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TIMING AND TECTONIC SETTING OF TERTIARY LOW-ANGLE NORMAL FAULTING AND ASSOCIATED MAGMATISM IN THE SOUTHWESTERN UNITED STATES

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Abstract. Major episodes of Tertiary low-angle normal faulting in the southwestern United States south of latitude 37°N moved northward with time, occurring about 25 million years ago in southern Arizona, 20 million years ago in the Mojave Desert region, and 10 to 15 million years ago in the Las Vegas area. In most areas, faulting and associated volcanism occurred when the Mendocino triple junction lay to the west. This correspondence probably resulted from the unstable configuration of the triple junction. East-west to northeast-southwest horizontal stretching, as plates pulled apart at the triple junction, prevented development of a hole in the lithosphere at the triple junction. The regional strain history predicted by this model is consistent with observed Tertiary low-angle faults, strike-slip faults, and folds.

INTRODUCTION

Low-angle normal faults of Tertiary age are common in the southwestern United States. These faults, many of which are associated with metamorphic core complexes [Crittenden et al., 1980], occur in a belt from northern Sonora to the Death Valley region [Coney, 1980, Figure 1]. Recent studies of these faults have focused on their structural style and upper plate/lower plate relations [e.g., Davis et al., 1980; Rehrig and Reynolds, 1980]. Less attention has been paid to spatial variation of their ages.

The age of faulting is important because these faults have apparently played a major role in extending the upper crust of the western United States. Wernicke et al. [1982] inferred that the southern Great Basin has been extended 140 km or more, principally along low-angle normal faults of Tertiary age. Isotopic dates reported by Anderson et al. [1972] indicate that much of this extension occurred during a brief interval at 12 to 15 Ma (millions of years before present). Studies of other areas in the southwestern United States similarly suggest that most low-angle faulting and, by inference, most extension occurred during brief intervals in the Miocene and late Oligocene.

The age of faulting is also important because it can help distinguish between different environments of extension. As we show below, conservation of surface area limits the amount of extension which can occur inland of a transform fault plate margin. The timing of extension relative to development of transform fault tectonics in the southwestern United States [Atwater, 1970] distin-

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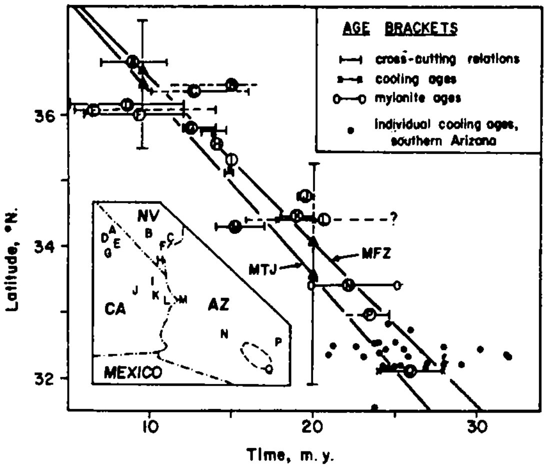

Fig. 1. Compilation of constraints on ages of low-angle normal faulting in the southwestern United States, plotted against latitude. Circled letters identify areas which are located on the inset map and identified in Appendix A. The dashed line on the inset encloses the area from which the individually plotted cooling ages came. Solid lines between brackets indicate probable age of principal extension event; broken lines include timing which is possible but less likely (see text and Appendix A). Lines show the latitude of the Mendocino triple junction (MTJ) and the latitude of the subducted Mendocino fracture zone (MFZ) beneath the extended terrane (see also Figure 2). These lines were derived by drawing straight lines (i.e., assuming constant relative plate velocity) through calculated positions of the MFZ for anomalies 5, 6, and 13 (solid triangles; points for anomaly 13 lie off of the figure), using rotation parameters from Molnar and Stock [1981] and the magnetic time scale of Lowrie and Alvarez [1981]. Vertical lines through triangles give maximum range of acceptable fits (J. Stock, written communication, 1981).

guishes whether extension occurred in an intraarc setting, or above a "slab window" inland from a transform fault plate boundary, as proposed by Dickinson and Snyder [1979a].

