THE NEOTECTONIC FRAMEWORK OF ARIZONA: IMPLICATIONS FOR THE REGIONAL CHARACTER OF BASIN-RANGE TECTONISM

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ABSTRACT

Recently completed studies of neotectonic (ie., latest Pliocene-Quaternary) deformation in Arizona provide new data that, when combined with regional geophysical and geological characteristics, assist in evaluation of the numerous interpretations proposed to date for Basin and Range tectonism. Basin and Range tectonism, sensu strictu, is hereby restricted to the post mid-Miocene ($\leq$15 m.y.B.P.) extensional block faulting event that produced the present valley and range topography. This tectonic interval may be distinguished in Arizona from earlier Oligocene-mid Miocene deformation and volcanism based on regional variations in stratigraphy and structural style.

Especially relevant aspects of Arizona neotectonics include: a) a band of high-angle faulting, primarily basaltic volcanism, and regional uplift-arching that has progressively migrated east- and northward into the margin of the Colorado Plateau; and b) a diffuse zone of lesser-magnitude faulting, possibly associated with regional arch-like uplift, that diverges from the Colorado Plateau boundary in central Arizona and continues into the Basin and Range province of southeastern Arizona. The first of these two partially overlapping tectonic patterns is interpretated as a Plio-Quaternary manifestation of Basin-Range tectonism that has been steadily encroaching into the Colorado Plateau margin since late-Miocene time. The other zone represents reactivated normal faulting and regional uplift that followed an earlier late-Miocene regional interval of

Basin-Range tectonism. This neotectonic belt now marks a more restricted deformational corridor absorbing limited horizontal and/or vertical strain adjustments between internally stabilized and coherent crustal blocks (e.g., the Sonoran Desert and Colorado Plateau interior). Neotectonic deformation in this zone may reflect increased tectonic activity in the late Quaternary that occurred during the gradual decline and cessation of regional Basin-Range deformation. Or it may signal the initial development of a slightly different new tectonic regime or readjustment following upon the termination of Basin-Range tectonism.

The Basin and Range Province is characterized regionally by a relatively thin and attenuated crust and lithosphere, located above an anomalously shallow asthenosphere; high heat flow; shallow-depth seismicity concentrated within diffuse bands at the margins of the province; and W- to NW-directed regional extension. Similar characteristics continue into the margin of the Colorado Plateau, coincident with the marginal zones of extensional tectonics, and in marked contrast to crust of the Plateau interior that is more transitional to that of the stable craton. Geologically, the Basin and Range Province experienced several late-Mesozoic to mid-Tertiary compressional and extensional tectonic events prior to Basin-Range deformation. The onset of this last deformation is marked by a 45°-90° clockwise rotation in horizontal extension, from SW to NW orientations. Mapping the position and timing of this reorientation, and the accompanying tectonic and structural changes, suggests a crudely-defined north- and eastward stepwise propagation of Basin-Range tectonism since late-Miocene time.

Tectonic interpretations of Basin-Range extension may be classified into three basic groups: active (asthenospheric controlled); passive (primary control derived from the San Andreas transform boundary); and composites of both. A composite mechanism best explains the observed complexity of the deformation that began in the mid-Tertiary with widespread pre-Basin-Range tectonism, including a mantle-derived thermal perturbation. This event was followed by superposition of WNW-directed extensional deformation (Basin-Range) propagating with and slightly ahead of the northward migration of the Mendicino triple junction along the adjacent plate margin.

Other important characteristics of Basin-Range tectonism suggested by the Arizona neotectonic and other data include: 1) likely propagation of the disturbance in an irregular stepwise fashion; 2) termination of the event in a pulsative manner accompanied by gradual localization of deformation into elongate corridors bounding more stabilized regions; 3) possible association of elongate regional uplft belts with the more generally recognized surface faulting; 4) probable nonuniformity in space and time of extensional deformation, with a possible tendency to develop elongate zones of more concentrated strain during the regional deformational process; 5) the general absence of pronounced shear in surface faulting, except within the western margin of the Great Basin. Recently published deep seismic reflection profiles in various parts of the Basin and Range and Rio Grande rift provinces additionally indicate the pervasiveness of multiple horizontal discontinuities, including such low-angle structures as detachment and thrust faults, throughout the crust. Given this horizontal crustal stratification, it seems likely that decoupling

and/or delamination may occur commonly within the crust and lower lithosphere, thereby strongly influencing the process and form of extensional deformation in the region.

INTRODUCTION

Geologists since the days of G. K. Gilbert, Darton, and W. M. Davis have puzzled over the complex Cenozoic extensional deformation evident in the landforms and structures of the Basin and Range Province. This region of the western North American Cordillera has spawned a bewildering array of tectonic interpretations for Basin-Range deformation. Although sharing a common basis of crustal extension, they range from active rifting driven by mantle diapirism in a backarc to intra-arc setting (e.g., Scholz and others, 1971; Eaton and others, 1978), to mixed lithospheric shearing and extension derived from the evolving transform tectonics along the west coast plate margin (Atwater, 1970; Livaccari, 1979). In part this interpretational diversity arises from the complexity of the tectonism, which includes a variety of superimposed styles of deformation, magmatism, and basin formation, that is often poorly constrained by currently available geological, geophysical, and geochronological data (e.g., Eberly and Stanley, 1978; Shafiqullah and others, 1980; Zoback and others, 1981). At present there exists no consensus as to the subsurface geometry, let along kinematic or dynamic setting, of Basin-Range normal faults (cf., Stewart, 1978). Many studies have been hampered by an imprecise discrimination between Cenozoic extensional events. A better understanding of Basin-Range tectonism might be fostered by treatment of the event as a discrete tectonic interval with a characteristic evolutionary development that, although complex and often refracted through local conditions, is nonetheless recognizable on a regional scale.

This paper presents an assessment of Basin-Range tectonism based primarily on its manifestations within Arizona. In particular, I will focus on regional time and space patterns of late-Tertiary to Quaternary tectonism in the state, with special emphasis on the neotectonic interval. (The term neotectonic is restricted to the most recent identifiable tectonic event in Arizona, of latest-Pliocene to Quaternary age; post 3-2 m.y.B.P.) Neotectonic deformation in Arizona affords an unusual, and perhaps unique, view of spatially juxtaposed developmental stages, including both the initiation and the waning-termination, of Basin-Range tectonism. Also, Arizona contains a relatively well-exposed and well-dated regional Cenozoic stratigraphy that permits isolation of potentially useful variations in structural style among extensional events of that age (Figure 2; discussed below).

The primary new source of data underlying subsequent analyses is a recently completed comprehensive study of neotectonics in Arizona that focused on temporal-spatial patterns of surface faulting, volcanism and regional uplift. Regional neotectonic activity, and surface fault patterns, were poorly defined and little understood prior to this study, due to an absence of any systematic mapping or data collection. The results of the neotectonic study will be summarized first, and then these data will be combined with regional compilations of critical geophysical and geological properties of Basin-Range tectonism. The combined data will then be applied to evaluations of the various geodynamic and tectonic interpretations proposed for Basin-Range tectonism, with a special emphasis placed on those aspects accentuated by the Arizona neotectonic study.

Definitions of Basin-Range and Mid-Tertiary deformations in Arizona. Throughout this paper, I will adopt a restricted definition of Basin-Range tectonism that follows the original definition of Gilbert (1875) and, more recently, that of Eberly and Stanley (1978), Scarborough and Peirce (1978) and Shafiqullah and others (1978, 1980). These workers confined the Basin-Range disturbance, *sensu strictu*, to that event, mostly late-Miocene in age, that produced the present set of physiographic ranges and basins by means of block-fault extension. As so defined, Basin-Range tectonism displays several diagnostic characteristics: a) range-bounding normal faults, steeply dipping at the surface, that define subsurface grabens or half-grabens; b) undeformed to mildly deformed basin-fill sediments derived strictly from adjacent range blocks; and c) association with alkali basalts or bimodal basalts-rhyolites, with geochemistries commonly indicative of an upper mantle origin.

In Arizona, this style of tectonism may be differentiated from at least one, and perhaps two or three, variably distinct Oligocene to mid-Miocene deformations (Figure 2; references cited above). This mid-Tertiary tectonism exhibits complex and at present poorly understood stratigraphic-magmatic-structural characteristics. More important among them are: a) widespread, voluminous calc-alkalic rhyolitic to basaltic volcanism, commonly considered to be either subduction or backarc in origin; b) development of sedimentary basins of different geometries and/or orientations than the younger Basin-Range system; c) regional-scale homoclinal rotation of sediments and volcanic rocks, commonly geometrically associated with closely-spaced shallowly-dipping normal to listric normal faults and/or subjacent detachment faulting; d) enigmatic

regional metamorphism and brittle-to-ductile cataclasis of large tracts of crystalline basement in "metamorphic core complexes" that is commonly ascribed to large magnitude regional extension (see above references; also Coney, 1978a, b; Davis and others, 1979). Recently a similar distinction between Basin-Range and earlier deformations has been recognized to the north in the Great Basin section of the province (Dickinson and Snyder, 1979b; Zoback and others, 1981; Eaton, 1982; Stewart, 1983).

The specific time boundaries used in this paper for relevant Cenozoic epochs are listed in Table 1. Also, the boundaries and locations of the three major physiographic provinces - Basin and Range, Colorado Plateau, and Transition Zone - used in this text, plus other important place names, are depicted in Figure 3.

PART I: SUMMARY OF THE NEOTECTONIC FRAMEWORK OF ARIZONA

The neotectonic data summarized in this section results from a multidisciplinary statewide study of faulting, uplift, and volcanism, conducted by C. M. Menges, P. A. Pearthree, and R. B. Scarborough through the Arizona Bureau of Geology and Mineral Technology, with principal funding from the U. S. Geological Survey. The project utilized both compilations of available literature, and, more importantly, original research, based primarily on photointerpretation and aerial and ground reconnaissance surveys. Specific methods and the principal results of the study are summarized in subsequent subsections. More detailed treatments are contained in a series of maps and a final report (Menges, Pearthree, and Scarborough, in prep., 1983; and Pearthree and others, 1983, also manuscript in prep.).

METHODS

Surface faulting. Known or probable faults with documented or suspected neotectonic activity were initially identified and mapped by sysematic statewide photointerpretation of black-and-white high-altitude (U2) aerial photography (nominal scale of 1:125,000). This photointerpretation was supported by more limited aerial and/or ground reconnaissance of principal features and compilation of available literature and geologic maps (generally spotty in coverage and variable in quality). These results are presented in accompanying map and Tables (Menges and Pearthree, 1983). Mapping was limited to faults and geomorphic features that satisfied certain minimum criteria designed to exclude more ambiguous scarps or lineaments of uncertain and possibly nontectonic origins. Emphasis was placed throughout the study on documentation of the presence, timing, amounts, and rates of Plio-Quaternary displacements on faults, based principally upon reconnaissance field studies of about 50 individual fault scarps distributed throughout the state, with secondary support provided in some areas by compiled literature. The field studies collected geologic and geomorphic data (see below) applicable to estimation of the age and size of the most recent rupture along a given structure, and, where possible, the number, timing, and cumulative amounts of any prior recurrent neotectonic displacements.

We used a combination of two basic data types and analytical procedures to estimate displacement ages: a) the observed offset relationships of Plio-Quaternary rocks or geomorphic surfaces along a given fault; and b) quantitative analyses of fault scarp morphologies. Offset relationships furnish a stratigraphic bracket (between the youngest unit offset and the oldest unit unruptured) of the most recent surface

displacements, as well as a measure of recurrent fault displacements where offset amounts increase with the age of the units. In this study, we concentrated on those faults offsetting either dated or correlatable Plio-Quaternary volcanic rocks or alluvial geomorphic surfaces. The approximate surface ages were estimated by the relative degree of relict soil development with some calibration provided by comparison with established soil chronosequences in Arizona and New Mexico (e.g., Gile and others, 1981; Bachman and Machette, 1977; McFadden, 1978, 1982; Pearthree and Calvo, 1982; Mayer, 1982; and Soule, 1978).

Morphologic dating techniques use the degree of scarp degradation to directly estimate the age of most recent ruptures along fault scarps in alluvium, based on the pioneering work of Wallace (1977). In the present study, topographic profiles measured perpendicular to scarps (commonly ~5-7 per scarp) were quantitatively analyzed for age of rupture using some combination of regression analyses of scarp-height vs. maximum slope angle (Bucknam and Anderson, 1979; Machette, 1982); discriminant function analyses of populations of Holocene vs. late Pleistocene age scarps (Mayer, 1982); and diffusion equation modeling of scarp erosion rates, as developed by Nash (1980) and modified by Mayer (1982).

There is substantial uncertainty inherent to both soil-stratigraphic age estimates and scarp morphologic dating techniques, and the degree of resolution significantly decreases with increasing age of the soil or scarp. Consequently, we have emphasized composite estimates for displacement ages, using combined offset and geomorphic scarp data, that are placed within broadly defined age categories (Table 1).

Volcanism. Identification of late-Miocene to Quaternary volcanism in Arizona was based on regional tabulations of radiometric age dates, drawn primarily from several existing regional-scale compilations (Hamblin and Best, 1970; Keith and Reynolds, 1977; Luedke and Smith, 1978; Ulrich and others, 1979; Aldrich and Laughlin, 1981). We mapped outcrop distribution both from maps accompanying the above compilations and locally from original photointerpretation on the U2 aerial photographs (see accompanying map, Scarborough and others, 1983). The compilation in this study consistently emphasized temporal and spatial variations in volcanic activity, with decidedly minor attention given to detailed geochemistry or petrology. In general, this phase of the study was restricted to post-15 m.y.B.P. volcanism - mostly alkali basalts, with localized andesites, rhyolites and dacites - that is characteristic of Basin-Range extensional tectonics, as defined earlier.

Regional uplift. This aspect of the study focused on the identification of areas of large-scale regional uplift and/or subsidence of tectonic origin with minimum lateral dimensions of several hundred kilometers. In some areas, vertical uplift could be identified within a geomorphically distinct region bounded by tectonically active faults (e.g., the western Colorado Plateau; Hamblin and other, 1981). More typically, areas possibly undergoing neotectonic uplift are more poorly defined, without specific structural boundaries; and the uplift mechanism likely involves nonlocalized epeirogenic processes that respond to perturbations of crustal-upper mantle scale. Thus we had to rely upon indirect analyses of inherently more ambiguous regional geomorphic data. Information on absolute Plio-Quaternary changes in altitude are lacking in Arizona, with

the exception of a sea level-controlled stratigraphic datum in the lower Colorado River valley (the estuarine Bouse Formation; Lucchitta, 1979). Instead we analyzed the regional distribution and rates of Plio-Quaternary dissection in the state; based on the theory developed by Hamblin and others (1981) that interrelates the downcutting responses of fluvial systems to local and regional uplift. Four types of specific indicators of neotectonic dissection were compiled from literature and topographic maps. These indicators are: a) topographically inverted basalt flows throughout the state; b) regional dissection patterns into Plio-Quaternary basin-fill of intermontane basins in southern, central, and western Arizona; c) downstream-convergent Quaternary terraces in the Transition Zone near Phoenix (Pewe, 1978); and d) downstream decreases in the depth of canyon-cutting beneath probable Plio-Quaternary bedrock erosion surfaces of the Mogollon slope located along the Colorado Plateau margin of Central Arizona (the primary indicators of type a and b (above) are listed in Appendix 1, this report). Minimum rates of downcutting were then estimated by measurement of the depth of dissection of adjacent stream channels beneath those datums with relatively good age control (Appendix 1, this report). The distribution of these downcutting indicators were then compared with the regional physiography of Arizona, as depicted by a) a generalized regional topographic map derived by computer-contouring of digitized terrain data (H. Godson, unpublished map, 1982); and b) regional topographic cross-sections prepared from subenvelope terrain analysis of 1:250,000 scale topographic sheets. Subenvelope maps and cross-sections depict generalized minimum-altitude surfaces derived by contouring the elevations of stream channels larger than a certain specified minimum size (Stearns, 1967; Mayer and others, 1977; Mayer, 1979, 1982).

FAULTING PATTERNS

The general character and distribution of faulting. Figure 4 shows the general distribution of faults with reliable control on neotectonic activity. Most structures observed in surface exposures are steeply-dipping ($\gtrsim 60^{o}$-90°) normal-separation faults that typically dip away from adjacent bedrock escarpments or range blocks. The scale of faulting varies widely across the state, ranging from less than 2 m on 2-3 km long scarps in southwestern Arizona, to $\gtrsim$ 310-470 m cumulative offsets along much of the 260 km+ length of the Hurricane fault zone of northwestern Arizona-southwestern Utah.

The majority of Quaternary faulting in Arizona occurs within a diffuse and poorly defined northwest-trending belt that extends diagonally across the state (Figure 4). This zone separates two large regions of rare and dispersed to no neotectonic faulting in the southwestern and northeastern corners, respectively, of Arizona. This primary band of faulting contains two marked concentrations of faults located along the western and southwestern margins of the Colorado Plateau in northwestern Arizona, and in the Mexican Highland section of Basin and Range Province in the southeastern corner of the state. An additional swarm-like cluster of small faults coincides with the north and east edges of the San Francisco volcanic field near Flagstaff (Figure 4; see following section). Also embedded in the main zone are several smaller, narrow ($<$ 100 km wide) and elongate corridors or bands of relatively more concentrated faulting. Notable among them are the northwest-to-north-trending zones within the Verde Valley of central Arizona and along the southern Arizona-New Mexico border (Figures 4, 5b).

Historical seismicity. Historical felt and instrumentally-recorded seismicity defines a broad and diffuse northwest-trending belt (Sumner, 1976; DuBois and others, 1981) that generally corresponds with, and even partially fills in gaps within, the primary band of neotectonic faulting described above (Figure 5). However, with the exception of several larger fault systems in northern Arizona, there is little direct spatial coincidence between individual epicenters, (which lack surface rupture), and mapped Quaternary faults. In part this may arise from imprecise locations of many seismic events; however, in part the discrepancy may derive from sampling different populations of seismic events (magnitudes $\leq$5-6 in the historical record, vs. estimated magnitudes of 6.0-7.5 for rupture events on Quaternary scarps).

Hypocenter locations are not known for the majority of seismic events in Arizona, but where calculated, they occur at focal depths of $\sim$10-15 km on moderately to steeply-dipping (40°-72°) fault surfaces (Brumbaugh, 1980; Eberhardt-Phillips and others, 1981; Natali and Sbar, 1982; Krueger-Knuepfer and others, 1983). Single event and composite focal mechanisms indicate mostly dip-slip normal faulting, with the exception of one possible, but poorly constrained, thrust solution in the southwestern margin of the Colorado Plateau (op. cit.).

Timing, Rates, and Amounts of Quaternary Faulting. Interpretations of fault displacement timing and rates is based primarily on scarp profile and surface offset data described above. We have the best control on the timing of those ruptures that have occurred within the last 150,000 years (ie., late Pleistocene to Holocene time; Figure 6a). This time interval is best suited for consistent and reliable identification and

age estimation of alluvial fault scarps. Rather interestingly, late Pleistocene and younger ruptures are evenly spread throughout the areas of neotectonic deformation in Arizona, including not only the entire breadth of the primary northwest-trending belt of faulting, but also all but one of the scarps mapped in southwestern Arizona. Further, the youngest set of ruptures ($\lesssim$15,000-20,000 yrs) define a relatively pronounced narrow zone extending discontinuously from the Hurricane-Toroweap fault system in northern Arizona south- and eastward into the central and southeastern parts of the state. This most recent pattern of ruptures seems to fill in gaps left by the more dispersed group of older late-Pleistocene displacements. The youngest ruptures also accentuate the narrow corridors of more concentrated faulting (discussed earlier) in the Verde Valley and Arizona-New Mexico border zone.

However, a more heterogeneous regional picture emerges from the data on the amounts and rates of surface displacements throughout the Quaternary. Estimates of longer-term fault activity vary by more than an order of magnitude within Arizona (Figure 6b; Table 2). The largest displacement amounts and the shortest recurrence rates ($\sim 10^4$ yr/event) of faulting occur along a narrow zone in northwestern Arizona centered on the continuations of the Hurricane and Toroweap-Sevier fault systems from southwestern Utah (Arizona Strip, Table 2; NW-1, Figure 6b). These high faulting rates have likely persisted throughout the Quaternary, as indicated by offsets of local late Quaternary basalts (Holmes and others, 1978) and the formation of steep bedrock escarpments along these faults. The tectonic geomorphology of these cliffs further supports high rates of Quaternary displacement on these bounding faults, based on quantitative land-form

analyses adapted from the methods of Bull and McFadden (1977) and Bull (in prep., 1982; oral and written communication, 1975-1980). High rates of Quaternary activity are required for the northern Hurrican fault in particular by the 410 m offset of a 1 m.y.B.P. basalt (Holmes and others, 1978), a relationship that led Anderson and Mehnert (1979) to propose a late Pliocene to Quaternary origin for this structure. The rates and amounts of neotectonic faulting along the other major and minor structures within the Shivwitz and Kaibab regions of the western Colorado Plateau, may be relatively high, but are not well constrained by present data.

A transitional zone of faulting with mixed high and low recurrence rates ($\sim 10^4$ to 10^5 yr/event) continues along the southern ends of the Hurricane and Toroweap faults southeastward to a series of faults south of the base of the topographic boundary of the Colorado Plateau in north-central Arizona (North-central, Table 2; NW-2, Figure 6b). In addition, these faults offset mid to late Pleistocene alluvium adjacent to the boundary cliffs by a maximum of 8-30 m, thereby suggesting smaller and/or more intermittent cumulative amounts of Quaternary activity on these structures. Similar intermediate rates of neotectonic activity are evident along a fault near Yuma in southwestern Arizona that appears more closely related to extensional tectonics in the Salton Trough region of southern California (Y, Figure 6b; also Bull, 1974).

Recurrence rates between surface ruptures fall abruptly to 10^5+ yrs/event on neotectonic faults throughout southern Arizona, as well as the Lake Mead area (SE, SW, LM, Figure 6b; Table 2). Similar low rates probably characterize the neotectonic fault activity of central Arizona and the San Francisco volcanic field, although the timing data is poor in

these areas (C, SF, Figure 6b; Table 2). Further, fault scarps in central and southern Arizona commonly offset piedmont alluvium located above the outer edge of shallowly buried bedrock pediments that extend from 2 to 10 km basinward from the present topographic mountain fronts. These fault scarps typically lie near the surface projections of the primary basin-bounding structures to the main set of Basin-Range grabens, as defined in the subsurface by gravity (Aiken and Sumner, 1974; Oppenheimer and Sumner, 1981). The total amount of offset on early- to mid-Pleistocene surfaces generally is no more than 3-10 m, and does not exceed 20 m, thereby implying low rates and amounts of Quaternary faulting that stands in marked contrast to the surface evidence of an earlier period of greater magnitudes and/or rates of tectonic activity.

Indeed, the combined offset and scarp morphology data suggest that much of the observed neotectonic activity in southern and central Arizona is middle to late Quaternary in age (ie., ~500,000-200,000 yrs). This suggests neotectonic reactivation on these former range-bounding structures following a Pliocene and early-Pleistocene tectonic lull (Menges and others, 1982; Pearthree and others, in prep., 1983). The association of the scarps with broad bedrock pediments reinforces this interpretation, because the latter landform generally forms only after tectonic activity on range-bounding faults decreases to extremely low rates or ceases entirely (Bull and McFadden, 1977; Bull, 1978; Bull, oral and written communication, 1975-1980). The possibility of neotectonic fault re-activation in southern Arizona is also supported by stratigraphic and geomorphic evidence for regional waning and cessation of large-magnitude Basin-Range tectonism by latest-Miocene to Pliocene time discussed in a later

section (Eberly and Stanley, 1978; Shafiqullah and others, 1980; Menges and McFadden, 1981; Menges, 1981). Further, a comparison between the patterns of the most recent and prior ruptures (Figures 6a, b) suggests a possible additional acceleration of activity in the latest Quaternary ($\lesssim$15,000-20,000 yr.) in southern Arizona, although this might represent a short-term transient fluctuation with little overall tectonic significance.

