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MIDDLE TERTIARY TECTONICS OF ARIZONA AND ADJACENT AREAS

by
Jon E. Spencer and Stephen J. Reynolds
Arizona Geological Survey
845 N. Park Ave., Tucson, Arizona 85719

ABSTRACT

Middle Tertiary tectonics in the Basin and Range Province of Arizona and adjacent parts of southeastern California and southern Nevada were dominated by large-magnitude lithospheric extension accommodated at upper crustal levels primarily by formation of and movement on regional, low-angle normal (detachment) faults. Unidirectional tilting of upper-plate fault blocks over large areas referred to as tilt-block domains reflects the geometry and movement direction of underlying detachment faults. Large displacements on detachment faults resulted in denudation and isostatic uplift of lower-plate mylonitic crystalline rocks that are now exposed in archlike structural culminations known as metamorphic core complexes. Mylonitic fabrics in these complexes formed by ductile shear along the deeper, downdip projections of detachment faults. Crustal extension occurred in the lower crust beneath the Transition Zone, which was probably tilted one to two degrees to the southwest as a result of greater crustal thinning beneath its southwestern margin. Relative elevation changes between the Basin and Range Province and Colorado Plateau occurred in association with tilting of the Transition Zone and were marked by a reversal in drainage direction and formation of many of the basic features of modern Arizona physiography. Crustal extension was accompanied by widespread, dominantly silicic magmatism that migrated from east to west across Arizona. Both extension and the westward sweep of magmatism are inferred to be related to steepening and perhaps disintegration of the subducted lithospheric slab beneath southwestern North America.

INTRODUCTION

The middle Tertiary tectonic evolution of Arizona and adjacent areas was dominated by two processes: lithospheric extension and a resurgence of magmatism following a 10- to 30-Ma period of magmatic quiescence. Both extension and magmatism were related to the evolving plate-tectonic setting of the continental margin of western North America, which is fairly well understood based on marine magnetic-anomaly data and global plate reconstructions (Atwater, 1970; Jurdy, 1984).

Middle Tertiary magmatism and extensional deformation in the Basin and Range Province of Arizona (fig. 1) and adjacent areas overprinted crust that had experienced previous periods of magmatism and compressional deformation. The most significant earlier period of widespread magmatism, compressional deformation, and inferred crustal thickening was in middle to Late Cretaceous and early Tertiary time. The fact that mid-Tertiary tectonism occurred largely in areas that had experienced earlier deformation and magmatism (the Colorado Plateau consistently escaped significant deformation) suggests that the earlier tectonic history of the crust exerted control over the locus of later mid-Tertiary activity. The nature of this

Figure 1. Map of the major physiographic provinces of Arizona.

control is only very general, however, as specific mid-Tertiary faults and related structures generally do not have any obvious relationship to older structures (e.g., Wernicke and others, 1985).

The Basin and Range Province extends from the Snake River Plain in Idaho southward through Arizona into Mexico. It is characterized by numerous, typically north-trending (± 30°) ranges bounded by Cenozoic sedimentary basins that are as deep as several kilometers. Whereas high-angle normal faults bounding one or both sides of these ranges have been recognized as characteristic features of the Basin and Range Province for some time (e.g., Nolan, 1943; Stewart, 1971, and references therein), low-angle normal faults have only been widely recognized since the 1970s (e.g., Anderson, 1971; Armstrong, 1972) and are now considered to be fundamental structural features of the region (Crittenden and others, 1980; Frost and Martin, 1982). High-angle normal faults did not accommodate more than about 20 to 30 percent extension (Stewart, 1980) and possibly much less in parts of Arizona and southeastern California, yet 50 to 100 percent extension is indicated by paleogeographic reconstructions (Hamilton and Myers, 1966; Hamilton, 1969), inferred changes in crustal thickness (Hamilton, 1978), and strike-slip fault displacements (Wernicke and others, 1982). Low-angle normal faults accommodated much of the large-magnitude crustal extension.

In Arizona and perhaps most areas of the Basin and Range Province, low-angle normal faulting preceded formation of large, range-bounding, high-angle normal faults. Middle Tertiary crustal extension associated with low-angle normal faulting was directed east-northeast-west-southwest in Arizona and much of the southern Basin and Range Province, whereas late Tertiary extension associated with high-angle normal faulting was directed in an east-west to east-southeast-west-northwest direction (Zoback and others, 1981). In Arizona, this change in extension direction and style was approximately coeval with a change from dominantly intermediate and silicic magmatism in an intra-arc setting to dominantly basaltic magmatism following cessation of subduction and development of the San Andreas transform system (Lipman and others, 1972). Changes in extension direction were possibly the result of a component of right-lateral shear associated with the San Andreas transform system superimposed on the extensional tectonic regime of the Basin and Range Province. The cause of the change in style of extension is not understood, but was possibly cooling and strengthening of the distended lithosphere (England, 1983).

In this paper we review evidence for the nature and character of mid-Tertiary magmatism, space-time patterns of magmatism, and the character and timing of extensional deformation. Reversal of the relative elevations of the Colorado Plateau and the Basin and Range Province also occurred in mid-Tertiary time and must be incorporated into any synthesis of mid-Tertiary tectonics in Arizona and the southwest. We do not discuss high-angle normal faulting and associated basaltic magmatism that occurred after about 13 Ma (late Tertiary and Quaternary).

MAGMATISM AND PLATE-TECTONIC SETTING

Between Oligocene and middle Miocene time, many areas in the Basin and Range Province were blanketed by hundreds to thousands of meters of volcanic rocks and were punctured by calderas, granitic plutons, and numerous dikes. The volcanic sections are dominated by silicic to intermediate flows and pyroclastic rocks, including widespread silicic ash-flow tuffs (Shafiqullah and others, 1978, 1980; Damon, this volume; Nealey and Sheridan, this volume). True basalts are sparse in middle Tertiary volcanic fields in southeastern Arizona, but are more common in central and west-central Arizona where some volcanic fields are fundamentally bimodal in composition (e.g., Suneson and Lucchitta, 1983; Capps and others, 1985). Volcanism in many areas was synchronous with middle Tertiary tectonism, as demonstrated by synvolcanic angular unconformities and by the restriction of some volcanic units and synvolcanic sedimentary deposits to fault-bounded troughs or half grabens. In other areas, volcanism was either earlier or was spatially separated from tectonism, as indicated by regionally extensive volcanic units that were erupted across large areas of low relief.

Volcanic rocks are locally associated with dikes and subvolcanic intrusions, some of which represent magmatic conduits for the volcanics. Deeper level middle Tertiary plutons, some as large as 15 km in diameter, are more widely distributed than previously appreciated and are present in Arizona in the Dos Cabezas, Swisshelm, Pinaleno, Santa Teresa, Dragoon, Santa Catalina, Tortolita, Picacho, South, White Tank, Belmont, Little Ajo, Painted Rock, Palomas, and Black Mountains, and Bouse Hills (Shafiqullah and others, 1978, 1980; Marvin and others, 1978; Keith and others, 1980; Banks, 1980; Erickson, 1981; Rehrig, 1982; Reynolds, 1985; Reynolds and others, 1985; R. Tosdal and G. Haxel, personal commun., 1985). The apparent lack of large middle Tertiary plutons in some uplifted crustal blocks, such as the Harcuvar and Harquahala Mountains, indicates that such plutons do not underlie the entire region, but were generally isolated, point sources of magma and heat.

Although there is general agreement that the main pulse of magmatism occurred between 30 and 15 Ma, there has been some disagreement about the precise timing of the change to fundamentally basaltic magmatism related to the Basin and Range disturbance (Damon and Mauger, 1966; Lipman and others, 1972; Elston, 1976; Coney and Reynolds, 1977; Shafiqullah and others, 1980; Damon and others, 1984). The timing of this switchover is clearly indicated on a plot of initial $^{87}Sr/^{86}Sr$ ratio (Sr_0) versus age

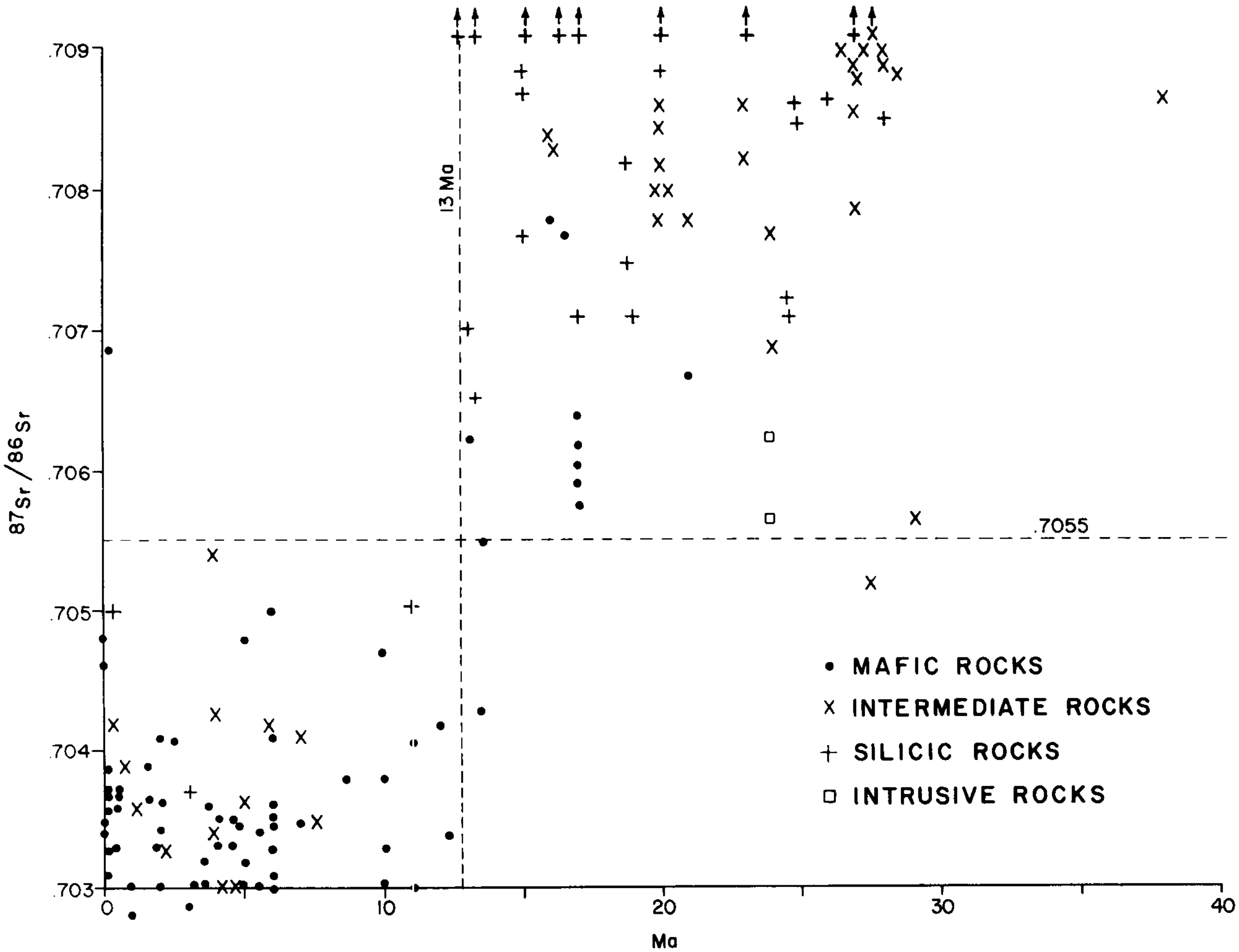


Figure 2. Plot of age versus initial $^{87}Sr/^{86}Sr$ for post-40-Ma igneous rocks in Arizona. Note that igneous rocks older than 13 to 15 Ma have initial $^{87}Sr/^{86}Sr$ ratios greater than 0.7055, whereas those younger than 13 to 15 Ma have initial $^{87}Sr/^{86}Sr$ ratios less than 0.7055. Data from various sources, most of which are listed in Reynolds, Florence, and others, (1986) or Sheridan and Nealey (this volume).

for post-40-Ma igneous rocks in Arizona (fig. 2). This plot reveals that a fundamental change in magma chemistry occurred at 13 to 15 Ma (see also Annis and Keith, 1986). Magmatic rocks formed prior to this time are characterized by Sr_0 of greater than 0.7055 (averaging 0.7086; see Damon, this volume). Magmatic rocks formed after this time, including the dacitic to rhyolitic rocks of the San Francisco and Hackberry Mountain volcanic fields, generally have Sr_0 of less than 0.7055 (see references in Reynolds, Florence, and others, 1986). The magmatic change at 13 to 15 Ma is also reflected by major changes in mineralogy, petrochemistry, metallogeny, and overall lithologic abundances of the magmatic rocks (Keith and Wilt, 1985; Annis and Keith, 1986). In essence, igneous suites older than 13 to 15 Ma are mostly alkali-calcic to calc-alkalic, are compositionally diverse, and contain minor true basalts (except in central and west-central Arizona), whereas those younger than 13 to 15 Ma are dominated by alkaline basalts with only local intermediate to felsic rocks. The precise age of the switchover varies slightly with geographic area; it is 15 Ma in central Arizona, 12.5 Ma in the Castaneda Hills of west-central Arizona, and probably 11 to 12 Ma in the Lake Mead area.

The initiation, climax, and termination of middle Tertiary magmatism were diachronous across Arizona and adjacent states. A compilation of all radiometric age determinations in Arizona (Reynolds, Florence, and others, 1986) and adjacent areas confirms that the main pulse of magmatism and volcanism is time transgressive from east to west across southern New Mexico and Arizona (fig. 3; Coney and Reynolds, 1977; Dickinson, 1979; Damon and others, 1981; Lipman, 1981; Seager and others, 1984; Reynolds, Welty, and Spencer, 1986). Magmatism began in southern New Mexico at 40 to 36 Ma, crossed the Arizona-New Mexico border before 30 Ma, and had transgressed westward across southeastern Arizona by 25 Ma (Reynolds, Welty, and Spencer, 1986). At about 25 Ma, the simple westward progression of magmatism was complicated by the apparent initiation of significant volcanism in southwestern Arizona and southeastern California synchronous with continued magmatism in southeastern Arizona. By 20 Ma, the locus of magmatism had shifted

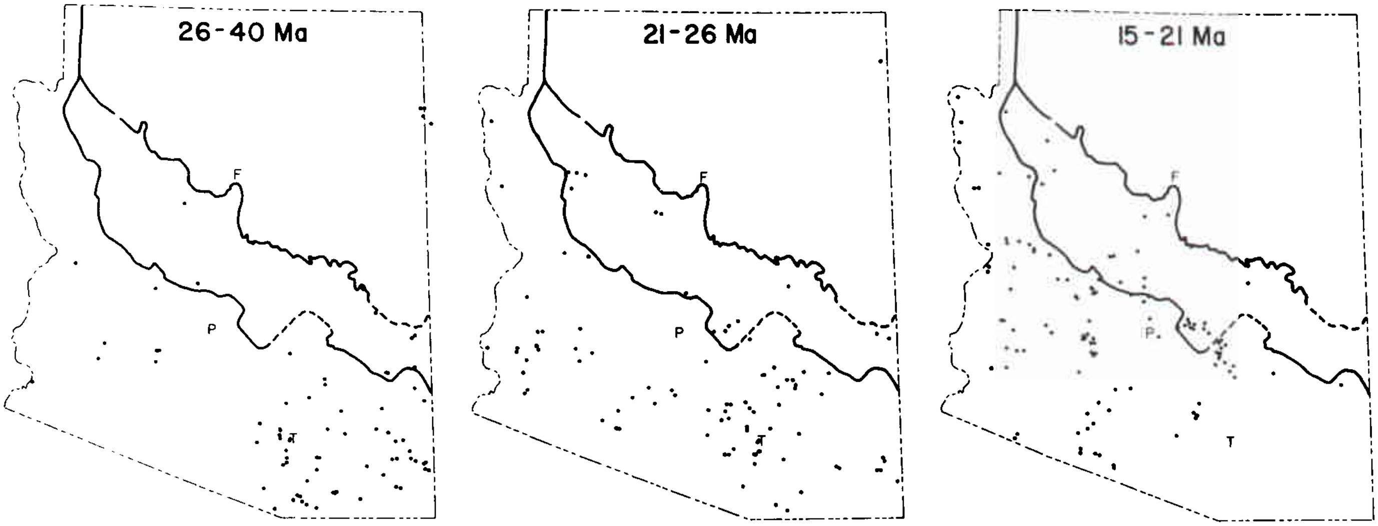


Figure 3. Maps showing distribution of K-Ar dates in Arizona for different time periods between 40 and 15 Ma. The maps include only those dates that can be reasonably regarded as the true emplacement age of the dated igneous rock (see comments in Reynolds, Florence, and others, 1986). The maps demonstrate that middle Tertiary magmatism was concentrated in eastern Arizona between 40 and 27 Ma, was widespread between 21 and 27 Ma, and was largely restricted to western Arizona after 21 Ma. Magmatism therefore migrated westward with time. T=Tucson, P=Phoenix, F=Flagstaff.

westward out of southeastern Arizona and into western Arizona, southeastern California, and coastal Sonora. An analogous westward progression of magmatism across northern Arizona may be represented by the emplacement of diatremes and alkalic rocks in northeastern Arizona at 25 to 30 Ma and subsequent eruption of similar alkaline rocks in central and northwestern Arizona at 20 to 25 Ma (fig. 3; see references in Reynolds, Florence, and others, 1986). The clear westward younging of volcanism contradicts the conclusions of Glazner and Supplee (1982) who proposed that magmatism throughout Arizona migrated northward with time.

