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A tectonic boundary for the southern Colorado Plateau

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Abstract

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A tectonic boundary should be defined by changes in tectonic elements. Tectonic elements would include such parameters as structural style, stress orientations, volcanism, heat flow, seismicity and changes in crustal thickness. Examination of these tectonic elements for the southern Colorado Plateau suggests that the southwestern part of the physiographic plateau appears to be tectonically part of the Basin and Range province. I therefore propose a boundary at 112° W longitude, the locus of seismicity and recent volcanism and also the site of crustal thickening and a change of structural style.

The tectonic boundary of the southern Colorado Plateau is suggested to form part of the eastern boundary of the southern Basin and Range seismotectonic region. This seismotectonic region is bounded on the north by the Las Vegas shear zone/Nevada seismic zone and has a different stress orientation than the Northern Basin and Range from which it began to evolve separately 13 m.y. ago.

The present principal stress orientation of the southern Basin and Range of Arizona appears to be the result of compound movements of the San Andreas transform and Garlock–Las Vegas shear zone resulting in a shear couple affecting the crust in Arizona and an associated NE–SW least principal stress orientation.

Introduction

The location and nature of the tectonic boundary between the southern Colorado Plateau and Basin and Range provinces has been a much debated subject recently. Tectonic boundaries have been suggested for the southern plateau based on structural style (Stewart, 1978), heat flow (Lachenbruch and Sass, 1978), and stress (Zoback and Zoback, 1980; Humphrey and Wong, 1983). These boundaries all lie within the physiographic boundary for the southern plateau (Fig. 1). They do not all agree in configuration or location.

I discuss seismicity and crustal thickness as additional elements of the tectonic pattern that aid in determining the tectonic boundary for the southern plateau. The tectonic implications of the boundary and its associated stress system will be analyzed, in comparison to previous hypotheses.

Seismicity in northern Arizona

The plot of epicenters for the Rocky Mountain area of the western United States (Fig. 2) reveals a N–S-trending band of events known as the Intermountain Seismic Belt. Across Utah this band of seismicity is reasonably well centered on the physiographic boundary of the Colorado Plateau. Between latitudes 36° and 37° north the relationship is no longer evident. The band of seismicity splits into two branches one of which trends southwesterly into Nevada. The branch in northern Arizona swings sharply to the east, no longer coincident with the plateau physiographic boundary. Further, the seismicity loses its linear character and sweeps out a broad arc concave to the southwest.

The epicenter map (Fig. 2) shows data primarily on events during 1950–1976. Thus the band

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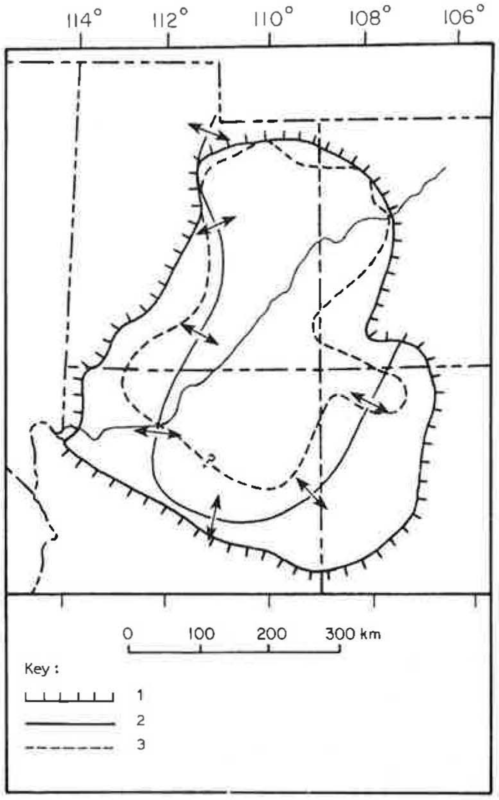

Fig. 1. Boundaries for the Colorado Plateau: *1*—physiographic, *2*—stress (Humphrey and Wong, 1983), *3*—heat flow (Lachenbruch and Sass, 1978).

of seismicity in Arizona and the aseismic zones on both sides could be an apparent pattern/distribution due to the time period represented or due to a lack of adequate monitoring. The events plotted in Fig. 2 within the state of Arizona are all $M_L \geq 3.0$. These were events that were easily monitored by existing networks outside the state for the time period represented. Coverage of the entire northern portion of the state was adequate down to $M_L = 3.0$.

An examination of a plot of epicenters in Arizona for both instrumentally and non-instrumentally located earthquakes covering the period 1830–1980 (Fig. 3) shows the same arcuate pattern of seismicity and bordering aseismic zones of Fig. 2. Therefore this arc-like band of events is a real element of the tectonic pattern.

The sharp swing to the east of the arc-like band of epicenters at the latitude of the Colorado River (Fig. 4) can be compared to other elements of the tectonic pattern in northern Arizona, including stress directions, structural grain, and volcanism.

A few focal mechanisms are available for the southern plateau from various workers (Fig. 4). At the latitude of the Colorado River there is a sharp change in orientation of potential fault planes derived from the focal mechanisms. South of the Colorado River only NW-trending fault planes result from the focal mechanism solutions. Event 5, on the Sinyala fault to the north of the Colorado River shows N–S-trending fault planes. Although movement on pre-existing fractures can complicate the interpretation, this seems to suggest a sharp change in stress orientation at this latitude. This change is not based solely on the Sinyala fault system solution, since solutions farther north in Utah agree with it in orientation of potential fault planes.