This paper reviews the ages of low-angle normal faults south of latitude 37°N in the southwestern United States. We conclude that time of faulting correlates with the changeover from subduction to transform fault tectonics, i.e., when the Mendocino triple junction lay to the west of a given faulted area. Ingersoll [1982] noted that the configuration of this triple junction tends to open a hole, which may be filled by extension within the North American plate. We propose that low-angle normal faulting and associated volcanism were triggered by a combination of two processes: (1) extension of the lithosphere of the southwestern United States into this hole, and (2) flexure of the same lithosphere above the subducted Mendocino fracture zone.

AGE OF FAULTING

Figure 1 is a compilation of constraints on the timing of extensional faulting in various terranes in the southwestern United States, plotted as a function of latitude. Appendix A summarizes the sources of these data and describes the specific constraints. Timing constraints are provided mainly by isotopic dates of units that cut or are cut by faults. Many of the data from southern Arizona come from pre-Tertiary footwall rocks, and represent cooling ages, or apparent ages caused by partial resetting of K/Ar mineral systems.

In any given area, extension may have occurred during a protracted period of deformation ranging from Oligocene (or earlier) to Recent. Constraints on the end of deformation are better than those on its initiation because (1) later events overprint and obscure evidence of earlier ones, and (2) this region is characterized by a widespread hiatus in the early Tertiary that precludes stratigraphic dating of possible early Tertiary structures [Shafiqullah et al., 1980]. However, the general space-time correlation between volcanism and deformation in this region suggests that the two are genetically related [Bartley and Glazner, 1983; J. M. Bartley and A. F. Glazner, manuscript in preparation, 1984]. Thus the absence of earlier volcanism may indicate an absence of pre-Oligocene extension in the southern Basin and Range.

The following section focuses on aspects of the timing which we consider critical to tectonic interpretation. We infer that in each area a pulse of intense magmatism and extensional deformation occurred which was responsible for the dominant Tertiary structures. The ages of such pulses of deformation appear to be diachronous, older in the south and younger in the north.

Northern region (latitude 35.5°-37°N). In the northern part of the area of Figure 1, well-constrained ages for the principal period of extension range from 5 to 6 Ma (Amargosa Chaos; Fleck [1970]) to 13 to 15 Ma (Black/Eldorado Mountains area; Anderson et al. [1972]). With the exception of the Amargosa Chaos, the ages cluster around 10 to 14 Ma. Deformation younger than 10 Ma in the Death Valley area may reflect a different tectonic regime, which is suggested by a change in orientation of the principal extension direction (see below). At this latitude, Tertiary extension appears not to have begun until around 15 Ma.

Central region (latitude 34°-35.5°N). The Tertiary geology of this area is less completely described than other areas included in Figure 1, and timing constraints are comparably sparse. However, there appears to be little or no temporal overlap with extension in regions to the north. Spencer [1983] reports a minimum age for low-angle faults in the Homer Mountain/Sacramento Mountains area of 14.6 Ma. Flat-lying basalts that are not cut by low-angle faults in the Whipple Mountains area give an age of 15.9 ± 2.8 Ma [Davis et al., 1982]. Tilting and extension was completed in most areas by 18 to 20 Ma.

The period of extension was no more than 3 m.y. (million years) in most areas (e.g., in the Newberry-Cady Mountains area, ages of pre- and posttilt volcanic rocks are statistically indistinguishable; see Appendix A), but may have been somewhat longer in the Whipple Mountains. Frost [1979] and Davis et al. [1982] observed that the Gene Canyon Formation (which has yielded dates ranging from 31.8 to 25.7 Ma) dips more steeply than the unconformably overlying Copper Basin Formation (18.7 to 17.3 Ma), indicating pre-Copper Basin tilting. If the coarse clastic rocks in the Gene Canyon Formation indicate it was syntectonically deposited, then extension may have occurred over as much as 10 to 15 m.y. However, Howard et al. [1982] determined that faulting in the inferred breakaway region of the Whipple Mountains detachments occurred at 18 to 20 Ma, which agrees with the cluster at 17 to 20 Ma of resetting and cooling ages of footwall rocks in the Whipple Mountains [Dokka and Lingrey, 1979; Davis et al., 1982]. We interpret this to mean that the bulk of the extension in the Whipple Mountains area occurred after deposition of the Gene Canyon Formation, the tilting of which could have begun as late as 19 or 20 Ma.

