivalent of tuffs in the Almond Mountain volcanic section (Fig. 4).

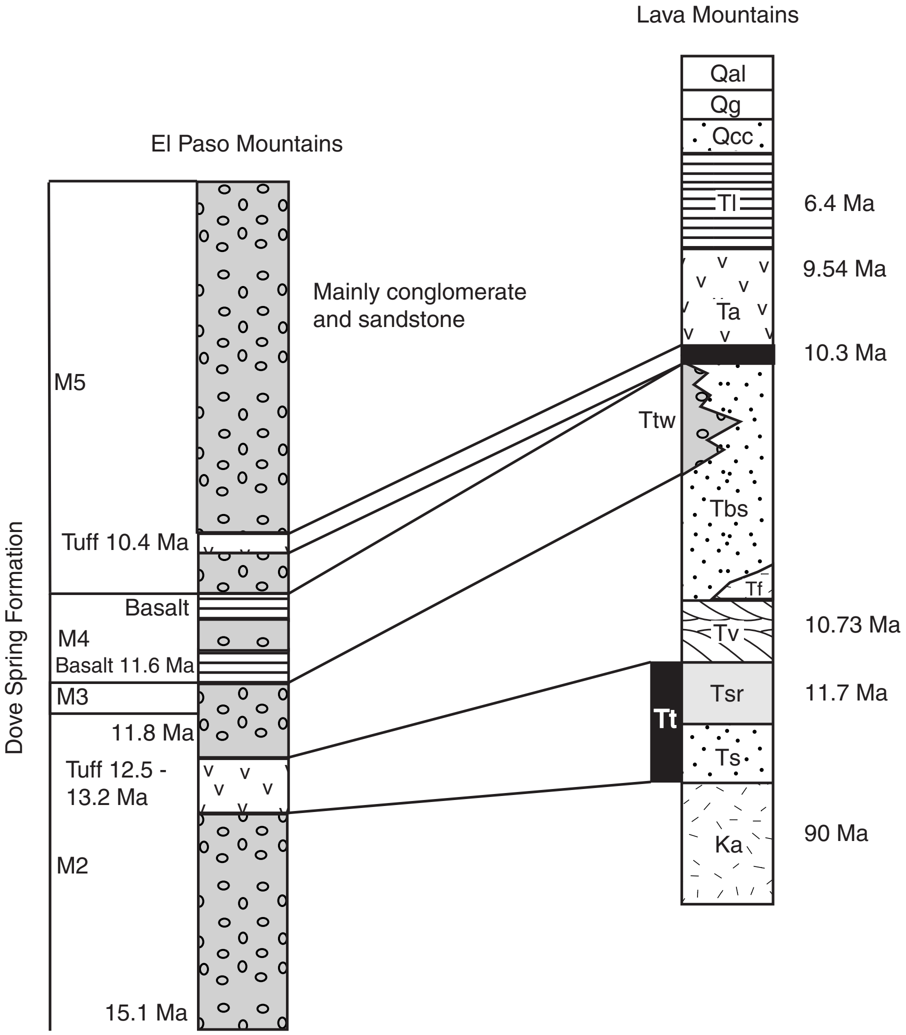

Figure 4. Comparison of the stratigraphic section in the El Paso Mountains (modified from Loomis and Burbank, 1988) with the section in the Lava Mountains. Note that the stratigraphic sections are not to scale. Correlations of tuff and basalt units proposed in this paper are shown by tie lines between sections.