The lines on Fig. 4 represent faults which have been mapped on the southern Colorado Plateau of northern Arizona. An examination of the overall pattern of all fault trends shows a change in structural grain at about the latitude of the Colorado River (Fig. 5). To the south of the river the grain is predominantly northwest trending and to the north has a north–south trend. Note that the change in fault orientation derived from the map of faults occurs at the same latitude and has the same sense of rotation in strike as the fault trends derived from focal mechanism solutions. Therefore the geometry for these two elements of the tectonic pattern is similar and suggests the possibility of a common cause.

A striking comparison can be made between late Cenozoic volcanism of the southern plateau and the arc-like plot of epicenters for the same area (Fig. 6). Note that if isochrons are drawn in for the radiometric ages for southwest plateau basaltic volcanism that an arc-like pattern emerges which is nearly identical in geometry to that for the seismicity. The arcs for seismicity and volcanism both develop between 36° and 37°N latitude.

Thus a comparison of the arc-like pattern of seismicity to focal mechanism solutions, fault trends, and volcanism show a change in orientation in all four elements of the tectonic pattern at the same latitude, suggesting tectonic control.

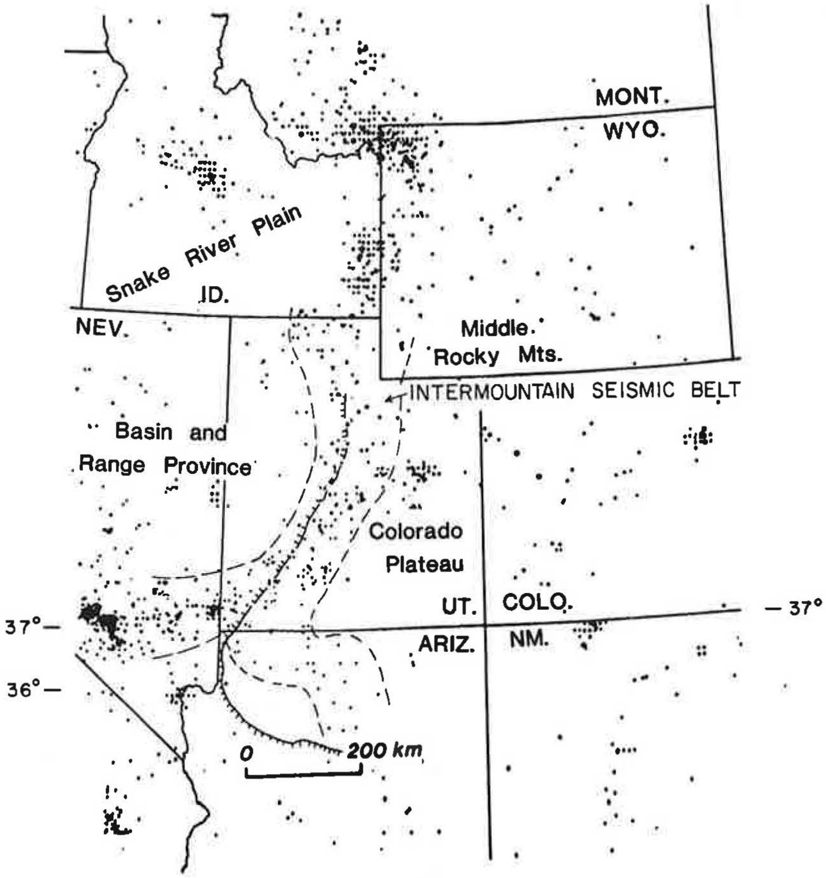

Fig. 2. Epicenter map of western U.S. (after Smith, 1978).

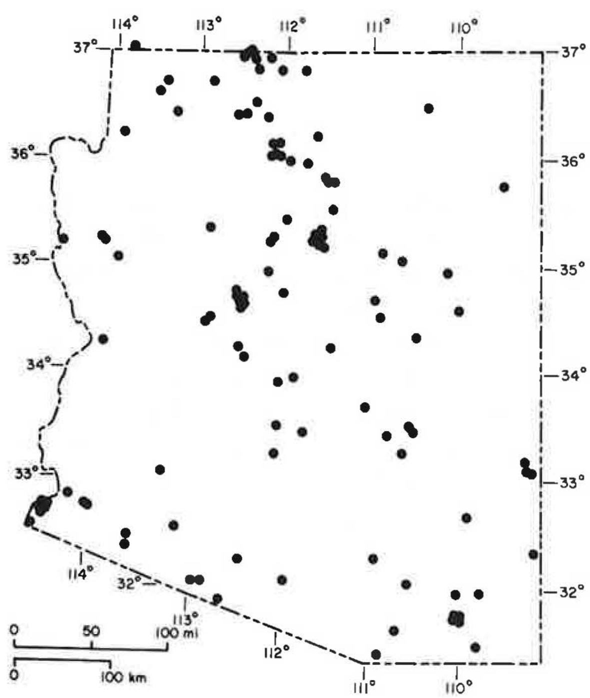

Fig. 3. Historical epicenters in Arizona 1830–1980 (after DuBois, et al., 1981, fig. 14). Epicenters include both instrumentally and non-instrumentally located events.

Crustal thickness and structural style of the southern Colorado Plateau

A contrast exists between crustal thickness of the Basin and Range and Colorado Plateau. The crust under the central part of the plateau in northeastern Arizona and southwestern Colorado is greater than 40 km thick (Roller, 1965). The crust under the Great Basin and southern Basin and Range provinces ranges from 20 to 36 km thick (Fig. 7).