Space-time patterns of Cretaceous and Tertiary magmatism can be related to changes in plate-tectonic setting. Based on the interpretation that calc-alkaline and alkali-calcic magmatism was triggered by subduction and that magmatism occurs at the Earth's surface above areas where the top of a subducted slab comes into contact with the asthenosphere (depth typically 80-150 km, e.g., Barazangi and Isacks, 1976), migrating patterns of magmatism at convergent plate margins can be used to determine the changing inclination of a subducted slab. During the Late Cretaceous and early Tertiary Laramide orogeny, the eastward sweep of magmatism across Arizona is interpreted as a consequence of a decreasing dip of an east-dipping subduction zone (Coney, 1976; Coney and Reynolds, 1977; Dickinson and Snyder, 1978; Dickinson, 1981). The decrease in dip has been attributed to rapid convergence between the North American and Farallon plates, rapid westward absolute motion of North America, and possible subduction of aseismic ridges (Coney, 1976; Keith, 1982; Henderson and others, 1984). By Eocene time, the subducted slab had a very shallow dip that resulted in complete cessation of all magmatism in Arizona except crustally derived, peraluminous, two-mica granites (Keith and Reynolds, 1980, 1981). The westward return sweep of magmatism from 40 to 20 Ma was probably a result of an increase in dip of the subducted plate (Coney and Reynolds, 1977; Dickinson, 1981; Lipman, 1981). The widespread distribution of volcanism at 20 Ma may reflect complete foundering or breaking up of the subducted slab (Coney and Reynolds, 1977). The termination of middle Tertiary magmatism and switch to fundamentally basaltic volcanism was probably a response to cessation of subduction due to creation of the lengthening North America-Pacific transform and resulting growth of a no-slab window beneath Arizona (Lipman and others, 1972; Shafiqullah and others, 1978, 1980; Dickinson and Snyder, 1979; Lipman, 1981; Damon and others, 1984).

Plate-tectonic setting, migration patterns, and geochemistry of middle Tertiary magmatism in Arizona provide constraints on the origin of the magmas. Keith (1978, 1982; see also Keith and Wilt, 1985) has presented evidence that changes in alkalinity, both in time and in space, are supportive of a steepening subduction zone. These migration patterns and alkalinity variations cannot be accounted for by models that attribute middle Tertiary magmatism to nonsubduction-related crustal melting due to mantle diapirs (see review by Elston, 1976) or Mesozoic crustal thickening (Glazner and Bartley, 1985). Such models also do not account for geochemical differences between Eocene peraluminous granites, which are known to be crustal melts, and middle Tertiary igneous rocks, which were derived in part from the mantle (Farmer and DePaolo, 1984). However, modeling of possible mantle and crustal contributions to middle Tertiary magmas using Sr, Nd, and Pb isotopes (Farmer and DePaolo, 1984) is hindered by uncertainties about the isotopic signatures of lower versus middle crust and of lithospheric mantle versus asthenospheric mantle. The local presence of relatively radiogenic late Tertiary basalts with Sr_0 of up to 0.7055 demonstrates that the mantle below Arizona is compositionally heterogeneous (Leeman, 1982).

CRUSTAL EXTENSION

Middle Tertiary tectonic activity in Arizona was dominated by widespread normal faulting and fault-block rotation that accommodated major northeast-southwest to east-northeast—west-southwest crustal extension. Movement occurred on low- to high-angle normal faults, and many high-angle normal faults are known or suspected to be truncated downward by, or to flatten downward and merge with, major detachment faults. Detachment faults in Arizona and the southwest have several to several tens of kilometers of displacement and are the most important structural features of mid-Tertiary age in the Basin and Range Province.

Upper-plate rocks above major detachment faults are, in most cases, tilted dominantly in one direction—toward the breakaway fault and opposite to the direction of upper-plate displacement (fig. 4). Areas of uniform tilt direction are referred to as tilt-block domains (fig. 5) and are known or inferred to be representative of distension above one detachment fault or several faults that dip regionally in the same direction. Tilting and distension above detachment faults produced numerous half grabens and associated asymmetric sedimentary basins that received abundant clastic detritus from nearby upper-plate rocks. Conglomerate, sandstone, and siltstone, in many areas with associated volcanic rocks and sedimentary breccias representing catastrophic debris avalanches (e.g., Krieger, 1977), are typical. Sedimentary and volcanic sequences within some half grabens are progressively less tilted upsection because sedimentation occurred during tilting.

Lower-plate rocks typically consist of plutonic and high-grade metamorphic rock exposed in antiformal or domal

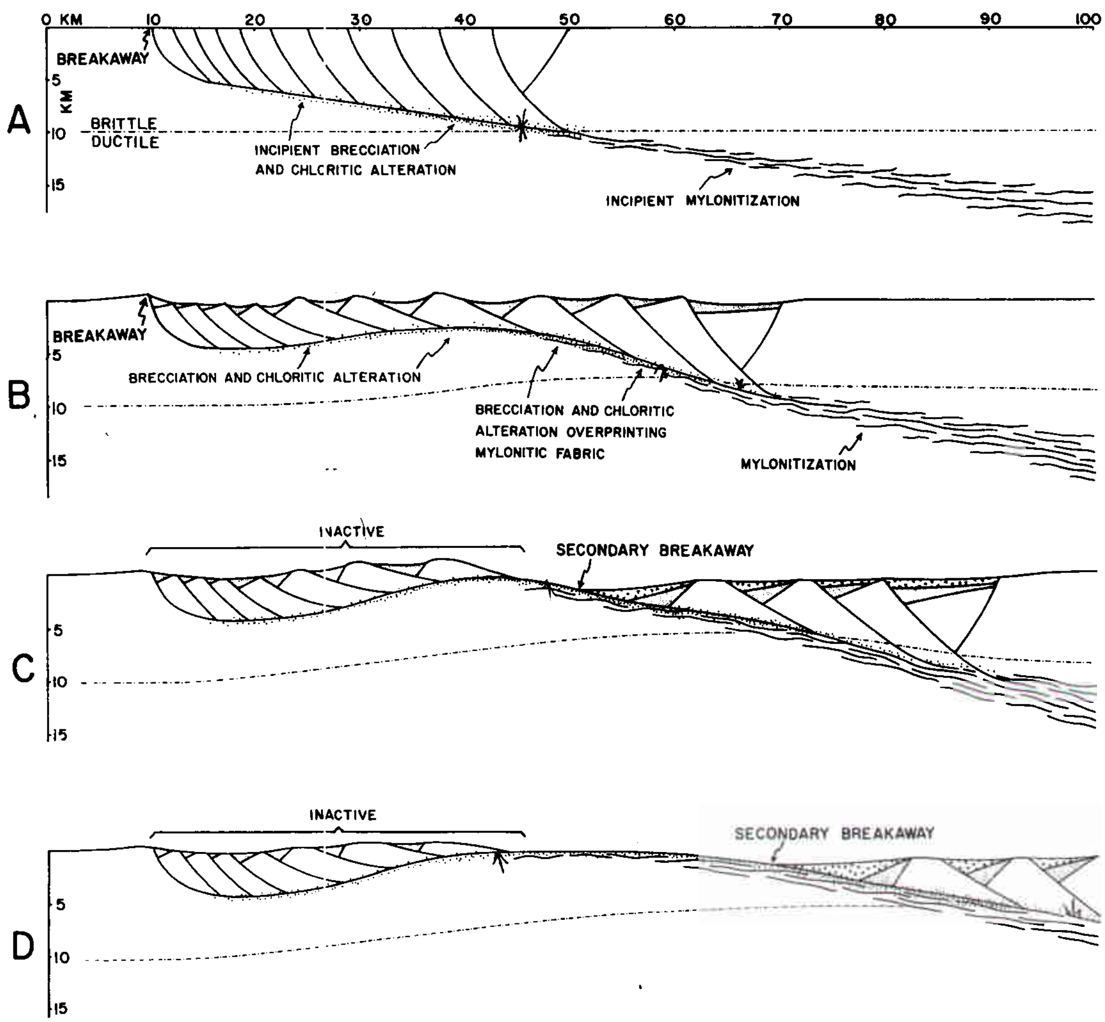


Figure 4. Evolutionary cross sections of a hypothetical detachment fault-ductile shear zone and the formation of a metamorphic core complex. (A) Detachment fault is shown as initially planar below 5 km and listric above. The detachment fault projects downward across the brittle-ductile transition to become a ductile shear zone. (B) Isostatic uplift of the lower plate due to denudation leads to arching of the footwall. Footwall rocks originally mylonitized below the brittle-ductile transition rise isostatically through the transition and are overprinted by brittle structures adjacent to the detachment fault. Syntectonic sediments fill grabens and half grabens. (C) Continued arching and uplift of the footwall result in termination of detachment-fault movement to the left of the arch and formation of a secondary breakaway to the right. In some complexes, displacement of the arch *above* moderately dipping listric normal faults results in further arching due to reverse drag. Syntectonic sediments locally include clasts derived from the lower plate adjacent to the secondary breakaway.

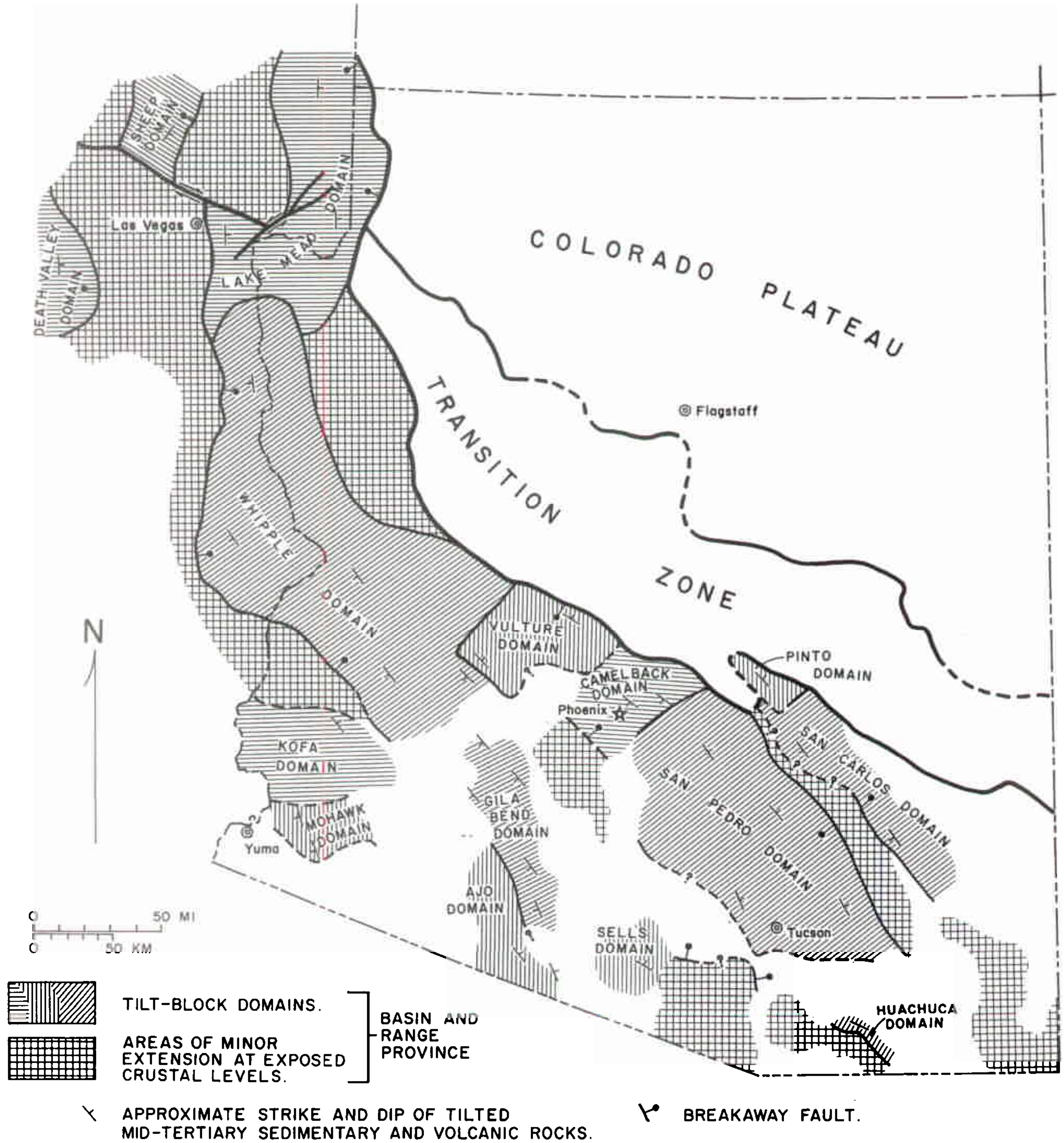


Figure 5. Mid-Tertiary tilt-block-domain map of Basin and Range Province in Arizona and adjacent parts of Nevada and California.

uplifts termed "metamorphic core complexes" (figs. 6, 7; Crittenden and others, 1980). A penetrative, lineated, mylonitic fabric that progressively dies out downward is a characteristic feature of metamorphic core complexes in Arizona. Mylonitic lineation is generally parallel to the direction of upper-plate displacement and distension, and the sense of shear during mylonitization, as indicated by S-C fabrics and other asymmetric petrofabrics (fig. 7; e.g., Berthe and others, 1979; Simpson and Schmid, 1983; Lister and Snoke, 1984), is the same as the sense of shear inferred for the overlying detachment fault based on offset indicators and tilt directions of upper-plate fault blocks (Reynolds, 1985; Davis and others, 1986; fig. 5). The mylonitic fabric ranges from being well developed over the entire uplift to being restricted to a small area along the edge of the uplift. Mylonitic and nonmylonitic rocks within a few tens to hundreds of meters below the detachment fault are fractured or brecciated and contain secondary chlorite,

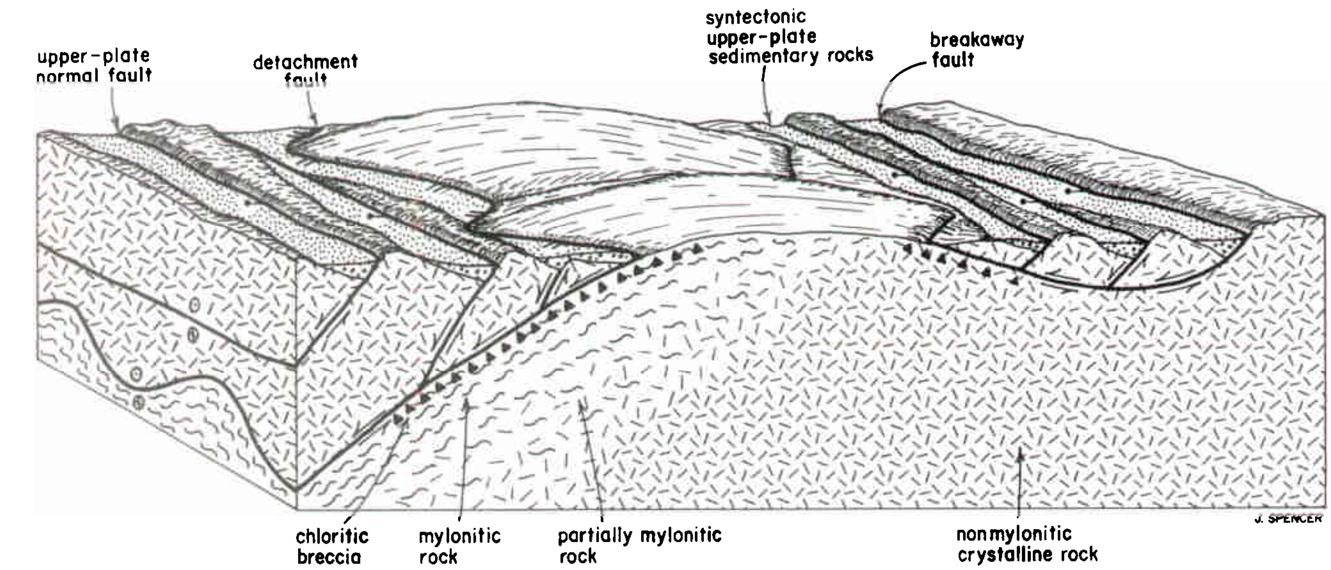


Figure 6. Idealized block diagram of a metamorphic core complex.

epidote, and hematite. Lower-plate rocks within a few centimeters to locally as much as several meters below the detachment fault commonly have been converted to hard, flinty cataclasite.