LATE-MIOCENE TO QUATERNARY VOLCANISM

Two basic temporal and spatial patterns are evident in the age-distribution data of late-Miocene to Quaternary volcanism in Arizona (Figure 7). Except for rare and isolated late-Miocene basalt flows interbedded locally with basin fill, the majority of late Cenozoic volcanism in the southern Arizona Basin and Range occurs within four latest-Pliocene to Quaternary basalt fields apparently scattered randomly throughout the province. These fields consist primarily of monogenetic basaltic cones, complexes and flows. All of the fields lack significant internal deformation, with the possible exception of the San Bernardino volcanic field, which lies perhaps not coincidentally within the border zone of more concentrated faulting in southeasternmost Arizona and southwest New Mexico (Figures 7, 4, 6). Peripheral faulting and subsequent tectonic subsidence of the small enclosing basin may have accompanied the main eruptive phase of the field between 3 and 1 m.y.B.P. (this study; also Lynch, 1972, 1978).

By far the largest volume and longest duration of late Cenozoic volcanism in Arizona is concentrated in three regions that straddle and extend into the southern and western margins of the Colorado Plateau

(Figure 7). Northcentral Arizona contains the largest and most complex centers of volcanism with a fairly persistent eruptive history from late-Miocene to Quaternary. Within this region, there is a progressive decrease in age north- and eastward from the Transition Zone of central Arizona into the southwest margin of the Colorado Plateau near Flagstaff (Figure 7). Further, widespread high-angle normal faulting has migrated along or slightly ahead of this moving loci of volcanism, beginning with the development of basins and ranges in central Arizona, progressing to ubiquitous Pliocene faulting of basalt flows along the Mogollon Rim, and ending with the mid-late Quaternary fault swarm along the northeastern border of the San Francisco volcanic field (Figures 4, 7; also Menges and Pearthree, map in prep.; Scarborough and others, map in prep., 1983; Ulrich and others, 1979, in press; Ulrich and Wolfe, oral and written communication, 1981; Ulrich, 1983).

This volcanic tectonic migration pattern is defined less well in the other two main volcanic fields of northern Arizona (Figure 7). Volcanism in the Shivwitz-Uinkaret region of northwestern Arizona displays a more irregular eastward decrease in ages that suggests a crudely-defined migration of volcanism into the Colorado Plateau margin in a fashion similar to that described for contiguous late Cenozoic basalts in southwestern Utah (Best and Hamblin, 1978). Any space-time variation in the latest Cenozoic basaltic volcanism of the Springerville-Show Low field is not apparent. In general, various ages of basalts are superimposed on one another (Crumpler, oral communication, 1982; Aubelle and Crumpler, 1983), although the field as a whole lies on the Colorado

Plateau, north of a voluminous mid-Tertiary volcanic field in the Transition Zone of east-central Arizona.

REGIONAL UPLIFT

Generalized Regional Topography. A generalized regional topographic map prepared by R. Godson (unpublished map, 1982) defines a relatively distinct, northwest-trending, broad band of irregular, generally elevated terrain within the dashed lines of Figure 8a. This physiographic belt separates two areas of much flatter and more featureless regional topography in the southwestern and northeastern corners of the state. This topographic band is itself a composite feature that transects obliquely across parts of all three main physiographic provinces in Arizona (Figures 3, 8a). It also encompasses all of the individual structures in the similarly northwest-trending primary belt of neotectonic faulting described earlier (Figures 6, 8b).

Regional cross-sections were constructed across the band of anomalous topography (Figures 8a, c), using subenvelope maps (1:250,000 scale) prepared as part of this study. The central feature in all the cross-sections is a broad zone of elevated topography, arch-like in form, with a wavelength of 200- 350 km (dashed line, Figure 8c). This arch coincides with the statewide physiographic anomaly identified in the generalized contour map (Figure 8a). In cross-section A-A', the arch is definitely bounded by faults and/or monoclines, most with known or suspected neotectonic activity; and it also correlates with the area along the western margin of the Colorado Plateau known to be undergoing rapid regional uplift (Hamblin and others, 1981). In central Arizona, the arch-like character of the feature's profile is especially pronounced,

with its crest straddling the Mogollon Rim and Slope region of the southern border of the Colorado Plateau (Figure 8c, sections B-B', C-C'). Cross-section D-D' extends east to west transversely across the dominant north-trending structural and physiographic grain of basins and ranges in southeastern Arizona. This profile shows a gradual but steady eastward rise in both the averaged and smoothed altitude across the region and the minimum altitudes of successive basins. This elevational trend thus defines the western limb of broad regional arch, similar, albeit more subtle and gradual, to those observed in northern and central Arizona (Figures 8a, c). Interestingly, the highest averaged basin elevations occur near the crest of the arch in profile D-D', centered over the zone of relatively concentrated late Quaternary faulting near the southern Arizona-New Mexico border (Figures 6, 8c).

Regional Patterns and Rates of Neotectonic Dissection. The regional distribution of the various indications of dissection described earlier (ie., topographically-inverted basalts, dissected intermontane basins, downstream-convergent regional terraces, and downstream-shallowing entrenched canyons) rather strikingly coincides with the regional topographic anomaly defined above (Figure 8d). The Quaternary terraces and bedrock canyons on both flanks of the arch are particularly intriguing, as they converge downstream in height/depth in opposing directions (Figure 8a-c and e).

The minimum rates of Plio-Quaternary downcutting may be inferred from the better-dated elements of this dissection compilation (Figure 8e, Appendix 1). Those rates are consistently high (375 - 90 m/my) in the tectonically active western Colorado Plateau area of northwestern Arizona and southwestern Utah (Hamblin and others, 1981). To the south

and east, the downcutting rates continue at generally more moderate, but significant, levels of 100 - 70 m/my within the central dissected regions of the topographic arch, but drop off to lower values of 30 - 50 m/my along its flanks (Figure 8e, Appendix 1). In fact, stream downcutting ceases, and is replaced by aggradation or subsidence along the Phoenix basin reaches of the Gila-Salt River system in south-central Arizona (Figures 8d, e; also Pewe, 1978).

Basin dissection is rare and where present, is not very intense throughout the Sonoran and Mojave subprovinces of the western Arizona Basin and Range (Figures 3, 8). Well-dated late-Pliocene to early-Quaternary terraces of the lower Gila River do re-emerge near Gila Bend (Euge and other, 1978) and indicate very low downcutting rates of 5 - 9 m/my (Figure 8e, Appendix 1). Another elongate zone of extensive basin dissection follows the south flowing course of the lower Colorado River (Figure 8d), where there are other stratigraphic indicators of possible regional uplift (see below).

Proposed Zone of Regional Uplift. The above data suggests a broad elongate zone of Plio-Quaternary uplift, arch-like in cross-section (Figure 8f) that closely corresponds to the primary belts of neotectonic faulting and seismicity in Arizona. In fact, the Physiographic expression of this proposed zone of uplift is more persistently evident throughout its extent than is the more discontinuous distribution of faulting, and expecially so in the region of minimum faults in east-central Arizona (Figures 4, 8a-b).

Further, the eastern boundary of the uplift strikingly coincides with the eastern limit of neotectonic faulting and basaltic volcanism in the Colorado Plateau north of Flagstaff. This compound boundary corresponds to the eastern border of the deep Plateau canyon-cutting by the Colorado River and its tributaries in the Grand Canyon region to the west (Figures 8a, b, f). Perhaps not coincidentally, Cole and Mayer (1982) have estimated a Pliocene (3 - 4 m.y.B.P.) inception for Colorado River canyon-cutting in the eastern Grand Canyon, based on modeling of cliff retreat rates as judged from ages of fossil packrat middens. This age agrees with the estimated time of initiation for faulting, basaltic volcanism, and proposed regional uplift derived independently from other data.

Also, the minimum rates of downcutting, approximately correlative to rates of regional uplift in the model of Hamblin and others (1981), drop off from the very high rates of northwestern Arizona to more moderate levels in the central and eastern parts of the state (see above, Figure 8e). This fairly abrupt transition coincides with the observed decrease in the rates and amounts of neotectonic faulting in these areas described earlier (Figure 6b, 8e), a correlation consistent with the proposed tectonic uplift origin for the downcutting. Several earlier workers (e.g., Cooley, 1968, 1977; Scarborough, 1975) have also suggested a vaguely-defined regional uplift to explain the observed basin dissection of southeastern and central Arizona.

Lucchitta (1979) proposed high rates of Plio-Quaternary uplift in the Lake Mead area which may decrease in a step-wise fashion southward along the lower Colorado River Valley (Figure 8e). Post-early-Pliocene

uplift in the latter area is suggested by anomalously high and varied altitudes of the preserved outcrops of the lower Pliocene Bouse Formation, an estuarine deposit assumed to have formed at or near sealevel. However, Mayer (1982) successfully modeled the observed Bouse Formation elevations in southwestern-most Arizona as the forebulge portion of lithospheric flexure induced by Plio-Quaternary sediment loading in the Colorado River delta region to the south. Still, the anomalously high Bouse altitudes in the lower Colorado River valley between Parker and Lake Mead, may reflect regional uplift.

Alternative Hypotheses. As noted earlier, the available geomorphic-topographic data is not diagnostic of uplift and may be explained to varying degrees by other nontectonic interpretations. For example, any neotectonic uplift that may exist in Transition Zone and Mogollon Rim-Slope area in central Arizona is certainly superimposed upon older, and perhaps more dominant relief inherited from prior early to middle Tertiary tectonic events. These earlier deformations to large degree responsible for the initial structural and physiographic differentiation between the Colorado Plateau and the Basin and Range provinces (Peirce and others, 1979; Mayer, 1979).

Shafiqullah and others (1978) and Damon and others (1974) have interpreted the regional Plio-Quaternary downcutting patterns in the Colorado Plateau and sothern Basin and Range as a fluvial response to isostatic uplift induced by regional late Cenozoic degradation and dissection. This hypothesis is weakened by the general lack of correspondence between the observed downcutting patterns and the Free-Air gravity anomaly map of Arizona, which shows an approximate

condition of isostatic equilibruim statewide (Figure 9; Sumner and others, 1976; Lysonski, 1980; Sumner, in prep., 1982). In fact, the southern and western margins of the Colorado Plateau exhibits a slight, but well defined, positive Free-Air anomaly, that directly coincides with the Mogollon -Flagstaff portion of the proposed band of regional uplift (Figures 8f, 9). This condition suggests either a crustal mass excess and/or dynamic disequilibrium created by regional uplift. The free-air anomaly also implies that this region would tend to subside in order to achieve isostatic equilibrium (Lysonski, 1980; Sumner, oral communication, 1982). Unfortunately the Free-Air anomaly pattern is more ambiguous in central and southern Arizona (Figure 9) due to interference from high local topographic relief. However, Sumner and others (1976) noted an average zero anomaly in southeastern Arizona that suggests relatively low rates and/or magnitudes of any possible regional uplift in the area as recorded in gravity data.

Bull (written communication, 1982) interprets the regional downcutting pattern in central and eastern Arizona as more likely derived from either climatically-induced fluvial downcutting or some combination of nontectonic downcutting that is enhanced by a positive feedback mechanism of isostatic rebound. In either case, he suggests that regional terraces would converge downstream as a result of diminishing downcutting along a stream profile graded to a lower reach with a stable base level. Certainly it seems probable that the stream backfilling, strath-cutting and some component of downcutting associated with individual Quaternary terrace levels in Arizona represents a fluvial response to climatic fluctuations (Menges, 1981; Menges and McFadden,

1981). Only the longer-term Plio-Quaternary dissection and downcutting or the systematic and often dramatic downstream variations in terrace profile heights might be reasonably ascribed to any possible uplift. Also, one must be aware of the complicating influence of progressive regional drainage integration on the specific timing and amounts of dissection within and between given individual basins (Menges, 1981; Menges and McFadden, 1981).

In summary, better resolution of the possible origin of the observed Plio-Quaternary regional dissection awaits more detailed investigations and availability of less ambiguous data. Pending this, we consider the proposed regional zone of neotectonic uplift a viable, if not unique, hypothesis that adequately explains all presently known time and space patterns of dissection on a regional scale.

TECTONIC INTERPRETATIONS OF ARIZONA NEOTECTONICS

The combined neotectonic data summarized above suggests two fairly distinct, in part spatially overlapping, regional-scale tectonic patterns that are schematically depicted in Figures 10 and 11.

Tectonic Encroachment into the Colorado Plateau Margin. The most prominent and active neotectonic region in Arizona occurs within the Colorado Plateau margin in the northwestern and north-central parts of the state. This zone appears to be co-extensive with the southern branch of the Intermountain Seismic Belt of Smith and Sbar (1974) and Doser and Smith (1982) in southwestern Utah (Figure 10). In that area, Best and Hamblin (1978) have proposed that Basin and Range tectonism, as evidenced by E.-W- Directed extension along large-scale N-S-trending normal faults and associated basaltic volcanism, has migrated eastward into the edge

of Colorado Plateau at an average rate of 1 cm/yr. Arizona neotectonic data suggests that this general pattern continues southward into northern Arizona, but that very likely the faulting and volcanism is accompanied by a coincident band of regional uplift similar to that of Hamblin and others (1981).

However, detailed analysis of the currently available age control on the initiation of normal faulting and volcanism suggests that the eastward progression of tectonism occurs in a more complex and irregular manner than that implied by the average linear migration rate. For example, in southwestern Utah, the major loci of faulting migrated eastward into the margin of the Colorado Plateau about 10 m.y.B.P. and less than 5 m.y.B.P. (Rowley and others, 1981). Near the Arizona-Utah border the most active and possibly youngest structure in the area is the Hurricane fault, with most, if not all, of its 600 - 850 m total offset likely occurring in latest-Pliocene to Quaternary time (see earlier section; Anderson and Mehnert, 1979). However, this fault lies between the Cedar City and Sevier-Paunsaugunt localities described above. Similarly in northwestern Arizona, the Plio-Quaternary fault activity within the western Plateau margin contrasts with the largely late Miocene to Pliocene (~10 to 6 m.y.B.P.) main phase of Basin-Range tectonic activity to the west along the Lake Mead part of the boundary between the Basin and Range and Colorado Plateau (this study; Hamblin and Best, 1970; Lucchitta, 1979). But again, mid- to late Quaternary fault activity is clearly focused on the Hurricane-Washington fault zones in the center of this transect (Figure 6). Given this timing data, perhaps the tectonic migration pattern proposed by Best and

Hamblin (1978) is better modeled as a step-wise eastward movement, with diachronous initiation of faulting, volcanism, and perhaps uplift, across a broad regional band within time intervals at least as long as the Quaternary.

As noted previously, a more uniform and well-defined migration pattern is evident in the systematic northeastward decrease in ages in volcanism and coincident faulting of the San Francisco volcanic field in north-central Arizona (Figures 6, 7, 10, 11a). The volcanism is generally similar to typical Basin and Range magmatic activity. Also, some larger preexisting structures (faults, and possibly some Laramide monoclines) have been reactivated by neotectonic normal faulting (Shoemaker and others, 1978). However, most of the neotectonic faulting in and about the field occurs as variably-oriented swarms of short, discontinuous nearly-vertical faults that do not seem to indicate significant coherently-directed regional extension. Rather this fault pattern suggests predominantly vertical displacements on both newly created and reactivated structures that are governed by more localized uplift (thermotectonic doming?) related to the volcanism (see section B-B', Figure 8c). Swarm-like concentrations of faulting are also observed within and near other Plio-Quaternary basaltic and bimodal silicic-basaltic volcanic fields in southwestern Utah and eastern California (Clark, 1977; Roquemore, 1982).

The possible continuation into eastern Arizona of a similar tectonic encroachment pattern along the Colorado Plateau margin is not as well defined. The volcanism of the Springerville-Show Low field appears more stationary through time (see earlier section), and Quaternary

faulting occurs only rarely in the area and is poorly constrained in age. However, the northern edge of the postulated band of regional uplift does project continuously through eastern Arizona. Farther to the east in New Mexico, Laughlin and others (1982) report a better defined pattern of migration of neotectonic faulting and volcanism into the southeastern margin of the Colorado Plateau (Figure 10). Thus it appears that at least some manifestations of this migrating style of neotectonics extends through eastern Arizona into New Mexico, where tectonic activity again becomes more pronounced.

Stationary Boundary Deformation Belts. A second style of neotectonic deformation, fixed in space, is characterized by more diffuse, elongate belts of intermittent faulting embedded in a more continuous broader region of possible regional uplift or arching (Figure 10). Volcanism is a relatively minor element in these belts, generally restricted to a few scattered small to moderate-sized fields and flows.

The best defined belt of this type emerges from the migrating band of neotectonic activity (described above) as a set of faults that follow the rim of the Colorado Plateau in north-central Arizona (see earlier section, Figures 6, 10). This belt then continues southeast ward across the Transition Zone as commonly indistinct feature to join with the region of neotectonic activity centered on the southern Arizona-New Mexico border. To the east, this zone likely merges in some manner with the southern Rio Grande rift system (Figure 10). A second extremely diffuse belt may follow the course of the lower Colorado River in western Arizona and southeastern California. Ano malies observed in the region include the area of possible post-Pliocene uplift described by

Lucchitta (1979); a few scattered late-Quaternary faults, and a possible eastern boundary to recent vertical crustal movements detected in southeastern California to west (see earlier sections; Figures 6, 8e, 10; also Gilmore and Castle, 1983).

The distribution pattern of these deformational belts tends to border and in part delineate, relatively more tectonically stable regions (e.g., the Colorado Plateau interior, the Sonoran Desert, the Mojave Desert in southeasternmost California, and possibly the Sierra Madre Occidental of northern Mexico; Figure 10). These belts may function as deformational corridors, often aligned approximately north-south and thus perpendicular to average direction of regional extension, that absorb most of the regional extensional and/or vertical strain between adjacent and more coherent crustal blocks (Figure 10).

Within the deformational corridors themselves, Quaternary normal-faulting is dispersed and discontinuous spatially, with typically low recurrence rates and small cumulative offsets. Thus the total regional extensional strain accommodated by neotectonic fault activity is relatively minor and of decidedly lesser magnitude than the possible regional uplift across which the faults are super-imposed. Indeed, the scale of the proposed regions of uplift/arching suggest that these zones, if real, may be the dominant features in the deformation thus they may represent potentially significant manifestations of the geodynamic processes that are responsible for the neotectonics observed at the surface.

Relationship Between Neotectonics and Basin-Range Tectonism. In Arizona, the regional stratigraphic-structural geochronology (Figure 2) constrains the main pulse of Basin-Range tectonism, sensu strictu, to a general late-Miocene time interval. More specifically, the Basin-Range disturbance may have initiated slightly earlier in southwestern Arizona (post 15 - 12 m.y.B.P.; Shafiqullah and others, 1980; Eberly and Stanley, 1978; Lucchitta and Suneson, 1983) relative to southeastern and northwestern Arizona (~13 - 10 m.y.B.P.; Scarborough and Peirce, 1978; Anderson and others, 1972) and central Arizona (~10 - 8 m.y.B.P.; McKee and Anderson, 1971). Pedimentation characteristics and the ages of undeformed sediments and volcanic rocks imply a cessation of the largest peak of Basin-Range tectonism in southwestern Arizona between 10 and 6 m.y.B.P., and elsewhere in the southeastern, northwestern, and central parts of the state by 6 to 3 m.y.B.P. (Eberly and Stanley, 1978; Shafiqullah and others, 1980; Menges and McFadden, 1981; Wolfe, oral communication, 1981).

This tectonic chronology suggests a 5 - 7 m.y. pulse of major regional Basin-Range extension, responsible for the primary set of topographic-structural basins and ranges, that may have migrated in crudely-defined broad bands north- and eastward across Arizona from the southwestern corner of the state. However, available timing data is sparse and irregularly distributed, often with poor age resolution, and thus it may be also interpreted as indicative of regionally synchronous deformation. At present, the proposed statewide propagation pattern is best considered a tenable, but still undocumented, hypothesis.

The relationship between Arizona neotectonics and the main interval of Basin-Range tectonism in southern and western Arizona is a critical

element in the interpretations of both deformations. I agree with Best and Hamblin (1978) that the neotectonic activity observed within the western margin of the Colorado Plateau represents a recent phase of a migrating Basin-Range disturbance (see above; Figure 10, 11a). Further I would place the neotectonic activity of the San Francisco and Springerville-Show Low volcanic fields, as well as the intervening Mogollon Slope region, in a similar category. This correlation thus carries the band of migrating Basin-Range tectonism around the southern corner of the Colorado Plateau to join with similar tectonic activity in west-central New Mexico. Thus, the neotectonic manifestation of Basin-Range tectonism appears to completely encircle, and progressively to engulf, the western and southern margins of the Colorado Plateau.

As so reconstructed, the deformation in the Plateau border areas represents the initiation and/or early stages of Basin-Range tectonism. Further, the late Miocene to Quaternary volcanism and associated faulting in central Arizona is considered part of the Basin-Range disturbance in this interpretation; thus the strong migration pattern of tectonism observed in this area (discussed above) strengthens the hypothesis of a spatial progression of Basin-Range disturbance through southern Arizona proposed above.

Certainly the style and magnitude of the tectonism ascribed to the Basin-Range disturbance differs markedly between the Basin and Range and Colorado Plateau provinces. The generally more dispersed deformation observed in the Colorado Plateau has exerted a lesser physiographic and structural impact on upper crustal rocks of the area, at least in comparison to the greater amounts of late Cenozoic deformation encountered

to the south and west. To a large degree this contrast may reflect either strong rheological variations in at least the upper crusts of the two areas, which have experienced such vastly different geologic and tectonic histories, and/or a progressive decline in the strength of tectonic disturbance itself, especially as it encounters the relatively more coherent rocks of the Colorado Plateau.

The relationship between the main Basin-Range event and the fixed corridors of neotectonic deformation is somewhat more enigmatic (Figure 10, 11b). Traditionally, the Quaternary faulting in southeastern and central Arizona has been considered as simple continuations of Basin-Range tectonism (e.g., Shafiqullah and others, 1978, 1980; Drewes and Thorman, 1978; Schell and Wilson, 1981). This impression is fostered by general similarities in the orientations, geometries, and positions of neotectonic fault scarps and observed or inferred basin-bounding structures.

However, there are some significant complications. For example, Quaternary fault activity has occurred on only a relatively few of the primary regional set of Basin-Range structures. Those faults exhibiting neotectonic activity are not uniformly distributed throughout the area, but instead are restricted to the narrower bands described earlier. The majority of basin-bounding structures throughout southern Arizona are currently buried beneath undeformed Pliocene and Quaternary sediments (Scarborough and Peirce, 1978; Menges and McFadden, 1981), indicating cessation of activity on these Basin-Range faults by or during Pliocene time. Further, a mid- to late-Quaternary reactivation of faulting is implied by the low rates and amounts of neotectonic activity, both regionally and on individual structures, as well as the geomorphic

position of Quaternary fault scarps at the outboard margins of extensive suballuvial bedrock pediments (see earlier section). This neotectonic reactivation apparently followed a significant decrease or lull in regional tectonic activity in latest-Pliocene to early-Quaternary time, and may include an additional latest Quaternary acceleration of in faulting as well.

Also, there is the additional geologic-geomorphic evidence suggesting the development of a broad arch-like uplift in Plio-Quaternary time throughout southeastern and central Arizona (see earlier section). A similar scale of regional neotectonic uplift does not seem to have affected southwestern Arizona, with the possible exception of the lower Colorado valley, although by analogy with the more tectonically active Great Basin part of the province, epeirogenic regional uplift likely accompanied the main phase of Basin-Range tectonism throughout southern Arizona (e.g., Stewart, 1978; Eaton and others, 1978).