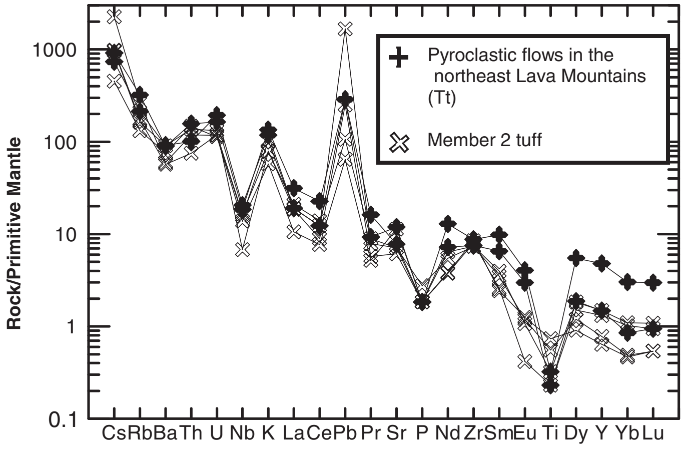

Figure 5. Trace element diagram emphasizing that the pyroclastic flows in the northeastern Lava Mountains (Tt) probably correlate with member 2 tuff in the El Paso Mountains. Elements are normalized to primitive mantle of Sun and McDonough (1989).

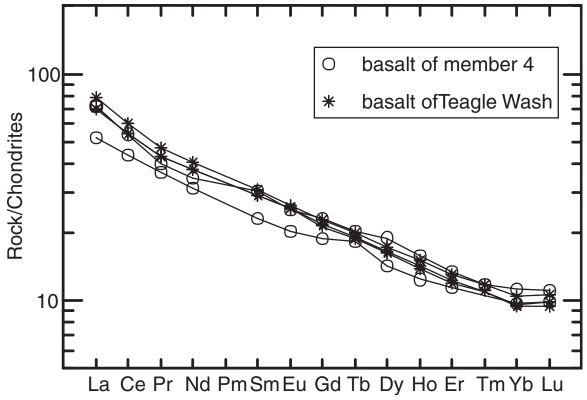

Figure 6. REE plot normalized to chondritic abundances showing the geochemical similarities between samples of the basalt of Teagle Wash in the Lava Mountains and samples of the basalt of member 4 of the Dove Spring Formation in the El Paso Mountains. REEs are normalized to the chondritic abundances of Sun and McDonough (1989).