All of these structures and associated lithologies are best explained in the context of an evolving crustal shear zone (fig. 4; Wernicke, 1981; Davis, 1983; Davis and others, 1986). According to the shear-zone model, large-magnitude normal displacement on gently dipping shear zones resulted in tectonic denudation and isostatic uplift of footwall rocks that resided at depths of perhaps as much as 15 km before fault movement. Footwall rocks initially below the brittle-ductile transition (temperatures greater than about 300° C corresponding to depths greater than about 5 to 15 km) underwent ductile shearing along the downdip projection of detachment faults, resulting in formation of lineated mylonitic fabrics that die out downward away from the shear zone. As a result of tectonic denudation and associated isostatic uplift, the lower plate cooled and passed upward through the brittle-ductile transition, and deformation style changed from ductile shearing to brittle faulting and related brecciation. This change occurred at about the closure temperature for argon in biotite, and K-Ar biotite ages from lower-plate rocks record the approximate age of this transition. Hot water circulated through freshly shattered rocks near and along the fault, resulting in hydrothermal alteration and growth of chlorite and epidote. Continued uplift and cooling was associated with formation of a thin (typically 10-100 cm) layer of microbreccia adjacent to the fault surface, and finally with formation of fault gouge (Davis and others, 1986). In some areas, lower-plate mylonitic rocks were completely denuded by detachment faulting, and clasts of mylonitic rock, eroded from below the fault, were deposited in basins formed by ongoing tilting of upper-plate fault blocks (e.g., Spencer, 1984; Spencer and Reynolds, 1987).

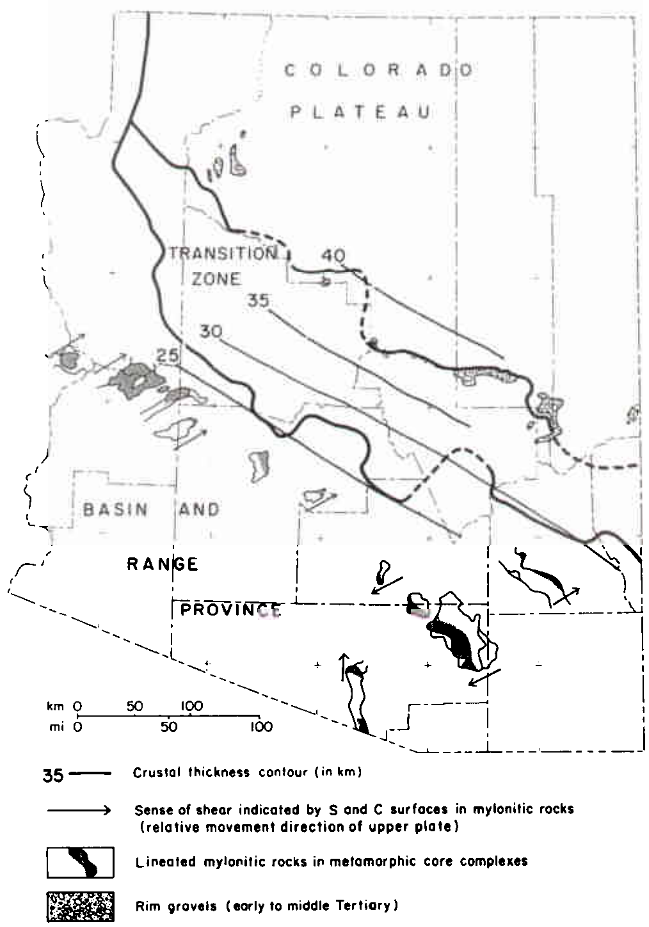


Figure 7. Map of Arizona showing crustal thickness changes associated with the Transition Zone and location of metamorphic core complexes and early to middle Tertiary rim gravels. The rim gravels are located along the presently topographically high margin of the Colorado Plateau and were deposited by northeast-flowing streams that drained the presently topographically lower Transition Zone and Basin and Range Provinces. The arrow next to each metamorphic core complex indicates the direction the upper plate moved based on sense-of-shear indicators in mylonitic rocks.

Detachment faults typically have a complex, undulatory form that appears to represent an interference pattern between two sets of approximately perpendicular folds or warps (fig. 6; Cameron and Frost, 1981). The axes of one fold set, typically represented by a single broad upwarp in any individual complex, are perpendicular to mylonitic lineation and the direction of displacement on the detachment fault. These folds or warps appear to be largely, if not entirely, the product of some combination of (1) differential isostatic uplift due to tectonic denudation, and (2) reverse drag above a deeper, concave-upward detachment fault (Spencer, 1984). Periodic, shorter wavelength corrugations with axes parallel to the direction of transport on the detachment fault and to mylonitic lineation are of uncertain origin. Some corrugations are probably true folds, whereas others are probably primary irregularities of fault surfaces.

Southeastern Arizona

Santa Catalina-Rincon-Tortolita-Picacho Mountains Area. Major displacement on detachment faults in southeastern Arizona resulted in unroofing and uplift of lower-plate mylonitic rocks from depths where rocks deformed ductilely and where muscovite and biotite were open to argon loss. Mylonitic rocks characterized by a strong east-northeast-trending lineation and mid-Tertiary K-Ar ages are exposed in the southwestern Rincon, Santa Catalina, Tortolita (figs. 8, 9), and Picacho Mountains. In all of these areas, the mylonitic rocks are known or inferred to have been overlain by a Tertiary detachment fault.

Lower-plate mylonitic fabrics with a characteristic gentle dip and northeast- to east-northeast-trending lineation have been overprinted on a wide variety of rock types. Mylonitic rocks in the Rincon and Santa Catalina Mountains were largely derived from Porphyritic Proterozoic granite and Eocene Wilderness-suite, garnet-muscovite-bearing granites, whereas those in the Tortolita and Picacho Mountains were also derived from large middle Tertiary plutons (Keith and others, 1980; Davis, 1980; Banks, 1980; Rehrig, 1982). Mylonitic fabrics are best developed along the southwest side of each range and are remarkably consistent in character, lineation trend, and overall sense of shear (top to the southwest). These mylonitic fabrics were formed by noncoaxial, ductile shear along deep levels of the detachment faults now exposed along the southwest side of the ranges. Mylonitic fabrics formed within the main top-to-the-southwest shear zones in each range are locally overprinted by small- to large-scale shear zones with antithetic (top-to-the-northeast) shear. These antithetic shear zones are either conjugate zones (Naruk, 1987) or are related to folding of the shear zone about an axis perpendicular to lineation (Reynolds and Lister, 1987).

We make a sharp distinction between these middle Tertiary fabrics and older, in part pre-Eocene mylonitic fabrics present on the east side of the Rincon and Santa Catalina Mountains (Keith and others, 1980; Bykerk-Kauffman, 1986; Bykerk-Kauffman and Janacke, 1987). These older fabrics, which occur in Proterozoic granitoids, middle Proterozoic and Paleozoic sedimentary rocks, and Late Cretaceous to early Tertiary plutons, are probably related to Laramide compression (Thorman and Drewes, 1981).

The Catalina fault northeast of Tucson places a variety of rock types, including Precambrian crystalline, Paleozoic and Mesozoic metasedimentary, and Tertiary sedimentary rocks, over lower-plate mylonitic granitic and gneissic rocks (Pashley, 1966; Drewes, 1977). The stratigraphically highest, tilted conglomerates contain clasts of mylonitic rock derived from the lower plate (Pashley, 1966), which indicates that the lower plate was locally denuded and exposed to erosion before faulting ended. The San Pedro fault on the east side of the Rincon Mountains places similar upper-plate rocks on a lower plate of tectonized Paleozoic and Mesozoic metasedimentary rocks that do not have a lineated mylonitic fabric and that are cut by dikes of undeformed muscovite granite related to the 45-50-Ma Wilderness-suite granites (Lingrey, 1982). The similarity of upper-plate units above the Santa Catalina and San Pedro detachment faults, which sit above the same, structurally continuous lower plate, supports the interpretation that the two faults are correlative, and that the fault surface is broadly arched about a northwest-trending axis. Upper-plate granodiorite on both sides of the Rincon Mountains is, in part, correlative with the Precambrian Johnny Lyon granodiorite in the Johnny Lyon Hills just east of the Rincon mountains (Silver, 1978; Lingrey, 1982). In the northwestern Johnny Lyon Hills, a pre-mid-Tertiary thrust fault places the granodiorite over Paleozoic and Mesozoic rocks (Cooper and Silver, 1964; Drewes, 1974; Dickinson, 1986). This thrust fault, and rocks above and below it, is preserved in fault blocks above the Catalina and San Pedro detachment faults, which suggests at least 20-30 km of west-southwest displacement of upper-plate rocks (e.g., Lingrey, 1982, fig. 52). The breakaway of the San Pedro-Catalina detachment fault, or of a structurally deeper, southwest-dipping normal fault, is exposed east of the Rincon Mountains in the southwestern Galiuro Mountains (Dickinson and others, 1987) and in the Johnny Lyon Hills and Little Dragoon Mountains (Cooper and Silver, 1964; Dickinson, 1984).

We infer that the Catalina fault projects beneath middle Tertiary and older rocks of the Tucson Mountains. The overall gentle northeast dip of these rocks is probably the result of antithetic rotation that accompanied relative top-to-the-southwest translation of rocks above the Catalina fault. Restoration of 20 to 30 km of transport places rocks in the Tucson Mountains approximately over the forerange of the Santa Catalina Mountains prior to detachment faulting. Total displacement could have been 40 km or more.

Low-angle normal faults are also exposed north and west of the Santa Catalina Mountains between the San Manuel

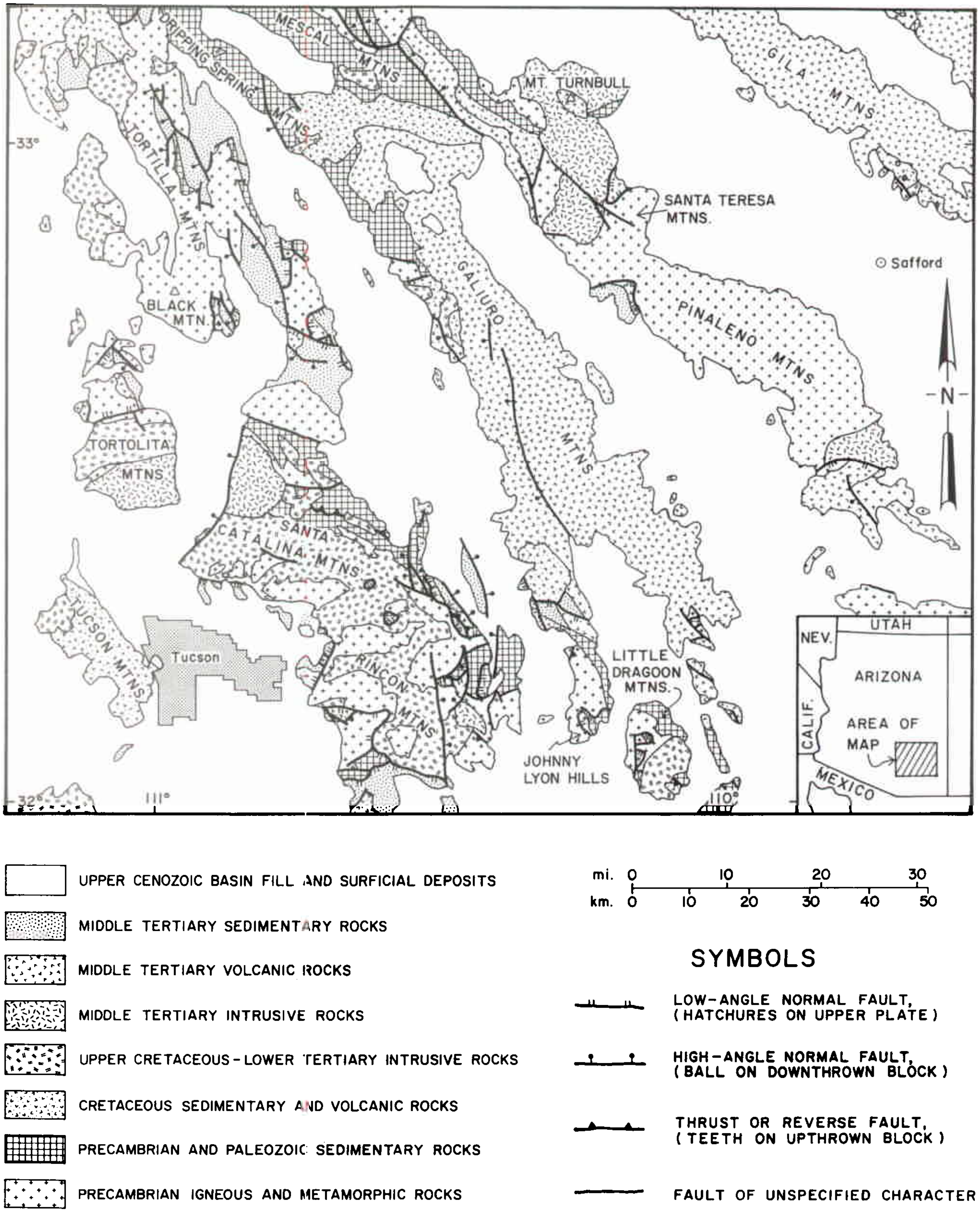


Figure 8. Simplified geologic map of part of southeastern Arizona.