The crust in Arizona thickens to the northeast across the transition zone in the central part of the state (Warren, 1969). The eastern part of the plateau physiographic boundary (Mogollon Rim)

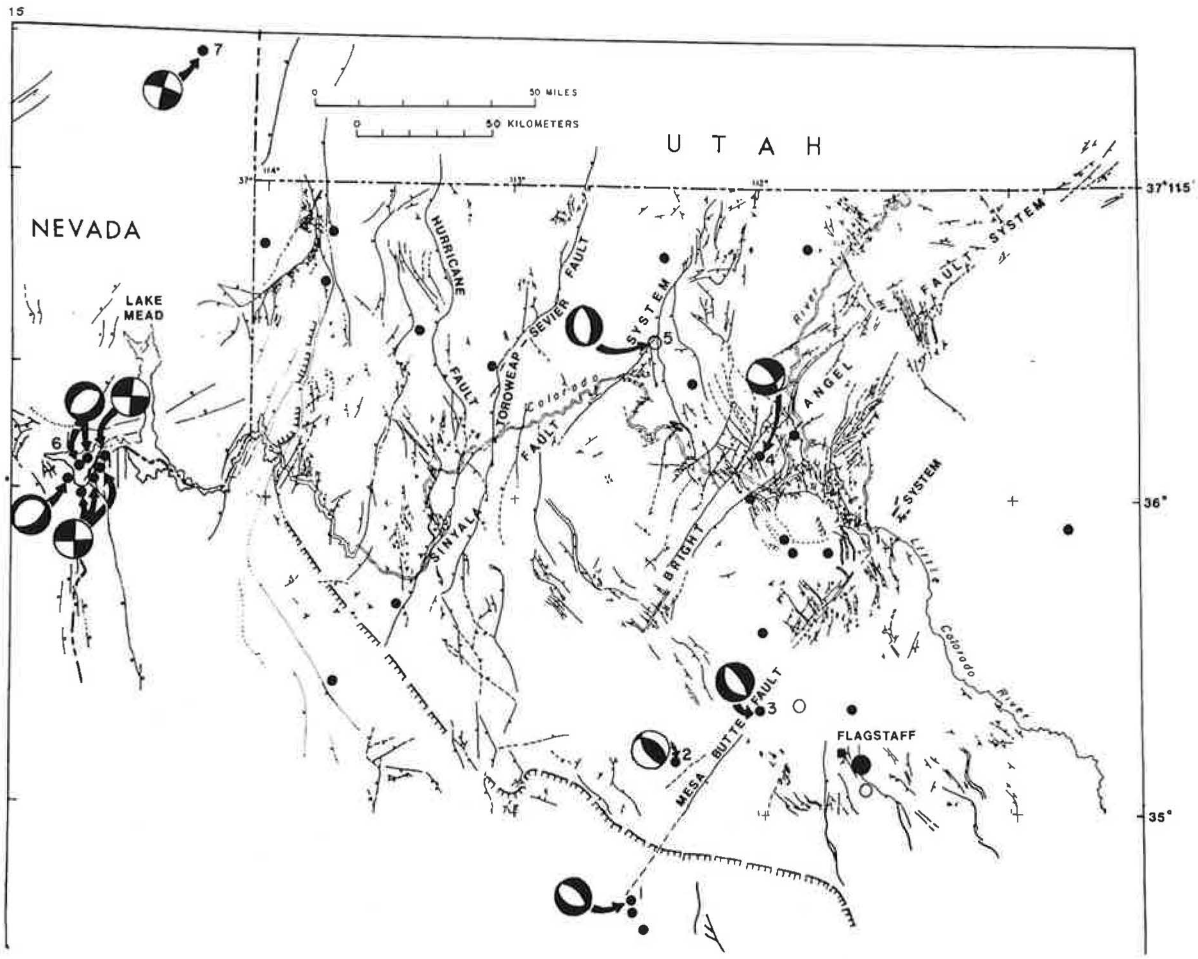

Fig. 4. Structure-tectonic map of northern Arizona. Straight lines are faults from geologic maps (after Shoemaker et al., 1974, fig. 2a). Focal mechanism solutions are from: *1*—Eberhart-Phillips et al. (1981); *2*—Brumbaugh (1980); *3*—Wong and Humphrey (1985); *4*—Brumbaugh (unpub.); *5*—Kruger-Kneupfer et al. (1985); *6*—Rogers and Lee (1976); *7*—Smith and Sbar (1974).

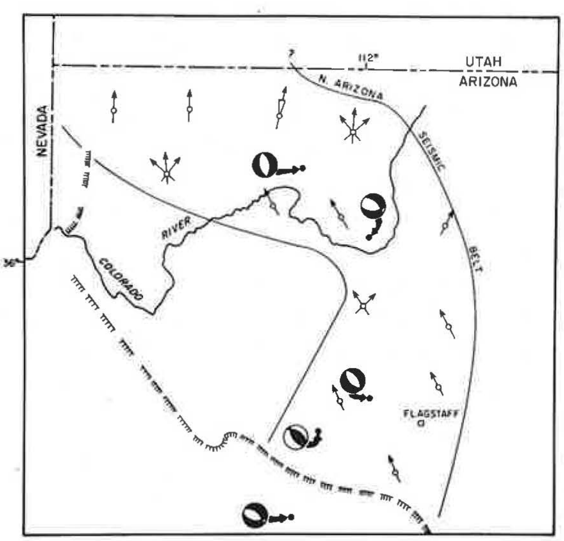

Fig. 5. A comparison of structural grain derived from fault trends to fault trends derived from focal mechanism solutions. Arrows represent the predominant trend of faults for 50 km^2 sub-areas of the northern Arizona seismic belt.