These time-space patterns of late Cenozoic deformation in southern Arizona can be interpretated in several ways. Neotectonic activity may indeed be a late-stage manifestation of regional Basin-Range tectonism. If so, the observed patterns suggest that this tectonic event has declined via a series of pulses of progressively constricted areal extent. Alternatively, the present fixed deformational belts may indicate a developing neotectonic regime, in part spatially superposed upon, but tectonically distinct from, the structure and physiography produced by the now-inactive Basin-Range disturbance. It is difficult to unambiguously differentiate between these two alternatives with presently available data; indeed, the actual situation may include elements of both.

Rather interestingly, the general distribution, orientation, and physiographic expression of the more concentrated belts of neotectonic faulting in southern Arizona bear some resemblence to the less active parts of the southern Rio Grande rift in New Mexico (Figure 10). This similarity is enhanced by the location of faulting across the crest of a possible associated regional arch/uplift in Arizona that resembles in many ways the uplift zone known to exist within the Rio Grande rift (Seager and Morgan, 1979; Eaton, 1983). In this scenario, the fixed deformational zones in southern Arizona represent more diffuse elements of the latter regional-scale continental rift zone, as postulated by Seager and Morgan (1979), Natali and Sbar (1981), Bull (oral communication, 1980-81), and Machette and Colman (1983).

However, the question of whether the Rio Grande rift itself reflects a active or passive intra-continental rifting process is still not resolved. The entire rift system, including both New Mexico and Arizona components, may simply comprise localized linear zones of more concentrated regional extension that exhibit varying degrees of rift-like morphology, in part dependent on the relative stage and intensity of tectonic development. Within a passive model, much of the observed rift-like characteristics of the deformation may also result from a focusing of regional extensional strain into more elongate belts by interaction with regional zones of pre-existing structural weakness (J. Callendar, oral communication, 1983).

PART II: REGIONAL GEOPHYSICAL AND GEOLOGICAL CHARACTERISTICS OF THE BASIN AND RANGE AND COLORADO PLATEAU PROVINCES

This section briefly summarizes the more important regional geophysical and geological properties of the Basin and Range and Colorado Plateau regions (Table 3). This data base provides a more regional perspective for critical evaluation of the relevance of the Arizona neotectonic data to interpretations of Basin and Range tectonism in general. The basic regional data, as present in Table 3, has been compiled from a number of published sources, and thus only the highlights are discussed below in the text. Among the more important regional summaries are: Smith and Eaton, eds., 1978; Thompson and Burke, 1974; Thompson and Zoback, 1979; Keller and others, 1979; Bird, 1979; Lysonski, 1980; Eaton, 1980, 1982; Eaton and others, 1978.

Properties of the Crust and Upper Mantle. The crust and the lithosphere of the Basin and Range province is notably thin (18-30 km) relative to both the Colorado Plateau interior (42 km) and particularly the stable craton of the Great Plains (50 - 52 km). The Basin and Range crust itself overlies an anomalous zone of low seismic (P_n) velocities within the uppermost mantle that is generally interpreted as hot and/or partially melted asthenosphere located slightly below or immediately subjacent to the base of the crust. A more pronounced lithospheric upper mantle lid lies between the crust and asthenosphere in the Great Plains and parts of the Colorado Plateau interior.

Recently published deep seismic reflection profiles indicate the pervasive presence of multiple, prominent subhorizontal reflectors, probably corresponding to lithologic and/or structural discontinuities

(including low-angle thrust and detachment faults), throughout the crust of the Basin and Range, and perhaps that of the Colorado Plateau (Eaton, 1980, 1982; Keith, 1980; Reif and Robinson, 1981; Oliver and others, 1983; Allmendinger and others, 1983; Zoback, 1983). Some of these horizontal and seismic reflectors-discontinuities may correspond to the mid-crustal seismic low velocity zones commonly observed at 9 - 15 km depths in seismic refraction surveys of the Basin and Range crust (Smith, 1978; Eaton, 1980). Significantly, the transition between the crustal properties of the Basin and Range province and the interior of the Colorado Plateau outlined above occurs not at their physiographic border, but instead at the interior margin of extensional deformation and volcanism within the Plateau itself (described earlier; Smith, 1978; Thompson and Zoback, 1979; Keller and others, 1979).

Heat Flow. Average heat flow measurements within the Basin and Range province are decidedly higher ($\geq$ 2.0 HFU) than those of the Colorado Plateau interior (1.3 - 1.6 HFU) and the Great Plain ($\sim$1.0). Again, the region of elevated heat flow characteristic of the Basin and Range crust extends into the margin of the Colorado Plateau, coincident with the transition to the thicker and tectonically stable crust/lithosphere of the Colorado Plateau interior.

Seismicity. Historical seismicity in the Basin and Range province occurs primarily in the Great Basin and Rio Grande Rift sections (aside from the lesser amounts within the Arizona seismic belt described earlier). Further, the majority of epicenters tend to cluster into indistinct, but definable, elongate belts, with widths of several hundreds of kilometers and lengths on the scale of the province itself (Figure 12; Smith, 1978).

These seismic belts are located primarily at the borders of the Great Basin, although several do transect its interior both parallel and transverse to the north-south-trending topographic and structural grain of the region. Also, the eastern boundary of seismicity is well east of the physiographic boundary of the Colorado Plateau, and coincides with the interior limit of the other tectonic and geophysical parameters described above (Figure 12; Smith, 1978).

Most hypocenters in the Basin and Range occur above 15 - 10 km depths, and all are shallower than 20 - 25 km depths. These maximum depths to earthquake hypocenters are interpreted to approximate the base of the seismogenic crust, and hence define the limits of crustal regime of brittle failure above the transition to aseismic more ductile deformation (Smith, 1978; Eaton and others, 1978; Eaton, 1980, 1982). These seismically-determined estimates for the brittle-ductile transition agree well with the 20 km thickness calculated for the brittle lithosphere of the eastern Great Basin based on isostatic modeling of the crustal rebound observed after draining of the late Pleistocene Lake Bonneville (Walcott, 1970).

Contemporary Stress Orientations. Focal mechanism solutions, *in situ* measurements, volcanic vent alignments, and fault slip indicators all provide measurements of the orientations of the contemporary stress field (Zoback and Zoback, 1980). All stress indicators in the Great Basin and Rio Grade Rift delineate a relatively consistent WNW- to EW-directed axis of horizontal minimum compression (σ_{Hmin}, which approximately corresponds to the more general term of regional horizonal extensional stress). This orientation is also consistent with longer-

term geologic evidence (fault and volcanic vent data) for an approximately similarly directed σ_{Hmin} and associated regional extensional strain during the course of Basin-Range tectonism, sensu strictu, in this region (Eaton and others, 1978; Zoback and others, 1981; Eaton, 1982).

However, focal mechanism solutions indicate that both the direction of horizontal regional extensional stess, as well as the character of the extensional strain reponse, changes from east to west across the Great Basin (Smith, 1978; Smith and Sbar, 1974; Eaton and others, 1978). Fault plane solutions along the eastern boundary are characterized by predominantly EW-directed σ_{Hmin} accommodated by extension along normal-slip high-angle faults. In contrast, the focal mechanisms along the western boundary area indicated more NW-oriented σ_{Hmin} that controls regional extension along a mixture of normal-slip, oblique-slip, and strike-slip faults. The relative proportions of vertical vs. horizontal slip components is governed primarily by the orientations of the faults with respect to a uniform extension direction (Thompson and Burke, 1973; Ryall and Malone, 1971). The more northwesterly extension direction and the increasing strike-slip components are aligned with the orientation and style of deformation along the San Andreas transform fault system to the west, suggesting a greater infuence of that plate boundary on the regional deformation of the western Great Basin.

More limited stress indicators indicate a generally similar EW- to NW-directed regional σ_{Hmin}, accommodated mostly by normal-slip to oblique-slip faults, in the southern Basin and Range province and Rio Grande Rift. Exceptions include possibly SW-directed and variably oriented σ_{Hmin} in the Sonoran Desert and southern margins of the

Colorado Plateau, respectively (Aldrich and Laughlin, 1982, 1983). In contrast, a NW-directed maximum horizontal compressional stress field appears to dominate the interior of the Colorado Plateau, inboard from the western, eastern, and southern margins that are affected by extensional tectonics (Thompson and Zoback, 1979; Zoback and Zoback, 1980).

Prior Geologic and Tectonic History. The crust of the Basin and Range province experienced a number of superposed Mesozoic and Cenozoic tectonic events prior to the onset of Basin-Range extension, *sensu strictu* (Coney, 1978a; Dickinson, 1981). Those with probably the most influence on Basin-Range deformation are the Sevier-Laramide compressional tectonics of late Mesozoic-early Tertiary age, which produced a regional system of low-angle thrusts, and the mid-Tertiary extensional tectonism (described earlier) that immediately preceded the Basin and Range disturbance. Both of these tectonic events contained significant deformational and magmatic components that greatly altered the crust at both regional and local scales. Both deformations produced large-scale low-angle structures in the brittle upper and probably the ductile lower crust. These structures responded to SW-NE-oriented compression and thrusting in the Sevier-Laramide and mid-Tertiary regional extension of similar orientation (Eaton, 1982; Rehrig and Heidrick, 1976). Both tectonic events included widespread and often voluminous silicic to intermediate composition volcanism and plutonism, often of batholithic proportions. In particular, the abundant magmatism, including shallow depth intrusions and/or ash-flow eruptions, as well as the deformational fabric of the "metamorphic core complexes" accompanying mid-Tertiary tectonism suggest a profound thermal perturbation of the crust. This relatively rapid and

regional influx of heat likely produced a shallow-level transition from brittle to ductile deformation, high strain rates, and elevated geothermal gradients (Eaton, 1982).

Apparently the rocks of the Colorado Plateau were much less affected by the tectonic events described above. This region experienced only widely-spaced monoclinal flexuring and/or reverse faulting of probable Laramide age and scattered mid-Tertiary-aged intrusion or volcanism. In fact, the extensional Basin-Range tectonism found along the Colorado Plateau margins in many places is of equal or greater magnitude than any previous Phanerozoic tectonic event.

Paleostress Rotations. The above discussion implies that the orientations of horizontal minimum compressional stress rotated clockwise ($\sim 45^{o}$ - 90°) from SW to W-NW directions during the transition from the mid-Tertiary to Basin-Range tectonic events. A systematic and often abrupt change in the preferred orientations of normal faults of mid vs. late Tertiary age from NW-NNW to N-NNE was first recognized in southern Nevada (Ekren and others, 1968; Anderson, 1971; Anderson and Ekren, 1977). This fault and stress reorientation was typically accompanied by the initial appearance of characteristic Basin-Range block faulting and/or magmatism, as defined earlier. Since then, a similar extensional stress rotation has been identified elsewhere throughout the Basin and Range province (Figure 13; also Zoback and others, 1981), including northern Nevada (Zoback and Thompson, 1978), west-central Arizona, (Lucchitta and Suneson, 1983), northern New Mexico (Lipman, 1981) and southeastern Arizona (Menges and others, 1981; Menges, 1981).

PART III: REGIONAL INTERPRETATIONS OF BASIN-RANGE TECTONISM

GENERAL TECTONIC MODELS

The many interpretations proposed to date for Basin-Range tectonism may be classified into three main categories - active, passive, and composite - that differ on the fundamental mechanism controlling the initiation and development of the disturbance. Active models basically invoke some type of intracontinental rifting that is actively driven by mantle diapirism; that is, asthenospheric upwelling initially rises beneath the lithosphere of the Basin and Range province and rifts it apart by subsequent lateral flow. The mantle driving force for active rifting has been modeled variously as a subducted oceanic ridge (Menard, 1960), an ensialic backarc or interarc basin (Scholz and others, 1971; Profett, 1977), and a more vaguely defined mantle upwelling initiated by rapid steepening and/or fragmentation of a subjacent subducted slab (Coney, 1978a, b). However, rarely does the post-30 m.y.B.P. replacement of subduction by transform faulting along the adjacent west coast plate margin (Atwater, 1970; Atwater and Molnar, 1973) play a significant role in controlling the development of Basin-Range tectonism in these models.

In contrast, the evolution of the San Andreas transform boundary is the fundamental control for the at least the initiation, if not the overall deformation itself, of Basin-Range tectonism in passive models. These interpretations typically view Basin-Range deformation as some combination of regional extension and/or shearing of the lithosphere developed in response to north-westward relative motion of the North American plate along the adjacent transform margin. The asthenosphere may upwell beneath the extending and fragmenting lithosphere and crust

and assist in the rifting process, but this mantle influx is considered a secondary respose to initial lithospheric rifting controlled by plate margin tectonics. The exact mechanism of control exerted by the San Andreas transform varies widely, including distributive shear across a broad, thermally-softened plate margin (Atwater, 1970; Livaccari, 1979); interaction between a mosaic of small to large crustal blocks within a uniform stress field generated by the San Andreas boundary (Wright, 1976; Hill, 1982); regional extension generated by a migrating set of unstable triple junctions (Dickinson and Snyder, 1979a; Ingersoll, 1982); and progressive enlargement of a subjacent slab window which then controls the area of asthenospheric upwelling beneath the Basin and Range (Dickinson and Snyder, 1979b; Best and Hamblin, 1978).

Composite models include varying proportions of both active and passive rifting mechanisms. Most such interpretations postulate an initial SW-directed interval of mantle-driven active regional extension in the mid-Tertiary, usually within a backarc or interarc setting. Then a passive type of rifting related to the evolving San Andreas transform boundary is superimposed across this already extended terrane at some later time (Zoback and Thompson, 1978; Zoback and others, 1981; Eaton, 1982). Some models make a clear distinction between the two extensional processes, considering the later more passive one more akin to Basin-Range tectonism, whereas other models do not.

Finally, several types of models are not easily placed in any of the above categories. Subplate hypotheses view the contemporary tectonics of the western Cordillera interior as intraplate deformation concentrated along diffuse boundaries of ill-defined subplates, with the

Great Basin as one such plate fragment (Smith and Sbar, 1974; Smith, 1978). Either active or passive mechanisms may provide the driving force for deformation between and within subplates.

In a departure from pure plate tectonic models, Bird (1979) developed a model of crustal delamination whereby upper crustal uplift and extension results from some initial vertical and lateral penetration of the asthenosphere into mid-lithospheric levels by means of some process like cracking, slumping or plume erosion. This condition sets up an inherent gravitational instability that triggers consequent stripping and sinking of the negatively-buoyant lower crust or mantle lithosphere as a self-propagating disturbance. He then quantitatively applied this model in two stages (mid-Tertiary and Plio-Quaternary) to explain the mid-late Cenozoic tectonic evolution of the Colorado Plateau.

IMPLICATIONS OF ARIZONA NEOTECTONIC ACTIVITY FOR THE BASIN-RANGE EVENT

No one model or explanation presented to date satisfies completely all of the presently available data on Basin-Range tectonism. Clearly this is a complex tectonic event partially obscured by the effects of many earlier deformations and further masked by ambiguous, incomplete, and often seemingly contradictory data concerning the subsurface character of deformation at all levels of the crust. Consequently, rather than construct yet another tectonic model, I will instead emphasize certain results of the Arizona neotectonics study, in combination with other recently published data, that hopefully will better define the character of Basin-Range tectonism itself.

Superposition across earlier extensional events. There is abundant evidence summarized earlier for superposition of the Basin-Range disturbance across slightly earlier widespread extensional tectonism that profoundly altered the crust of the region. The resultant spatial juxtaposition of deformations makes unraveling of the geometries, let alone kinematics or dynamics, exceedingly difficult. Undoubtedly in many areas, Basin-Range interacted with pre-existing structures inherited from the earlier extensional and/or compressional tectonic intervals. For example, COCORP seismic reflection lines in southwestern Utah show steeply-dipping basin-bounding structures merging in the subsurface with a major low-angle reflector (Allmendinger and others, 1983; Zoback, 1983) that possibly originated during earlier mid-late Tertiary volcano-tectonics or Sevier-age thrusting. Certainly the thermal effects of the mid-Tertiary tectonism influenced subsequent deformational styles, including the depth of the temperature-sensitive transition between brittle and ductile deformational fields (Eaton, 1980, 1982; Sibson, 1983).

One key structural element in the inception of Basin-Range deformation, sensu strictu, is the transition from shallow-depth listric or low-angle normal faults to high-angle normal faults that flatten at depths exceeding 5 - 10 km, if at all (see later subsection). This change in fault geometry may simply reflect depression of the brittle-ductile transition boundary, lowering of geothermal gradients, and/or decreasing strain rates during the progressive cooling of the crust within one continuous tectonic event that initiated with a large mid-Tertiary thermal impulse (Eaton, 1980, 1982; Lucchitta and Suneson, 1983). Although probably true to some degree, certain aspects of Basin-Range

tectonism suggest it may be a more distinct event. These include the stress rotation described above, abrupt changes in magma geochemistry indicative of sudden tapping of deeper and more primitive sources (Keith and Dickinson, 1979; Leeman, 1982), and the often dramatic superposition of basins with constrasting styles and orientations.

Neotectonic activity observed along the margins of the Colorado Plateau may afford a relatively unfiltered view of Basin-Range tectonism at its early developmental stages (see preceding section), as significant mid-Tertiary deformation never affected this region. If this interpretation is correct, then the primary tectonic elements of the Basin-Range disturbance comprise: a) scattered to locally concentrated volcanism; b) regional extension with attendant production of local vertical relief, across high-angle normal faults that probably shallow at some intermediate depth (Hamblin, 1965); and c) possibly intimately associated zones of regional uplift marked by broad topographic swells with wavelengths of several hundreds of kilometers or more.

Initiation-Propagation Patterns. The specific set of structural, magmatic, and physiographic data described above serve to fingerprint the tectonic transition from mid-Tertiary to Basin-Range deformations in a given area of the Basin and Range province (Zoback and others, 1981; Dickinson and Snyder, 1979b). And the initiation of Basin-Range tectonism is easily recognized within the Colorado Plateau by the onset of extensional faulting, uplift and/or volcanism in an area of previous tectonic stability.

Regional compilations of the locations and timing of these tectonic transitions suggest an irregular northeastward migration of the Basin-Range disturbance outward from its earliest manifestations in the Sonoran

Desert-southern Mojave Desert area from mid-Miocene to Quaternary time. Certainly at a gross regional scale, a minimum two-stage northward progression from the southern Basin and Range to the Great Basin seems evident in the regional tectonic analyses of Dickinson and Snyder (1979b) and Zoback and Snyder (1981). This inference is supported by the obvious contrasts in physiography and degree of contemporary tectonism between the two areas. The data of Best and Hamblin (1978) and the Arizona neotectonic analyses strongly suggests an additional late Cenozoic east and northeastward migration of extension into the Colorado Plateau. Further, the regional geochronology in southern Arizona suggests that the Basin-Range disturbance may have initiated across the province in two to three poorly defined migrating stages (see earlier section), although the data does not unambigously establish this smaller sub-regional scale. If this latter pattern exists, the neotectonic timing control along the western margin of the Colorado Plateau implies that the Basin-Range disturbance likely propagates laterally in an irregular, stepwise fashion, initiating diachronously (within a time frame as great as several million years) across a broad strip-like band. Deformation during the course of the tectonism may be somewhat pulsative and irregularly distributed in time and space, with loci of activity shifting from one zone or set of structures to another.

Waning and Cessation Stages. Latest-Miocene to Quaternary tectonism in Arizona affords a rather unusual view of the Basin-Range disturbance in its waning and perhaps termination stages. The data suggest that the rates and magnitudes of extensional faulting regionally declines over a time span of several million years ($\sim$2 - 5 m.y.), following a maximum

interval of extensional deformation and basin formation of approximately similar or slightly longer duration. The gradual decline in tectonic activity is marked regionally by: a) the initial development of bedrock pediments along fault-bounded mountain fronts; b) the progressive burial of the range-bounding faults beneath slightly deformed to undisturbed upper basin fill deposits; and c) a notable decrease in the rates of basin fill sedimentation (Menges and McFadden, 1981; Menges, 1981). In some areas, the final morphologic stages of basin evolution additionally involve internal basin stabilization at a high elevation or "stand", often marked by development of a pronounced geomorphic surface of sub-regional extent, and/or the progressive integration of formerly closed basins into a regional drainage system. The latter process often triggers locally extensive basin dissection with consequent development of regional terraces. However, as noted earlier, the specific processes of basin degradation and regional terrace formation are undoubtedly influenced, and perhaps largely controlled, by contemporaneous climatic changes and/or possible regional uplift.

The timing and distribution of neotectonic faulting in southern Arizona further implies that surface faulting both decreases in a pulsative manner, and spatially constricts into zones or belts of more focused activity, often with rift-like aspects. These relationships between neotectonic and earlier main-phase Basin-Range deformations, regardless of their exact genetic linkage, suggests a progressive localization of extensional strain into elongate corridors. The deformation in these corridors is characterized by discontinuous belts of surface faulting, with low rates and amounts of cumulative displacements,

that are likely superimposed across broad regional arches or uplifts (Figure 10). These deformational corridors occur along or project between the boundaries of large, relatively stable crustal blocks that lack significant internal neotectonic deformation (e.g., the Colorado Plateau interior and the Sonoran Desert-eastern Mojave Desert regions of the southern Basin and Range).

This latter condition implies a progressive tectonic consolidation of formerly active terranes that were highly distended along a well-developed internal deformational fabric. Currently these terranes behave as relatively coherent blocks that do not significantly experience, at least in the upper crust, the extensional and/or shear deformation in adjacent areas (Figure 10). This tectonic behavior is most easily explained by gradual definition through time of indistinct "subplates" or regional crustal blocks (in some ways larger-scale analogs to the block tectonics of Hill, 1982), as deformation becomes concentrated along the boundary corridors. These border zones between blocks may be localized along pre-existing regional structural or lithologic crustal discontinuities with long histories of tectonic reactivation such as the western and southern borders of the Colorado Plateau. Also, the internal tectonic stabilization of deformed crustal blocks within a larger region of active deformation is perhaps more easily understood if the upper crust of these blocks are decoupled to varying degrees at mid to lower crustal levels along subhorizontal discontinuities (see below; J. Callendar, oral communication, 1983). This decoupling would at least partially isolate the undeforming upper levels of the block from regional tectonic stresses transmitted in the subjacent lower lithosphere.

Modification of the Crust and Lithosphere. The available geologic and geophysical evidence suggests that Basin-Range and earlier extensional deformation fundamentally modified the thickness and structure of the crust and lithosphere. This is strikingly illustrated by the crustal characteristics of the margins of the Colorado Plateau, which display a greater affinity to the crust of the geologically dissimilar Basin and Range province than to that of the more superficially similar Colorado Plateau interior. The main tectonic process common to both the Basin and Range and the Colorado Plateau margins is the late Cenozoic extension of the Basin-Range disturbance.

This modification is most obviously exhibited in the pronounced attenuation of the crust and lithosphere, as well as the consequent shallow depth to the asthenosphere (see earlier section; Table 3). This thinning may itself occur nonuniformly in vertical profile, involving both brittle extension in the upper crust, and more ductile laminar flow at lower levels, each possibly with different strain rates, as well as some form of basal tectonic erosion or stoping process (see below; Eaton, 1982; Mayer, 1982, 1983; Hamilton, 1983).

Perhaps of equal significant is the probable development and/or enhancement of numerous low-angle structures throughout the mid to lower crust during both brittle (faulting) and ductile (cataclastic) phases of Basin-Range and mid-Tertiary deformations, as well as earlier compressional tectonics. These structures, in combination with compositional layering, are likely responsible for production of the horizontally stratified crust observed in the COCORP and other seismic reflection lines (Oliver and others, 1983; Allmendinger and others,

1983; Zoback, 1983; Eaton, 1980, 1982; Reif and Robinson, 1981; Keith, 1980).