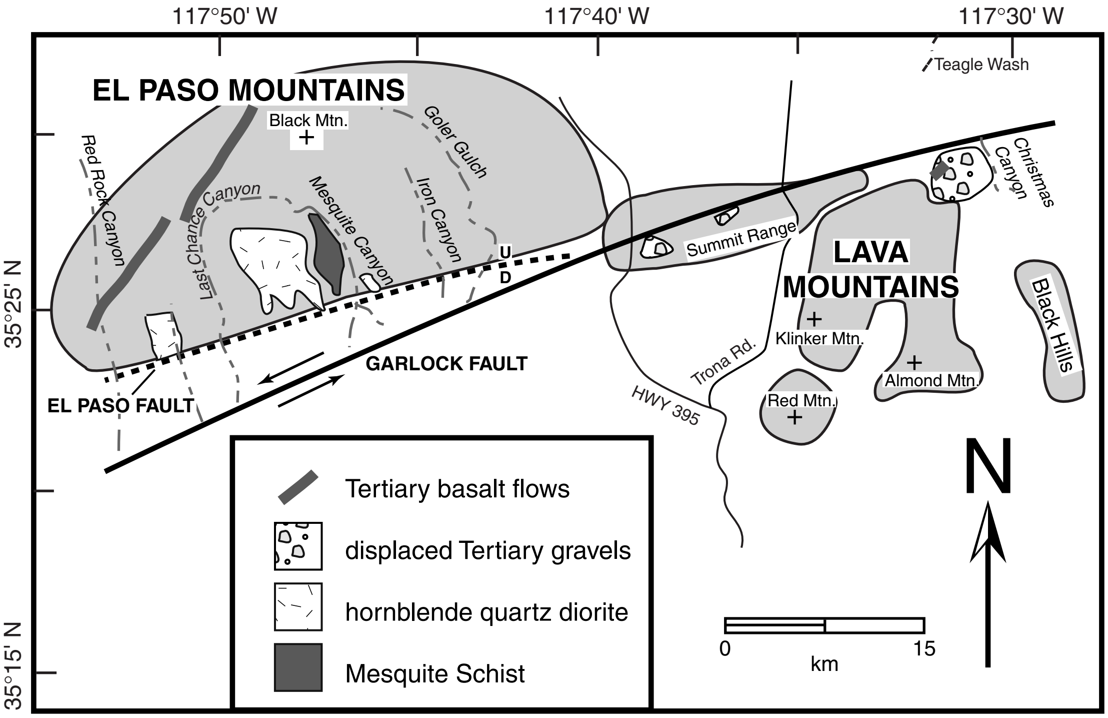

Figure 7. Location map of the central Garlock fault area.

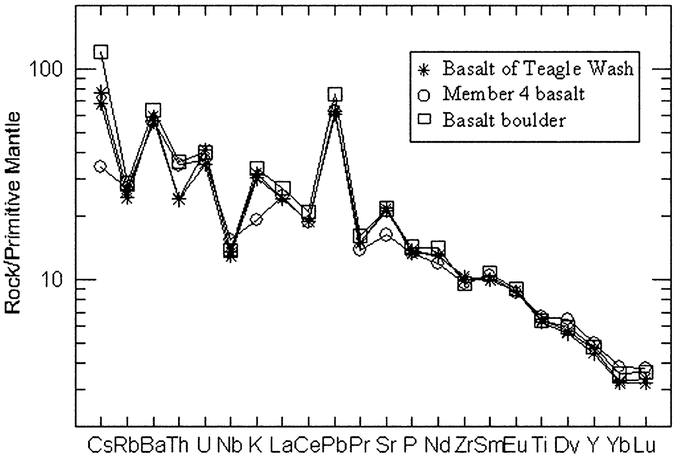

Figure 8. Trace element diagram showing that the chemistry of a basalt boulder in the conglomerate beneath the basalt of Teagle Wash (Lava Mountains) is similar to both the basalt of member 4 (Dove Spring Formation, El Paso Mountains) and the basalt of Teagle Wash, Lava Mountains. Elements are normalized to primitive mantle of Sun and McDonough (1989).

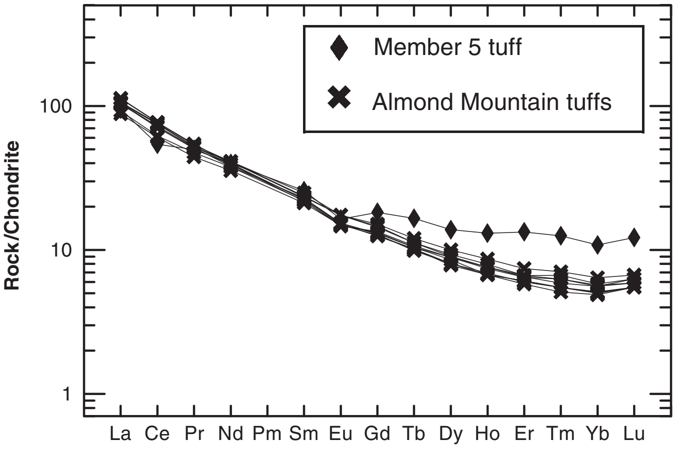

Figure 9. REE plot showing that tuff of member 5 of the Dove Spring Formation (El Paso Mountains) is chemically similar to and probably correlates with tuffs of the Almond Mountain volcanic section (Lava Mountains). Member 5 tuffs (El Paso Mountains), however, have higher heavy-REE abundances than Almond Mountains tuffs.