Southern region (latitude 31.5°-34°N). There are relatively few published dates which directly constrain the ages of structures in this region. Rocks as young as 10 Ma have been reported to be tilted [Shafiqullah et al., 1980; Reynolds, 1982], but these ages represent only the final increment of deformation. The majority of data suggest that the peak of activity occurred 20 to 25 Ma and predated the main extension north of latitude 34°N. In particular, a compilation of 64 cooling and resetting ages by Banks [1980] has a mode of 24 Ma; the youngest K/Ar or fission track age (excluding apatite) is 21 Ma. Lee et al. [1970] and Davis et al. [1982] showed that the younging of K/Ar ages upward toward similar detachments in other areas opposes a simple unroofing and cooling model for the age discordances, which would predict younging toward deeper structural levels. Thus the K/Ar ages probably reflect partial to complete resetting in a dynamic event. We therefore follow Damon et al. [1963] and Davis [1975] in interpreting these cooling ages to reflect the disturbance of lower plate rocks by low-angle faulting.

Correlation of Faulting With the Position of the Mendocino Triple Junction

The diagonal lines on Figure 1 give the latitude of the Mendocino triple junction and subducted Mendocino fracture zone as a function of time. These curves and Figure 2, which shows the evolving plate boundaries in map view, were derived by rotating magnetic anomalies on the Pacific plate according to rotation parameters calculated by Molnar and Stock [1981; P. Molnar and J. Stock, written communications, 1981]. Stock and Molnar [1983] calculated the maximum possible errors in the points on Figure 1, and found them to be large (approximately ±100 km latitude for anomaly 5, 9.5 Ma, and ±200 km latitude for anomaly 6, 20 Ma). These large uncertainties permit a large variety of plate reconstructions that are consistent with the marine magnetic anomalies. However, the correla-

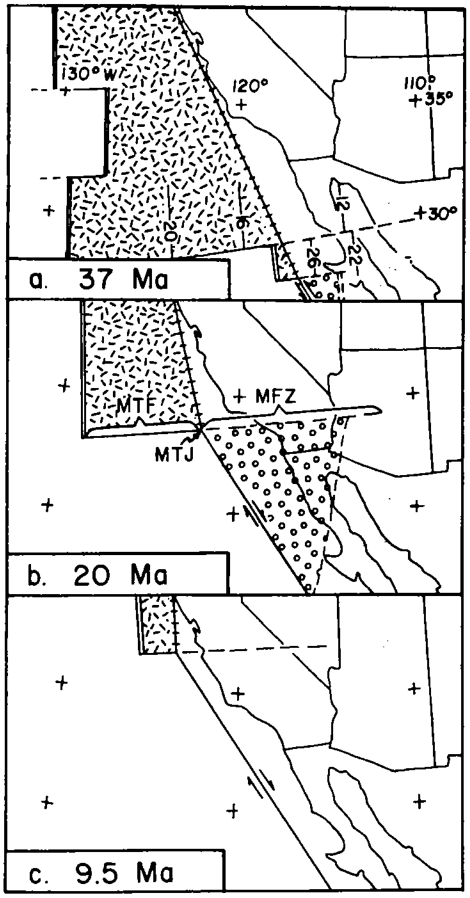

Fig. 2. Plate boundaries and calculated position of the Mendocino fracture zone (MFZ) at 37.0, 20.0, and 9.5 m.y. ago, relative to the stable North American plate, superimposed on an unrestored map of western North America. Double line indicates the Pacific-Farallon spreading ridge; solid line indicates the Mendocino transform fault (MTF); dashed line indicates the MFZ; crossed line indicates the trench (drawn along the present-day continental slope). Farallon plate is shown by dash pattern. Isobaths on the Farallon plate represent calculated elevation of the seafloor, in hundreds of meters, above an abyssal depth of 6 km [Glazner, 1981]. Circle pattern in Figures 3a and 3b represents the approximate position of the slab window postulated by Dickinson and Snyder [1979a]; omitted from Figure 3c.