The actual process of crustal extension, including that associated with Basin-Range tectonism, may be enhanced by crustal decoupling and/or delamination along these inherited or newly created low-angle structures at varying depths in the crust. For example, crustal decoupling may facilitate the internal tectonic stabilization of both previously deformed and undeformed crustal blocks embedded in a tectonically active region (see above; also, Hill, 1982). The delamination process of Bird (1979) may also play a large role in subcrustal erosion or stoping processes that possibly contribute to lithospheric attenuation. Some type of crustal delamination may also assist in the relatively rapid migration of Basin-Range deformation across large tracts (described earlier), via the self-propagating subcrustal stripping mechanism described by Bird (1979).

Regional Zones of Uplift. Large domal or arch-like zones of regional uplift are a common feature in areas of continental rifting and extension (Illies, 1981). Examples in the western Cordillera include the Rio Grande Rift, which Eaton (1983) compared topographically with physiographic expression of the slow spreading Mid-Atlantic oceanic ridge, and at a larger scale, the province-wide regional uplift across the Great Basin (Eaton and others, 1978; Stewart, 1978).

Perhaps one of the more intriguing results of the Arizona neotectonic study is the association between narrow concentrated bands of surface faulting and broad elongate physiographic arches indicative of possible neotectonic regional uplift (Figure 6, 8, 10). These topographic features

extend across and beyond the length of Arizona (hence $\gtrsim$ 500 - 1000 km), with typical elevational amplitudes of 1 - 2 km and wavelengths exceeding 200 - 350 km in cross-section (Figure 8). The scale of the possible uplift zones thus suggests a source in the lower crust to upper mantle, an inference reinforced by close association with intermediate wavelengths Free-Air anomalies of similar dimensions (Figures 8, 9).

The scale of these features is akin to the better documented elongate zone of uplift that follows the Rio Grande rift (Seager and Morgan, 1978; Eaton, 1983). Regional topographic swells of similar proportions seem to exist as secondary features within the overall regional uplift of the Great Basin itself (personal observation; also, Hoover, oral communication, 1983). Thus it appears that intermediate-scale belts of regional uplift may constitute a generally unrecognized component of broadly distributed continental extension.

It seems probable that these arches, if tectonic in origin, reflect epeirogenic uplift produced by thermal expansion. They would thus record regional influx of heat likely related to extension penetrating through the crust. The additional heat may entirely diffuse conductively through the crust, in which case the causative thermal perturbation would predate the present surficial manifestations by at least 10^6 - 10^7 yrs. (ie. mid- to late-Tertiary time). Alternatively, the heat may rise much more quickly via convective intrusion of magma into mid to lower crustal levels, in the fashion described by Lachenbruch and Sass, (1978), Eaton (1982) and Thompson (1959, 1983). More likely, the uplifts respond to some mixture of conduction and convection, given the geologic evidence for both neotectonic and earlier periods of extension.

The only other tectonic alternative to thermal sources for the formation of these topographic arches would be large wavelength buckling of the elastic lithosphere in response to lateral compression. This seems a less attractive hypothesis due to: a) an uncertain tectonic source for the lateral compression in this region of otherwise extensional tectonics; and b) the excessively large magnitudes of the critical horizontal compressive stress (35 - 57 kbars) required to initiate buckling of lithosphere with thicknesses of 15 to 40 km, based on the elastic flexure theory of Turcotte and Schubert (1982).

Nonuniform Deformation in Space and Time. The patterns of surface faulting in Arizona discussed earlier emphasizes the nonuniform areal distribution in time and space of the deformational processes. There is clear evidence in the data for clustering of faults in space (e.g., the swarm-like concentrations and long linear rift-like zones; Figures 4, 10), as well as in time (e.g., the apparent increase in surface ruptures within latest-Quaternary time, Figures 6a, b).

Rather similar time-space deformational variations are suggested by the tendency of historic seismicity and surface ruptures to occur within discrete narrow zones enclosed within a broader region of Quaternary tectonic activity in the Great Basin (e.g., the Nevada-California seismic belt; Figures 10, 12, 14; Wallace, 1978, 1981; Smith, 1978). The longer-term geologic-tectonic significance of this type of nonuniform surface faulting probably varies, depending on whether they represent short-term transient phenomena that average out regionally over geologic time scales, or true quasi-stable, stationary variations in process (see below).

Of special interest in this regard is the possible existence within the interior of the Great Basin of elongate regional topographic swells, of similar cross-sectional wavelengths and amplitudes (i.e., 100 - 300 km, 1 - 2 km, respectively) to the topographic arches described in central and southern Arizona. In the Great Basin, these topographic features trend generally NS-NNE, subparallel to the average orientations of the axes of individual basins and ranges. They are characterized in cross-section by systematic rise and fall of the generalized minimum altitude surface of successive series of basins (2 - 5 in number), as measured transverse to their axes (similar to profile D-D', Figure 8c). These physiographic phenomena may represent the surface expressions of intermediate-scale loci of nonuniform deformation and uplift - related to more persistent perturbations in the lower crust-upper mantle - that are embedded in the larger province-wide region of broadly distributed extension. In this hypothesis, the observed uplift welts reflect thermo-tectonic doming at crustal scales in response to broad zones of accentuated crustal distension.

The above patterns in the Great Basin suggest that extensional deformation is nonuniform over geologic time scale not only in vertical profile, but also in horizontal dimensions (Hamilton, 1983). Further, regional variations in extension may begin to focus nonuniformly into definable elongate zones or belts at relatively early stages in its development. Except for the greater degree of extensional tectonic activity, these zones in the Great Basin resemble the fixed deformational corridors of Arizona neotectonics (Figure 10). Thus the two types of features may represent different stages of development of a similar basic

process of extensional strain concentration.

One somewhat speculative model of nonuniform extension worth additional testing begins with the initiation of Basin-Range deformation across a large region as widespread and fairly uniformly distributed normal faulting contemporaneous with broad regional uplift. With time, extension localizes somewhat as discrete basins and subregional sets of basins preferentially develop at wavelengths of tens of kilometers. At still later, more mature stages, certain elongate zones of basins/faults, more widely spaced across the extending region, preferentially absorb most of the regional strain. As these extensional welts develop into crustal scale features, they sympathetically stimulate regional zones of thermo-tectonic uplift-arching and subsidence, with longer intermediate-scale wavelengths, that are marked at the surface by large topographic swells. This process of progressive strain concentration perhaps occurs as a result of some combination of strain softening (LePichon and Sibuet, 1981), strain localization along pre-existing crustal weaknesses, or development of fundamental lower crust-upper mantle perturbations during the course of the extension. In later stages of the Basin-Range disturbance, tectonic activity gradually(?) diminishes and eventually ceases in the intervening areas between the already developed deformational corridors. These zones continue to absorb the declining amounts of regional extension. Eventually a system of tectonically stabilized crustal blocks bounded by diffuse belts of residual activity emerges in the final stages of the regional deformation.

It is interesting to compare this hypothesis with other models of nonuniform horizontal extension. For example, Wernicke (1983) similarly

interrelates regional doming and large-scale localized extension of the lithosphere in the southern Basin and Range, except crustal attenuation here is ascribed to through-going low-angle normal faults. Also, Stewart (1980) defined a series of antiformal-synformal features in the Great Basin, of approximately similar scale to the topographic swells defined earlier, on the basis of the regional tilt patterns of individual range blocks. It is not yet clear if these structurally-defined features spatially correspond to the physiographic uplift belts described above. However, as defined by Stewart (1980), the tilt patterns do indicate nonuniformity in regional extension. However, his proposed mechanism of formation differs, in an opposite sense, from the model described above. For he postulates that the antiformal range tilts develop from stress relief extending outward from their crestal areas, which represent the initial localization of strain along preferential rupture sites during early stages of regional extension.

Shear vs. Extensional Modes of Deformation. The relative proportions of shear and extension represent an important difference between passive and active tectonic models for Basin-Range deformation, with northwest-directed shear more important in the former. As noted earlier, focal mechanisms in eastern California-western Nevada indicate significant intermixing of NW-oriented strike-slip and normal- to oblique-slip solutions that occurs on both transcurrent and normal faults (Eaton and others, 1978; Smith, 1978). These patterns suggest that this region does experience some NW-directed right-lateral shear probably derived from the San Andreas system, and thus this western border of the Great Basin does likely function as part of a "soft" plate margin deforming in distributive shear, as proposed by Atwater (1970).

However, stress and geologic data indicates that direct manifestations of surface shear do not occur east of western Nevada. The central and eastern interior parts of the Great Basin demonstrate more WNW- to EW-directed extension or oblique extension, with commonly a large component of vertical slip (Smith and Sbar, 1974; Smith, 1978). Although not conclusive, the Arizona neotectonic data and available focal mechanisms suggest that the primary belt of faulting is characterized more by EW- to SW-directed extension, oriented perpendicular to the trend of the belt itself, on high-angle normal faults. This deformational mode resembles that observed along the eastern boundary of the Great Basin. Further, structural analysis of an exposed range-bounding fault in southeastern Arizona, that was active during the main phase of Basin-Range tectonism in the region indicates primarily oblique extension related to uniform basin opening of that time (Menges, 1981).

Eaton (1979) and Livaccari (1979), among others, have suggested left-lateral shear along a proposed transform-type structure(s) situated along the southwestern margin of the Colorado Plateau in central Arizona. They require this shear structure in order to accommodate proposed clockwise rotation of the Plateau in response to Plio-Quaternary opening of the Rio Grande rift (Figure 10). The Arizona neotectonic data precludes the existence of any active regional strike-slip faults at the surface along this boundary; rather, post-mid-Miocene deformation in central Arizona occurs as a discontinuous set of normal-separation faults that crudely suggest a left-stepping en-echelon pattern (Figures 4, 15). Limited available geologic data suggests at most oblique-extension across the zone in an approximate EW-direction, although specific slip data is lacking.

As an alternative hypothesis, the central Arizona fault corridor may be modeled as secondary surface extension above a subsurface basement shear zone. The orientations of individual faults in central Arizona are quite variable (Figure 15), corresponding in part to the trends of reactivated older structural grains. Thus this group of faults do not readily define any systematic set of secondary normal faults, tension gashes, or Reidal shears commonly attributed to uniform basement shear (Figure 15; after Tchalenko and Ambrays, 1970; Wilcox and others, 1973; Groshong and Rodgers, 1978; Illies, 1981). Certain specific faults may be correlated with a mixed set of Reidel, and tensional fracture components in a northwest-trending left shear system. Thus the central Arizona fault corridor may at best reflect a diffuse secondary surface expression of a very broad distributive left shear in the subsurface basement that is oriented subparallel to slightly oblique to the adjacent Plateau boundary (Figure 15). However, data constraints on this interpretation are absent, and this zone may simply reflect EW- to NW-directed oblique extension accommodated along a narrow band of faults trending slightly oblique to the primary deformation belt. Either interpretation remains speculative without improved kinematic data.

Low-angle vs. High-angle Faulting. Resolution of the basic controversy about the subsurface geometry of Basin-Range normal faults in Arizona requires subsurface information not acquired during the neotectonic study. Only steeply-dipping ($\geq 60^{\circ} - 90^{\circ}$) mostly normal-separation faults were observed in outcrop, but these fault surfaces might flatten at some unknown depth. In fact, Hamblin (1965) suggests that the Hurricane fault zone in the western Colorado Plateau margin probably does flatten

with a listric geometry in the near subsurface, based on antithetic back-rotation of the downthrown block and observed decreases in dip (from 90° to 55°) across a 1500m vertical range of exposure. Previous gravity and seismic studies in the southern Basin and Range province of Arizona have modeled Basin-Range structure as high-angle normal block faulting with little, if any, downdip flattening in the upper crust (Eberly and Stanley, 1978; Aiken and Sumner, 1974; Oppenheimer and Sumner, 1981).

However, more recently published COCORP and industry deep seismic reflection profiling in western Utah and northern New Mexico indicate the probable importance in the formation of Basin-Range and Rio Grande rift basins of low-angle detachment and listric normal faults that flatten at depths no greater than 5 - 10 km (Wernicke and Burchfiel, 1982; Cape and others, 1983; Allmendinger and others, 1983; Zoback, 1983; Smith, 1983). However, rather paradoxically, focal mechanism solutions in these areas indicate that probable high-angle normal faulting extends down to depths exceeding the levels of the shallowly-dipping structures observed in the seismic profiles (Arabasz, 1983; Smith, 1983; Sanford and others, 1983). Any fault slip on the low-angle faults is apparently aseismic, in western Utah (Smith, 1983). Also, as noted in an earlier section, the more limited focal mechanism solutions available in the Arizona seismic belt similarly indicate that mostly high-angle faulting ($\gtrsim 45^{\circ}$ dips) continues down to at least 15 km depths. Perhaps the easiest way to accommodate these apparently contradictory data is to invoke extension in the seismogenic upper crust that is developed across a mixed vertical sequence of alternating high- and low-angle fault

systems, similar to the model proposed by Cape and others (1983). If correct, a mostly aseismic failure occurs along one or more lower-angle structures, (perhaps due to a low yield strength on these faults), with seismicity accompanying stick-slip activity on high-angle structures within the intervening blocks. Also, these observations and interpretations do not preclude the possibility, and even probability, that extension in the ductile lower crust occurs primarily by subhorizontal laminar creep/flow (Eaton, 1980, 1982; Smith, 1983; Hamilton, 1983; Sibson, 1983).

SUMMARY AND CONCLUSIONS

If nothing else, the Basin-Range disturbance is a complex deformational and magmatic event that has resisted complete and satisfactory description and understanding for over a hundred years. I believe that some sort of composite tectonic model perhaps best approaches an adequate characterization of the currently available data. Regional structural and stratigraphic patterns suggest at least two, and perhaps three or more, sequential and spatially superposed extensional tectonic events in mid- to late-Cenozoic time within the Basin and Range province, with the most recent corresponding to Basin-Range tectonism, sensu strictu. It is not clear whether these tectonic events are of significantly different tectonic origins or various parts of one long post-Oligocene thermotectonic extensional deformation with several discrete, and often abrupt, transitions. Certainly some of the observed variations in structural style and geometry between Basin-Range and earlier deformations may reflect a progressive cooling of the crust following a profound thermo-

tectonic perturbation, uplift, and lithospheric attenuation in the mid-Tertiary. For example, decreasing thermal gradients would lower strain rates and depress the depth to the brittle-ductile transition, thereby introducing more widely spaced and higher-angle normal faults in the brittle upper crust that flatten at greater depths (Eaton, 1980, 1982). The origin of the mid-Tertiary tectonism itself is unclear, but it likely involved some mantle interaction with the extending lithosphere within an interarc to backarc setting at an early stage in its development.

However, other characteristics of Basin-Range tectonism - the clockwise rotation in extension direction, the relative abruptness of the tectonic transition, and the apparent northward propagation pattern of the disturbance - suggest some element of external control, probably related in some fashion to the evolution of the San Andreas transform margin. In particular, the stress transition rotated the horizontal extension axis from a SW-direction to an EW-WNW orientation more closely aligned with the motion direction along the adjacent plate margin. Also, the northward migration of the Basin-Range disturbance in a crude fashion moved with and somewhat ahead of the migration of the Mendocino triple junction along the plate margin (Dickinson and Snyder, 1979a, b). However, the actual mechanism of any control that may exist remains obscure. The style and type of extension within the Basin and Range province argues against direct distributive shear derived from the San Andreas transform boundary except along the western margin of the Great Basin. Perhaps some more indirect control such as the slab window concept (Dickinson and Snyder, 1979b) that basically determines the area of asthenosphere-lithosphere interaction in the adjacent plate interior

best explains the progressive development of the Basin-Range disturbance.

Regardless of the exact nature of its origin, the Basin-Range disturbance appears to evolve through time in any one area as a distinct tectonic pulse, of perhaps 5 to 7 m.y. duration, that is characterized by a rapid rise time and a more gradual decay interval (Figure 11). One or more additional secondary pulses of slightly increased tectonic activity may be locally superimposed upon the general decline of the disturbance. During its waning stages in Arizona, extensional deformation also tends to concentrate spatially into more elongate, often discontinuous, corridors or belts of faulting and/or regional arch-like uplift. These belts absorb the majority of horizontal and/or vertical strain between regional-scale crustal blocks that either are undeformed or have tectonically consolidated following earlier extensional deformation. The progressive concentration of strain into elongate belts of enhanced extensional faulting and associated regional arching may possibly start earlier, within the primary phases of deformation in the tectonic disturbance. Thus this process may represent a more fundamental characteristic, perhaps related to development of intermediate-wavelength perturbations in the lower crust-upper mantle, within the evolution of broadly distributed regional extension. Although intriguing, this speculative hypothesis requires further study.

The pulse-like character of the Basin-Range disturbance outlined above resembles the time-derivative decay profile of a thermal perturbation. This is consistent with the abundant geophysical and geological data indicating substantial heating and attenuation of the lithosphere in the region affected by the disturbance. The heat source clearly arises

from a shallow-depth asthenosphere at the base of an extensionally-thinned crust-lithosphere and/or magmatic invasion into the lower crust (Eaton, 1980, 1982; Thompson, 1959; 1983).

The exact mechanism of regional crustal extension remains obscure. Some high-angle faulting at mid-crustal levels is indicated by contemporary seismicity, and some fracture penetration through the crust is required by the rapid ascent of uncontaminated basaltic magma of upper mantle origin. Recent seismic reflection profile data indicate a crust with pronounced subhorizontal stratification. Some of those reflectors likely represent low-angle structures related to Mesozoic compressional and mid-late Tertiary extensional tectonics. Thus, it appears that low-angle to subhorizontal deformation plays a significant role in the extension process at all levels of the crust, and especially so in the ductile deformation region of the lower crust. In fact, it seems possible that decoupling and/or delamination processes along subhorizontal discontinuities in the crust and lithosphere may strongly influence, and even dominate, certain aspects of Basin-Range and earlier episodes of regional extension.

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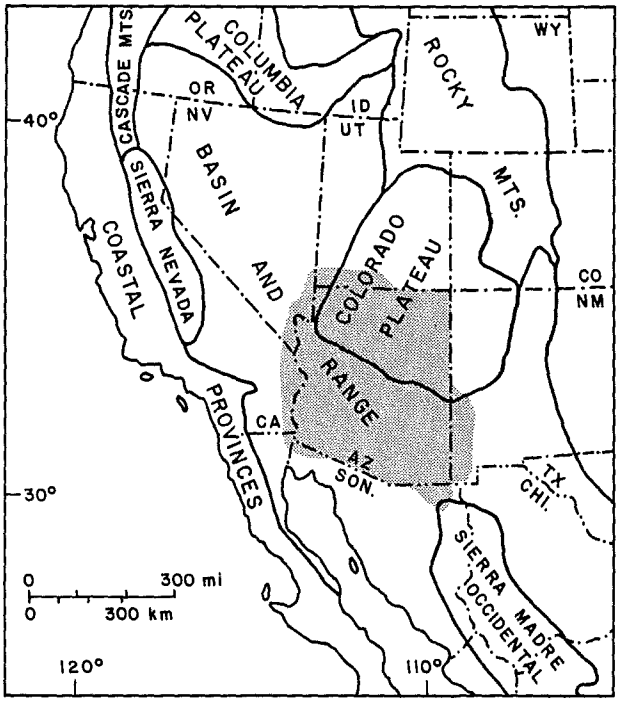
gure 1.



Location map of Arizona neotectonic study area, in relation to Basin and Range and Colorado Plateau physiographic provinces.

Figure 2.

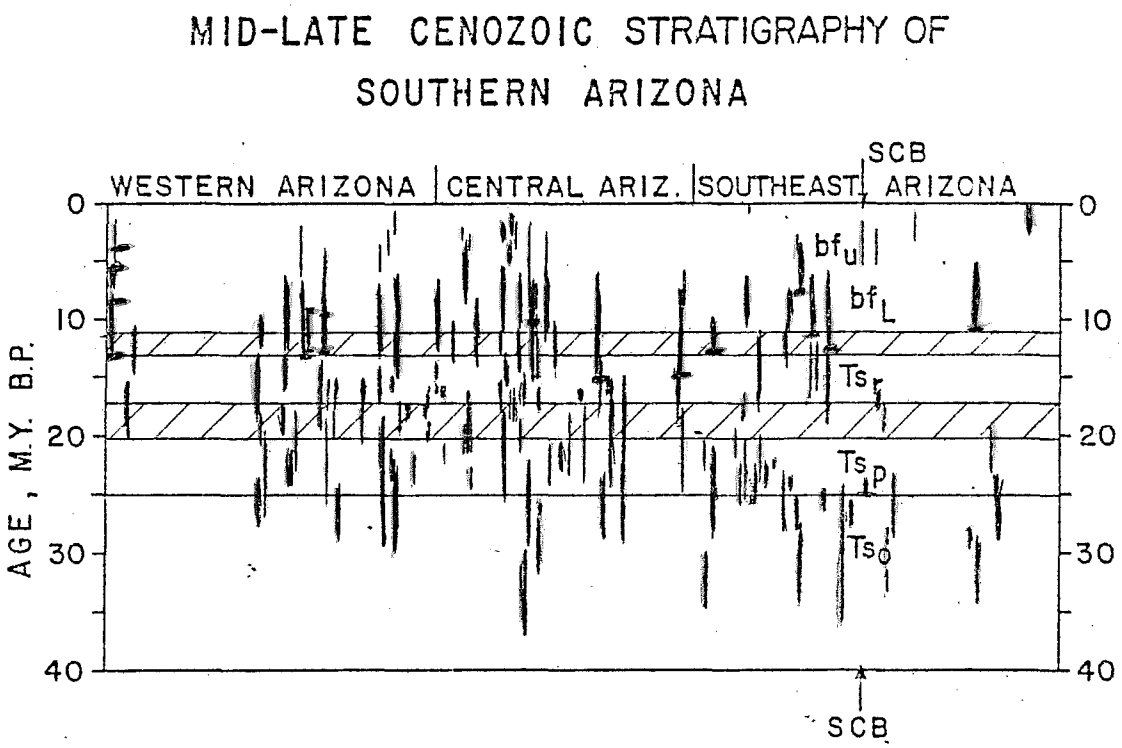


Diagram of the Proposed Correlation Scheme between the Local Sonoita Creek Basin Stratigraphy and the Regional Geochronology of the Arizona Basin and Range Province. -- Projected into a northwest-southeast-trending axis. Adapted from Fig. 30, Scarborough and Wilt, 1979. Individual vertical lines and horizontal dashes indicate the estimated time ranges of various sedimentary and volcanic rock units. The prominent horizontal lines and slashed bands that extend across the diagram indicate important regional transitions in stratigraphy and tectonics which have been correlated with various units in Sonoita Creek basin. These transitions occur in latest Oligocene (~25-24 m.y.B.P.; lower line); early- to mid-Miocene (20-17 m.y.B.P.; middle slashed band); and mid- to late-Miocene (13-11 m.y.B.P.; upper slashed band). The units are coded as follows: Oligocene sediments (olive-green); late-Oligocene to early-Miocene sediments (purple); mid-Miocene transitional sediments (light-green); Oligocene to late-Miocene calc-alkaline volcanic rocks (yellow); mid- to late-Miocene basalt sequences (yellow-green); late-Miocene to Quaternary alkalic basalts (red); lower basin-range fill deposits (orange); upper basin-range fill deposits (blue). The nomenclature for the Sonoita Creek basin local stratigraphy

PHYSIOGRAPHIC SUBDIVISIONS OF ARIZONA
(Based on Regional Subenvelope Maps)