Correlations based on lithology, age, and geochemistry suggest that the El Paso Mountains lay just to the north of the Lava Mountains between ca. 11.6 and 10.3 Ma. Although these were adjacent areas, sedimentary units were transported to the south from the El Paso Mountains into the Bedrock Spring basin (the future site of the Lava Mountains), and volcanic units from the Lava Mountains traveled to the north into the El Paso Mountains. In the past 10.4 m.y, the El Paso Mountains moved 32 to 40 km to the west along the Garlock fault. This distance and time translate into a displacement rate of ~3.1–3.8 mm/yr. The calculated rate is less than the average Holocene rate of 6–8 mm/yr (McGill and Sieh, 1993) and the Pleistocene rate of 7 mm/yr (Carter, 1987). It is very similar, however, to the rate inferred from the work of Monastero et al. (1997) who assumed

64 km of offset in ~17 m.y., resulting in an average displacement rate of 3.5 mm/yr.

From the preceding information, we suggest the following history for the central Garlock fault (Fig. 10).

Rhyolite tuff erupted from sources to the south of the Lava Mountains or from domes in the eastern Lava Mountains and flowed to the north across the Garlock fault into the El Paso Mountains (Fig. 10A). This tuff forms the tuffs in the northeastern Lava Mountains and the member 2 tuff in the El Paso Mountains.

Fanglomerate fans from the El Paso Mountains extended across the trace of the Garlock fault into the Bedrock Spring basin (Fig. 10B). These fans contain clasts and slide blocks of Mesozoic basement rock and boulders of basalt from member 4 of the Dove Spring Formation. Member 4 basalt flows erupted from sources in the El Paso Mountains and flowed to the south through channels cut into the fan. Inclusion of the basalt boulders in the fanglomerate fan and the overlying basalt requires that the fan formed during the eruption of the member 4 basalt (11.6 to 10.4 Ma). Distinctive clast types, especially hornblende quartz diorite, indicate that the fan may have originated at the mouth of Mesquite Canyon in the El Paso Mountains (Figs. 7, 10B). Similar conclusions were reached by Carter (1982, 1987, 1994).

At ca. 10.3 Ma, pyroclastic flows from the western Lava Mountains crossed the trace of the Garlock fault and are now