coincides with a crustal thickness of 40 km. This is not true for the western part of the Mogollon Rim or the Plateau north of it. West of Flagstaff, Arizona, crustal thicknesses less than 40 km underlie the physiographic plateau. These are thicknesses more characteristic of the Basin and Range. If 40 km is taken as a crustal thickness signifying the tectonic boundary of the Colorado Plateau, then the plateau boundary would have to be drawn in somewhere to the east of the physiographic

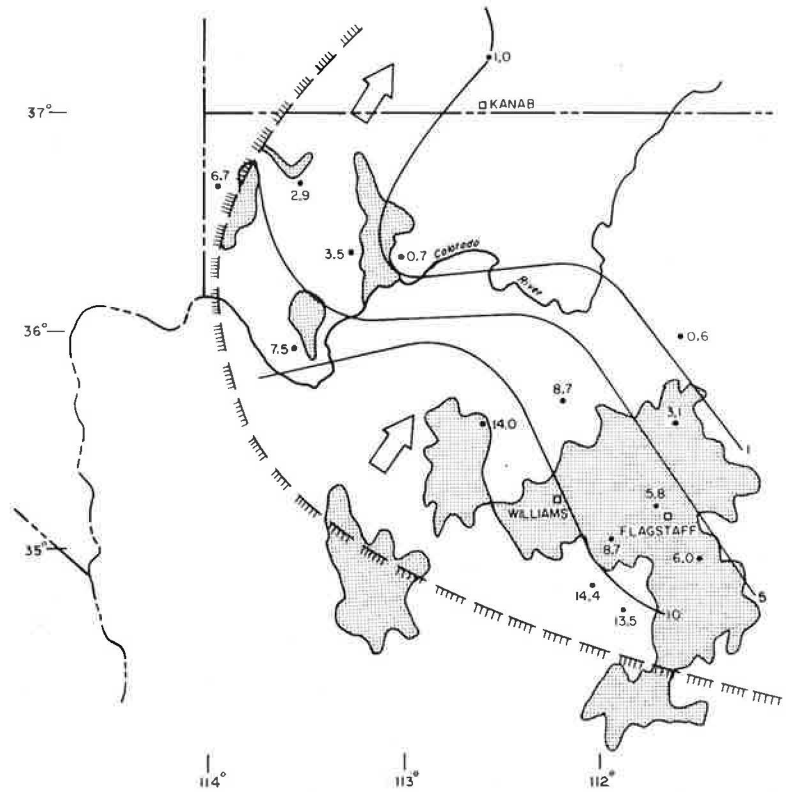

Fig. 6. Late Cenozoic volcanism of the southern Colorado Plateau. Numbers at the end of lines (e.g. 5) represent the age in millions of years of the isochron. Other numbers (e.g. 14.0) represent K/Ar dates at specific localities. Shaded areas are volcanic fields of the southern Plateau (after Best and Hamblin, 1978, fig. 14-7).

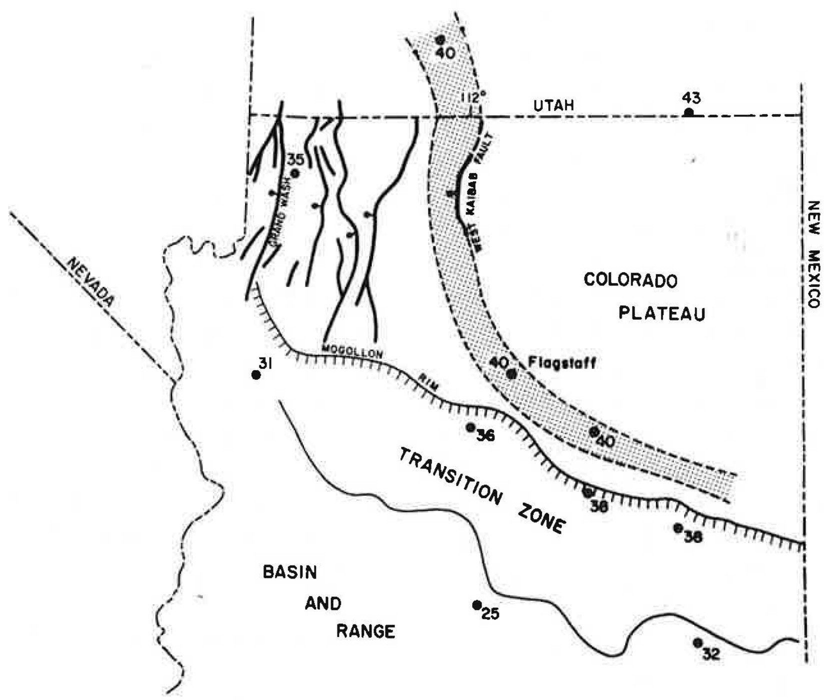

Fig. 7. Crustal thicknesses for the Colorado Plateau and Basin and Range provinces: Data are from: Roller (1965), Warren (1969), Stauber (1982), Damon et al. (1985), ——— high angle listric normal fault. Shaded area represents estimated location of crustal thickness boundary between the Colorado Plateau and Basin and Range provinces.

boundary which is located along the Grand Wash Cliffs of Arizona. This southwestern section of the Colorado Plateau has been recognized by others as being anomalous with respect to structural style (King, 1977; Stewart, 1978). The dominant structures of the southwest plateau are listric normal faults with tilted fault blocks, a style characteristic of the Basin and Range. Stewart (1978) includes the west Kaibab fault zone as the easternmost fault in northern Arizona having this Basin and Range structural style.

A combination of data from crustal thickness and structural style (Fig. 7) suggests an approximate position for the southern Plateau structural/tectonic boundary. This boundary would be close to the physiographic boundary (Mogollon Rim) through Flagstaff where it would swing to the North approximately on strike with 112° W longitude (Fig. 7). The boundary is shown as a band with dashed margins because of a lack of constraining data.