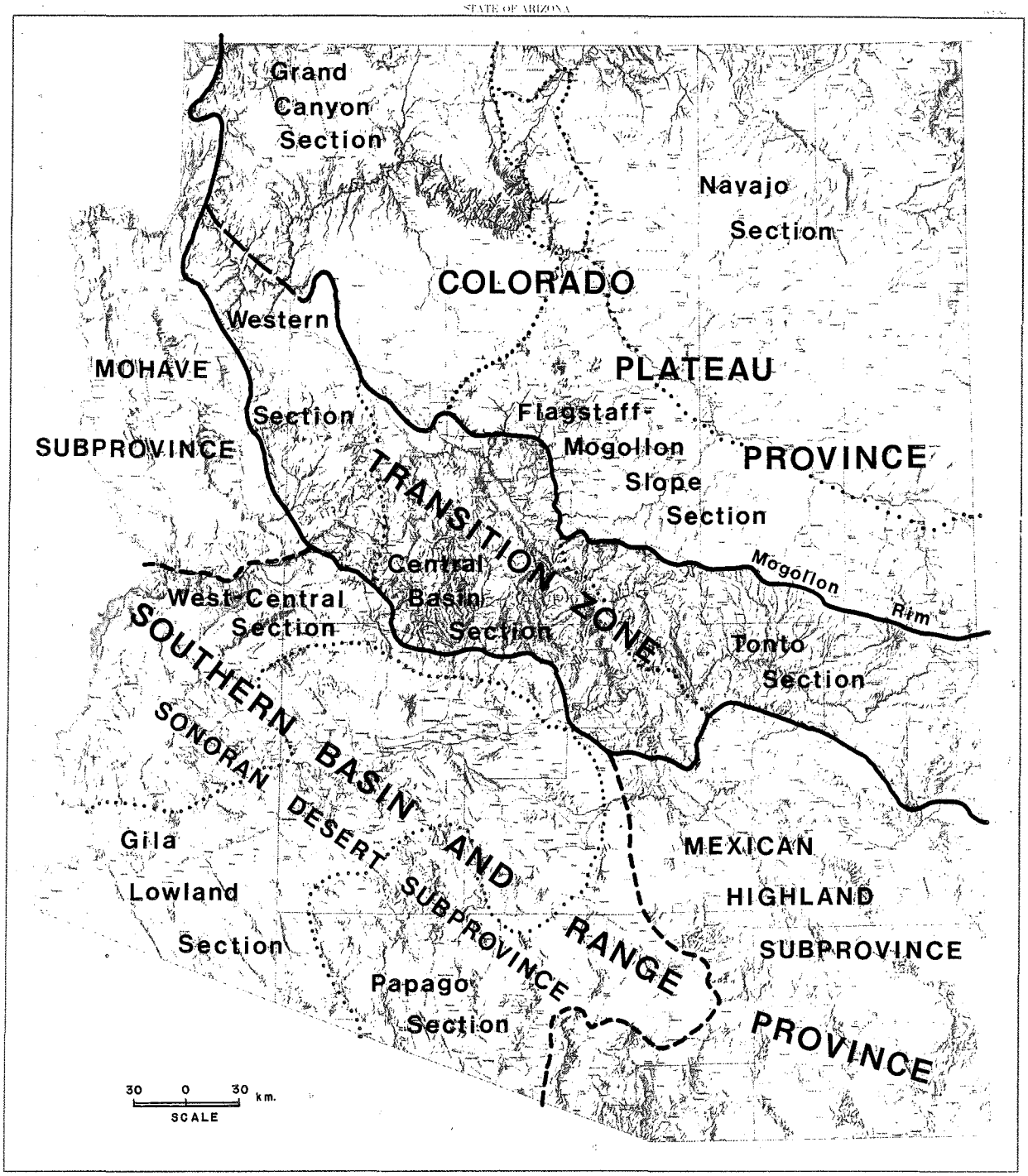
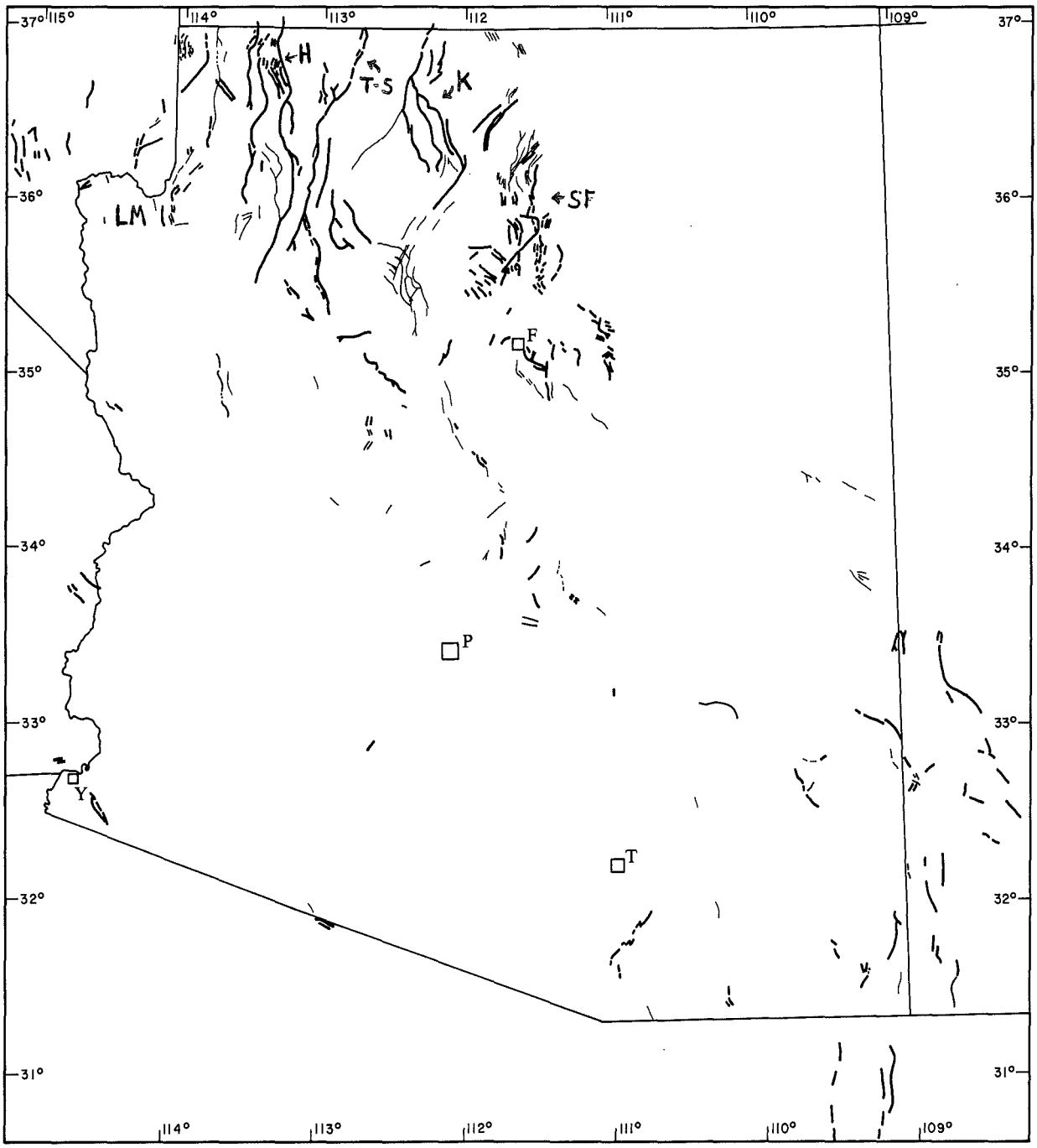


Figure 4.



Map of Known or Probable Neotectonic Faults in Arizona. The letter symbols refer to: F: Flagstaff; H: Hurricane fault zone; K: Kaibab Plateau; LM: Lake Mead; SF: San Francisco volcanic field faults; T-S: Toroweap-Sevier fault zone; P: Phoenix; Y: Yuma.

ure 5

relation Between Seismicity and Quaternary Faulting

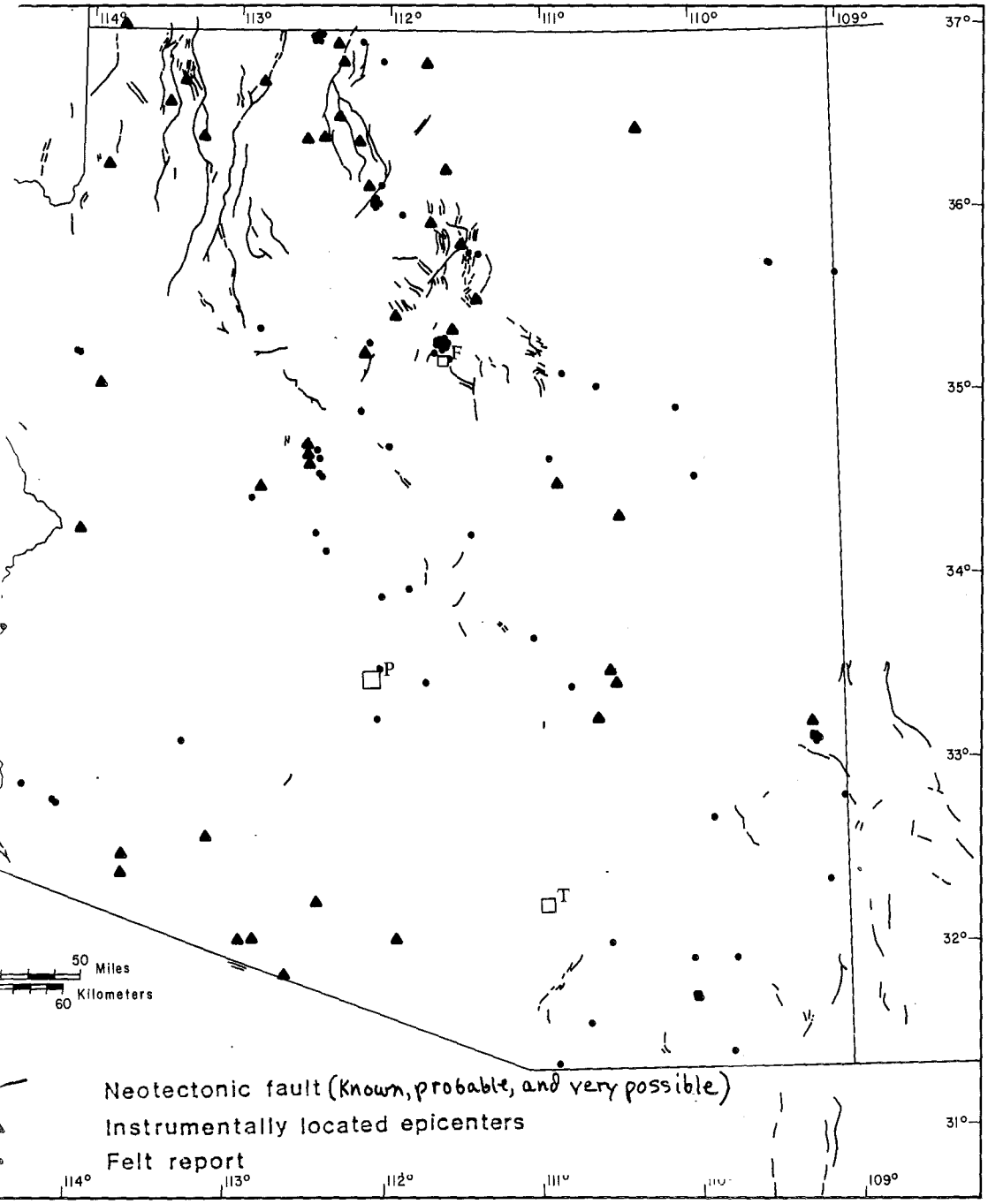


Figure 6a.

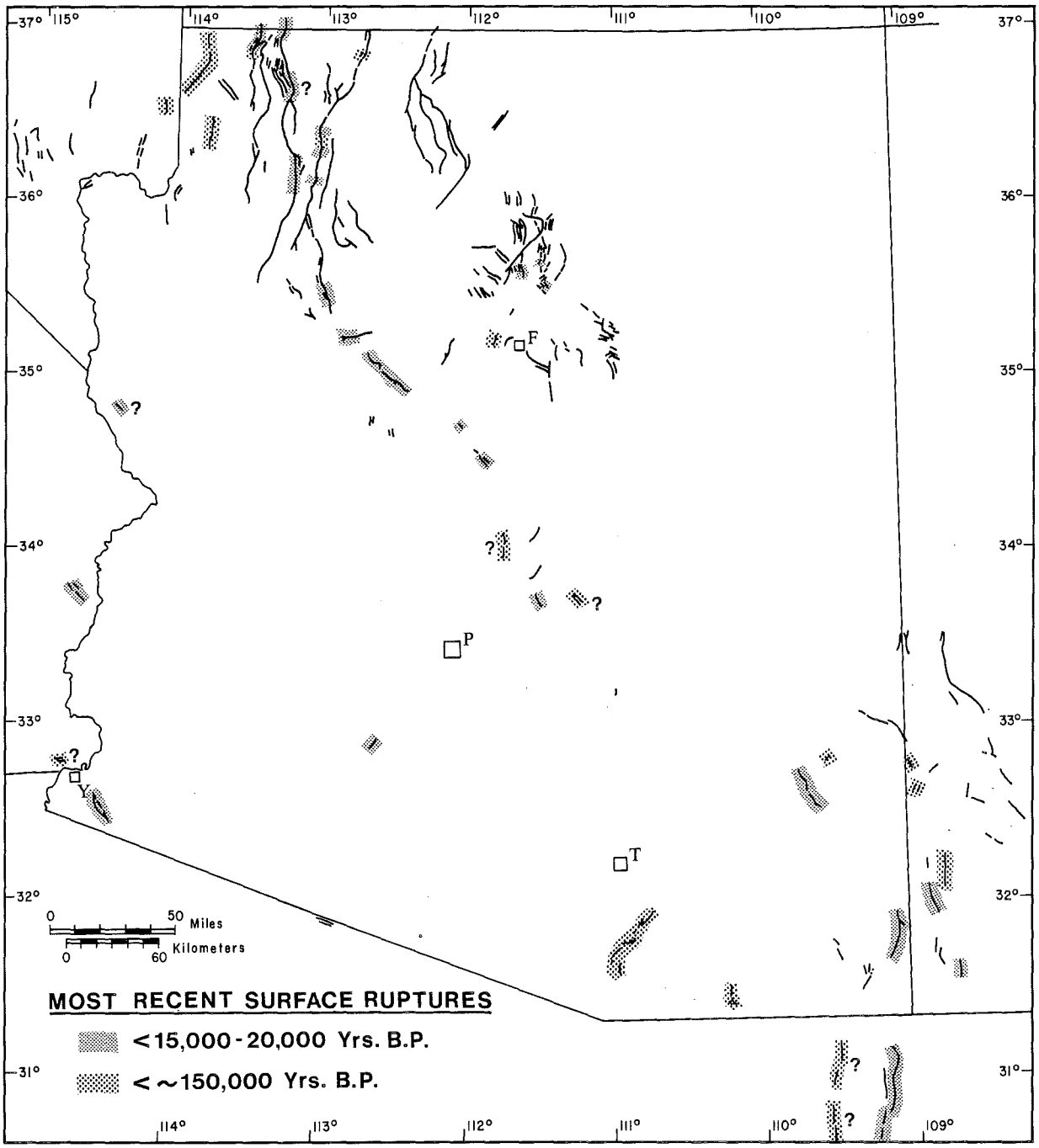

37°
115°
114°
113°
112°
111°
110°
109°
36°
35°
34°
33°
32°
31°
F
P
Y
T
0
50 Miles
0
60 Kilometers
MOST RECENT SURFACE RUPTURES
<15,000-20,000 Yrs. B.P.
< ~150,000 Yrs. B.P.

Figure 6b.

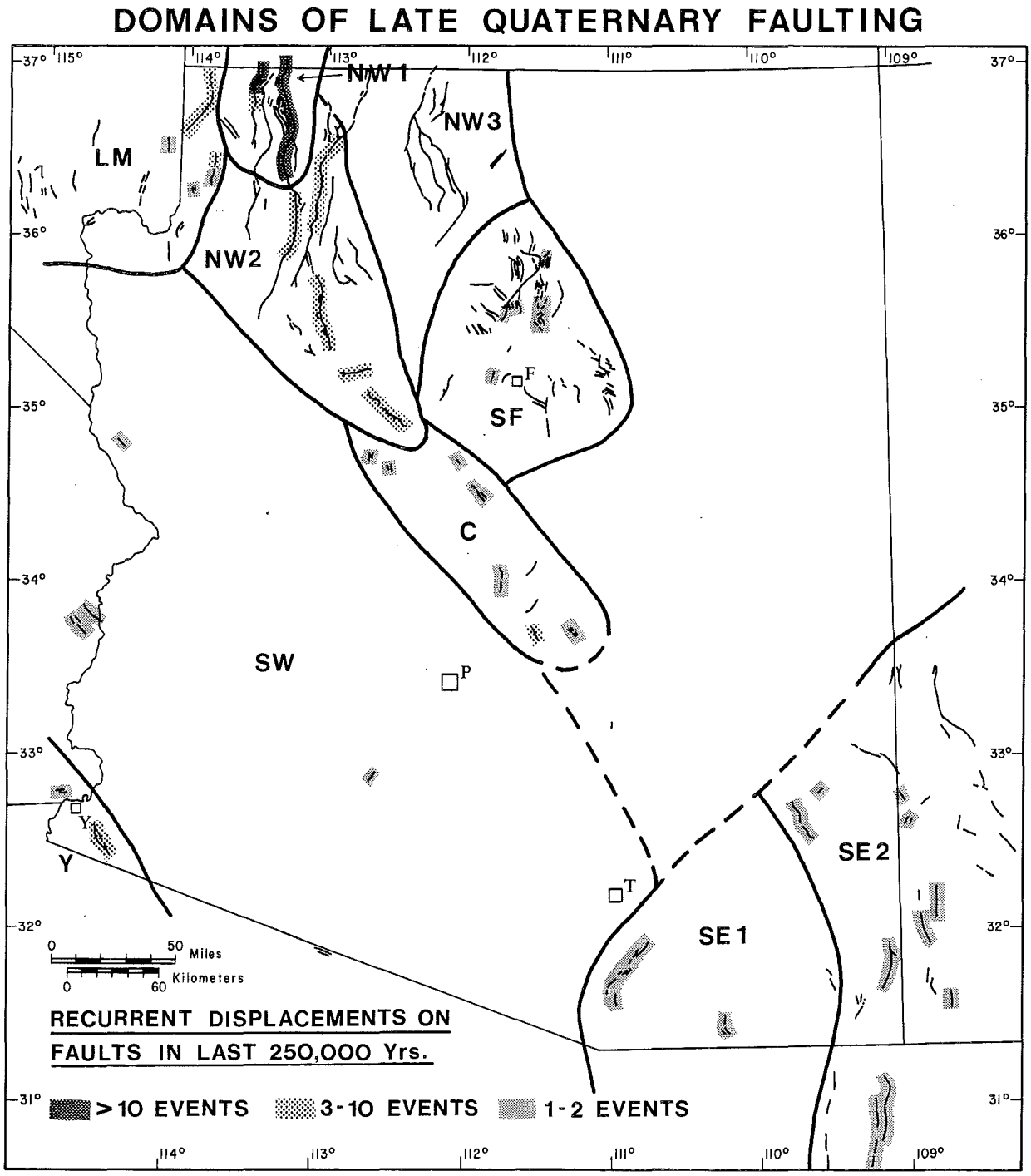
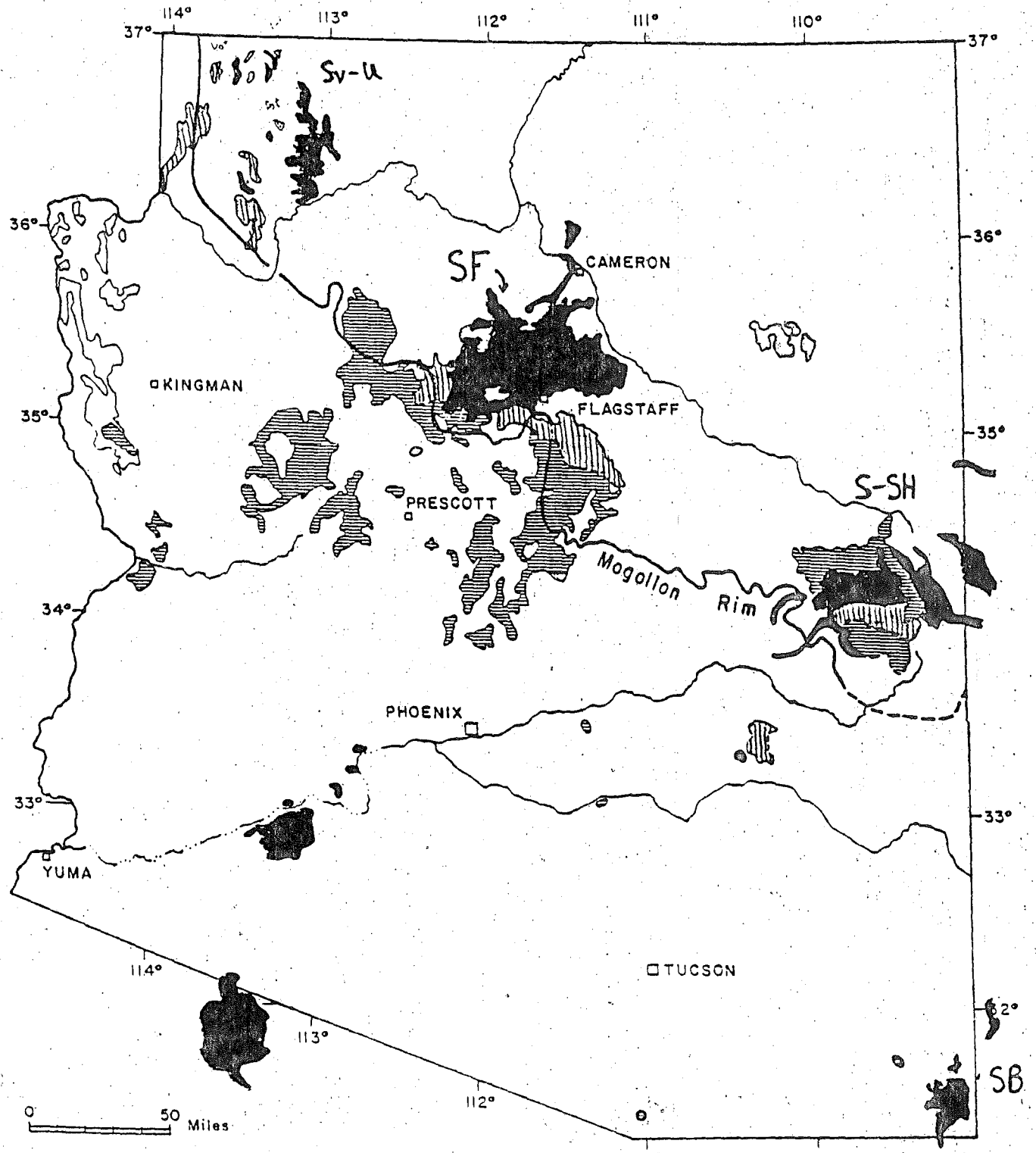

DOMAINS OF LATE QUATERNARY FAULTING
NW1
NW2
NW3
LM
SF
C
SW
Y
SE1
SE2
F
P
T
Y
0 50 Miles
0 60 Kilometers
RECURRENT DISPLACEMENTS ON FAULTS IN LAST 250,000 Yrs.
>10 EVENTS
3-10 EVENTS
1-2 EVENTS
37°
36°
35°
34°
33°
32°
31°
115°
114°
113°
112°
111°
110°
109°

Figure 7. LATE CENOZOIC VOLCANISM IN ARIZONA
(Post 15 my B.P.)