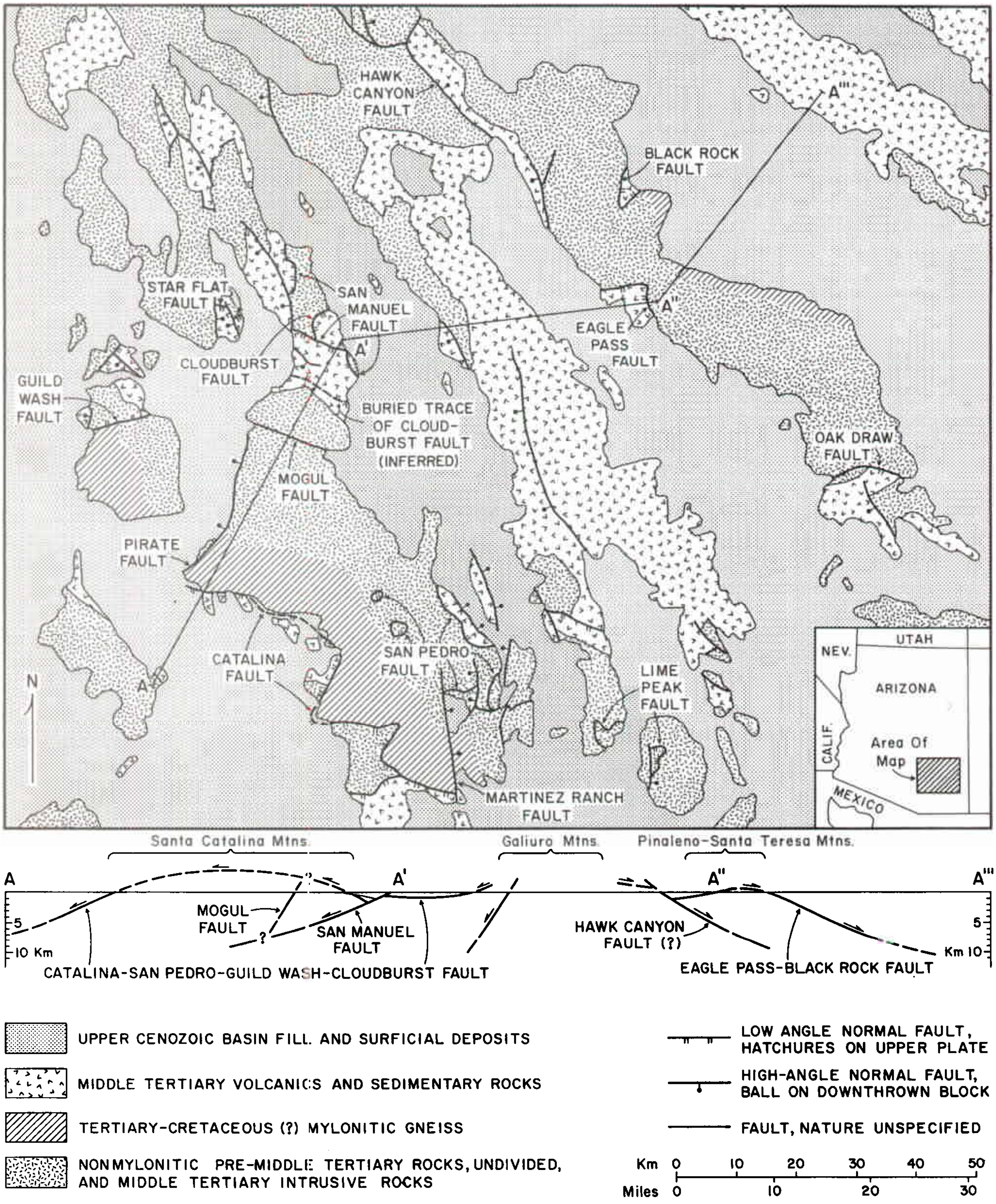


Figure 9. Tectonic map and cross sections showing major mid-Tertiary tectonic features in part of southeastern Arizona. The northern segment of the San Manuel fault, as shown here, was named the Camp Grant fault by Krieger (1974b). We correlate the Camp Grant fault with the San Manuel fault based on geographic proximity, lithologic similarity of upper and lower plates associated with each fault segment, and the fact that both faults cut the same footwall block.

area and the Tortolita Mountains (figs. 8, 9). In the San Manuel area, the subhorizontal Cloudburst fault places sedimentary and volcanic rocks of the mid-Tertiary Cloudburst Formation over Precambrian granitic rocks, and the fault is cut by the gently to moderately southwest-dipping San Manuel fault (Creasey, 1965). The Star Flat fault, located east of Black Mountain, places volcanic and sedimentary rocks of the Cloudburst Formation over Precambrian granite (Krieger, 1974a). Correlation of the Star Flat fault with the Cloudburst fault is suggested by the fact that both faults place tilted Cloudburst Formation over largely Precambrian crystalline rocks and that the two faults are separated by only 10 km, a distance that would be less if displacement on the younger San Manual-Camp Grant fault (Krieger, 1974b; fig. 9) were restored. The Guild Wash detachment fault in the northern Tortolita Mountains places upper-plate Tertiary volcanic and sedimentary rocks (Banks and others, 1977) that are probably correlative with the Cloudburst and San Manuel Formations (Dickinson, 1983) over typically mylonitic, lower-plate crystalline rocks forming most of the Tortolita Mountains. If the Guild Wash fault is correlative with the Star Flat and Cloudburst detachment faults, as suggested by similar upper- and lower-plate lithologies and geographic proximity of the three faults, then the Cloudburst-Star Flat-Guild Wash detachment fault appears to cut structurally deeper into lower-plate, mylonitic and nonmylonitic crystalline rocks to the southwest in the western Tortolita Mountains.

Correlation of the Guild Wash and Cloudburst faults raises an interesting geometrical problem. The Cloudburst fault is offset about 2.5 km by the San Manuel fault (Lowell, 1968), and the down-dropped, southwest continuation of the Cloudburst fault is buried under San Manuel Formation and is not exposed. Three possible geometries for the southwestward continuation of the Cloudburst detachment fault are: (1) it projects beneath the Santa Catalina Mountains and is at a much deeper structural level than the Catalina fault; (2) it projects beneath the Oracle granite north of the Mogul fault, is offset by south-side-up movement on the Mogul fault, and projects over the Santa Catalina Mountains to connect with the Catalina detachment fault; and (3) it continues upward to the base of the San Manuel Formation, which postdates the fault and buries its trace, and projects over crystalline rocks on both sides of the Mogul Fault to connect with the Catalina fault. The first geometry is considered unlikely because it would allow correlation of the Guild Wash fault with the Cloudburst fault only if the Santa Catalina and central and southern Tortolita Mountains are in the upper and lower plates, respectively, of the Cloudburst fault. This seems highly unlikely given the structural and lithologic similarity of crystalline rocks in the two areas. In other words, we view the first geometry outlined above as prohibitive of a correlation between the Guild Wash and Cloudburst faults. Because we favor this correlation, we find this first geometry unlikely. The second geometry is considered unlikely because it would require major movement on the Mogul fault after detachment faulting, making the Mogul fault a young Basin and Range fault of anomalous trend and peculiarly reduced geomorphic expression. We thus favor the third geometry, as shown in the cross section of figure 9, which correlates the Guild Wash, Star Flat, Cloudburst, Catalina, and San Pedro detachment faults. This geometry is consistent with major movement on the Mogul fault before, not after, detachment faulting. This pre-detachment movement could have been south-side-down in order to account for the fact that the footwall of the detachment fault is middle Proterozoic Oracle Granite north of the Mogul fault, but includes upper Proterozoic and Paleozoic metasedimentary rocks south of the Mogul fault. Alternatively, a pre-mid-Tertiary thrust fault lies beneath the Oracle granite north of the Mogul fault and has been offset by pre-detachment south-side-up movement of the Mogul fault to a position where the thrust fault projects over rocks south of the Mogul fault (Keith, 1984).

The San Pedro fault is locally cut by younger, west-dipping normal faults, and the Cloudburst fault is likewise cut by the southwest-dipping San Manuel fault. These younger faults project beneath the Santa Catalina and Rincon Mountains, and movement on them has resulted in southwestward displacement of crystalline rocks in the Santa Catalina-Rincon Mountains relative to the Galiuro Mountains. The west flank of the Galiuro Mountains forms the breakaway zone for the regionally southwest-dipping Catalina and related detachment faults (Dickinson and others, 1987). This breakaway zone trends about N. 30° W. in contrast to the N. 50° W. trend of the belt of uplifted, arched, lower-plate rocks exposed in the Rincon, Santa Catalina, Tortolita and Picacho Mountains. This 20-degree discordance, with northward-increasing distance between the Galiuro Mountains breakaway and the belt of uplifted mylonitic crystalline rocks, is possibly the result of northward-increasing displacement on faults such as the San Manuel fault that would have accommodated counterclockwise movement of the Rincon-Santa Catalina-Tortolita-Picacho Mountains relative to the Galiuro Mountains. If so, the Rincon Mountains are least displaced by younger normal faults, and a northeast-trending cross section through the range to the Galiuro Mountains would be dominated by a single, warped detachment fault (e.g., Spencer, 1984). In contrast, ranges to the northwest such as the Tortolita and Picacho Mountains have possibly undergone major translation above underlying, southwest-dipping normal faults, and a cross section through one of these ranges to the Galiuro Mountains could contain several southwest-dipping imbricate detachment faults. The combined amount of transport on these imbricate faults, including the Picacho detachment fault, is not necessarily substantially different than the amount of transport on just the Catalina detachment fault in the Rincon Mountains.

Pinaleno-Santa Teresa Mountains Area. Two detachment faults are exposed in the area of the Santa Teresa

Mountains about 100 km northeast of Tucson (figs. 8, 9; Blacet and Miller, 1978; Rehrig and Reynolds, 1980; Davis and Hardy, 1981). Both faults displace a similar sequence of steeply southwest-tilted upper-plate rocks above a structurally continuous lower plate and are inferred to be correlative. Crystalline rocks of the Pinaleno Mountains are continuous with lower-plate rocks in the Santa Teresa Mountains and are strongly overprinted by a lineated mylonitic fabric at the northeast foot of the range (Swan, 1976; Thorman, 1981; Naruk, 1986). The top-to-the-northeast sense of shear indicated for the mylonites by macroscopic shear-zone geometry and by S-C structures (Naruk, 1986; Kligfield and others, 1984) is consistent with the southwest tilt of fault blocks above the Eagle Pass and Black Rock faults (fig. 9) and strongly suggests that the Pinaleno mylonite zone is mid-Tertiary and related to shear at deeper levels of the Eagle Pass-Black Rock detachment fault.

The Santa Teresa Mountains are structurally continuous to the north with the Mount Turnbull block, which is in the hanging wall of the moderately northeast-dipping Hawk Canyon normal fault (Willden, 1964). Rocks above the fault, including middle Tertiary volcanics and overlying San Manuel-like, postvolcanic fanglomerate, dip approximately 40° to the southwest. This requires moderate tilting of at least the western part of the Mt. Turnbull block by rotational movement above the Hawk Canyon fault. The southwest dip of the Eagle Pass fault is possibly due to rotation above a southeastward continuation of the Hawk Canyon fault or related faults that are now buried under younger basin fill in Aravaipa Valley.

The Hawk Canyon fault and related northeast-dipping normal faults continue to the northwest through the Hayes and Mescal Mountains to the vicinity of Globe. These faults project beneath the Globe Hills and San Carlos area and probably account for the overall southwest dip of Proterozoic and Paleozoic strata in these areas.

Summary of Extensional Tectonics in Southeastern Arizona. In summary, the extensional tectonics of the area north and east of Tucson were dominated by displacement above two major detachment faults, the Eagle Pass-Black Rock detachment fault and the Catalina-San Pedro-Guild Wash-Star Flat-Cloudburst detachment fault. Upper-plate rocks are displaced away from the Galiuro Mountains, and the flanks of the Galiuro Mountains approximately coincide with the inferred breakaway faults for both detachment systems. The mirror-image symmetry of mid-Tertiary structures about the axis of the Galiuro Mountains is further accentuated by younger moderate-angle normal faults that dip away from the Galiuro Mountains and project beneath adjacent ranges (cross section in fig. 9).

Central Arizona

In the South Mountains, a key locality for extension-related deformation in central Arizona (fig. 10), gently dipping mylonitic fabrics with the regionally extensive east-northeast-trending lineation have been dated by U-Th-Pb, Rb-Sr, and K-Ar methods at 25 to 20 Ma (Reynolds and Rehrig, 1980; Reynolds, 1985; Reynolds, Shafiqullah, and others, 1986). A top-to-the-east-northeast sense of shear in the mylonitic rocks matches the east-northeast transport direction of rocks above the overlying South Mountains detachment fault. The kinematic and timing relationships indicate that mylonitization and detachment faulting represent a ductile-to-brittle continuum of simple shear on a gently northeast-dipping, normal shear zone (Reynolds, 1985; Davis and others, 1986). The detachment fault projects in the subsurface to the northeast beneath southwest-dipping Tertiary volcanic and clastic rocks near Phoenix and Tempe and is visible on seismic reflection profiles (Frost and Okaya, 1986). The stratigraphic succession in the upper-plate Tertiary rocks, which are composed of a lower, coarse-grained sedimentary breccia, a middle sequence of fluvial red beds, and upper volcanics dated at 17 Ma, suggests that tectonism began before, and continued after, the local inception of volcanism (Scarborough and Wilt, 1979; Schulten, 1979).

Geologic relationships in the White Tank Mountains to the west of Phoenix (fig. 10) are similar to those in the South Mountains (Reynolds, 1980; Rehrig and Reynolds, 1980). Gently dipping mylonitic fabrics with an east-northeast-trending lineation are moderately well developed in the eastern third of the range and have been overprinted on Precambrian gneiss, Tertiary plutons, and middle Tertiary dikes. The overall sense of shear in the mylonites is interpreted to be top-to-the-east-northeast, although thin, late-kinematic shear zones have the opposite vergence (Reynolds and Lister, 1987). A detachment fault has not been recognized, although chloritic-breccia-style brittle structures are present along the eastern edge of the range. We infer that an unexposed detachment fault, correlative with the South Mountains detachment fault, originally overlay the range and dipped east-northeast beneath the volcanic rocks north of Phoenix.