tion between the calculated position of the triple junction/fracture zone and geologic events on land [Glazner and Supplee, 1982; Glazner and Loomis, in press] suggests that this reconstruction is basically accurate. Figure 1 shows that ages of faulting in the southern Arizona-Death Valley corridor generally correspond in time to passage of the Mendocino fracture zone under each area, when the Mendocino triple junction lay directly to the west. The available data show a clear trend with little or no young (less than 15 to 20 Ma) faulting at the latitude of southern Arizona, and no known old (greater than 15 to 20 Ma) faulting at the latitude of Las Vegas.

Relationship of Faulting to Volcanism

Faulting and volcanism were intimately associated in the southwestern United States during the Tertiary. Glazner and Supplee [1982] found that volcanism migrated northward with time, maintaining a position near the trace of the subducted Mendocino fracture zone. This correlation is shown in Figure 3. They proposed that volcanism was triggered by lithospheric flexure and deformation above the Mendocino fracture zone, which was a major topographic step in the subducted Farallon plate. We suggest that sudden release of compressive stress at the triple junction could also have facilitated volcanism. The two processes probably acted in concert to produce the voluminous and intense volcanism that characterized the southwestern United States in the middle and late Tertiary.

CONSERVATION OF SURFACE AREA

The apparent correlation between faulting and the change in plate boundaries suggests cause and effect. The reasons for this correlation may be explained by considering changes in lithospheric surface area that result from crustal extension. Extension of the lithosphere in one area requires contraction somewhere else. Extension of the lithosphere in the southern Basin and Range was mostly in a northeast-southwest direction; this requires contraction somewhere to the west or southwest, because no late Tertiary shortening has occurred within several hundred kilometers east of the Basin and Range.

During the Tertiary, the western margin of the North American plate changed from a subduction margin to a transform fault margin (Figure 2; Atwater [1970]). If extension occurred before the change