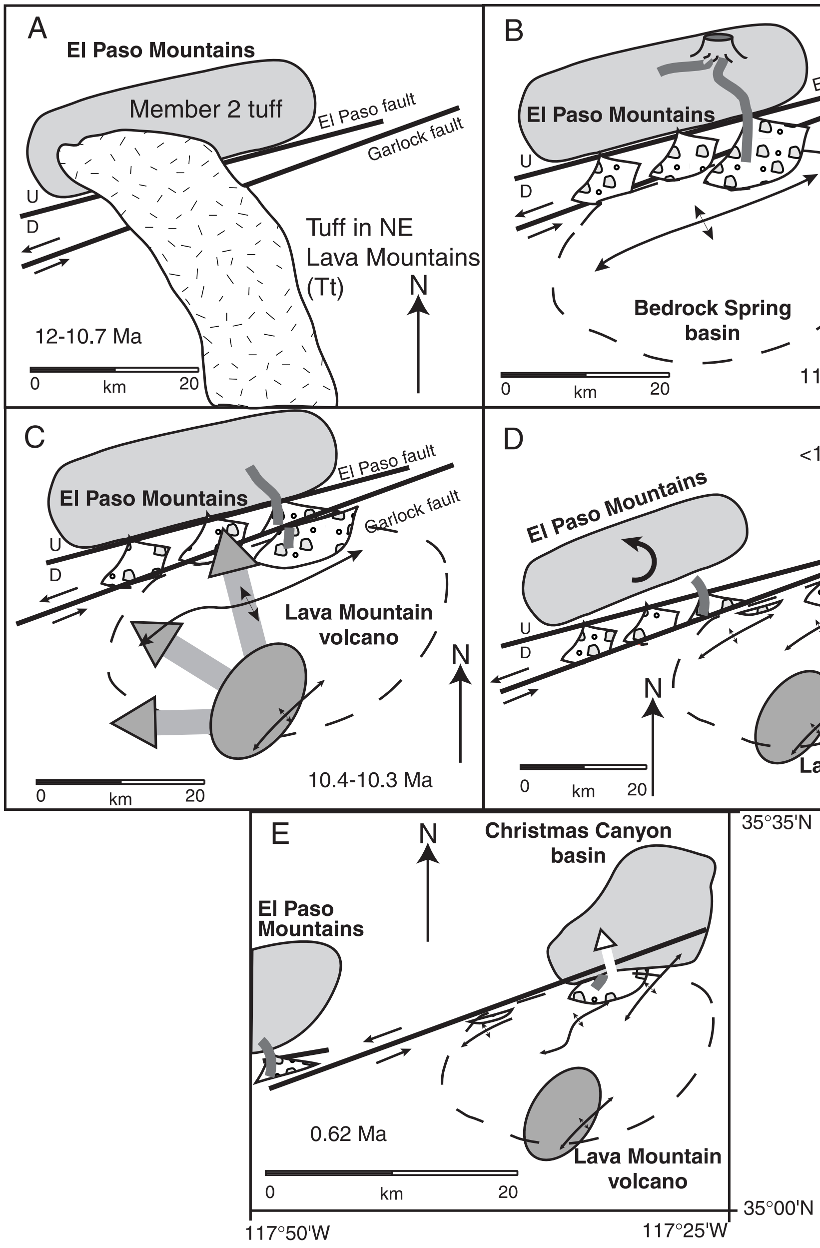

Figure 10. Five-step model for the evolution of the central Garlock fault. See text for details.

exposed in the western El Paso Mountains in member 5 of the Dove Spring Formation. This correlation requires that the Lava Mountains and El Paso Mountains were in close proximity at 10.3 Ma (Fig. 10C).

Sinistral motion on the Garlock fault after 10.3 Ma resulted in the separation of the Lava and El Paso Mountains, counterclockwise rotation of the El Paso Mountains (Loomis and Burbank, 1988), and folding in the Lava Mountains (Smith, 1964). The latter two events may have occurred simultaneously (Fig. 10D).

In Quaternary time, the sediment transport direction reversed, and sandstone accumulated north of the Garlock fault in the Christmas Canyon basin. At ca. 602 ka, ash from eruptions of the Yellowstone caldera accumulated in the upper part of the Christmas Canyon Formation (Gansecki et al., 1998). Topographically high gravels including member 4 basalt clasts were shed to the north and deposited on the sandstone facies of the Christmas Canyon Formation. These gravels produced the conglomerate facies described by Smith (1964) (Fig. 10E).

CONCLUSIONS

Volcanism in the Lava Mountains occurred between 11.7 and 5.8 Ma and was contemporaneous with sinistral motion on the Garlock fault (after 17 Ma to the present).

Three chemical groups of volcanic rocks erupted in the Lava Mountains in three episodes over a period of 5 m.y. These are (1) a main group consisting of the andesite of Summit Diggings, Almond Mountain tuff, and Lava Mountains Andesite, (2) the basalt of Teagle Wash, and (3) tuffs in the northeastern Lava Mountains and dacite in the Summit Range. Volcanic rocks of each group have distinctive chemical signatures useful for correlation of units across the Garlock fault. Tuffs in the Almond Mountain volcanic section may be equivalent to a thin tuff in member 5 of the Dove Spring Formation, El Paso Mountains. Basalt of Teagle Wash probably correlates with basalt flows in member 4, and tuffs in the northeast Lava Mountains may be equivalent to the tuff of member 2. Correlation of these units across the Garlock fault implies that the Lava Mountains were situated just south of the El Paso Mountains between 11.6 and 10.3 Ma and that 32 to 40 km of offset occurred on the Garlock fault in ~10.4 m.y., resulting in a displacement rate of 3.2 to 3.8 mm/yr. Projecting this rate to the total offset of 64 km on the Garlock suggests that left-lateral slip began at about 16.4 Ma. This value agrees with Monastero et al. (1997) and is very close to the time of onset of extension in the Death Valley area (15.7–15.1 Ma) (Davis and Burchfiel, 1973).

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