A higher structural level of middle Tertiary deformation is exposed in the Big Horn, Belmont, Vulture, and Hieroglyphic Mountains. In the western Big Horn Mountains, volcanic rocks dated at 20 to 16 Ma (J. Spencer, unpublished K-Ar data) dip moderately to gently to the southwest and are cut by northeast-dipping normal faults (Capps and others, 1985). Toward the east, in the eastern Big Horn and Belmont Mountains, the volcanics dip moderately to steeply to the northeast and are cut by southwest-dipping, low- to high-angle normal faults. Unconformities within the volcanic sequence indicate that volcanism was synchronous with normal faulting and tilting. Coarse sedimentary breccia and landslide-type megabreccia derived from fault scarps and oversteepened volcanic sections were deposited in the larger half grabens after the main pulse of silicic volcanism. Gently tilted to flat-lying basalts dated at 15 to 15.5 Ma occur north and south of the range and mark the termination of the main episode

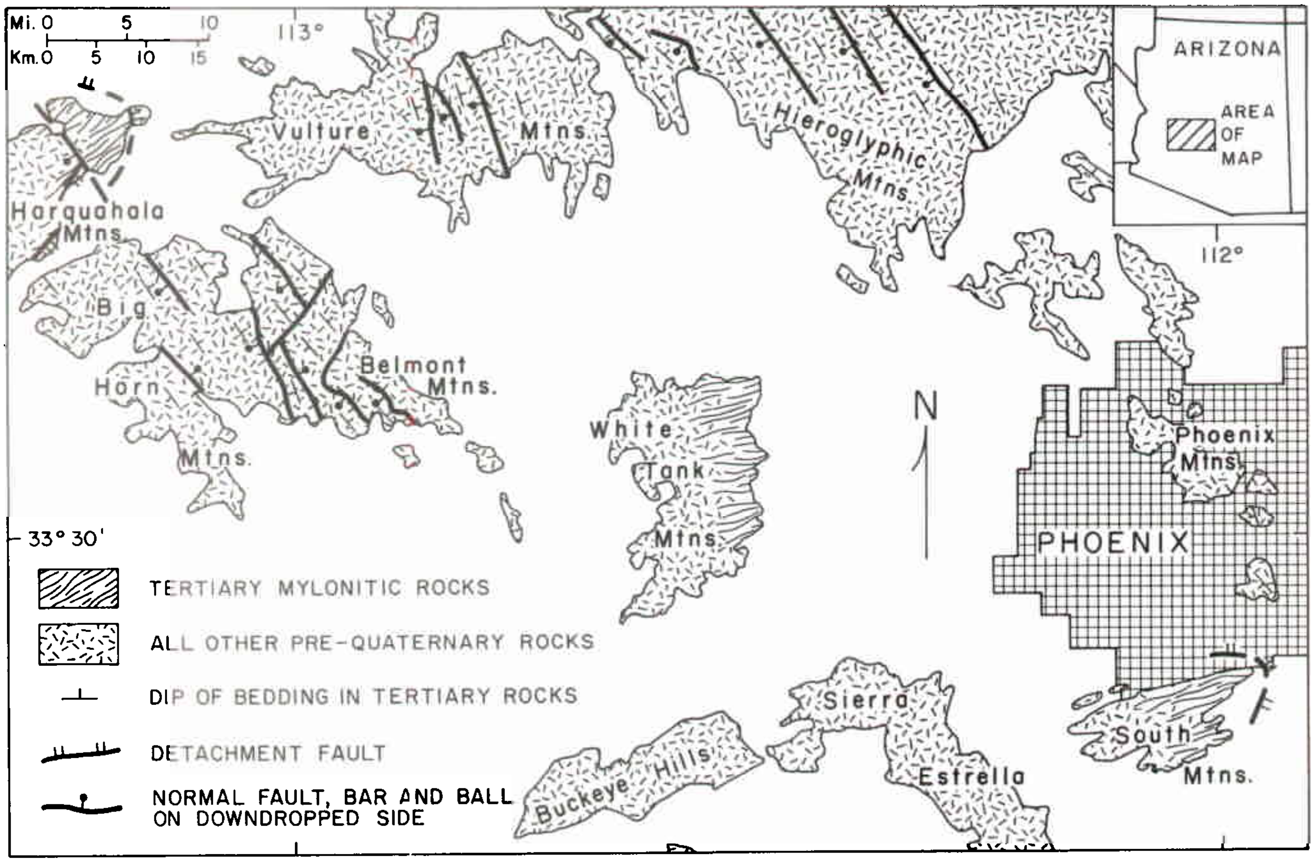


Figure 10. Map of central Arizona showing locations of mountain ranges and major Tertiary fabrics and structures.

of tilting (Scarborough and Wilt, 1979; Shafiqullah and others, 1980).

A nearly identical geologic setting has been documented in the Vulture Mountains to the northeast, where silicic volcanic rocks dated at 26 to 16 Ma dip moderately to steeply to the northeast and are cut by southwest-dipping, low- to high-angle normal faults (Rehrig and others, 1980). Termination of normal faulting and tilting is tightly bracketed by a 16-Ma date on a postfaulting potassic dike and a 13.5-Ma date on flat-lying basalt. Northeast-dipping volcanic rocks and southwest-dipping normal faults continue to the northeast through the Wickenburg and Hieroglyphic Mountains to the southwest edge of the Bradshaw Mountains (Capps and others, 1986; Stimac and others, 1987; Grubensky and others, 1987). Some of the southwest-dipping normal faults in the Wickenburg Mountains are very low angle, have displacements of approximately 3 to 5 km, and truncate higher angle normal faults in the overlying tilted Tertiary rocks (Stimac and others, 1987). The uniform northeast dip direction over the entire region from the central Bighorn Mountains to the Hieroglyphic Mountains suggests several possibilities: (1) the southwest edge of the Bradshaw Mountains is marked by the trace of the breakaway portion of a major southwest-dipping detachment fault or fault system that projects southwestward beneath the Hieroglyphic, Vulture, and Big Horn Mountains; (2) the northeast dip of the Tertiary units is due to movement on southwest-dipping antithetic faults related to a northeast-dipping detachment fault or fault system; or (3) northeast tilting occurred above a regionally southwest-dipping detachment fault or fault system that intersects a regionally northeast-dipping detachment fault or fault system. Northeast-dipping detachment faults in (2) or (3) would possibly link the South Mountains—White Tank detachment fault with the Bullard detachment fault of west-central Arizona. Resolution of these three possibilities is possible only by seismic reflection profiling.

Whipple Tilt-block Domain

One of the most extensive areas of detachment faulting, tilted upper-plate fault blocks, and tectonically denuded mylonitic and nonmylonitic rocks in western North America forms part of western Arizona and adjacent southeastern California and southernmost Nevada. This area composes the Whipple tilt-block domain, an area of approximately 25,000 km² in which Tertiary fault blocks dip predominantly to the west or southwest.

The Whipple tilt-block domain extends parallel to the strike of tilt-blocks (N-S to NW-SE) from the central Eldorado Mountains and northern Black Mountains in southernmost Nevada and northwestern Arizona, respectively, southward along the Colorado River and into west-central Arizona as far southeast as the Big Horn and Little Horn

Mountains (fig. 11). The nature of the northern and southern boundaries of the tilt-block domain is not known, although the boundaries could represent strike-slip faults in the lower plate that separate the Whipple tilt-block domain from areas with detachment faults of opposite dip (west or southwest) and sense of displacement (top to the west or southwest).

The southern part of the Whipple tilt-block domain contains a single regional detachment fault of great lateral extent and several smaller low-angle normal faults of more restricted lateral extent and displacement. The regional detachment fault is the Whipple-Buckskin-Rawhide-Bullard detachment fault (Davis and others, 1980, 1982; Carr and others, 1980; Dickey and others, 1980; Rehrig and Reynolds, 1980; Shackelford, 1980; Reynolds and Spencer, 1985; Spencer and Reynolds, 1987; fig. 12). Its northern continuation is probably represented by the basal detachment fault in the Chemehuevi (John, 1982), Sacramento (McClelland, 1982; Spencer, 1985a), Homer (Spencer, 1985a), Dead, Newberry (Mathis, 1982), and southern Eldorado (Volborth, 1973) Mountains (fig. 11). Multiple detachment faults in some of these northern ranges could represent northward bifurcations of the Whipple-Buckskin-Rawhide-Bullard detachment fault. Displacement on the Whipple-Buckskin-Rawhide-Bullard detachment fault is estimated to be about 40 to 60 km (Reynolds and Spencer, 1985).

Structurally deeper detachment faults appear to project beneath the Whipple-Buckskin-Rawhide-Bullard detachment fault in the southern part of the Whipple tilt-block domain. These faults include the Plomosa (Scarborough and Meader, 1983) and Moon Mountains detachment faults and low-angle normal faults exposed in the Riverside (Hamilton, 1964; Carr and Dickey, 1980; Lyle, 1982), Big Maria (Hamilton, 1982, 1984) and Arica (Baltz, 1982) Mountains (fig. 12). All of these northeast-dipping faults could extend beneath the Whipple-Buckskin-Rawhide-Bullard detachment fault (imbricate detachment faults) or could curve upward to connect with it forming a single warped regional detachment fault (fig. 12). A seismic-reflection profile from the area north of the Turtle Mountains (Frost and Okaya, 1986) dramatically confirmed that the concave-upward, curved geometry of the detachment fault predicted by Howard, Stone, and others (1982), and not an imbricate fault geometry, is the correct geometry for the detachment fault in the vicinity of the Turtle Mountains. Preliminary results of a COCORP seismic reflection survey across the Plomosa-Buckskin Mountains area suggest that the Plomosa detachment fault does not project at depth beneath the Buckskin Mountains (E. Hauser, personal commun., 1987), consistent with hypothesized profiles 2 and 3 in figure 13.

The Whipple tilt-block domain, including lower-plate rocks distended or unroofed by movement on the Whipple-Buckskin-Rawhide-Bullard detachment fault and subsidiary low-angle faults, is bounded on the west by an area that does not contain significant Tertiary extensional faults at surficial levels. This unextended area includes the central Kofa, southern Plomosa, southern New Water, and Dome Rock Mountains in Arizona, most of the Big Maria Mountains, the Little Maria, McCoy, Granite, Iron, Old Woman, and Piute Mountains, and the Piute Range, all in California, and the McCullough Mountains in southern Nevada (zone A in fig. 11). Upper-plate rocks of the Whipple tilt-block domain are separated from the unextended area by one or more breakaway faults that dip regionally eastward or northeastward. It should be noted that the unextended area itself probably sits above the deep-seated projection of detachment faults to the southwest in the central Mohave Desert area (Dokka and Glazner, 1982), and southern Colorado River trough (Garner and others, 1982), but surficial manifestations of extension above these faults are minor or not recognized.

The eastern boundary of the Whipple tilt-block domain is a zone in which normal faulting and fault-block rotation are progressively less significant toward the east (zone E in fig. 11). This zone includes ranges such as the Cerbat, Hualapai, and Poachie Mountains that are composed of large, slightly tilted to untilted, structurally coherent fault blocks that probably lie many kilometers above the northeastward, down-dip projection of the Whipple-Buckskin-Rawhide-Bullard detachment fault and related detachment faults.

The Whipple tilt-block domain can be approximately divided into three belts (zones B, C, and D in fig. 11)—a central belt of uplifted lower-plate rocks bounded on each side by belts of tilted upper-plate rocks. The eastern belt (zone D) is the tapered end of a wedge of upper-plate fault blocks above an east-dipping detachment fault or faults that project at depth toward zone E and the Transition Zone-Colorado Plateau (zones F and G, respectively). The western belt (zone B) is a detached, synformal keel of upper-plate fault blocks above a master detachment fault that projects over the central belt (zone C; see also Spencer, 1984). Zone B also includes tilted fault blocks above possible low-angle normal faults that project beneath the central belt (zone C) of uplifted lower-plate rocks.

Mid-Tertiary volcanic and sedimentary rocks in upper-plate fault blocks of the Whipple tilt-block domain were deposited between about 30 and 15 Ma. These mid-Tertiary rocks rest depositionally on Precambrian crystalline rocks and less commonly on younger metamorphic and igneous rocks. Sedimentary and volcanic rocks representing the time interval from about 100 to 30 Ma are completely absent; this indicates that the area was topographically high and undergoing erosional denudation before extensional faulting. Because the formation of sedimentary basins and deposition of coarse clastic sediments above rotating normal-fault blocks is viewed as a manifestation of crustal extension, the age of these tilted sedimentary and volcanic rocks is interpreted as the time of extensional faulting. K-Ar dates of tilted volcanic rocks in the Whipple Mountains

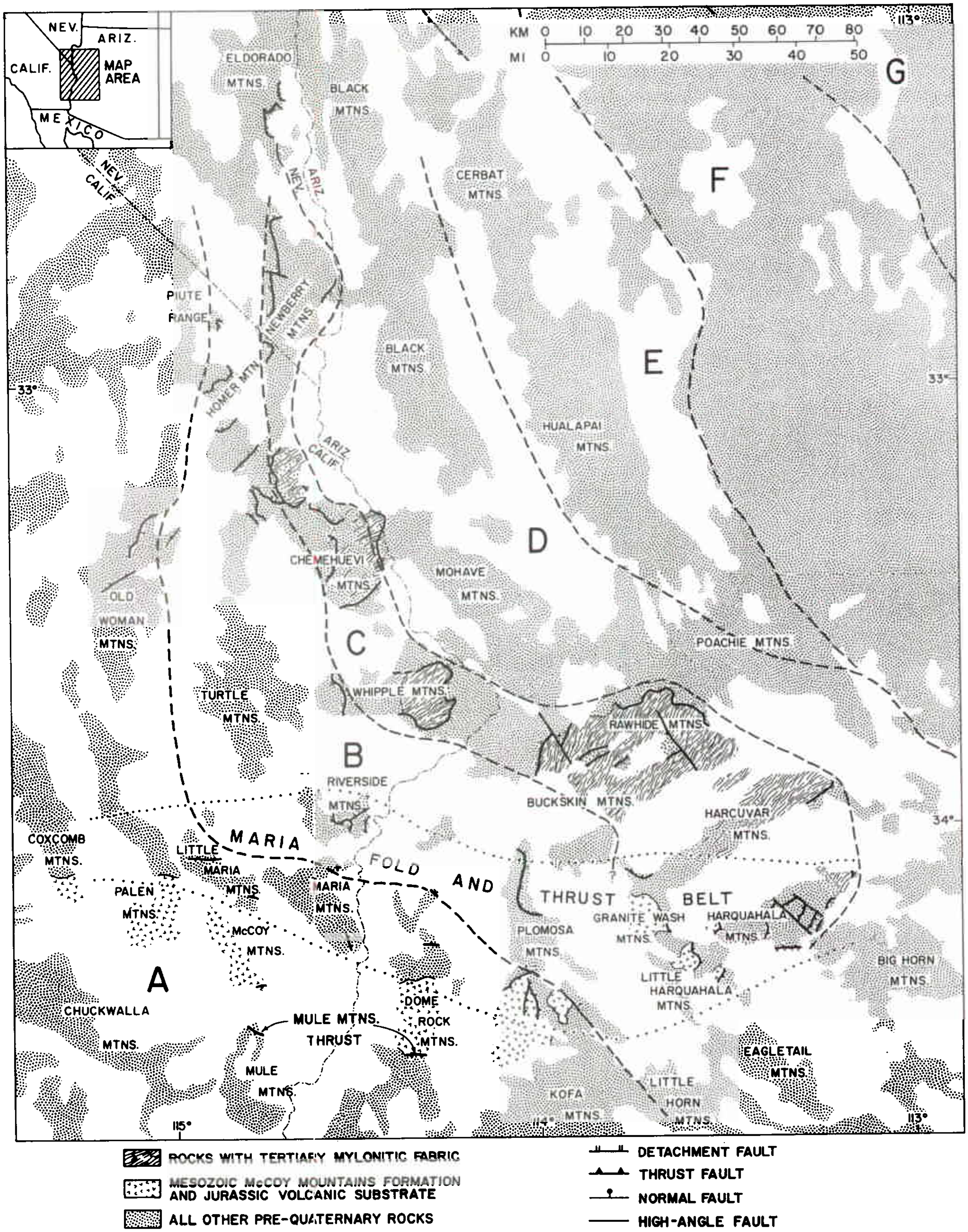


Figure 11. Generalized tectonic-domain map for mid-Tertiary structures in the Whipple tilt-block domain and surrounding area. (A) Area of minor extension at surficial levels, (B) synformal keel of distended upper-plate rocks above warped regional detachment fault, (C) zone of archlike uplifts of lower-plate rocks forming metamorphic core complexes, (D) wedge-shaped extensional allochthon of moderately to highly tilted and extended upper-plate rocks, (E) area of slight to moderate extension characterized by large fault blocks with little or no tilt, (F) Transition Zone, and (G) Colorado Plateau.