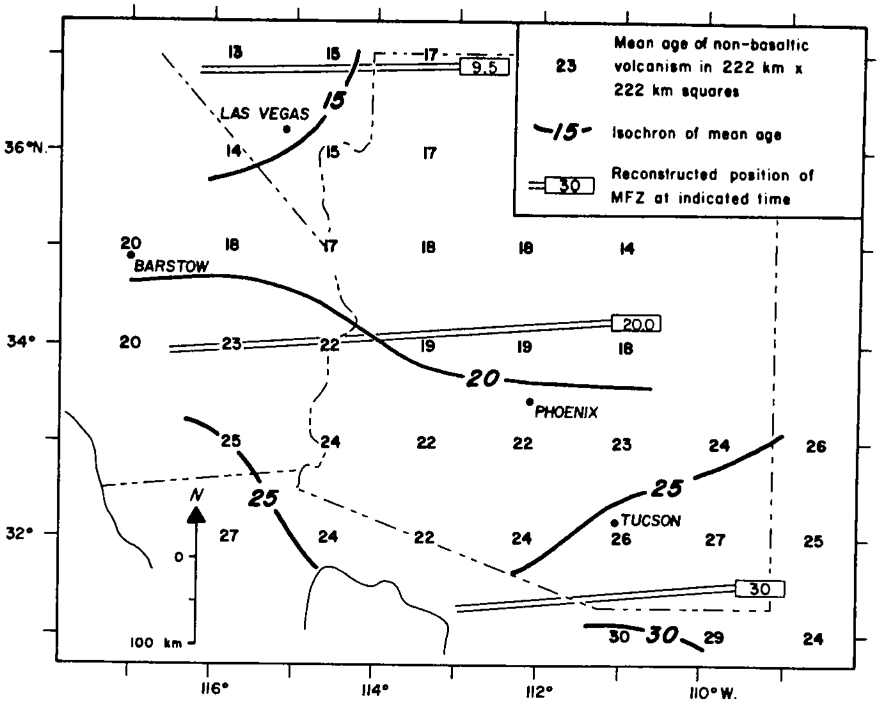

Fig. 3. Northward migration of nonbasaltic Tertiary volcanism in the southwestern United States, and estimated position of the subducted Mendocino fracture zone (double lines). This diagram, when compared with Figure 1, shows that volcanism and faulting were synchronous in most areas. Numbers at grid points give the mean age of nonbasaltic volcanism in 222 x 222 km squares; each number is the mean of all ages in the four 111 x 111 km cells that surround it. Numbers at the edge of the grid are not shown and were not included in contouring because of edge effects. Contours represent an average of contours hand-drawn independently by five different people. Data for this figure were taken from Glazner and Supplee ([1982]; see Figure 2 of that paper). Position of the fracture zone at 30 Ma was interpolated between positions at anomaly 6 (20 Ma) and at anomaly 13 (37 Ma).

to a transform fault margin, then shortening could have occurred at the subduction zone at the western boundary of the North American plate; the extension could be broadly labeled as "intraarc" (Figure 4a). If extension of the southern Basin and Range occurred after the transform fault margin developed, the extensional geometry is restricted by the rigid Pacific plate to the west. Our interpretation of the timing relationships in Figure 1 implies that major extension occurred only in a single east-west strip of North America at any one time. If the extension was directed at a high angle to the transform fault boundary, this would have distorted the boundary if compensating shortening did not occur within the North American plate (Figures 4b, 4c). Thus diachronous extension cannot be accommodated by simple divergence of the North American and Pacific plates (Figure 4c). This limitation does not apply to extension in a direction nearly parallel to the plate boundary, e.g., the post-Miocene extension in Death Valley (see below).

Conservative interpretation of Figure 1 does not require a smooth diachronous trend, but some kind of northward shift with time appears to be real. If this shift occurs after the triple junction lies at a latitude north of the extending area, the space problem we describe must be addressed, regardless of the details of timing or mechanism.

Accommodation by thrusting in southern California is ruled out because Oligocene

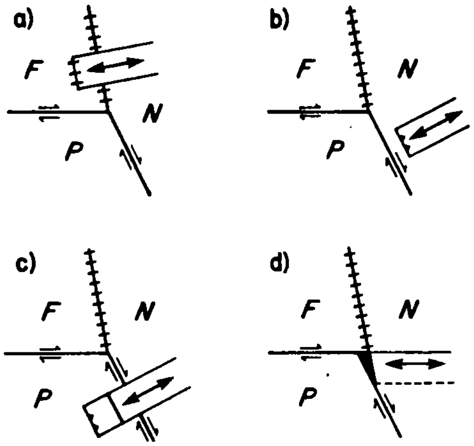

Fig. 4. Possible ways in which surface area was conserved during extensional faulting in the southwestern United States. (a) Thrusting at subduction zone; (b) Thrusting in southern California; (c) Thrusting in Pacific plate, with attachment of a piece of southern California to the Pacific plate; (d) Extension into triangular hole at the Mendocino triple junction. Double-headed arrow indicates extension. F, P, and N stand for Farallon, Pacific, and North American plates.

or Miocene thrusts reflecting east-west shortening have not been observed. Thrusting within the Pacific plate is possible, but it would require bulging of the transform fault boundary toward the Pacific plate (Figure 4c). This process would, in effect, transfer pieces of the North American plate to the Pacific plate, because the transform fault would tend to reestablish its straight course after formation of the bulge. The result would be inland stepping of the transform fault, a process which has occurred in California [e.g., Ingersoll, 1982].

Data on the age of faulting summarized in Figure 1 show that most low-angle faulting in the southwestern United States occurred during the change from subduction to transform fault tectonics, when the Mendocino triple junction lay directly to the west of a given faulted terrane. This suggests that extension was not coupled to subduction, and the area problem summarized above must be considered. A possible solution to the area problem lies in the unstable configuration of the triple junction (Figure 4d).