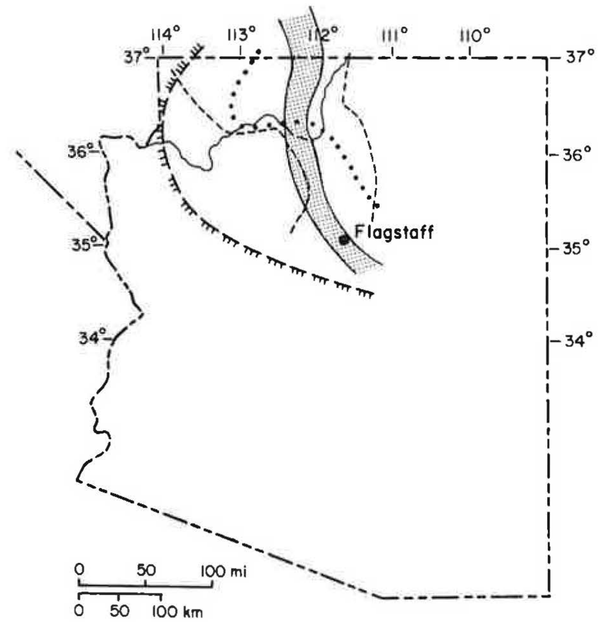

Fig. 8. Tectonic boundary for the southern Colorado Plateau. Dashed line—northern Arizona seismic belt; dotted line—limit of Basin-Range type volcanism on the southern Colorado Plateau. Shaded area represents change in crustal thickness.

Neotectonic boundary of the southern Colorado Plateau

A tectonic boundary is defined by changes in tectonic elements across the boundary. To define a boundary between the southern Colorado Plateau and Basin and Range provinces, it is necessary to identify the loci of changes for tectonic elements characteristic of the Plateau on the one hand and the Basin and Range on the other. The tectonic elements would include such parameters as structural style, stress orientations, volcanism and heat flow. Tectonic boundaries are also often the locus of seismicity and changes in crustal thickness.

The southwestern segment of the physiographic Colorado Plateau between the Grand Wash Cliffs and 112° W longitude has a structural style and thickness, as shown (Fig. 7) characteristic of the Basin and Range. Volcanism which has occurred in this part of the plateau over the last 10–15 m.y. is also chemically similar to volcanism of the adjacent Basin and Range. The heat flow regime for the southwestern plateau is not well known. Lachenbruch and Sass (1978) suggested a boundary for the southern Plateau based on heat flow which lay inside of the physiographic boundary (Fig. 1). This boundary was not well constrained, however. More recent data (Sass et al., 1984) suggest that this boundary may need to be modified.

Therefore the southwestern part of the physiographic Colorado Plateau appears to be tectonically part of the Basin and Range province. The southwestern tectonic boundary for the plateau today coincides with the arc-like band of seismicity in northern Arizona. This band of seismicity is characterized by normal faulting as shown by the available focal mechanism solutions (Fig. 4). This style of faulting suggests a horizontal extensional stress, a configuration characteristic of the Basin and Range stress field.

An examination of all available geologic/geophysical data thus suggests that the arc-like band of seismicity in northern Arizona marks the neotectonic boundary between the southern Colorado Plateau and Basin and Range (Fig. 8).

Tectonic boundaries through time

Best and Hamblin (1978) proposed a north and eastward migrating wave of essentially basaltic

Basin and Range volcanism (Fig. 6). This can be clearly seen by the isochrons showing the position of the front of this volcanic wave in northern Arizona over the last 10 m.y. This suggests an expanding Basin and Range province with activity concentrated along its boundaries. It also suggests the Colorado Plateau is shrinking at the expense of this expansion of the Basin and Range province.

If we superimpose approximate least compressive stress directions from focal mechanism solutions one can see a parallelism between the direction of suggested migration of the tectonic boundary as indicated by volcanism and extension occurring today (Fig. 9). Overall the suggestion of an advancing tectonic boundary for the Basin and Range appears valid. Furthermore this appears to be an ongoing process as suggested by the agreement between the present-day extension directions due to existing stresses and configuration of this boundary. The extension directions remain approximately perpendicular to the boundary as it sweeps out an arc-like shape in northern Arizona.

Zoback et al. (1981) suggest that southern Basin and Range block faulting occurred largely in the period 13–10 m.y. ago, in a NE–SW oriented horizontal least compressive stress. They suggest some activity with this stress orientation as late as 6.5 m.y. ago. Miocene dike trends give strong support for a NE–SW extensional stress in the southern Basin and Range (Zoback et al., 1981).

An examination of geologic and geophysical data from Arizona suggests that the NE–SW horizontal extensional stress associated with the southern Basin and Range did not cease to exist 6.5 m.y. ago, but in fact exists today, and has since Miocene time.

An examination of late Tertiary–Quaternary (18 m.y.–Present(?)) Basin-Range faulting in Arizona by Loring (1976) results in 74 documented trends from 51 localities primarily from central and southern Arizona which fall in this age range (Fig. 10). The dispersion of inferred trends of horizontal extension is probably due in good part to the presence of reactivated pre-existing fracture trends. Nevertheless 43% of the trends are northwesterly suggesting a possible NE–SW extension. Another 31% are N–S and E–W trends which could have been reactivated by a NE–SW extension. The remaining 26% represent NE-trending fractures.