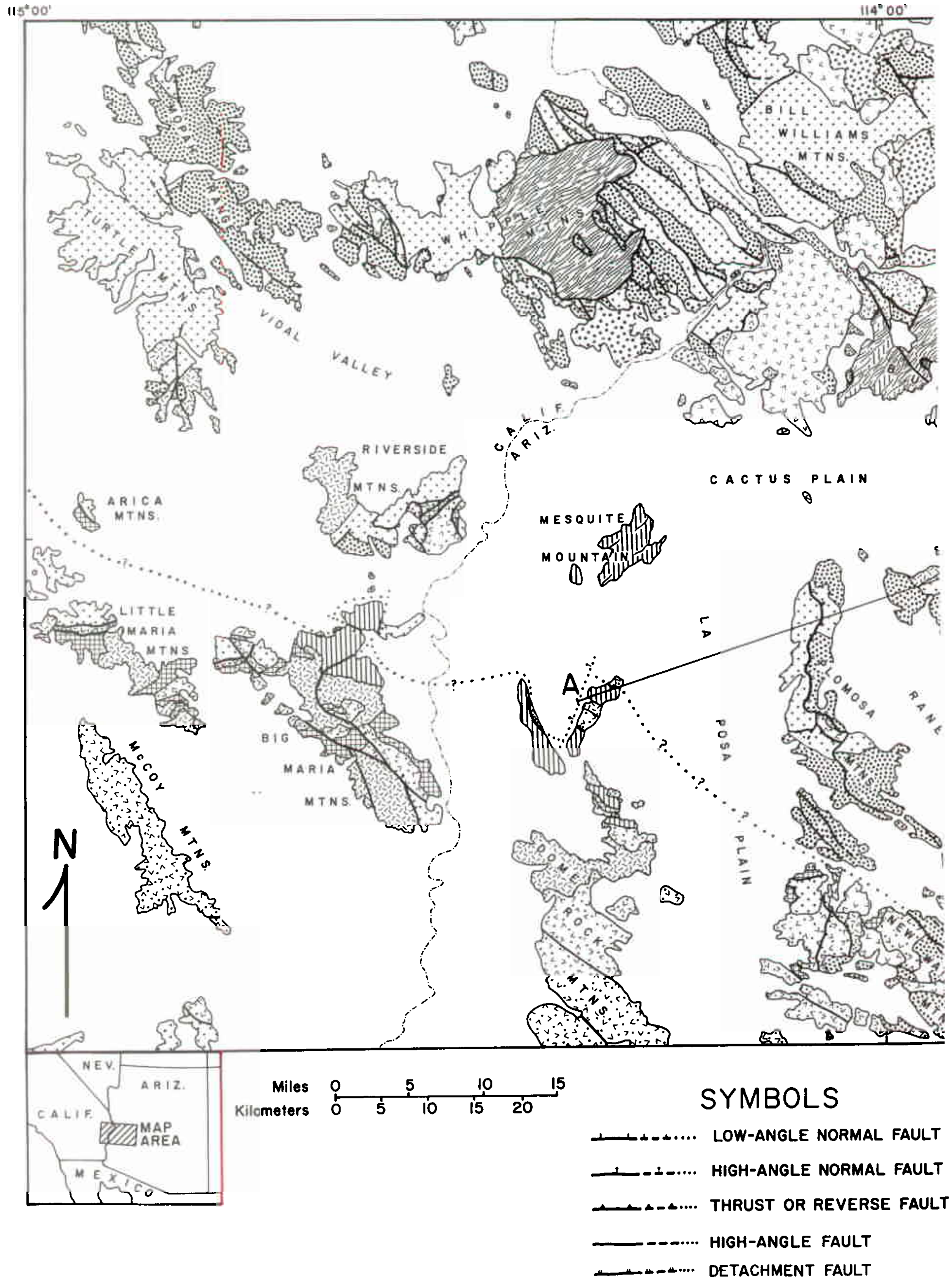
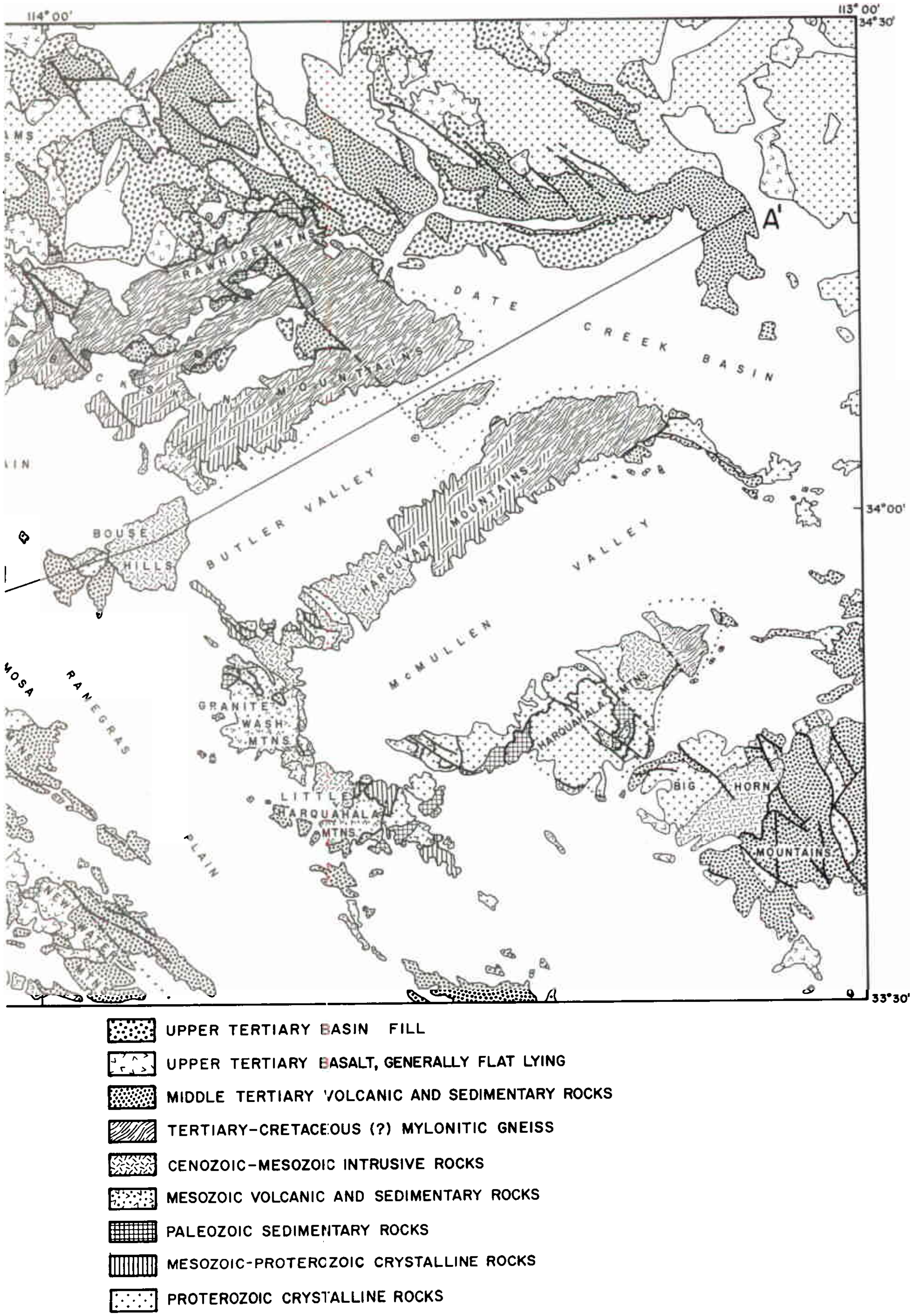


Figure 12. Simplified geologic map of west-central Arizona and adjacent parts of southeastern California.


114° 00'
113° 00'
34° 30'
A'
RAWHIDE MTNS
DATE CREEK BASIN
BUTLER VALLEY
BOUSE HILLS
HARCUVAR MOUNTAINS
McMULLEN VALLEY
34° 00'
GRANITE WASH MTNS
RANEGRAS
PLAIN
HARQUAHALA MTNS
LITTLE HARQUAHALA MTNS
BIG HORN MOUNTAINS
NEW WATER MTNS
33° 30'
UPPER TERTIARY BASIN FILL
UPPER TERTIARY BASALT, GENERALLY FLAT LYING
MIDDLE TERTIARY VOLCANIC AND SEDIMENTARY ROCKS
TERTIARY-CRETACEOUS (?) MYLONITIC GNEISS
CENOZOIC-MESOZOIC INTRUSIVE ROCKS
MESOZOIC VOLCANIC AND SEDIMENTARY ROCKS
PALEOZOIC SEDIMENTARY ROCKS
MESOZOIC-PROTEROZOIC CRYSTALLINE ROCKS
PROTEROZOIC CRYSTALLINE ROCKS

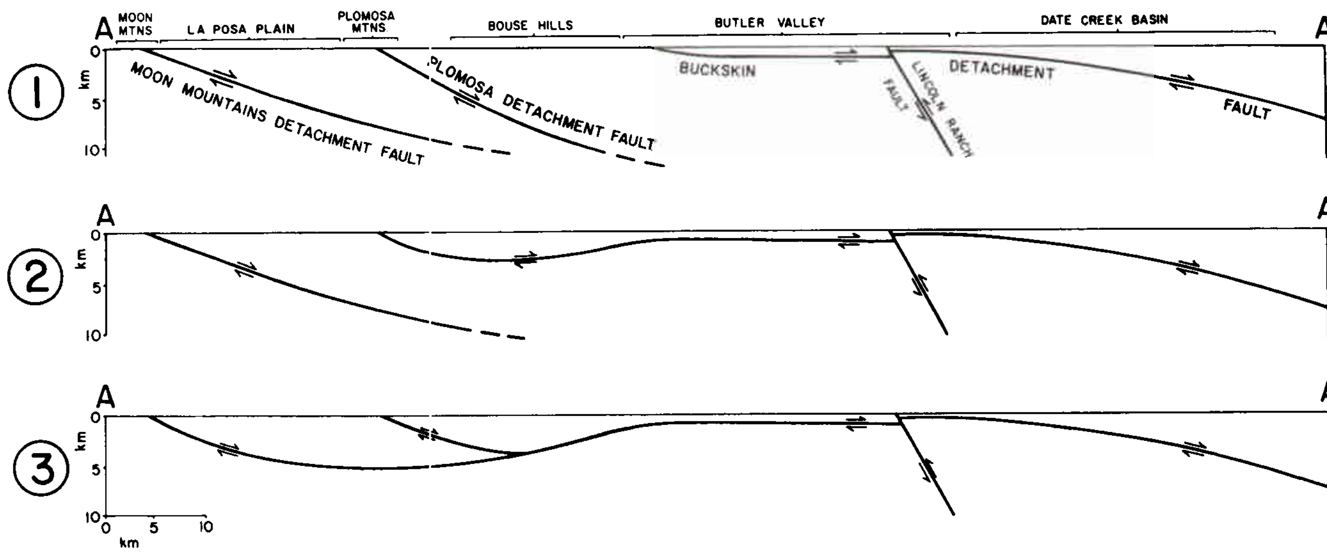


Figure 13. Three possible subsurface detachment-fault geometries for cross section A-A′ in figure 12.

tiltblock domain fall within a range of 32 to 12 Ma, although most dates fall in the range of 22 to 15 Ma (Frost and Martin, 1982, and references in Reynolds, Florence, and others, 1986), which is interpreted as the time of the most active extensional faulting.

The uplifted, lower-plate rocks exposed in the core complex belt of the Whipple tilt-block domain (zone C in fig. 11) have been variably overprinted by a weak to strong mylonitic foliation with a N. 50° to 60° E.-trending mylonitic lineation. Mylonitic fabrics are especially well developed in the Whipple, Buckskin, Rawhide, and Harcuvar Mountains (fig. 11). Mylonitization occurred largely if not entirely by top-to-the-northeast shear along the downdip projection of the regional detachment fault during mid-Tertiary time (Davis and others, 1986; Wright and others, 1986). The subhorizontal, undulating mylonitic foliation in the Whipple, Buckskin, Rawhide, Harcuvar, and Harquahala Mountains and the overlying regional detachment fault define at least eight northeast-trending arches that have axes parallel to mylonitic lineation and to the inferred direction of displacement of the upper plate (Rehrig and Reynolds, 1980; Davis and others, 1980; Frost, 1981a, 1981b). The geometric alignment between arch axes and mylonitic lineation is strongly suggestive of a genetic relationship between the two features, although the nature of this relationship and the origin of the arches is not clear.

The two elongate, east-northeast-trending arches in the Whipple Mountains are doubly plunging (Frost, 1981a), and the three east-northeast-trending arches in the Rawhide and Buckskin Mountains have long, horizontal crests that roll over to plunge gently to moderately beneath alluvium and upper-plate rocks along the northeast and southwest ends of the arches. The arches of the Harcuvar and Harquahala Mountains have approximately horizontal crests that roll over to plunge gently northeastward at the northeast ends of the ranges. Mylonitic foliation also rolls over to a southwest dip in the southwestern Harcuvar Mountains (Rehrig and Reynolds, 1980; Reynolds and Lister, 1987).

Two processes probably account for formation of the broad, north-northwest-trending monoclinal or anticlinal warps of the elongate east-northeast-trending arches and are responsible for the plunge at their ends: (1) differential isostatic rebound due to differential tectonic denudation (Rehrig and Reynolds, 1980; Howard, Stone, and others, 1982; Spencer, 1984), and (2) reverse drag (Hamblin, 1965) above deeper listric normal faults (Spencer, 1984; see also Bartley and Wernicke, 1984, and Gans and others, 1985). If the Plomosa fault extends under the Buckskin Mountains, reverse drag above this fault or above listric faults that merge downward with the Plomosa fault could be responsible for the southwest plunge of the arches in the southwestern Buckskin Mountains (fig. 13, cross section 1). However, the monoclinal warp at the northeast end of the Buckskin, Rawhide, and Harcuvar Mountains is too far (60-80 km) from the trace of any possibly structurally lower detachment faults to be due to reverse drag above such faults. Possibly the monoclinal flexure at the northeast ends of the east-northeast-trending arches is the result of differential isostatic rebound, and the monoclinal flexure at the southwest ends could have been produced by differential isostatic rebound or reverse drag, or both.

In summary, the dominant tectonic process affecting the Whipple tilt-block domain was detachment and distention of an enormous extensional allochthon and its displacement to the east relative to the lower plate. Rocks forming the eastern belt of tilted upper-plate fault blocks (zone D in fig. 11) were displaced from a position over the central belt of lower-plate rocks that underwent isostatic uplift due to denudational faulting (zone C in fig. 11). Another way of visualizing this process is to consider the lower plate as having been drawn up and out from beneath the distending upper plate. The largest exposed, tilted fault block in the Whipple tilt-block domain is in the Mohave Mountains in western Arizona; it forms a dominolike fault block, now tilted 50-60 degrees to the southwest, that was originally above a detachment fault at a depth of at least 12 km (Howard, Goodge, and John, 1982). The Mohave Mountains tilt block probably originated over lower-plate rocks between the Whipple and Chemehuevi Mountains in California.

Lake Mead Tilt-block Domain

Structures related to Tertiary extensional faulting are more complex in the Lake Mead area than in the Whipple tilt-block domain to the south. The Lake Mead tilt-block domain is characterized by east-tilted fault blocks, but unlike the Whipple tilt-block domain contains no large exposures of lower-plate mylonitic rocks or detachment faults. A detachment fault and underlying mylonitic rocks (Choukroune and Smith, 1985) with evidence of top-to-the-west shear are exposed on Saddle Island in Lake Mead. In addition, two major strike-slip faults cross the area and are associated with extensional faulting (fig. 14).

South of Lake Mead, between the area of strike-slip faulting and the northern end of the Whipple tilt-block domain, east-west to east-northeast--west-southwest extension occurred in an 80-100-km-wide corridor between the slightly extended McCullough Range and the Colorado Plateau-Transition Zone. In the western part of this corridor, extreme crustal extension in the northern Eldorado and northern Black Mountains resulted in steep tilting and intricate faulting of primarily volcanic rocks of Miocene age (Anderson, 1971). Plutonism accompanied faulting and has been interpreted as accommodating extension at depth (Anderson, 1971).