Geometry of the Triple Junction

Instability of the Tertiary Mendocino triple junction has been discussed in several papers [e.g., McKenzie and Morgan, 1969; Dickinson and Snyder, 1979b]. These authors noted that the Pacific-North American transform fault and the Farallon-North American trench probably were not parallel (Figure 5), and that this geometry allowed for extension within the North American plate. Relative motions of rigid plates would create a hole in the lithosphere at the triple junction if new lithosphere were not created to fill the hole (Figure 4d; Figure 5). Ingersoll [1982] noted that the hole could be filled by erupting new volcanic material or by extruding the surrounding lithosphere into the hole. The presence of scattered volcanic rocks of late-Tertiary age in the California Coast Ranges indicates that some volcanism accompanied movement of the triple junction, but the volume of these rocks is apparently small [Dickinson and Snyder, 1979b]. Therefore extension of the lithosphere into the hole seems likely. In this model, extension in the southwestern United States was, in effect, accommodated by thrusting at subduction zones at the far side of the Pacific plate.

STRAIN IN THE LITHOSPHERE NEAR THE TRIPLE JUNCTION

Before development of the Mendocino triple junction, the western margin of the North American plate had been above the Farallon-North American subduction zone for several tens of millions of years [Atwater, 1970]. Force-balance

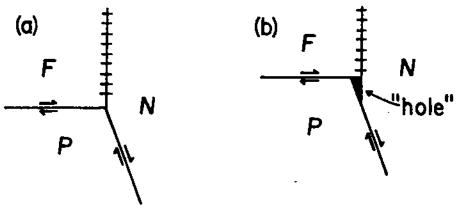

Fig. 5. Postulated evolution of the Mendocino triple junction, from Ingersoll [1982]. As the plate configuration evolves, a hole develops in the lithosphere at the triple junction. F, P, and N stand for Farallon, Pacific, and North American plates.

studies of lithospheric plates indicate that subduction may produce considerable compressive stress in the hanging-wall plate [Forsyth and Uyeda, 1975; Chapple and Tullis, 1977]. Development of the triple junction and consequent hole relieved some of this stress near the triple junction.

Deformation is strikingly absent between 50 and 30 Ma in the southwestern United States, even though subduction continued through this period [Atwater, 1970]. Beaumont [1981] inferred that the time constant for viscous relaxation of elastic stresses in cratonal lithosphere is about 30 m.y. and suggested that significantly less time is required in an active plate margin regime because of higher heat flow. Thus the lack of post-Laramide deformation before the ridge-trench encounter is consistent with achievement of a roughly hydrostatic stress state in the lithosphere at approximately 30 Ma.

If we approximate the stress state of the western North American plate as hydrostatic at 30 Ma, then stress relaxation caused by dilation at the triple junction would yield a stress field axially symmetric about the least compressive stress, σ_3, with σ_3 approximately east-west. This is at best a crude approximation of the actual situation, but it serves as a useful guide to the structural evolution of the area. This stress state could cause extrusion of the lithosphere inland of the triple junction into the hole. Extrusion could occur by two processes: (1) conjugate strike-slip faults, which conserve surface area and cause north-south shortening of the affected region [Hill, 1982]; and (2) high- and low-angle normal faults, which extend the lithosphere into the hole without north-south shortening. The first case results from a vertical σ_2 trajectory, whereas the second case reflects a vertical σ_1 orientation.

Both conjugate strike-slip faults and extensional terranes of the appropriate ages are present in the southwestern United States, in most cases acting together in an integrated system [Davis and Burchfiel, 1973; Wright, 1976; Bohannon, 1979; Wernicke et al., 1982]. This is consistent with Wright's [1976] suggestion of a stress field which was roughly axially symmetric, with σ_3 oriented east-west to northeast-southwest; minor deviations from axial symmetry would lead to one or the other mechanism being favored. In fact, in this model a feedback mechanism will keep the stress field near axial symmetry. Feedback results because (1) extension while σ_1 is vertical will decrease σ_1 by unloading, making it closer to σ_2, and (2) north-south compression while σ_2 is vertical will increase σ_2 by loading, making it closer to σ_1. Both cases tend to restore axial symmetry about σ_3 after a perturbation in the stress field.