Fracture trends which are closely controlled in age (7–1 m.y. ago) include three NW trends, one

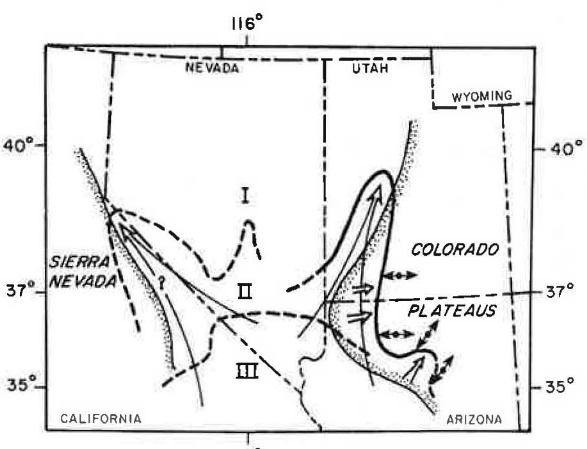

Fig. 9. A comparison between the direction of suggested migration of the Plateau tectonic boundary (open arrows) and direction of extension as indicated by focal mechanism solution (solid double arrows) (after Best and Hamblin, 1978, fig. 14-12).

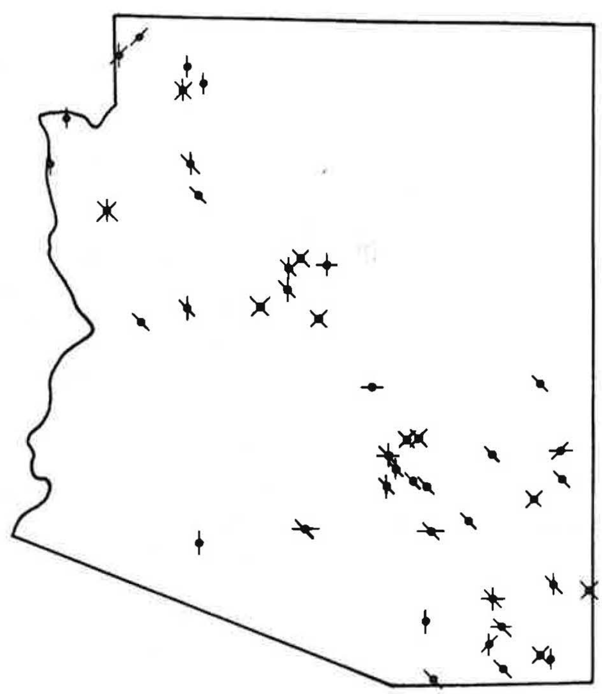

Fig. 10. Documented trends of Tertiary–Quaternary Basin-Range faulting in Arizona (after Loring, 1976, fig. 5).

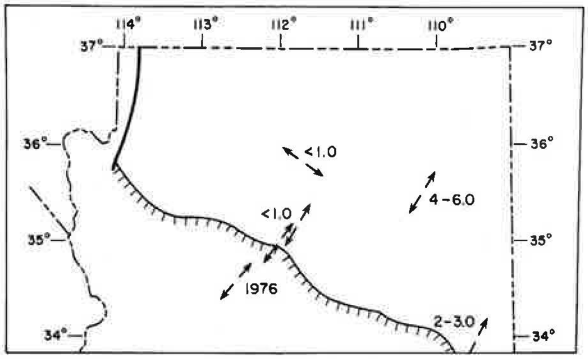

Fig. 11. Stress indicators for the southern Colorado Plateau. Arrows show direction of inferred horizontal extension and associated numbers (e.g. 1.0) represent the age of the stress direction (data from Zoback and Zoback, 1980, table I).

E–W trend and one N–S trend. It is conceivable that movement on all of these could have resulted from a NE–SW extension, especially if the N–S and E–W trends represent pre-existing fractures.

Stress indicators for the southern plateau (Fig. 11) were compiled by Zoback and Zoback (1980). The most reliable of these stress indicators reveal the configuration of the stress field for this part of the Plateau for the last 6 m.y. This suggests a dominantly NE–SW extension. This was also a time period as we have seen (Fig. 6) when Basin-Range type volcanism was occurring on the southwestern Plateau.

A detailed look at the San Francisco volcanic field is also instructive with respect to recent principal stress directions (Fig. 12). The southern part of the volcanic field has a well developed NW-trending fracture system (Moore et al., 1974). This is suggested by the strong preferred elongations and alignments of volcanic vents.

Recent seismicity in the volcanic field (Fig. 12) also supports NE–SW extension along NW-trending fracture systems. The alignment of microearthquake swarms with the epicenter of the 6-1-80 event suggest activity along the NW-trending faults. This is further supported by the suggested trends of fault planes for the 6-1-80 event. This is all compatible with a NE–SW extension.

Therefore it would seem plausible that tectonism in Arizona over the last 13 m.y. and up through the present has been dominated by a NE–SW extensional stress field. Also, the locus of