Basalt-dominated volcanism (low Sr ratios, low SiO_2)

0–4 my 4–7 my 7–15 my

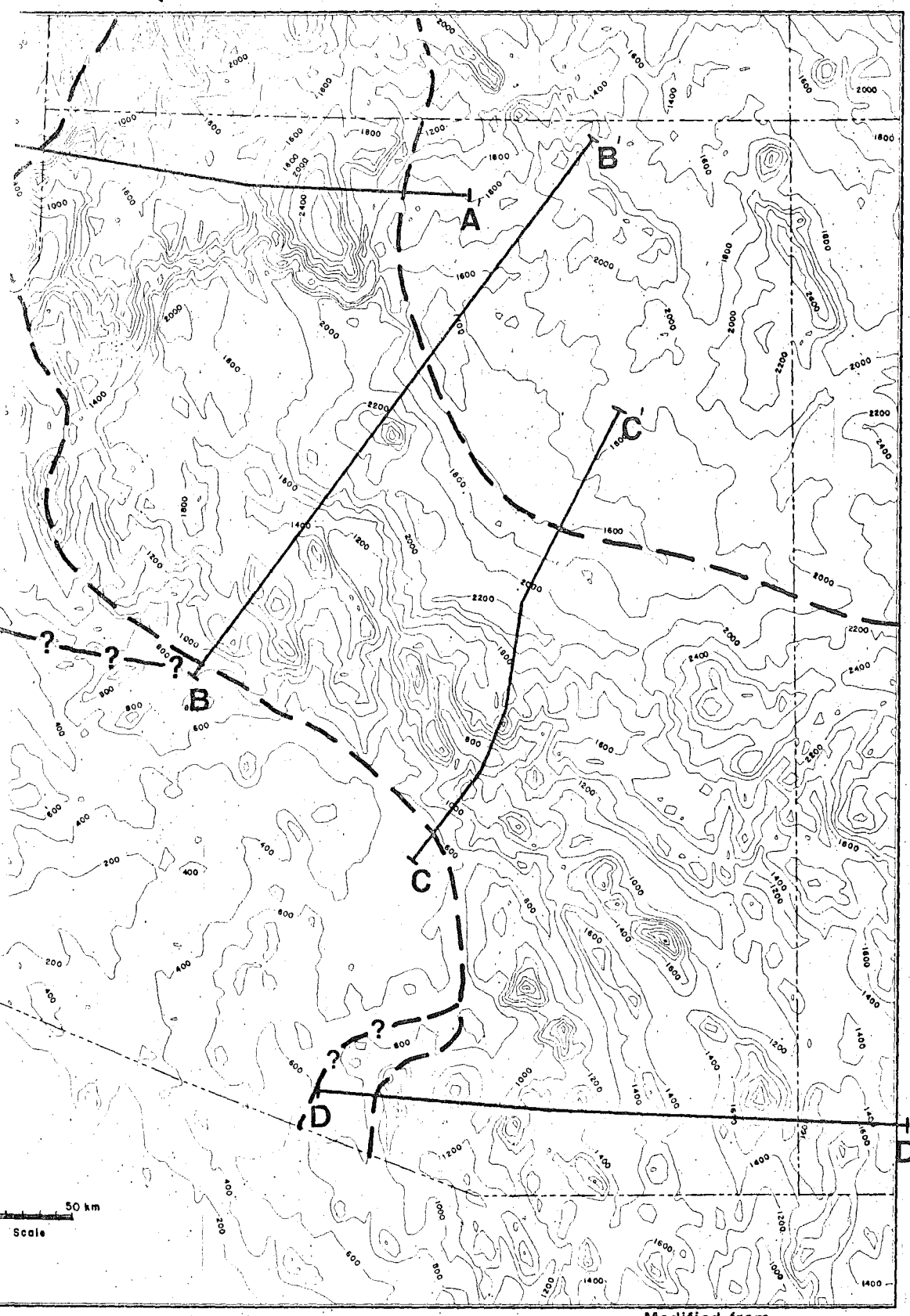
Subduction volcanism (high Sr ratios, higher SiO_2)

15–11 m.y.

Specific Volcanic Fields

Sv-U: Shivwitz - Uinkaret
SF: San Francisco
S-SH: Springerville - Show Low
SB: San Berardino

NERALIZED REGIONAL TOPOGRAPHY OF ARIZONA
(COMPUTER GENERATED)



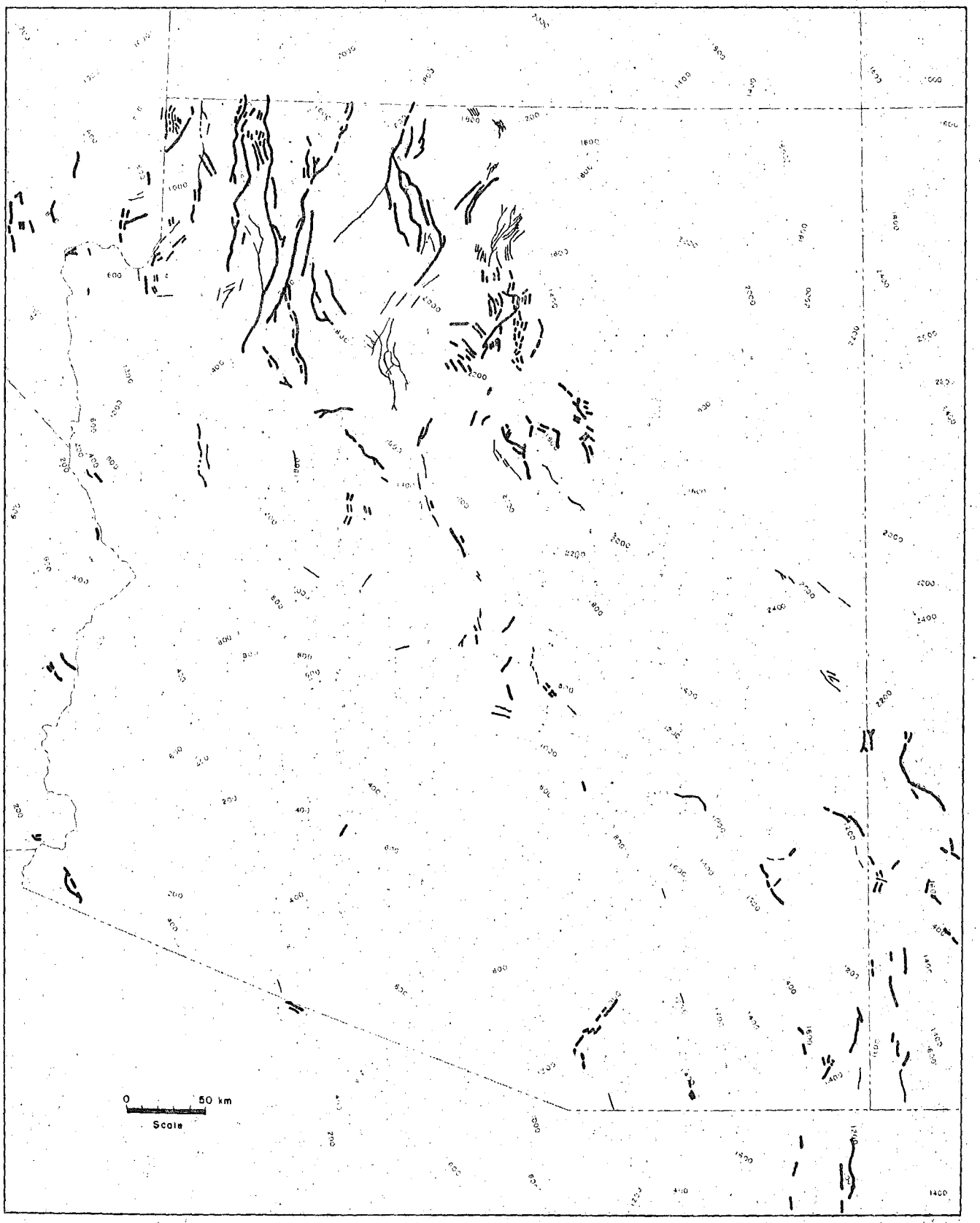
ne is boundary of zone of anomalous topography. (see text)

Modified from R. Godson, unpublished map (1980)

A — Cross-section locations (drawn from 1° x 2° subenvelope maps)

Figure 8b.

(refer to Fig. 8a for better contour definition)



Correlation Between Neotectonic Faulting and Generalized Topography

REGIONAL CROSS SECTIONS of GENERALIZED TOPOGRAPHY

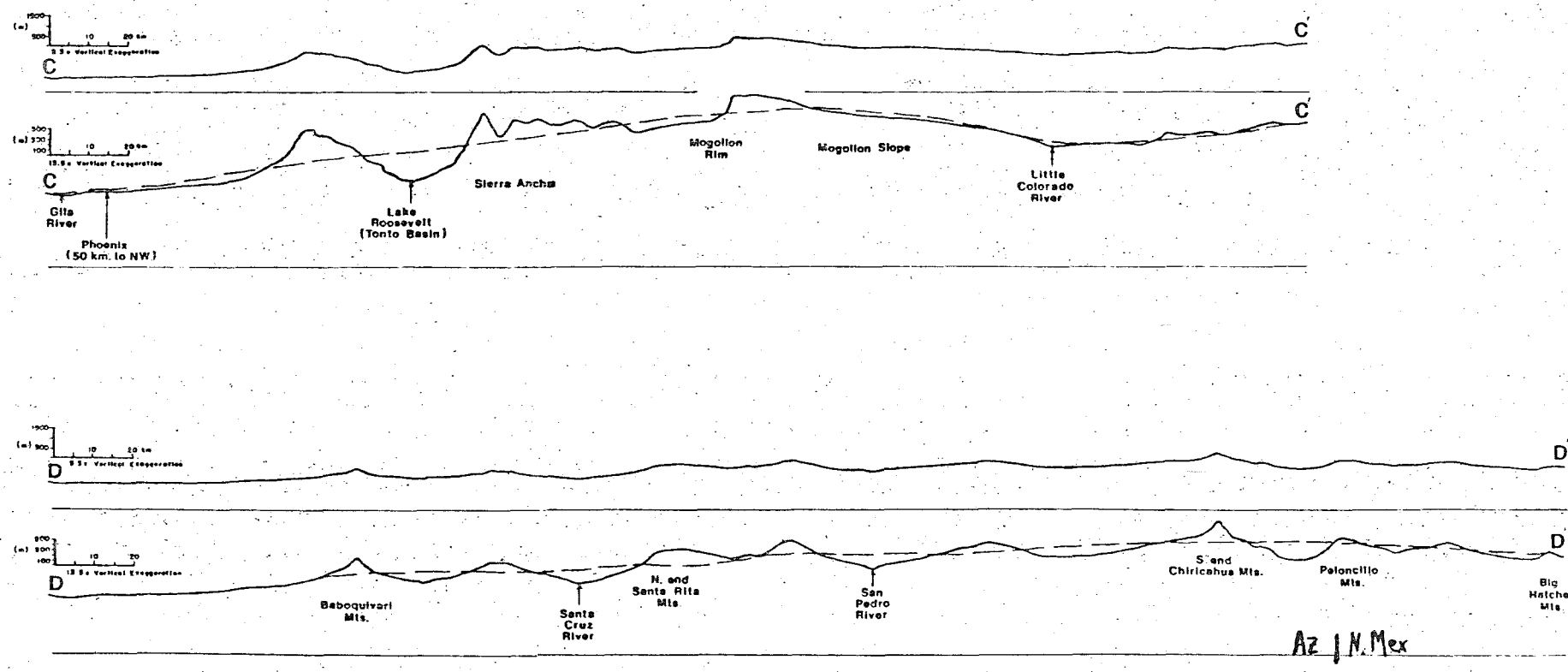


Figure 8c.

REGIONAL CROSS SECTIONS of GENERALIZED TOPOGRAPHY

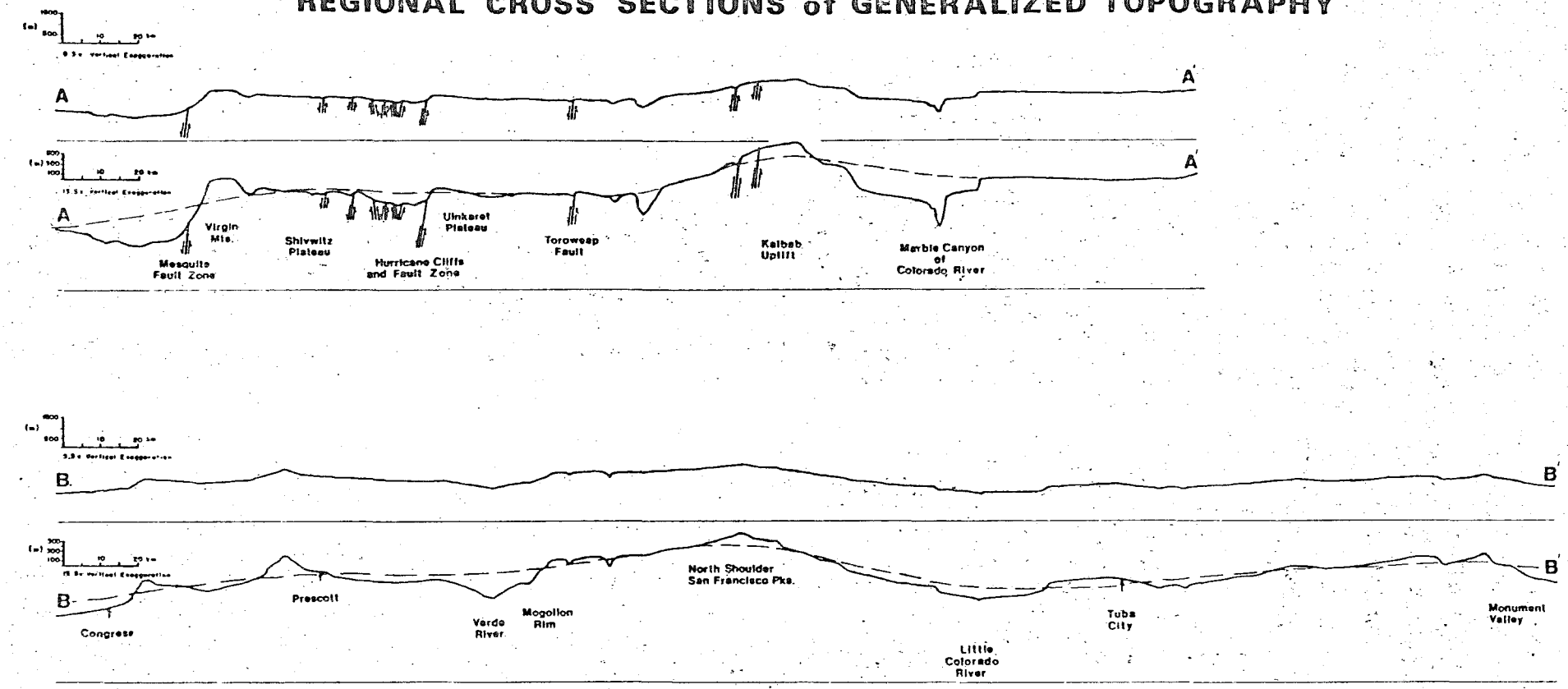
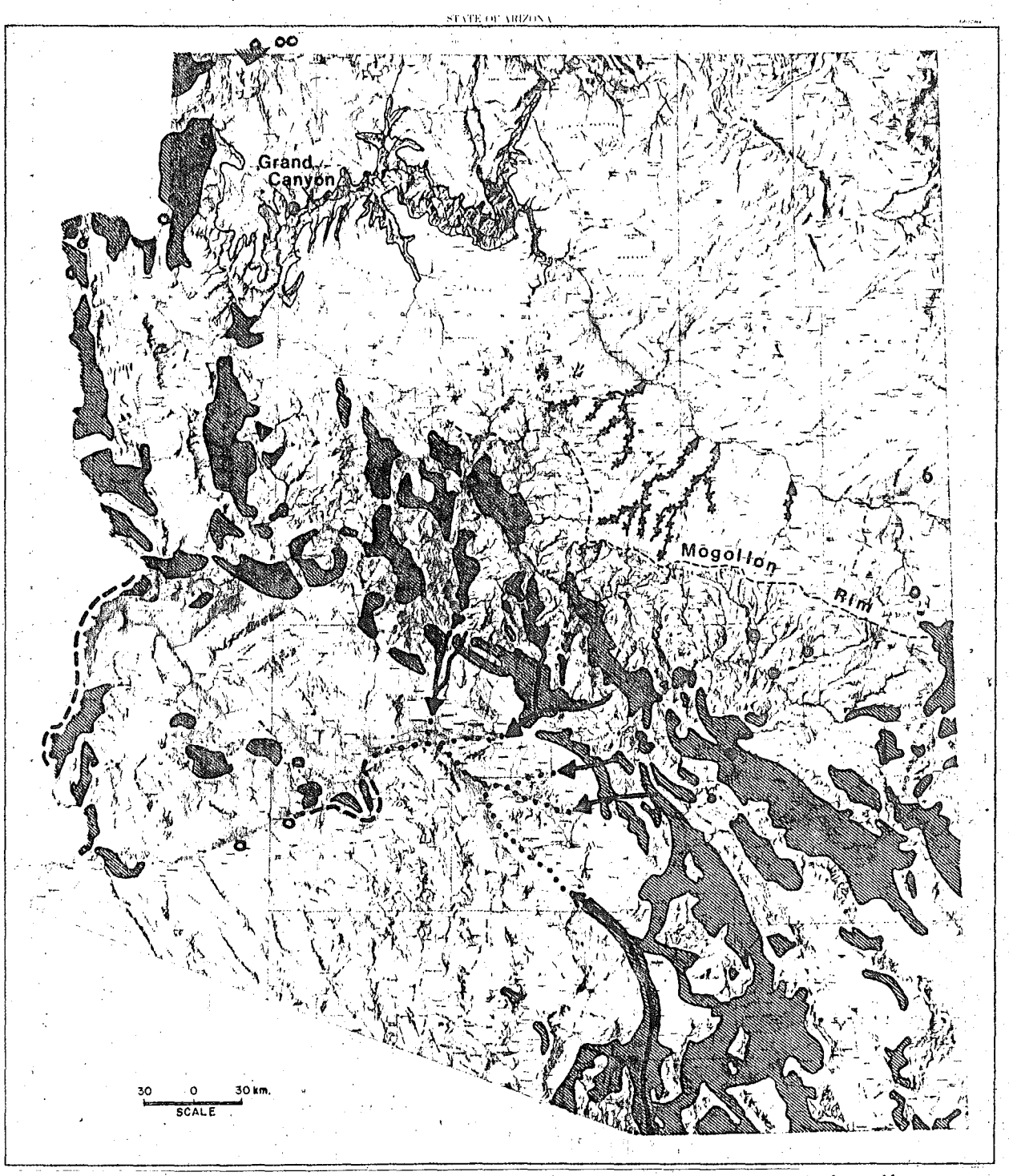


Figure 8c.

Figure 8d.

LATE CENOZOIC DISSECTION INDICATORS IN ARIZONA



Dissected intermontane basin

Regional terraces convergent in downstream direction

Regional terraces subparallel with modern channel

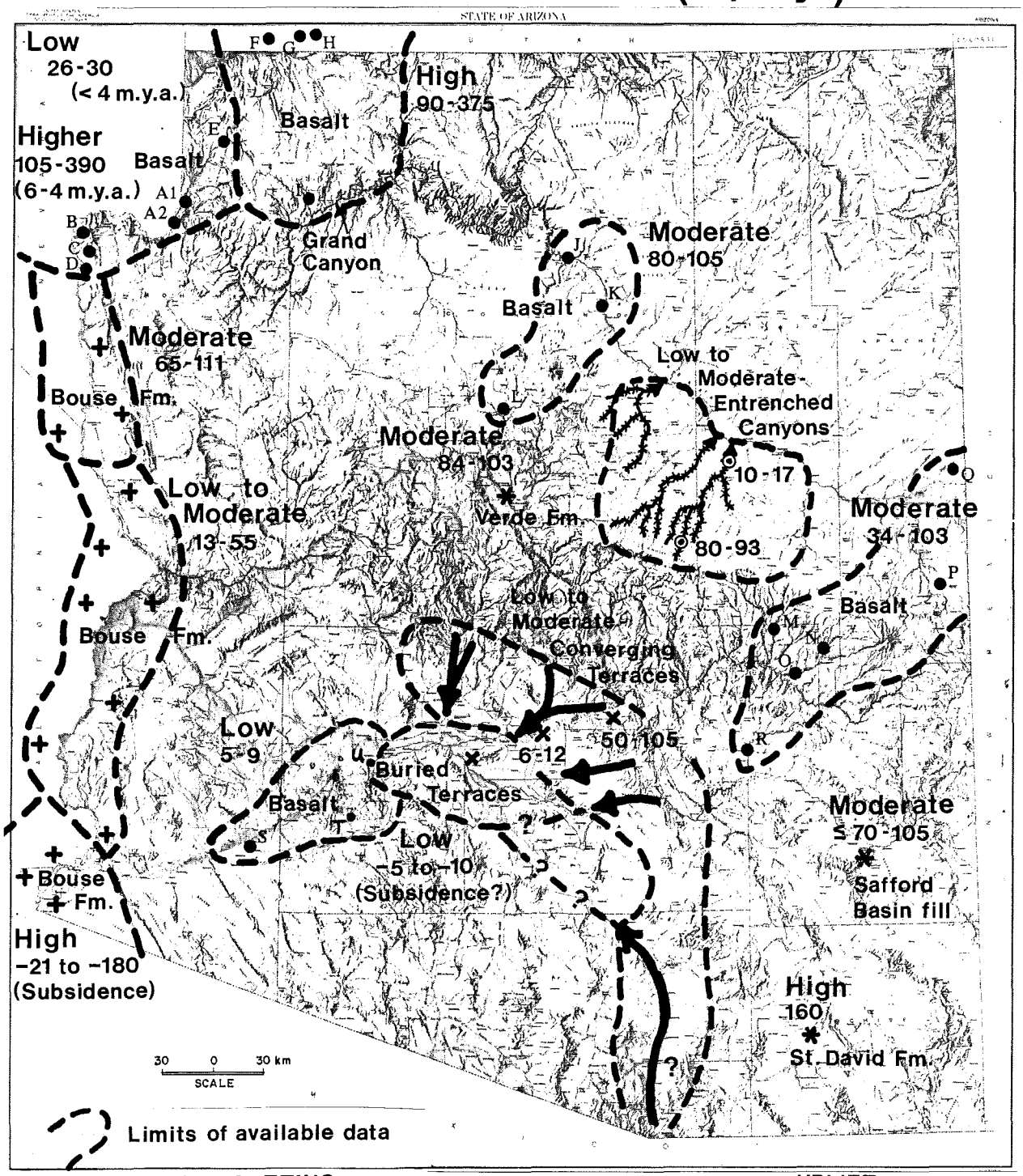
Absent and/or buried sections of regional terraces

Entrenched canyons (decreasing depth downstream)

topographically inverted basalts

Figure 8e.

MINIMUM ESTIMATES PLIOCENE—QUATERNARY RATES OF DOWNCUTTING AND UPLIFT (m/m.y.)



DOWNCUTTING UPLIFT

- ●S Dated basalt flow
- ✱ Dated uppermost basin fill
- ✖ Regional terrace heights (converging downstream)
- ⊙ Canyons entrenched into regional erosion surface (depth decreasing downstream)
- + Bouse Fm. outcrops (Lucchitta, 1979)

Figure 8f.