Oligocene-Miocene structures of this area also include numerous folds with axes trending east-west to northeast-southwest [Davis et al., 1980; Rehrig and Reynolds, 1980]. The stress field responsible for these folds may reflect a mechanism suggested by Spencer [1982]. Denudation of midcrustal rocks by low-angle extensional faults would reduce the vertical normal stress relative to the north-south horizontal stress. This would result in a north-south orientation of σ_1, consistent with shortening of the lithosphere in this direction. Both the conjugate strike-slip faults and the folds support the existence of this shortening. It is important to note that the resulting regional strain field in the southwestern United States probably did not approximate plane strain and cannot be adequately analyzed by conventional cross-section balancing techniques. Shortening occurred in both vertical and north-south to northwest-southeast directions, while extension occurred in an east-west to northeast-southwest direction.

DISCUSSION

The data summarized in Figures 1 and 3 show that faulting and volcanism in the southwestern United States swept northward with time and were short-lived in any given area. This conclusion conflicts with current plate tectonic models for late-Cenozoic lithospheric extension in the western United States. Such models can be divided into three groups: oblique rifting related to transform fault tectonics [Atwater, 1970; Livaccari, 1979]; extension in a back arc setting [Scholz et al., 1971]; and extension above a "window" in the subducted slab [Dickinson and Snyder, 1979a].

The oblique-rifting model predicts that extension began in a given area after the change to a transform fault boundary but does not explain why extension stopped shortly after that boundary developed. It also predicts that extension should have been in a northwest-southeast direction, which is inconsistent with the majority of terranes. However, it is consistent with extension in the Death Valley area [Stewart, 1983] (Figure 1, subarea E). This extension is considerably younger than our model predicts, and we consider it to be a result of oblique extension. The back arc extension model predicts that extension occurred before the change to transform fault tectonics. This is consistent with timing of some of the extension in areas to the north of Figure 1 but does not fit the southwestern United States, where little extension occurred during early Tertiary subduction. The slab window model does not address the conservation-of-area problem discussed above and does not explain why episodes of extension and volcanism were commonly brief.

Our discussion is intentionally limited to the area to the south of latitude 37°N. Tertiary extension further north in the Great Basin began at least as early as 35 Ma [Gans, 1982; Miller et al., 1983], when this area was clearly in a back arc setting. Although it has commonly been assumed that Tertiary extension throughout the western United States reflects the same tectonic mechanism, this is not necessarily the case. In the central Great Basin, extension must have occurred both in a back arc setting and inland of a transform fault margin regardless of the plate reconstruction chosen. Thus, while the model we present cannot explain all of the Tertiary extension in the Great Basin, neither will any other single mechanism, because extension there clearly has occurred in more than one plate tectonic regime.

The latest phase of extension in the eastern Great Basin may be related to the change in plate boundary type. Best and Hamblin [1978] described evidence that initiation of the most recent phase of volcanism and faulting at the eastern edge of the Great Basin migrated northward with time at about 3 cm/yr. Best and Hamblin emphasized that the termination of this phase of volcanism and faulting also migrated northward with time. This could be interpreted as a continuation of the trend shown in Figure 1. It is uncertain whether the structural style of extension changed between the Paleogene and the Miocene-to-Recent extension that controls the modern topography. However, it seems likely that the Paleogene and Neogene extension occurred in different plate-tectonic settings, with the latter perhaps related to the mechanism we propose.

CONCLUSIONS

1. Major low-angle normal fault events (and, by inference, most extension) in the southwestern United States migrated northward with time, occurring at about 25 Ma in southern Arizona and 10 Ma in the Death Valley region.
2. The duration of faulting at many localities was brief, generally of the order of a few million years.
3. The time of faulting in most areas generally correlates with two significant plate tectonic events: (1) passage of the Mendocino triple junction immediately to the west of the area and (2) passage of the subducted Mendocino fracture zone under the extended area.
4. Lithosphere of the southwestern United States may have been extruded into a developing hole at the triple junction by faulting. Deformation of the lithosphere may also reflect flexure above the subducted Mendocino fracture zone. Volcanism accompanied faulting and was probably triggered by the same processes.
5. The strain field predicted by this model is consistent with observed fault and fold orientations.