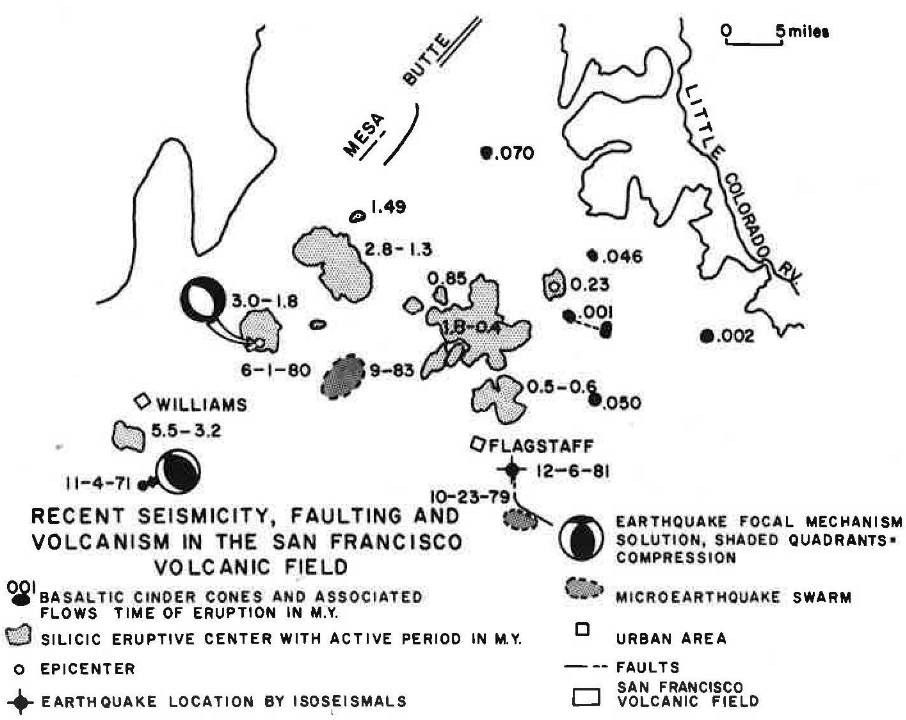

Fig. 12. Recent seismicity, faulting, and volcanism in the San Francisco volcanic field.

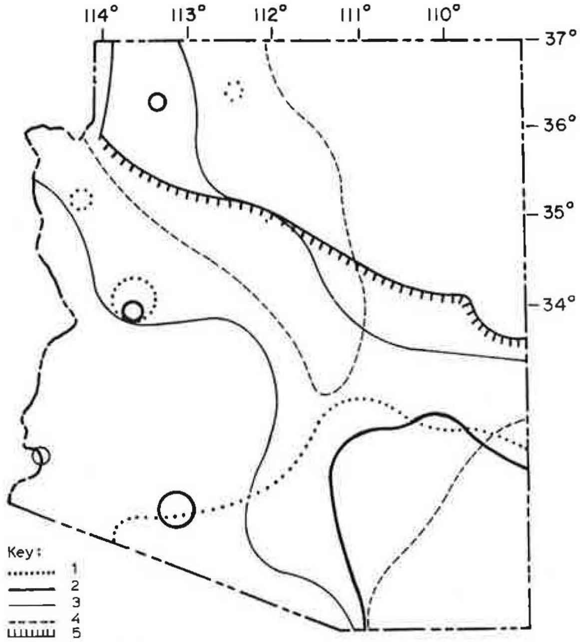

Fig. 13. Locus of Basin and Range type faulting in Arizona in Tertiary and Quaternary time. *1*—late Mesozoic–early Tertiary (65–37 m.y.); *2*—mid-Tertiary (37–18 m.y.); *3*—late Tertiary–Quaternary (18 m.y.–present) (data from Loring, 1976), *4*—late Quaternary (Pearthree et al., 1983). *5*—Colorado Plateau physiographic boundary.

this activity as represented by the loci of faulting, volcanism, and earthquake activity has migrated to the northeast since mid-Tertiary time, from the center of the southern Basin and Range province, through the transition zone of central Arizona, and onto the southern Colorado Plateau where it exists today (Fig. 13).

Tectonic implications of the boundary of the southern Colorado Plateau

Analysis of data presented in this article pertaining to the location of the tectonic boundary of the southern Colorado Plateau suggests several points which relate to hypotheses previously developed to explain the plate tectonic evolution of the Basin and Range rift terrane:

(1) The southwestern part of the physiographic plateau in Arizona, is tectonically part of the Basin and Range, and has developed as such within the last 15 m.y.

(2) This Basin and Range plateau terrane has had a dominant NE–SW least principal stress direction over the last 15 m.y. It is presently active with the same stress direction.

Any hypothesis advanced to explain the above two points must also consider the following:

(1) The Rio Grande rift to the east of the plateau today is dominated by NW–SE extension, similar to that in the northern Basin and Range.

(2) The Basin and Range terrane of Sonora, to the southeast of Arizona, is active today with a NW–SE extension, similar to the Rio Grande rift and northern basin and Range (Natali and Sbar, 1982).

Therefore, the NE–SW extension direction of northern Arizona appears to be bordered by dominantly NW–SE extension on all sides. Previous hypotheses proposed for the plate tectonic evolution of the Basin and Range rift terrane do not consider the contrast in extension directions between the Basin and Range of northern Arizona and surrounding parts of the rift terrane. Previous workers have treated the Basin and Range as a single seismotectonic region (Zoback et al., 1981). An exception to this is Sbar (1982) who treats the eastern Basin and Range boundary as a separate seismotectonic domain, the Intermountain Seismic Belt.

An examination of stress/extension directions derived from earthquake solutions suggests that the Basin and Range rift terrane may be subdivided into several segments which are (Fig. 14):

(1) The Great Basin or northern Basin and Range.

(2) The Arizona segment of the southern Basin and Range.

(3) The Sonora–Rio Grande Rift segment of the southern Basin and Range.