A regionally north-south-trending, west-dipping, low-angle normal fault in the White Hills, east of the northern Black Mountains, displaces Precambrian crystalline rocks and Miocene sedimentary and volcanic rocks westward relative to lower-plate crystalline rocks. A Cretaceous two-mica granite is cut and displaced by the fault, indicating about 5 km of top-to-the-west displacement (Theodore and others, 1982; Myers and others, 1986). The fault continues northward across Lake Mead and around the west flank of the southern Virgin Mountains, probably connecting with the Gold Butte fault (e.g., Bohannon, 1979, fig. 2). A small area of "mylonite breccia" at the western foot of the southern Virgin Mountains (Volborth, 1962) consists of crystalline rocks with an east-west lineation and top-to-the-west sense-of-shear indicators and is inferred to represent ductile shearing along the downdip projection of the White Hills-Gold Butte fault. The southern Virgin Mountains, which form part of the footwall of this fault, contain Precambrian crystalline rocks and depositionally overlying Paleozoic sedimentary rocks that dip 55-65 degrees to the east (Longwell and others, 1964). If the Precambrian crystalline rocks beneath the Paleozoic rocks are structurally coherent with respect to Tertiary faulting, then the entire southern Virgin Mountains represent a single 20-km-wide tilt block, and rocks now exposed at the western foot of the range were at a depth of 16-18 km prior to tilting and unroofing. Tilting of the southern Virgin Mountain block occurred above underlying gently dipping normal faults such as the Iceberg Canyon fault (Longwell, 1936). These gently dipping faults cut bedding at a high angle and thus formed as high-angle normal faults that were rotated, along with adjacent fault blocks, to their present attitudes. A basal detachment fault may underlie all of these tilted fault blocks, but is nowhere exposed. This hypothetical detachment fault would surface in a breakaway zone now under alluvium just west of the Grand Wash Cliffs and would extend under all of the southern Virgin Mountains, Lost Basin Range, and White Hills. It probably loses displacement northward toward the head of Grand Wash and dies out before reaching bedrock in the northern Virgin Mountains (Moore, 1972).

The corridor of extensional faulting in the northern Colorado River trough terminates northward at the right-lateral Las Vegas Valley shear zone and left-lateral Lake Mead shear zone. These faults acted as transform faults that connected areas of extensional faulting, much as an oceanic transform fault connects spreading centers (Fleck, 1970). Extension south of the Las Vegas Valley and Lake Mead shear zones was transformed northwestward along the Las Vegas Valley shear zone to the faulted and tilted Sheep, Pintwater, and Desert ranges (Guth, 1981) and was transformed northeastward along the Lake Mead shear zone to the Virgin River valley and Mormon Mountains (Wernicke and others, 1985). Both of these northern areas of extensional faulting are dominated by fault blocks tilted to the east above known or inferred, regionally west-dipping, low-angle normal faults. The two areas of extension north of the strike-slip faults are separated by a region that has not undergone significant extension and includes most of the Muddy Mountains and ranges to the northwest including the Las Vegas, Arrow Canyon, and Dry Lake ranges (fig. 14).

The amount of displacement on each strike-slip fault has been inferred to be approximately equal to the amount of extension in each associated northern area of extensional faulting, and the sum of the amounts of displacement has been considered as approximately equal to the total amount of extension south of the strike-slip faults. Estimates of extension are thus dependent on the inference that all of the offset is Tertiary. Offset on the Las Vegas Valley shear zone is estimated to be 44-69 km, based on offset of Mesozoic thrust faults and on estimates of the amount of bending that affected rocks adjacent to the fault zone (e.g., Longwell, 1974; Guth, 1981; Wernicke and others, 1982). Tertiary extensional faulting north of the Las Vegas shear zone terminated at the shear zone, and thus at least some of the movement on the shear zone is Tertiary in age (Guth, 1981). However, much of the net displacement across the shear zone is represented by bending of Mesozoic structures and is not clearly of Tertiary age (Royse, 1983). One branch of

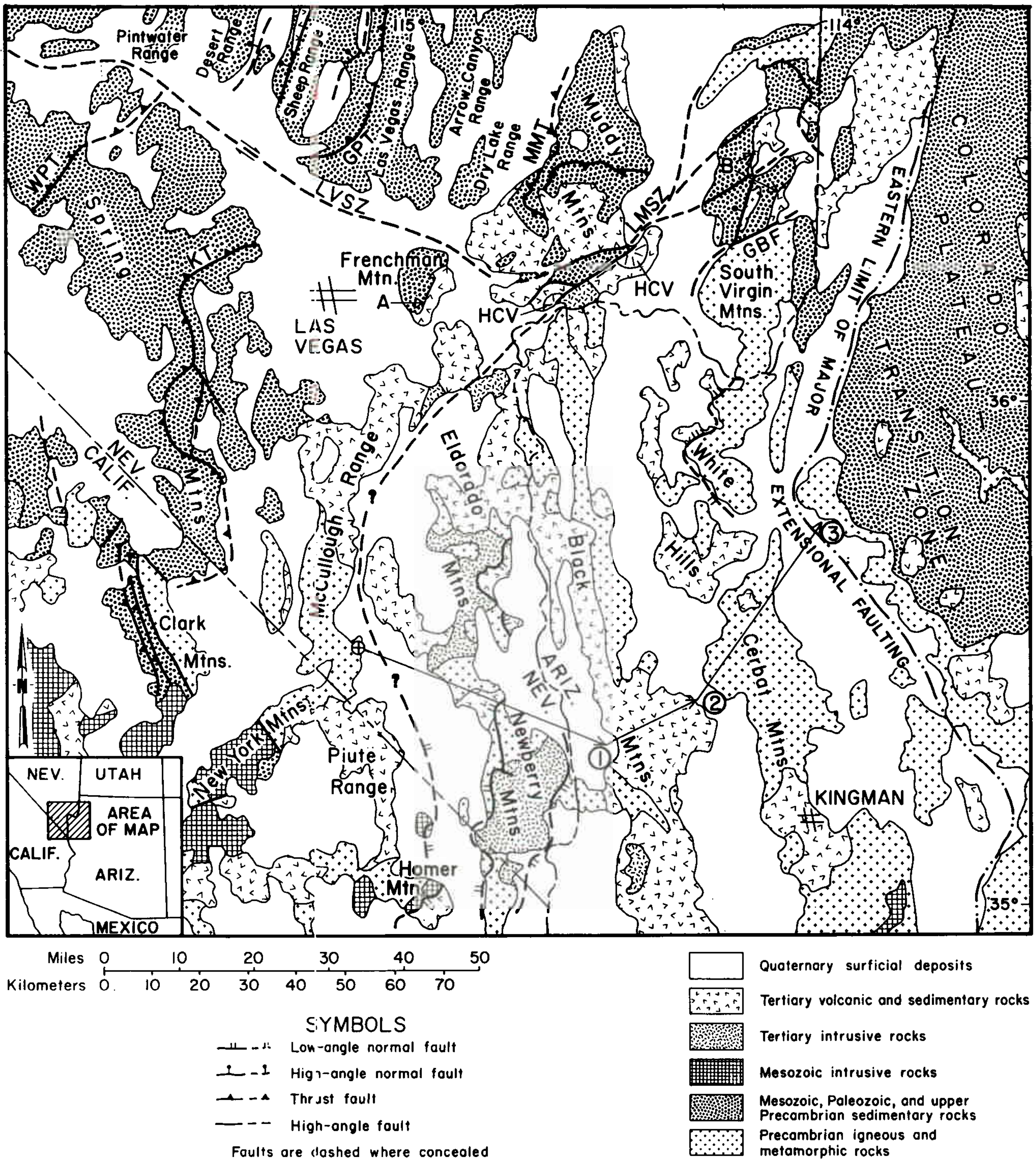


Figure 14. Highly simplified geologic map of the Lake Mead-northwest Arizona area. The Spring Mountains-Clark Mountains-McCullough Range-New York Mountains-Piute Range area has not undergone significant extension at upper crustal levels. Las Vegas Valley shear zone (LVSZ) and Lake Mead shear zone (LMSZ) connect areas of extensional faulting in a manner similar to that of transform faults that connect oceanic spreading centers. All of the extension in the northern Colorado River trough was transformed northwestward by the LVSZ or northeastward by the LMSZ. Reconstruction of offset markers on strike-slip faults allows reconstruction to a pre-extension configuration (e.g., Wernicke and others, 1982). Reconstruction of 55 km of right-lateral slip on the LVSZ restores the southeastern McCullough Range to locality (1) (arrow represents reconstruction vector). This reconstruction realigns the Wheeler Pass thrust (WPT) with the Gass Peak thrust (GPT) and the Keystone thrust (KT) with the Muddy Mountain thrust (MMT) (see references in Wernicke and others, 1982). Restoration of 20 km of movement on one branch of the LMSZ juxtaposes each half of the Hamblin Bay-Cleopatra volcano (HCV; Anderson, 1973) and moves the southeastern McCullough Range to the northeast to position (2). Restoration of 65 km of total displacement of the LMSZ realigns a distinctive depositional contact between Tertiary and pre-Tertiary rocks at Frenchman Mountain (location A) with a highly similar contact in the southern Virgin Mountains (location B; Bohannon, 1979), and restores the southeastern McCullough Range to a position adjacent to the Colorado Plateau (3). GBF=Gold Butte fault.

the Lake Mead fault system offsets a Miocene volcano 20 km (Anderson, 1973), and several lines of evidence have been interpreted to indicate that total displacement on the fault system is approximately 65 km (Bohannon, 1979). If all of the offset is considered to be Tertiary in age, these offset estimates indicate that 100-120 km of east-west extension has occurred in the northern Colorado River trough south of Lake Mead.

The McCullough Range, located along the west side of the northern Colorado River trough, appears to be structurally continuous with the New York, Clark, and Spring Mountains (Hewett, 1956), and together these ranges represent a large unextended area that was displaced westward, relative to the Colorado Plateau, by extension in the Lake Mead area. Restoration of 100-120 km of extension in the area south of Lake Mead, as indicated by strike-slip fault offsets, places the McCullough Range immediately adjacent to the edge of the Colorado Plateau (fig. 14). If this reconstruction is accurate, then all of the pre-mid-Tertiary rocks in the northern Colorado River trough must have been pulled up and out from beneath the McCullough Range and ranges farther west or from beneath the Colorado Plateau-Transition Zone to the east. Although these older rocks are poorly studied, they do not appear to have been at mid-crustal levels prior to middle Tertiary extension. For example, the Mineral Park porphyry copper ore body in the Cerbat Mountains, now exposed at the surface, was probably emplaced at a depth of no more than 3 to 4 km (Sillitoe, 1973; Wilkinson and others, 1982). Estimates of strike-slip fault offset are thus probably either in error or are not strictly applicable to amounts of extension. Possibly bending of Mesozoic structures along the Las Vegas shear zone occurred in Mesozoic time (Longwell, 1960) and is not applicable to estimates of Tertiary extension (Royse, 1983). Major extension certainly occurred in the northern Colorado River trough, but estimates of 50-80 km extension seem more consistent with the geology of the area.

Much of the extensional faulting in the Lake Mead area occurred between about 12 and 16 Ma, although the ages of inception and termination of faulting are not well constrained. In the northern Black Mountains, tilted volcanic rocks dated at 15 Ma occur near flat-lying basalt dated at 13.5 Ma (Anderson and others, 1972; ages recalculated for new constants following Dalrymple, 1979). Dates on tilted and untilted volcanic rocks in the northern Eldorado Mountains place similar constraints on the age of major tilting. In the Muddy Mountain area, the basal Rainbow Gardens member of the Horse Spring Formation was deposited on pre-Tertiary rocks in a broad sedimentary basin formed at about 18-20 Ma (Bohannon, 1984). Deposition of this unit represents a major change in tectonic regime from an uplifted area undergoing erosional denudation or nondeposition to a subsiding sedimentary basin; this change is inferred to be the result of initiation of extensional tectonism. Active faulting controlled facies distributions in parts of the Rainbow Gardens Member and overlying Thumb Member (dated at 17 to 13.5 Ma) and was especially significant during deposition of the upper part of the Thumb Member (Bohannon, 1984). The Muddy Creek Formation largely postdates extension and has yielded K-Ar dates as old as 11 Ma (Damon and others, 1967; McKee, 1982).

Extensional faulting and basin formation thus appear to have occurred over at least a 5- to 9-Ma period, with the most intense activity occurring between about 13 and 16 Ma. Although there is some overlap, these ages are in part younger than those from most of the tilted rocks in the Whipple tilt-block domain.

Southwestern Arizona

Middle Tertiary tectonism was widespread in southwestern Arizona, as evidenced by numerous low- to high-angle faults, steeply tilted middle Tertiary volcanic rocks, and coarse-grained clastic rocks. The best documented middle Tertiary structures occur along the lower Gila River and in the Trigo-Kofa Mountains area.

Lower Gila River Area. This area includes an east-west strip extending along the lower Gila River from Mohawk to Yuma (fig. 15). On the eastern end of the area, a gently east-dipping detachment fault is exposed along the east side of the Mohawk Mountains (Mueller and others, 1982). This fault separates lower-plate Precambrian gneiss from an upper plate composed of Laramide granites and depositionally overlying, southwest-dipping middle Tertiary conglomerate and sedimentary breccia that were derived from the granites. The lower-plate metamorphic rocks have been converted into chloritic breccia directly below the fault, but lack detachment-related mylonitic fabrics. We interpret the mismatch of upper- and lower-plate crystalline lithologies and relatively minor abundance of lower-plate metamorphic clasts in the upper-plate conglomerate as indicating that the detachment fault has a minimum of 5 km of top-to-the-northeast normal slip. The lack of detachment-related mylonitic fabrics suggests that the total amount of transport may be less than about 10 to 15 km.

West of the Mohawk Mountains in the Baker Peaks-Copper Mountains-Wellton Hills area, a detachment fault separates upper-plate middle Tertiary clastic rocks from lower-plate gneiss (Pridmore and Craig, 1982; Pridmore, 1983). The detachment fault has a broadly arcuate trace and dips 10° to 15° to the north and west. Upper-plate clastic rocks dip steeply to moderately southwest, are cut by northeast-dipping normal faults, and are interpreted to have been deposited in half grabens formed during detachment faulting (Pridmore, 1983). Approximately 5 to 10 km or more of relative northeast transport of the upper plate appears required by the lithologic mismatch across the fault and by the lack of lower-plate gneiss in upper-plate clastic rocks.

The northeast-trending Gila Trough, which is a structural basin that parallels the modern Gila River

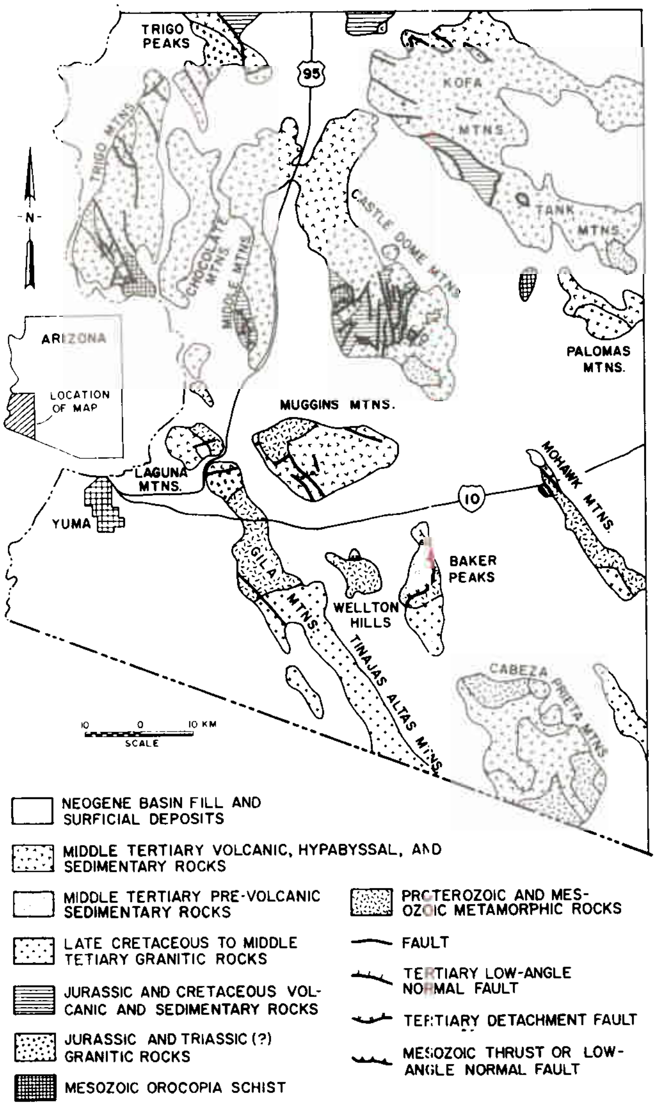


Figure 15. Simplified geologic map of southwestern Arizona. Sources of data referenced in text.

between the Gila Mountains and Sentinel volcanic field, has been variably interpreted as a fault-bounded graben (Eberly and Stanley, 1978) or a broad synform related to detachment faulting (Pridmore and Craig, 1982; Pridmore, 1983). The graben model is supported by drill-hole data and a seismic reflection profile oriented across the trough that show a lower sequence of sedimentary rocks that is thickest within the trough and thins dramatically across both trough-bounding faults (Eberly and Stanley, 1978). If this sedimentary sequence indeed underlies middle Tertiary volcanics, as interpreted by Eberly and Stanley, then the Gila Trough probably started to form before 20 to 25 Ma (the age of regional volcanism).