APPENDIX A:

DATA CONSTRAINING THE TIMING OF FAULTING

A. Grapevine Mts. Reynolds [1970, 1974, 1976] described low-angle faulting during the Miocene. Although there were several episodes of deformation, the majority of low-angle faulting appears to have occurred between 11 and 7 Ma.

B. Sheep Range. Guth [1981] stated that low-angle faulting occurred during deposition of the Horse Spring Formation, which he presumed to correlate with the lower clastic unit of Bohannon [1979]. Bohannon's isotopic dates on this unit range from 17.4 to 13.2 Ma, but most cluster around 15 Ma.

C. Lake Mead shear zone. Bohannon [1981] determined the age of movement of strike-slip faults, and, by inference, the age of major crustal extension. Major strike-slip faulting began at 14 to 15 Ma, although documentation is sparse. Extension continued until at least 12 or 11.5 Ma and waned by 11.5 or 10 Ma.

D. Megabreccias, Panamint Mts. Labotka et al. [1980] bracketed movement on major slide sheets in the western Panamint Mts. between 12 Ma (age of the Little Chief stock) and the 5 Ma Nova Formation basalts. Labotka et al. interpreted these basalts to be posttectonic, but B. Wernicke (written communication, 1984) reports that the Nova Formation is involved in deformation.

E. Amargosa Chaos. Fleck [1970] gives two interpretations for the age of the chaos structures. Both bracket faulting between 14 and 5 Ma, but the likeliest interpretation puts major faulting between 6.3 and 5.4 Ma. Stewart [1983a] cited evidence that major extension may have occurred before 6.3 Ma, and major extension may still be occurring today.

F. Wilson Ridge megabreccias. Anderson et al. [1972] related the megabreccias to uplift of the northern Black Mts., which they dated as occurring 12 to 6 Ma.

G. Owlshead Mts. Davis and Fleck [1977] bracketed low-angle faulting between 14 and 12 Ma.

H. Black-Eldorado Mts. Anderson et al. [1972] bracketed low-angle faulting in this area between 15 and 13 Ma.

I. Homer Mt.-Sacramento Mountains. Spencer [1983] bracketed an episode of low-angle movement between 15 and 14.6 Ma.

J. Central Mojave Desert. Age determinations by Dokka [1980] and Glazner [1981] date a major low-angle faulting and tilting event at 20 Ma. Bracketing K/Ar dates on this event overlap; in the Cady Mts., flat-lying ash-flow tuff dated at 20.0 ± 1.0 Ma caps steeply tilted units dated at 19.8 ± 1.4, 20.2 ± 1.3, and 19.9 ± 0.7 Ma [Glazner, 1981]. In the Newberry Mts., the same ash-flow tuff yielded a 21 ± 1 Ma fission-track date [Dokka, 1980].

K. Mopah-Turtle Mts. Howard et al. [1982] determined that tilting in the Mopah and Turtle Mts., which they consider to be the breakaway zone of the Whipple Mts. terrane, occurred between 18 and 20 Ma.

L. Whipple Mts. The main constraints are discussed in the text. Dokka and Lingrey [1979] determined reset fission-track dates of 18.9, 19.1, 20.4, and 19.8 Ma on lower plate rocks taken from just beneath the main detachment.

M. Castaneda Hills. Suneson and Lucchitta [1983] inferred that listric faulting in the Castaneda Hills area of western Arizona occurred between 16.5 and 14 Ma.

N. South Mts. Reynolds and Rehrig [1980] inferred that penetrative mylonitization occurred between 25 and 20 Ma. Cooling ages on granitoids are 20.3 and 20.1 Ma.

P. Pinaleño Mts. A dike with a biotite K-Ar age of 24.7 Ma is cut by a low-angle fault [Rehrig and Reynolds, 1980]. At Eagle Pass, Davis and Hardy [1981] report low-angle faulting of conglomerates that postdate the 28 to 22 Ma Galiuro volcanics.

Q. Rincon Mts. Davis [1975] inferred that major extension in this area occurred between 28 and 24 Ma, based on lower plate cooling and reset ages.

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