These segments of the Basin and Range rift terrane correlate with changes in configuration/nature of the major plate boundary to the west. The Great Basin/northern Basin and Range segment has been mechanically related (Atwater, 1970; Zoback, et al., 1981) to the San Andreas transform. The boundary between it and the Arizona segment occurs between 36° and 37° N latitude. This is the locus of the boundary between the northern and southern Basin and Range provinces recognized by Eaton (1979). This boundary

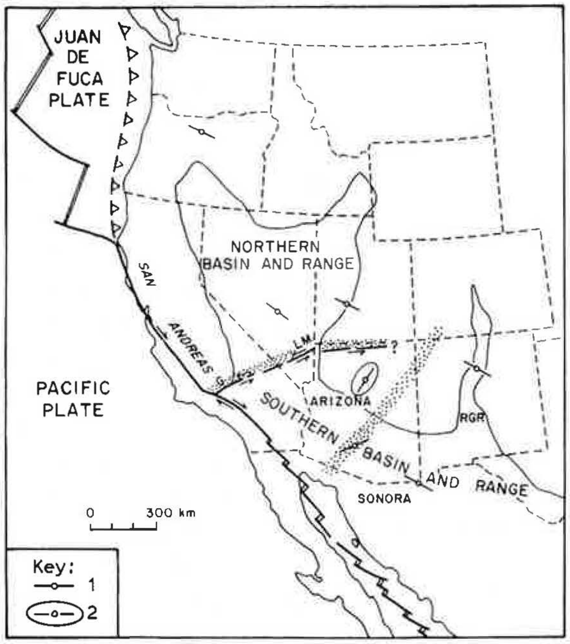

Fig. 14. Plate tectonic setting of the western U.S. and northern Mexico. The stippled pattern represents boundaries between segments of the Basin and Range province as defined by predominant orientations of least principal horizontal stress (*1*). *RGR*—Rio Grande Rift; *G*—Garlock fault; *LM*—Lake Mead fault zone; *2*—strain ellipse.

is also marked by a band of seismicity which splits off to the southwest from the Intermountain Seismic Belt of Utah (Smith and Lindh, 1978). Fault plane solutions (6 and 7, Fig. 4) from this belt of seismicity agree with surface geology in suggesting a significant component of left lateral offset. Furthermore this boundary can be carried eastward into the southern Colorado Plateau along the latitude of the E–W-trending Colorado River. At this latitude there appears to be a left-lateral offset in the northern Arizona seismic belt (Fig. 5), an offset in volcanic isochrons (Fig. 6), a change in orientations of fault planes suggested from focal mechanism solutions, and an overall change in the trends of Cenozoic to recent faults mapped at the surface.

The Arizona segment of the southern Basin and Range apparently began to develop about 13 m.y. ago as an entity separate from the northern Basin and Range. Evidence from the Lake Mead fault system (Bohannon, 1979) indicates this zone formed as a boundary at about this time. This is also the time of rotation of the stress system in the northern Basin and Range (Zoback et al., 1981). This rotation of stress has been related to the disappearance of a convergent plate boundary and replacement with a transform boundary. Therefore two important events occurred about 13 m.y. ago which signalled the partition of the Basin and Range province into separate segments:

(1) The change of the plate boundary from convergent to predominantly transform in character.

(2) The formation of a left-lateral transcurrent shear zone as a boundary between the northern and southern Basin and Range, which includes the Lake Mead, and Garlock shear zones.

An examination of the boundary between the Pacific and North American plates of today (Fig. 14) indicates that wherever there is a change in the configuration/nature of the plate boundary, there is also a change in stress orientation within the Basin and Range province which results in segmentation. The present NW–SE extension of the northern Basin and Range has been related to direct right-lateral traction along the San Andreas transform (Atwater, 1970; Zoback et al., 1981; Sbar, 1982). The transform boundary is not linear, however, and in southern California the Great Bend of the San Andreas marks a site of mechanical lockage or binding which may at least in part be relieved along the Garlock fault and the shear zone to the east of it in Nevada and northern Arizona. This left-lateral shear suggests that rotational shear is affecting the crust in much of Arizona resulting in NE–SW extension (Fig. 14). This stress situation changes again with a change in the plate boundary at the head of the Gulf of California/Salton-Sea area. At this point (Fig. 14) the transform boundary changes to one of spreading centers. Consequently, stresses in the Sonora–Rio Grande rift segment of the southern Basin and Range also change from that in Arizona to one with NW–SE extension, like that in the northern Basin and Range (Fig. 14).

Conclusions

An examination of the elements of the tectonic pattern for the southern Colorado Plateau indicates:

(1) The arc-like pattern of seismicity is real and is bordered on both sides by aseismic areas.

(2) The arc-like pattern of seismicity can be directly related to faulting, stresses, and volcanism through a common change in trend at about 36°–37°N latitude. Therefore, since these are all elements of the tectonic pattern, there appears to be tectonic control of the change in trend.

(3) A study of location and form of the band of seismicity in northern Arizona and comparisons to location of changes in structural style, volcanism and crustal thickening suggests the band of seismicity represents the present position of a tectonic boundary between the Colorado Plateau and Basin and Range (Fig. 8).

(4) An examination of the change in location of Basin and Range style volcanism and faulting for Arizona over the last 10–15 m.y. suggests the tectonic boundary between the Colorado Plateau and Basin and Range has been migrating to the northeast in Arizona at the expense of the Colorado Plateau.

(5) Study of present-day orientation of least principal stress for the Basin and Range indicates a strong contrast of direction for Arizona when compared to surrounding parts of the rift terrane. This in turn suggests segmentation of the Basin and Range into a northern stress province and a southern Basin and Range consisting in turn of two stress provinces, the Arizona and Sonora–Rio Grande Rift.

(6) The segmentation of the Basin and Range appears to correlate with changes in the Plate Boundary to the west. The Great Basin–northern Basin and Range has been related to right lateral movement along the San Andreas transform. It is here suggested that compound movement of the San Andreas (at the Great Bend) and Garlock–Lake Mead shear zone results in NE–SW least principal stress in northern Arizona, and that a change in the plate boundary in southern California–northern Mexico results in a change in stresses in Sonora–Rio Grande rift to NW–SE least principal stress (Fig. 14).

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