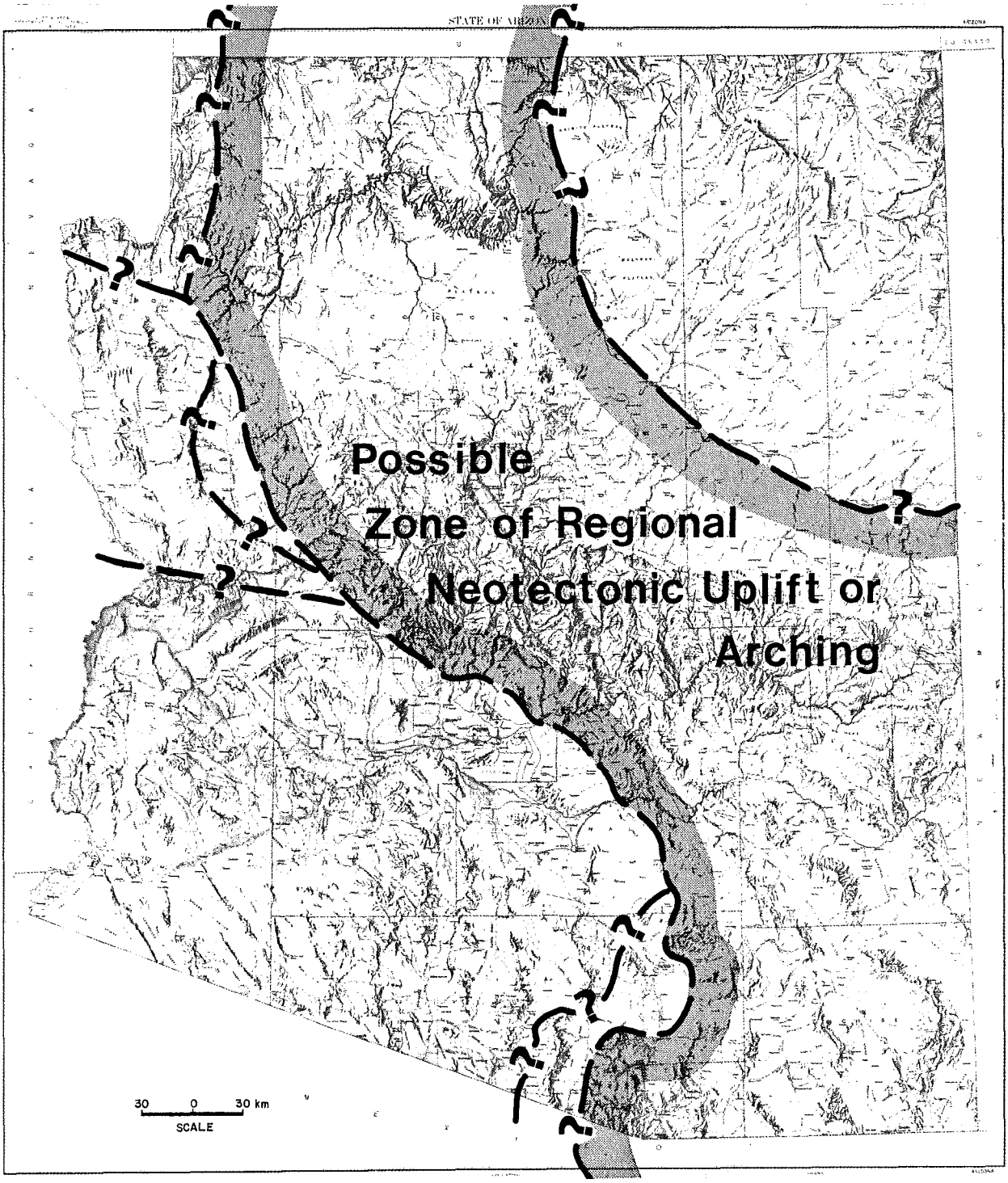
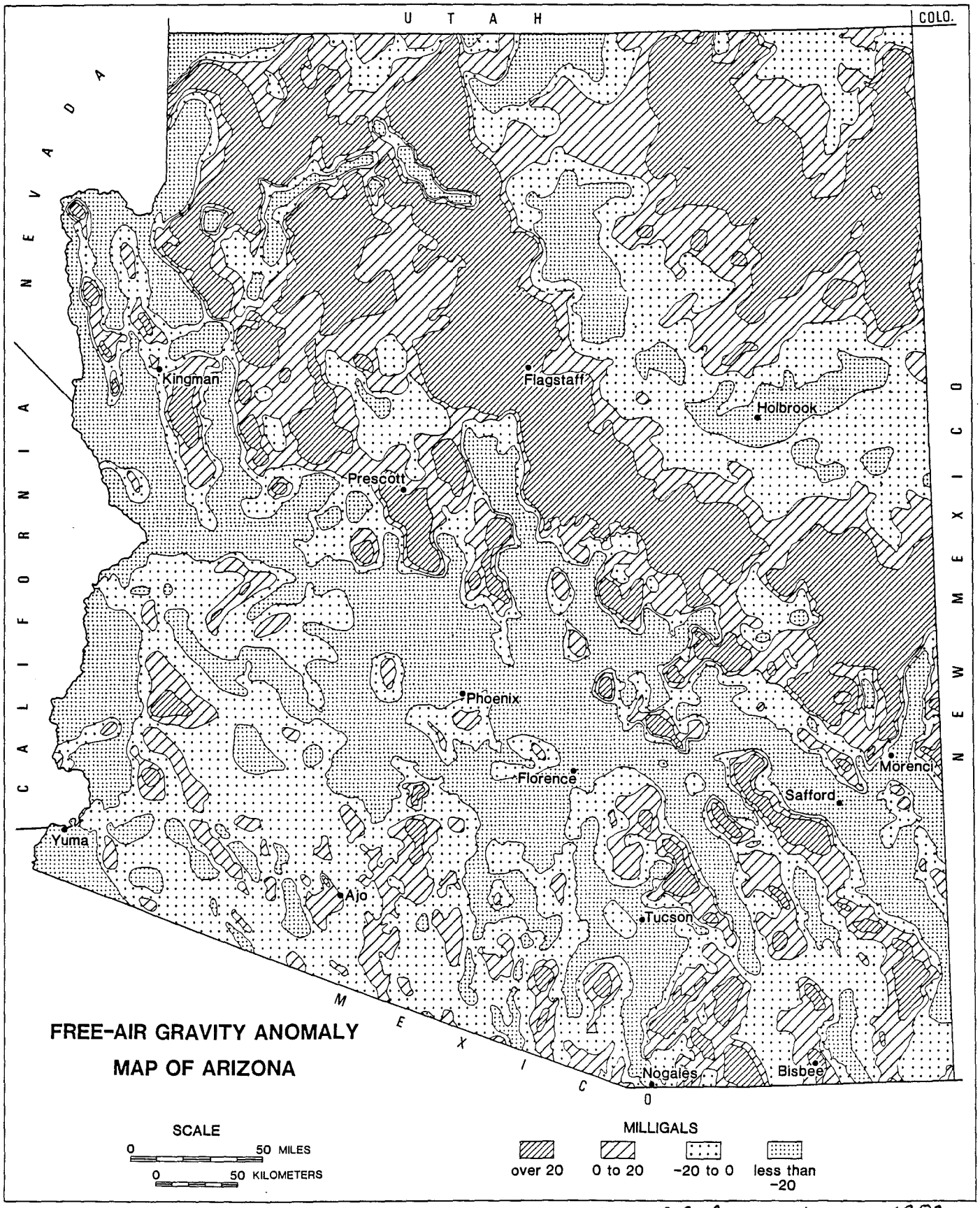

STATE OF ARIZONA
Possible
Zone of Regional
Neotectonic Uplift or
Arching
30 0 30 km
SCALE

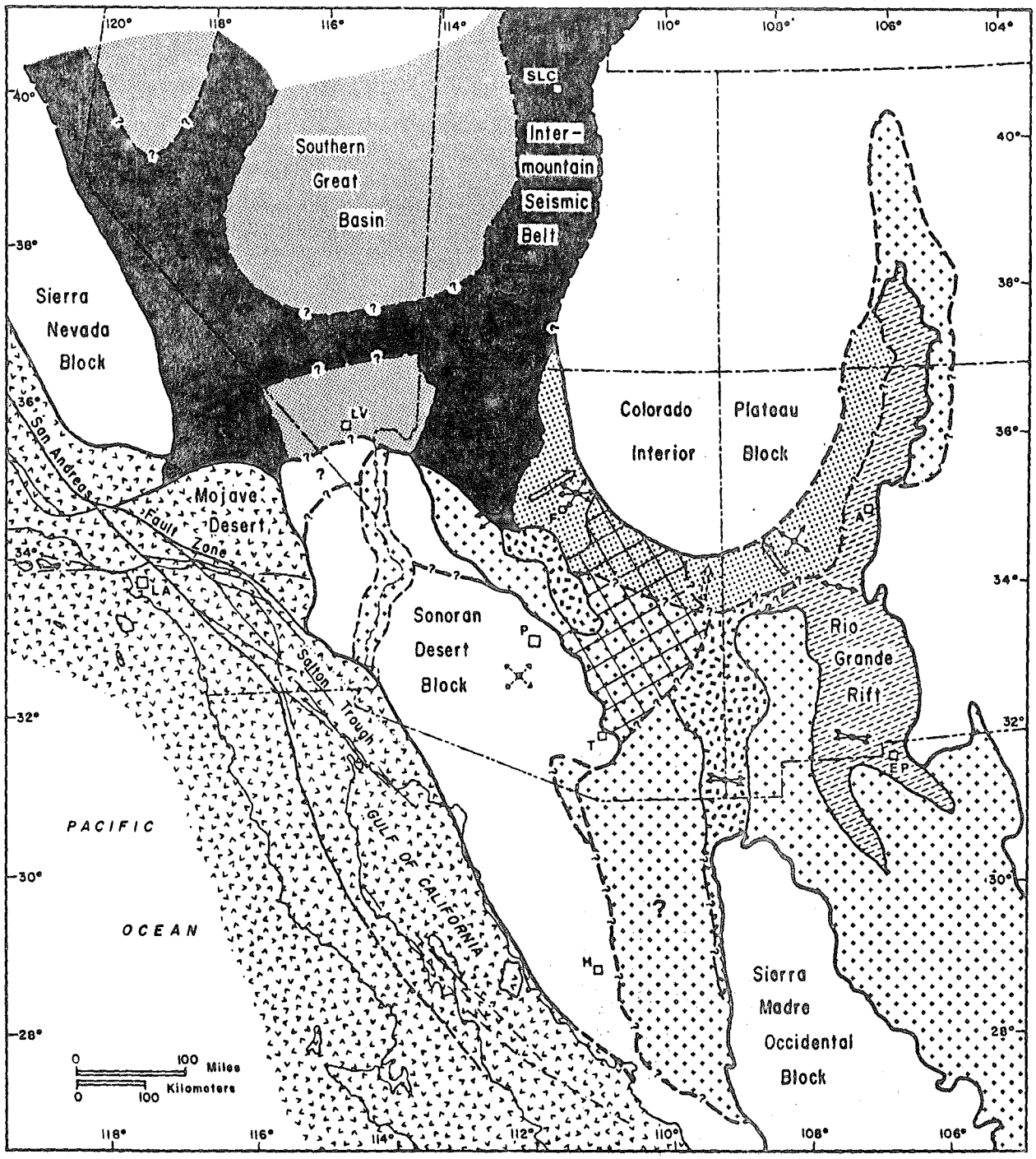
Figure 9.



From J.S. Sumner, in prep, 1982

Figure 10.

REGIONAL NEOTECTONIC FRAMEWORK OF ARIZONA



Widespread Regional Deformation
(Faulting, Volcanism and/or Uplift)

ACTIVITY

- High to Moderate (plus pronounced seismicity)
- Moderate to High (no volcanism, decreased seismicity)
- Moderate to Low (mostly volcanism, with limited to locally concentrated faulting)

More Restricted Deformational Corridors
(Faulting, Volcanism and/or Uplift)

ACTIVITY

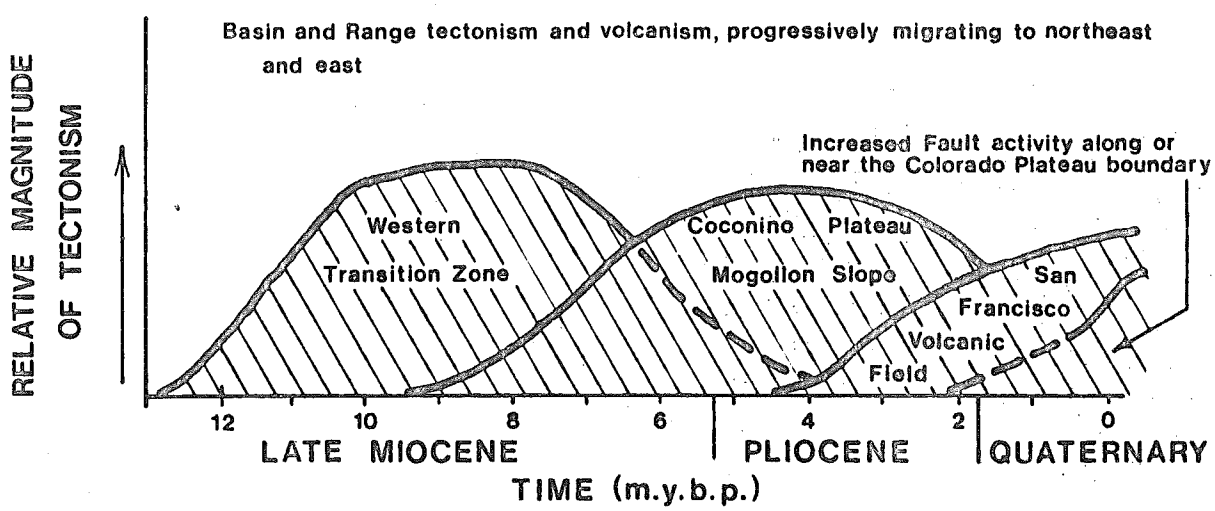
- High to Moderate (with rift-like characteristics)
- Moderate to Locally Concentrated (mostly faulting at low rates; only minor volcanism)
- Limited and Dispersed (mostly faulting and/or uplift)

- Relatively stable blocks
- Deformation related to San Andreas transform
- Primary boundary of neotectonic deformation
- Boundary between neotectonic provinces
- Migration direction, progressively younger volcanism and/or deformation
- Orientations of regional σ_{min}

Figure 11.

POSSIBLE MODELS OF LATE CENOZOIC TECTONISM

a)



b)

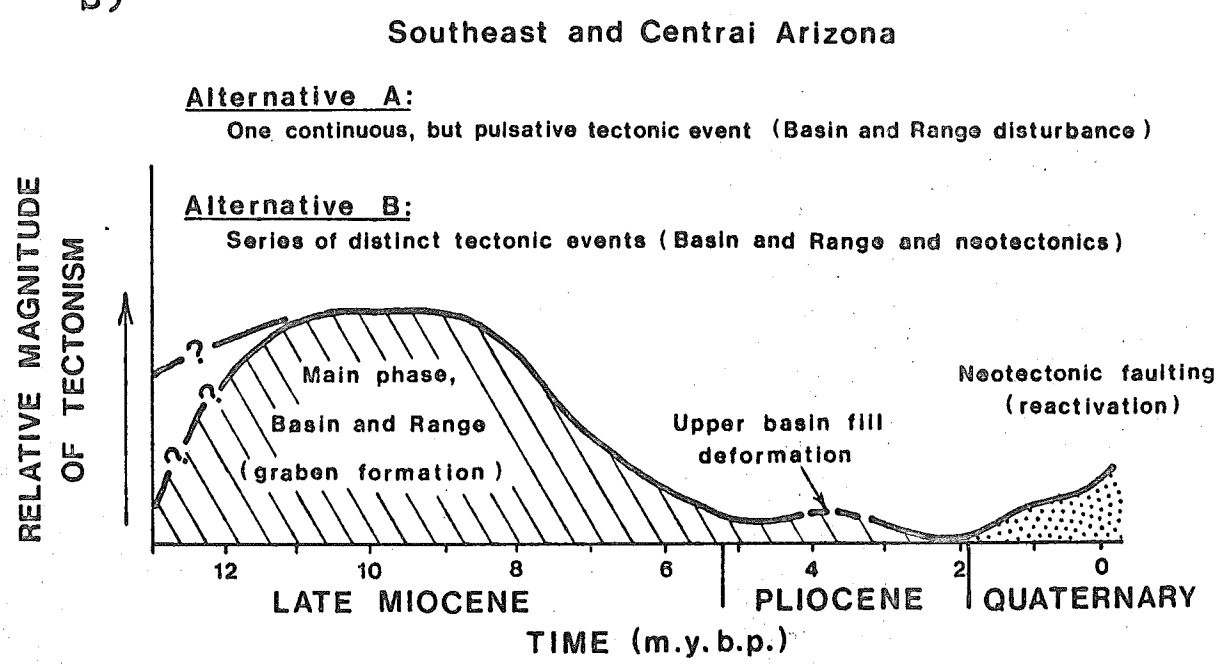
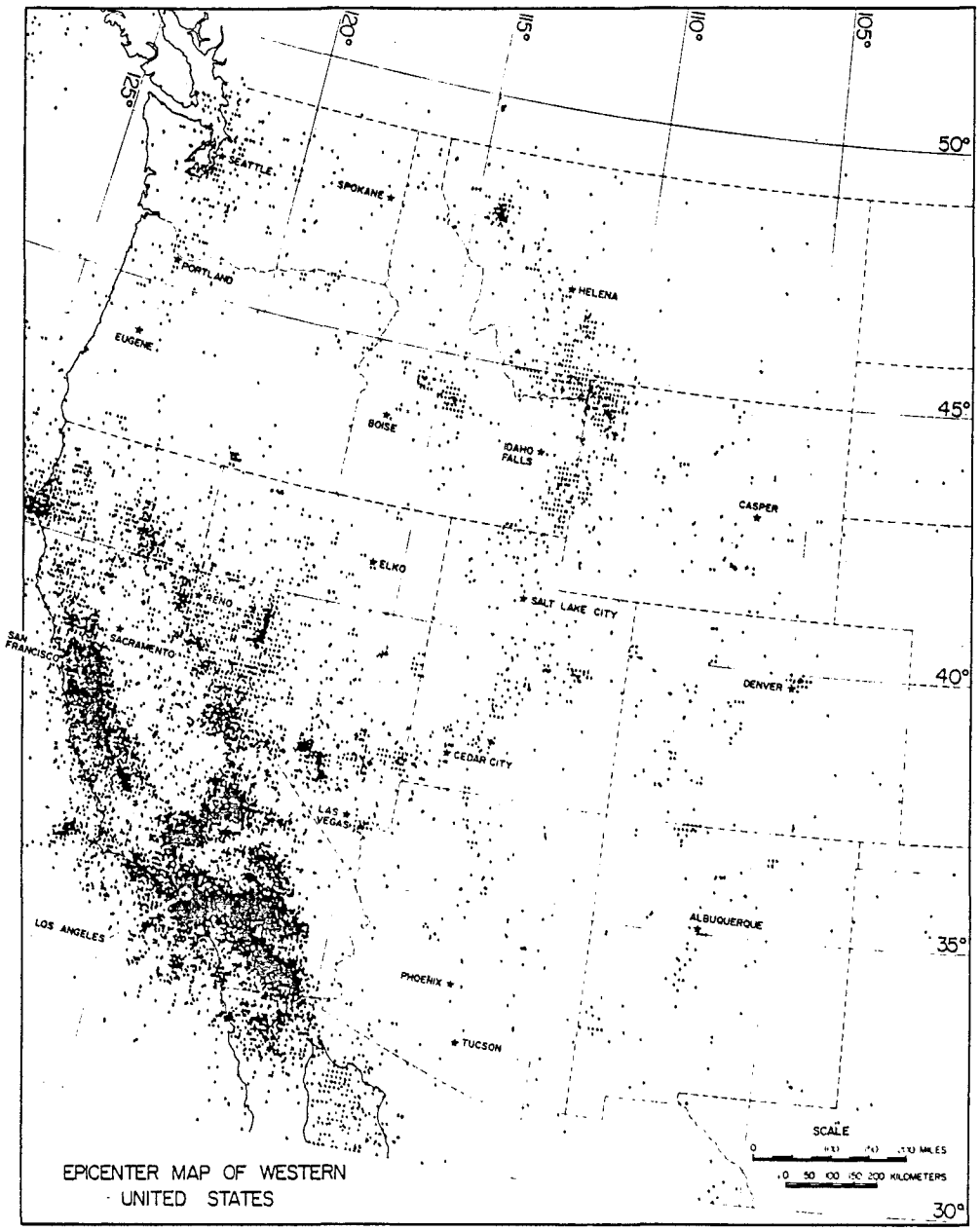


Figure 12.



Epicenter map of the western interior of the United States (reduced scale of Plate 6-1). Data taken from NOAA, National Earthquake Information Service catalog. Instrumentally located earthquakes principally from 1950 through 1976, but some older earthquakes data are incorporated. Epicenters plotted from NOAA Hypocenter Data file by Paul Grim and are courtesy of Wilbur A. Rinehart, both of the National Geophysical Solar-Terrestrial Data Center of NOAA, Boulder, Colorado. It is important to note that this map contains data from both the California Institute of Technology and the University of California, Berkeley, epicenter catalogs. Magnitudes have not been differentiated. For California, the minimum-magnitude earthquakes plotted were of $M \sim 1$, and for the rest of the Western United States, they were of $M \sim 3$.

From Smith, 1978

Figure 13.

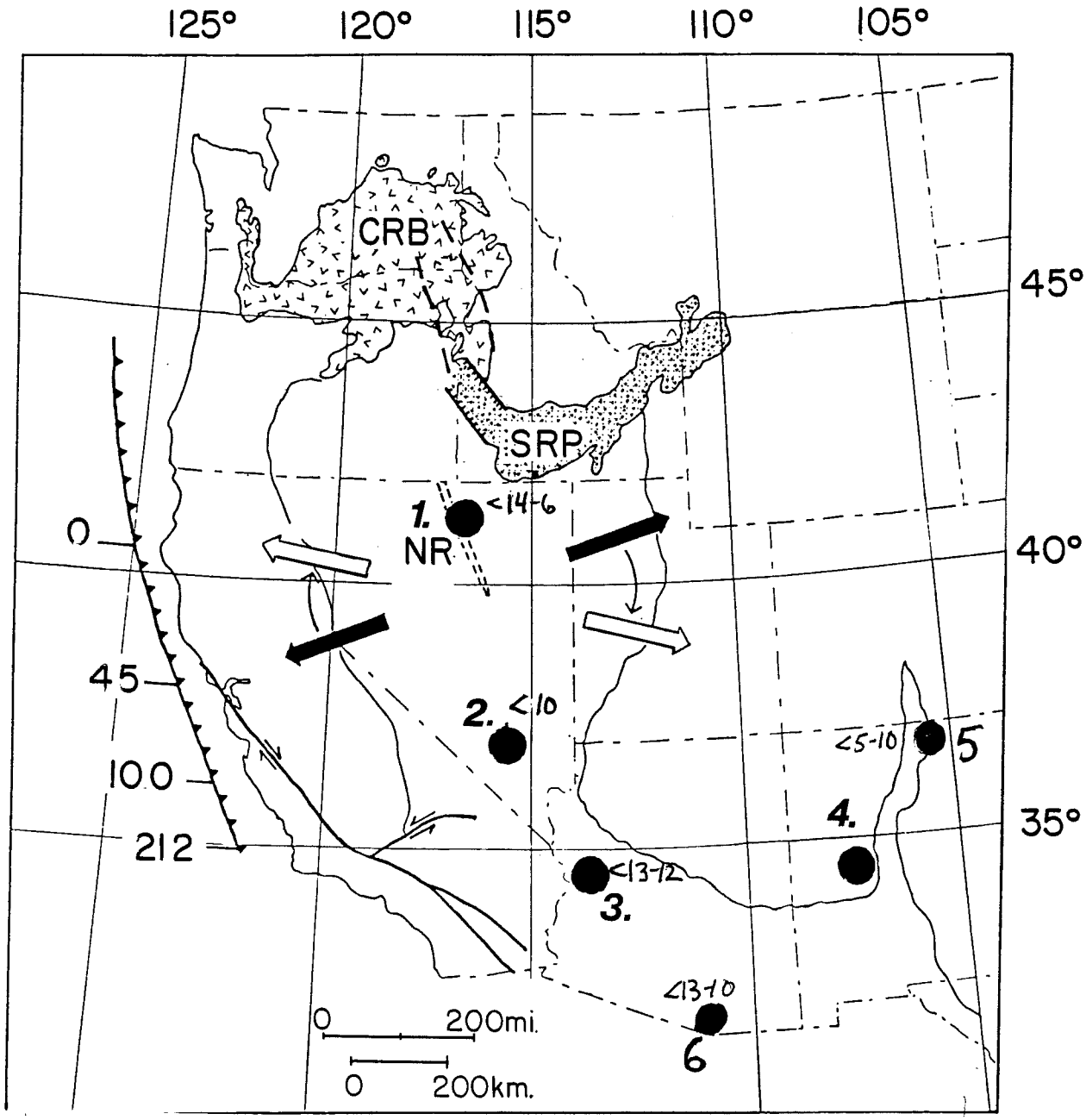
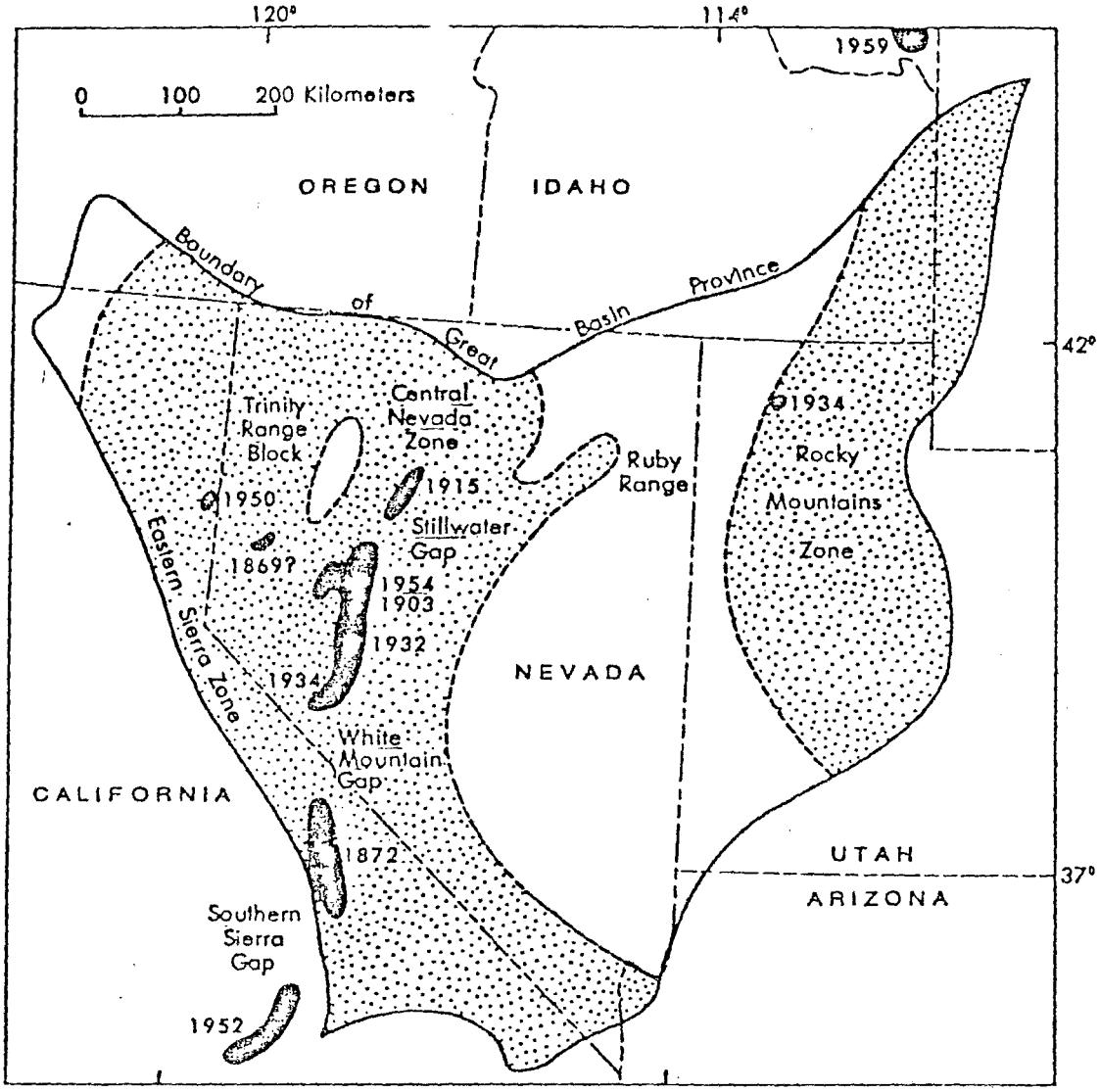


Figure 13: Map Showing Locations and Timings of Documentated Paleostress Rotations that Mark the Inception of Basin-Range Tectonism. Large dots indicate specific sites (keyed to following list) and smaller numbers give the maximum age of the rotation (m.y.B.P.). The sites and data sources are: 1. Northern Nevada: Zoback and Thompson, 1978; 2. Southern Nevada: Ekren and others, 1968; Anderson and Ekren, 1977: 3. West-central Arizona: Eberly and Stanley, 1978; Lucchitta and Suneson, 1983; 4. West-central New Mexico: Zoback and others, 1981; 5. North-central New Mexico: Lipman, 1981; 6. Southeastern Arizona: Menges and others, 1981; Menges, 1981.(The basic figure is adapted from Zoback and others, 1981).

Figure 14.



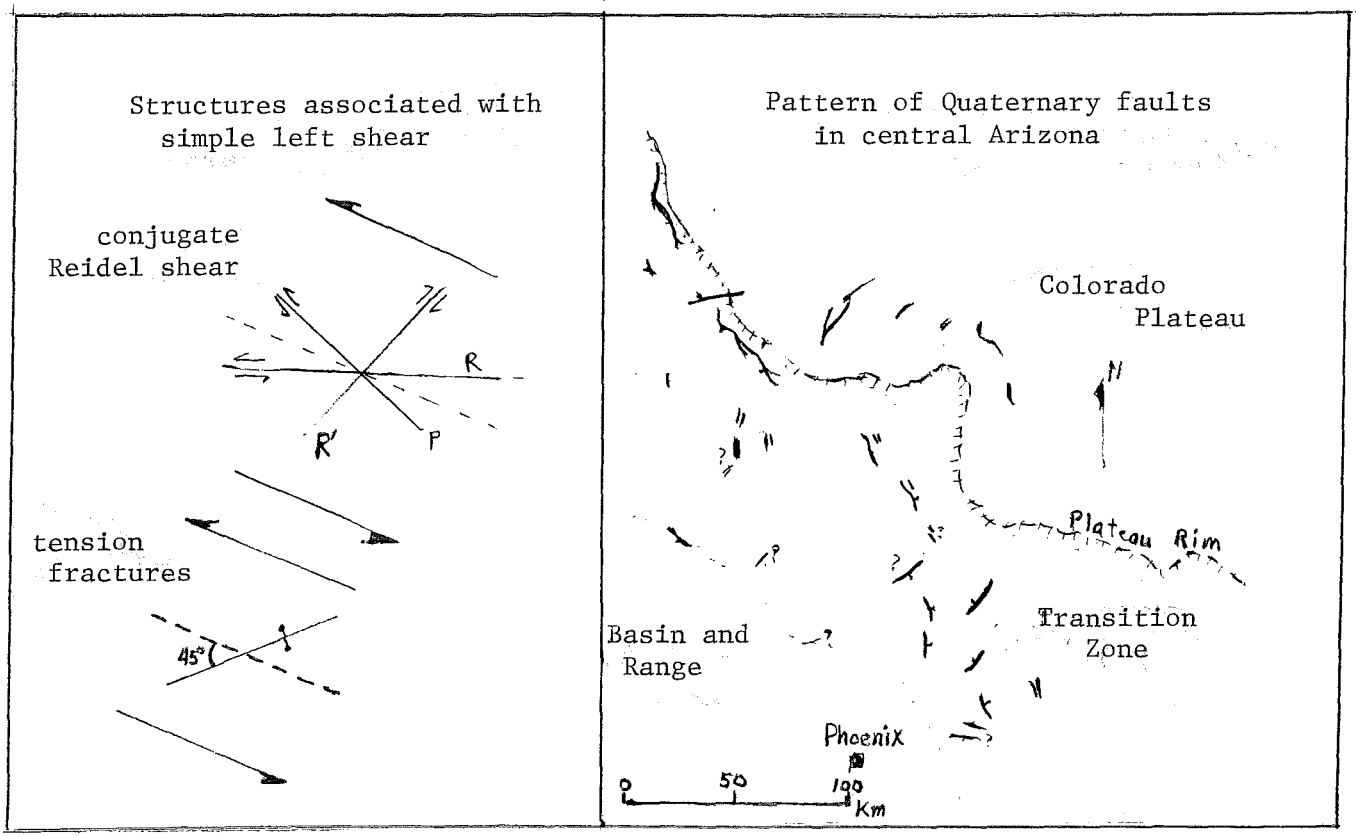
SURFACE FAULTING IN THE GREAT BASIN PROVINCE

HISTORIC FAULTING	HOLOCENE FAULTING	NO LATE QUATERNARY EVENTS
3×10^{-3} > event > 1×10^{-4} per year per 1000 KM^2	(last 12,000 years) 5×10^{-3} > event > 5×10^{-4} per year per 1000 KM^2	(last 5×10^5 years)

NOTE: An event is an occurrence of surface faulting large enough to have produced an earthquake >M7. Earthquakes of 1869, 1903, 1934 and 1950 were <M7. Those of 1872, 1915, 1932, 1952 and 1954 were >M7.

From Wallace, 1978.

Figure 15.



Comparison Between Quaternary Faults in Central Arizona and Structures Associated With a Left-Slip Shear Zone (the latter modeled after Tchalenko and Ambraseys, 1970).

Table 1. Time Boundaries Adopted in This Study for the Relevant Cenozoic Epochs. -- m.y.B.P.

Oligocene	38.0 - 24.0
Miocene	
early	24.0 - 16.0
mid	16.0 - 11.0
late	11.0 - 5.6
Pliocene	
early	5.6 - 3.2
late	3.2 - 1.8
Pleistocene	
early	1.8 to 0.7-0.5
mid	0.7-0.5 to 0.15
late	0.15 to 0.01
Holocene	0.01 - present

TABLE 2

SURFACE-RUPTURE RECURRENCE INTERVALS IN ARIZONA

REGION	RECURRENCE INTERVALS-- INDIVIDUAL FAULTS (in years)	AVERAGE REGIONAL RECURRENCE INTERVALS (inyears)	NO. EVENTS/YR/10^3KM^2
ARIZONA STRIP	10^4 - 10^5	1400 --4000	19-55 x 10^{-6}
NORTH CENTRAL	10^4 - 10^5	1700 - 4000	12-28 x 10^{-6}
CENTRAL BASINS	10^5	5000	12 x 10^{-6}
SOUTHEAST	10^5	3000	7.4 x 10^{-6}
SOUTHWEST	*10^4- 10^5	* 4000 - 15,000	0.7-1.9 x 10^{-6}

* Only one fault near Yuma has 10^4 recurrence rates and it is probable associated with Salton Trough tectonics

TABLE 3

COMPILATION OF REGIONAL GEOPHYSICAL AND GEOLOGICAL CHARACTERISTICS OF THE BASIN AND RANGE, COLORADO PLATEAU, AND GREAT PLAINS PROVINCES

PROPERTIES	BASIN AND RANGE	COLORADO PLATEAU MARGINS	COLORADO PLATEAU INTERIOR	GREAT PLAINS
Crust				
Thickness (km)	18 - 30	25 - 35	45	50 - 52
Lithosphere				
Thickness (km) (total)	25 - 60	25 - 45	60 - 80	120 - 130
Thickness (km) (elastic)	15 - 20	—	~30	~30
Seismic Velocitits (km/sec)				
Crust	5.8 - 6.7	6.2	6.2 - 6.8	6.1 - 7.0
Crustal Low Velocity Zone	5.5 - 6.0 (at 9 - 16 km depth)	—	—	—
P_n	7.4 - 7.9	7.8 - 7.9	7.8	8.2
Heat Flow (HFU)	2.0 - 2.5	2.2	1.3 - 1.6	1.0 - 1.2
Seismicity				
Focal Depths	≤15 - 25	(≤15 - 25)	15 - 45	—
Focal Mechanisms	Extension/ Strike-slip(west edge)			
σ_{Hmin} Orientation	EW - NW	SW - WNW (~EW)	NE	—

Appendix 1 : MINIMUM ESTIMATES OF PLIOCENE-QUATERNARY DOWNCUTTING IN ARIZONA

A. TOPOGRAPHICALLY INVERTED BASALT FLOWS

Identification No. (Figure 8e)	Name	Coordinates	Age (m.y.B.P.)	Amount of Downcutting (m) (name of stream)	Minimum Estimates Downcutting rate (m/m.y.)	Sources
	LAKE MEAD REGION					
A1	Grand Wash Bay Flow	36°12.3'N 114°01.0 W Alt: 470m	3.80 ± 0.11 K-Ar/W	110 16 (Colorado River)	30	Shafiqullah and others, 1980 Damon and others, 1978 1 Basalt flow overlying eroded Muddy Creek formation and older fluvial deposits (terraces?) of the Colorado River
A2	Sandy Point Flow	36°06.54 N 114°06.44 W Alt: ~420m	3.79 ± 0.46 K-Ar/W	~114 (Colorado River)	~30	Shafiqullah and others, 1980 Damon and others, 1978 2 Basalt flow overlying older fluvial deposits (terraces?) of the Colorado River [probably same flow as (A1) above]
B	Fortification Hill Flow	36°02.8'N 114°39.6°W Alt: 1085m	5.84 ± 0.18 K-Ar/W	815 (to level of flows A1 and A2 above) 925m total (Colorado River)	390 (between 6 and 4 m.y.B.P.)	Shafiqullah and others, 1980 Damon and others, 1978 3 Lowermost basalt flow at Fortification Hill (hence maximum age for downcutting); overlies top Muddy Creek Formation, prior to significant downcutting of Colorado River
C	Fortification Basalt Flow	35°56'39"N 114°39'25"W Alt: ~688m	4.9 ± 0.4 K-Ar/W	475 (Colorado River)	~100	Anderson and others, 1972; Anderson, 1978; Keith and Reynolds, 1976 4 Basalt flow overlying Muddy Creek Formation [may yield a minimum rate which averages the two rates isolated in (A1) and (A2) above]

Identification No. (Figure 8e)	Name	Coordinates	Age (m.y.B.P.)	Amount of Downcutting (m) (name of stream)	Minimum Estimates Downcutting rate (m/m.y.)	Sources
D	Malpais Flattop Mesa Flow (Fortification Basalt)	35°49'40"N 114°38'20"W Alt: 845m	5.8 ± 1.0 K-Ar/W	645 (Colorado River)	111	Armstrong, 1970; Anderson, 1978; Keith and Reynolds, 1976 5 Same comments as (C) above, except flow is older and at higher altitude
E	Grand Wash Flow	36°37'37" 113°53'23" Alt: 1340m	6.87 ± 0.20 K-Ar/W	178m (using 6.7 m.y. date) (Grand Wash)	26	Keith and Reynolds, 1976; Damon, 1968; Hamblin and others, 1981 6 Series of basalt flows overlying Muddy Creek Formation in Grand Wash Note: Downcutting rate is averaged over 7 m.y. which may include several different rates [see (A1), (A2) and (B) above]
	WESTERN COLORADO PLATEAU					
F	St. George Flows	a) 37°06'55"N ~113°36'20"W Alt: ~988m b) ~37°5' N ~113°55'40"W Alt: ~878m	a) 2.24 ± 0.11 K-Ar/W b) 1.07 ± 0.04 K-Ar/W	a) 200 b) 97 (Virgin River)	~90	Hamblin and others, 1981; Best and others, 1980 7 Two steplike series of basalt mesas above the Virgin River. They estimate 64 m/m.y. tectonic uplift of the St. George area for a total uplift rate of 90 m/m.y. [summation (E) and (F)]

Identification No. (Figure 8c)	Name	Coordinates	Age (m.y.B.P.)	Amount of Downcutting (m) (name of stream)	Mininum Estimates Downcutting rate (m/m.y.)	Sources
G	Hurricane Flow	37°10'32" 113°16'49" Alt: 1060m	0.293 ± 0.087 K-Ar/W	110m (Virgin River)	375	Hamblin and others, 1981; Best and others, 1980 8 Basalt flow remnant in middle of Hurricane Cliffs, above canyon of Virgin River; the flow is offset 87m by the Hurricane fault; they estimate 300 m/m.y. tectonic uplift of the block immediately east of the fault.
H	Flow near Virgin, Utah	Virgin, Utah, near confluence of North Creek and Virgin River	1.10 ± 0.08 K-Ar/W	401	365	Hamblin and others, 1981 9 Basalt mesa above Virgin River. They estimate 300 m/m.y. uplift for the northern Uinkaret Plateau, for a total of 390 m/m.y. [summation of (E), (F) and (H)]
I	Whitmore Wash Flows (2)	a) ~36°14' N 113°14' W Alt: 1170m b) 36°11.5°N 113°13.5 W Alt: 1048m	a) 0.203 ± 0.024 Thermoluminescence b) 0.088 ± 0.015 Thermoluminescence	a) 24-36 b) 12-18	118 - 177 136 - 204	Holmes, 1979; Holmes and others, 1978 10 Series of two basalt flows overlying piedmont alluvium in Whitmore Wash, tributary to the Colorado River

Identification No. (Figure 8e)	Name	Coordinates	Age (m.y.B.P.)	Amount of Downcutting (m) (name of stream)	Mininium Estimates Downcutting rate (m/m.y.)	Sources
	SAN FRANCISCO VOLCANIC FIELD					
J	Tappen Flow (Cameron area)	35°53'14"N 111°27'18°W Alt: 1310m	0.510 ± 0.079 K-Ar/W	50 - 55 (Little Colorado River)	105	Damon and others, 1974 11 Flow overlying channel gravels within former canyon of the Little Colorado River; river has since downcut an adjacent post-lava canyon
K	Black Point Flow	35°40'20"N 111°20'39"W Alt: 1475m	2.39 ± 0.32 K-Ar/W	215 (Little Colorado River)	90	Damon and others, 1974 12 Flow capping promentory above Little Colorado River. Fluvial gravels occur atop north end of flow, indicating position of river channel immediately following lava extrusion, but prior to subsequent downcutting
L	Volunteer Flow (uppermost)	35°07' N 111°56'30"W Alt: 2036m	4.30 ± 0.45 K-Ar/W	340 (Sycamore Creek)	80	Damon and others, 1974 (basalt date); Keith and Reynolds, 1976 13 Uppermost of series of eight flows (8.68 m.y. B.P. age for lowermost unit), which overlie a Kaibab erosion surface. Note: Downcutting rate may encompass several different individual rates related to more than one tectonic event including the younger formation interval of Verde Valley to the south, as well as neotectonic age downcutting

Identification No. (Figure 3c.)	Name	Coordinates	Age (m.y.B.P.)	Amount of Downcutting (m) (name of stream)	Minimum Estimates Downcutting rate (m/m.y.)	Sources
	EASTERN TRANSITION ZONE - WHITE MOUNTAINS AREA					
M	Corduroy Creek Flow	34°02.67'N 110°16.2'W Alt: 1609m	1.90 ± 0.06 K-Ar/W	110 (Carrizo Creek)	64	Peirce and others, 1979 14 Flow which moved down Corduroy Creek Canyon. Downcutting rates calculated at downstream end of flow, where Carrizo Creek has cut through the flow and reestablished its profile
N	Whiteriver Flow (upper mesa)	~33°51' ~109°59' Alt: 6000 ft.	3.25 ± 0.08 K-Ar/W	275 (White River)	84 (3.2-0 m.y.B.P.) 103 (3.25 m.y.B.P.)	Shafiqullah and Peirce, oral communication, 1982 15 Flow caps mesa above and parallel to the White River, & thus presumably represents topographically inverted former valley floor; the lower flow (O below) lies 274 in canyon bottom, parallel to and below the high mesa flow, indicating a rate of downcutting of 106 m/m.y. between 3.25 and 0.59 m.y.B.P. (the respective ages of the two flows).
O	Whiteriver Flow (lower terrace)	~33°49' ~109°57.5' Alt: 5120 ft.	0.59 ± 0.1 K-Ar/W	55 (White River)	93	Shafiqullah and Peirce, oral communication, 1982 16 Flow, forming low terrace along White River, below high mesa flow (N above); Downcutting measured at lower end of flow, where stream has cut through flow and reestablished its gradient to pre-flow conditions

Identification No. (Figure 8c)	Name	Coordinates	Age (m.y.B.P.)	Amount of Downcutting (m) (name of stream)	Minimum Estimates Downcutting rate (m/m.y.)	Sources
P	Springerville Flow	~33°49' ~109°57.5' Alt: 2200m	3.06 ± 0.08 K-Ar/W	104 (Coyote Creek)	34	Aldrich and Laughlin, 1981 17 Flow capping mesa above Coyote Creek (to E of Springerville) which overlies Tertiary sediments
Q	Zuni Flow	NA	1.41 ± 0.29 K-Ar/W	99 (Zuni River)	70	Aldrich and Laughlin, 1981 18 Mesa-capping flow following former erosion surface and part of inverted valley of Zuni River (dated sample located in New Mexico)
R	Peridot Mesa Flow	33°20.57'N 110°28.12'W Alt: 866m	0.93 ± 0.08 K-Ar/W	67m (San Carlos River)	72	Shafiqullah and others, 1980 19 Basalt flow overlying basin fill and/or fluvial (terraces) gravel of San Carlos River, a tributary of Gila River to south
	SOUTH WEST ARIZONA					
S	Sentinel Volcanic Field (primary flow)	32°56'06"N 113°18'05"W Alt: 152m	3.0 ± 0.1 K-Ar/W	24	8	Eberly and Stanley, 1978; Keith and Reynolds, 1976 20 Basalt flow overlying basin fill and/or fluvial sediments of the Gila River; flow now forms terrace above lower Gila River valley floor.

Identification No. (Figure 3c)	Name	Coordinates	Age (m.y.B.P.)	Amount of Downcutting (m) (name of stream)	Minimum Estimates Downcutting rate (m/m.y.)	Sources
T	Warford Ranch Flow	33°01.10'N 112°59.89'W Alt: 207m	3.19 ± 0.11 K-Ar/W	30	9	Shafiqullah and others, 1980 21 Flow and core complex overlying fluvial gravels of the Gila River (below and adjacent to north)
U	Gillespie flow	33°14.15'N 112°46.96'W Alt: ~207m	2.7-3.3 (typical range of 10 dates, varying from 4.2 ± 0.4 to 1.3 ± 0.4) K-Ar/W	12-24	5-9	Euge and others, 1978; Shafiqullah and others, 1980 22 Flow and core complex overlying terrace gravels of the adjacent Gila River

B. UPPERMOST SECTIONS - DISSECTED BASIN FILL

Site	Stratigraphic Unit	Estimated Age (m.y.B.P.) (uppermost part)	Amount of Downcutting (m)	Minimum Estimate, Downcutting Rates (m/m.y.)	Sources
Central Arizona					
Verde Valley	Verde Fm	2.45-3 (magnetopolarity stratigraphy and K-Ar, interbedded tuffs)	253	84-103	Bressler, 1977; Bressler and Butler, 1978
Southeast Arizona					
Upper San Pedro Valley	St. David Fm	$\leq$ 0.7 m.y.B.P. (magnetopolarity stratigraphy and K-Ar interbedded tuffs)	114	163	Johnson and others, 1975
Safford Valley	Frye Mesa sediments and uppermost basin fill	< 3.3 m.y.B.P. (K-Ar, interbedded tuffs at III Ranch locality)	~210	70-105	Scarborough, 1975; 1982 (oral communication)