Further evidence for the timing of middle Tertiary deformation has been documented in the Laguna and northern Gila Mountains, north of Yuma (Olmstead, 1972; Olmstead and others, 1973; Scarborough and Wilt, 1979; Shafiqullah and others, 1980). The oldest Tertiary unit consists of fine-grained clastic rocks that depositionally overlie Precambrian(?) gneiss in the Laguna Mountains. This unit coarsens upward and is overlain by coarse conglomerate and sedimentary breccia derived from porphyritic granite exposed to the southwest near Yuma. The conglomerate and breccia unit and underlying fine-grained clastic rocks dip moderately southwest and are unconformably overlain by 27-Ma volcanic rocks that also dip to the southwest. This entire sequence is unconformably overlain by the Kinter Formation, a sequence of lower fanglomerates and upper fine-grained clastic rocks that contains a 24-Ma tuff. Although the Kinter Formation is gently dipping in the Laguna Mountains, it dips moderately southwest in the adjacent northern Gila Mountains. K-Ar dates and stratigraphic relationships demonstrate that tectonism, represented by coarse conglomerate and sedimentary breccia, began in the Oligocene (prior to 27 Ma) and continued into the early Miocene.

A time-correlative sequence of middle Tertiary rocks is also exposed to the east in the Muggins Mountains where a coarse sedimentary breccia low in the Tertiary section is successively overlain by (1) rhyolitic flows and tuffs, (2) interbedded volcanics and a clastic unit correlated with the Kinter Formation, and (3) an upper sequence of dacitic and rhyodacitic flows (Smith and others, 1984). The entire Tertiary sequence dips to the southwest and is cut by northeast-dipping normal faults and associated northeast-trending transfer faults. Limited K-Ar dates from the Tertiary units range between 22 and 30 Ma (Shafiqullah and others, 1980).

In summary, the entire lower Gila River area is characterized by southwest-dipping Oligocene to early Miocene clastic and volcanic sections that are, at least locally, floored by low-angle detachment faults with significant top-to-the-northeast normal slip. Some clastic units represent syntectonic deposition in half grabens formed by growth faulting above the detachment fault. Tectonism began some unknown amount of time before volcanism. The oldest syntectonic sedimentary units underlie the main volcanic sequence, and it is possible that the prevolcanic, syntectonic units are broadly correlative in a time-stratigraphic sense (Pridmore, 1983). Tectonism, however, must have continued after widespread volcanism in order to account for tilting of the volcanic units and overlying fanglomerates in the Laguna, Gila, and Muggins Mountains. Comparison of the timing of tectonism in this area with that in southeastern Arizona suggests that although middle Tertiary magmatism becomes younger from east to west, the initiation of tectonism may be synchronous.

The exposed levels of detachment faulting in this area are probably higher than those exposed in the belt of metamorphic core complexes between Tucson and the Whipple Mountains. This is indicated by the lack of detachment-related mylonitic fabrics and by the lack of evidence for major middle Tertiary uplift and cooling; K-Ar cooling ages in the crystalline basement of southwestern Arizona are generally early Tertiary (Shafiqullah and others, 1980). Nevertheless, if the exposed detachment faults have displacements of approximately 10 km, then middle Tertiary tectonic denudation may help explain the general lack of middle Tertiary supracrustal rocks in mountain ranges south of the Gila River that are structurally beneath the Mohawk-Baker Peaks detachment system.

Trigo-Kofa Mountains Area. The Trigo, Castle Dome, and Kofa Mountains are all largely composed of middle Tertiary volcanic rocks and scattered exposures of metamorphosed and deformed Mesozoic supracrustal and granitoid rocks. Middle Tertiary volcanics in the Trigo Mountains range in age from 20 to 29 Ma and dip moderately southwest in the southern part of the range and northeast in the northern part (Weaver, 1982; Tosdal and Sherrod, 1985). Contacts between the tilted Tertiary sections and pre-Tertiary basement rocks are generally faulted, with most faulting and tilting being younger than the main episode of volcanism (Garner and others, 1982; Tosdal and Sherrod, 1985). Garner and others (1982) attributed the northeast stratal dips to southwest transport above a broadly folded detachment fault separating Tertiary and pre-Tertiary rocks. In contrast, Tosdal and Sherrod (1985) interpreted both the northeast and southwest dips as possibly being due to overall northeast-directed transport above the northeast-dipping Midway Mountains detachment fault, which would not, by this model, be exposed in the Trigo Mountains; they proposed that the "folded detachment fault" of Garner and others(1982) is actually a series of upper-plate synthetic and antithetic faults with only minor movement.

Northeast-dipping middle Tertiary sections continue from the northern Trigo Mountains eastward into the Castle Dome and Kofa Mountains. The presence of a middle Tertiary caldera between the Castle Dome and Trigo Mountains is indicated by changes in the volcanic stratigraphy and a large negative gravity anomaly (Gutmann, 1981, 1982). In the Castle Dome Mountains, low-angle normal faults with several kilometers of displacement cut the 20- to 25-Ma volcanics and underlying Mesozoic and Precambrian units (Logan and Hirsch, 1982; G. Haxel and M. Grubensky, 1984, personal commun.). The basement rocks have been intruded by numerous north-northwest-trending middle Tertiary dikes dated at 19 to 20 Ma.

Similar relationships occur in the nearby Kofa Mountains, where Tertiary volcanic units and the basal Tertiary unconformity dip moderately to the northeast (Dahm and Hankins, 1982; Hankins, 1984; D. Sherrod and M. Grubensky, personal commun., 1984). Rocks low in the volcanic sequence dip more steeply than higher units, which indicates that tilting and normal faulting occurred during volcanism at 24 to 18 Ma (Shafiqullah and others, 1980). Pre-Tertiary rocks exposed along the southwest flank of the range are cut by numerous north-northwest-trending dikes dated at 20 to 25 Ma. Low-angle normal faults of unknown displacement occur at most Tertiary-pre-Tertiary contacts (M. Grubensky, 1985, personal commun.).

Other Areas in Southwestern Arizona. Evidence of intense middle Tertiary deformation is also present in other parts of southwestern Arizona. In the Little Ajo Mountains near Ajo, poorly sorted conglomerate and sedimentary breccia of the Locomotive Fanglomerate dip moderately southwest against east- to northeast-dipping normal faults (Gilluly, 1937). The fanglomerate abruptly thins laterally, which suggests that it was deposited in a fault-bounded trough, probably a half graben. Upper units of the fanglomerate are interbedded with and overlain by the 15- to 22-Ma Ajo Volcanics (Gray and Miller, 1984). Based on the presence of a 25-Ma andesitic flow within the middle of the fanglomerate, deposition of the fanglomerate, and therefore the initiation of tectonism, may have predated eruption of the Ajo Volcanics by at least 3 Ma.

In the eastern Gila Bend Mountains, the lower member of the Sil Murk Formation is composed of a basal eolian sandstone overlain by coarse conglomerate composed of crystalline clasts (Heindl and Armstrong, 1963; Scarborough and Wilt, 1979). These units dip moderately southwest and are overlain by the upper member of the Sil Murk Formation, which contains more gently tilted volcanics dated at 27 Ma (Eberly and Stanley, 1978). These relationships demonstrate that tectonism represented by the conglomerates began in the Oligocene.

Summary of Tectonism in Southwestern Arizona. Middle Tertiary tectonism, represented by conglomerate and sedimentary breccia, strongly tilted Tertiary sections, and numerous low- to high-angle faults, began in southwestern Arizona in the Oligocene, in many areas prior to widespread volcanism. Formation of detachment faults and associated upper-plate, growth-fault basins (Pridmore, 1983) occurred during this early phase of crustal extension. In several areas, much of the tilting of Tertiary sections had occurred by the earliest Miocene. In other areas, notably the Trigo Mountains, normal faulting and tilting continued through the early Miocene, after the main pulse of volcanism. The amount of crustal extension (10-40 percent; Tosdal and Sherrod, 1985) is less than that which occurred in the belt of metamorphic core complexes. As the two areas have similar present crustal thicknesses, additional crustal thinning probably occurred in southwestern Arizona during low-angle Laramide subduction (Keith and Wilt, 1985) or late Tertiary Basin and Range faulting possibly related to opening of the Gulf of California.

PALEOGEOGRAPHIC RELATIONSHIPS BETWEEN THE COLORADO PLATEAU AND BASIN AND RANGE PROVINCES

The elevation of the Colorado Plateau in Arizona is generally between 5,000 and 7,000 feet, in contrast to the Basin and Range Province where the elevations between

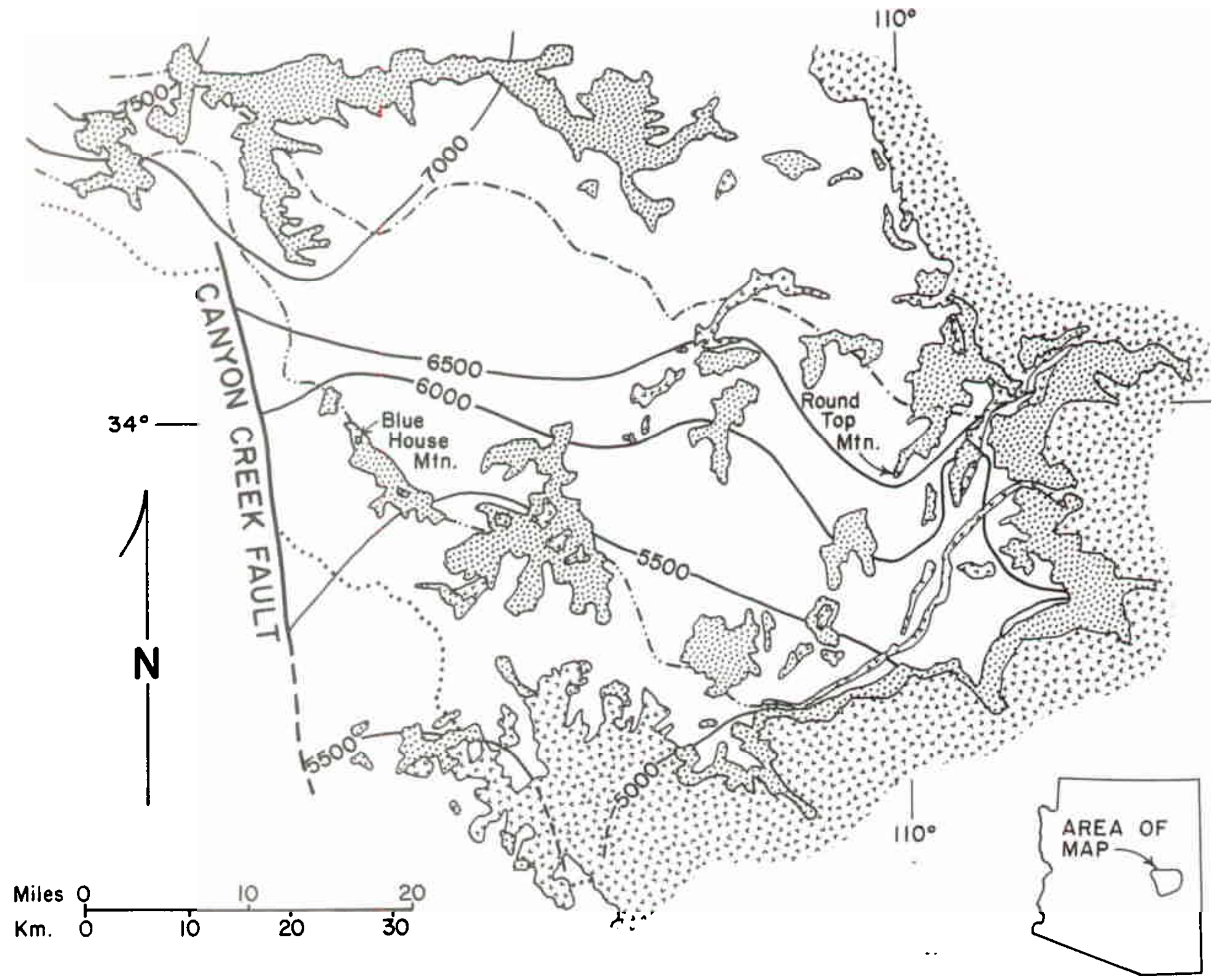
between 1,000 and 5,000 feet are typical. The Transition Zone, which trends diagonally across Arizona and separates the two provinces (fig. 1), is intermediate in elevation. The boundary between the Colorado Plateau and Transition Zone is a geomorphic boundary rather than a structural boundary along which the Colorado Plateau has been uplifted relative to the Transition Zone and Basin and Range Provinces (Peirce and others, 1979; Peirce, 1984). This boundary is most clearly defined by southwest-facing cliffs of Permian Kaibab Limestone and Coconino Sandstone. Permian units, along with underlying Paleozoic strata, dip very gently (less than 1 degree) to the northeast and form a regional dip slope within the southwestern Colorado Plateau. The geomorphic boundary defining the edge of the Plateau is a drainage divide that is most spectacularly developed in central Arizona where it reaches an elevation of over 7,500 feet and is referred to as the Mogollon Rim.

Prior to middle Tertiary extensional tectonism, much or all of what is now the Basin and Range and Transition Zone Provinces in Arizona was topographically higher than the Colorado Plateau, as indicated by conglomerate and sandstone that were shed northeastward onto the Plateau in early Tertiary time (fig. 7). Conglomeratic, proximal parts of this sedimentary assemblage are the rim gravels along the southwest edge of the Colorado Plateau in Arizona (Peirce and others, 1979, and references therein), whereas distal, fine-grained equivalents of the rim gravels occur in the Baca basin of western New Mexico and east-central Arizona (Cather and Johnson, 1984) and the Claron Formation of southern Utah (Young and McKee, 1978). The rim gravels in Arizona typically rest on Cretaceous marine strata or underlying Permian units and contain clasts of lower Proterozoic igneous and metamorphic rocks and middle Proterozoic and Paleozoic sedimentary rocks, with sparse clasts of Laramide volcanic rocks. Rim gravels in the Fort Apache region contain clasts of Laramide volcanic rocks, one of which yielded a K-Ar date of 54 Ma, and are capped by volcanic rocks dated at 28 Ma. These dates constrain the age of the rim gravels, in this area at least, to between 54 and 28 Ma (Eocene-Oligocene) (Peirce and others, 1979).

The Hualapai Plateau, located in the Transition Zone of northwestern Arizona, contains crystalline-clast conglomerate and arkose that were transported northeastward toward the Colorado Plateau. The conglomerate and arkose occupy paleocanyons cut deeply into Paleozoic sedimentary rocks and are overlain by the 18-Ma Peach Springs Tuff (Young and Brennan, 1974). Based on the distribution of facies and correlation with fossiliferous lacustrine and fluvial strata on the Coconino Plateau, the stratigraphically lowest arkose is inferred to have been deposited immediately prior to early Tertiary (Eocene?) monocline formation and drainage disruption (Young, 1979, 1982; Young and Hartman, 1984). Although these sedimentary units generally rest on pre-Permian rocks, in contrast to typical rim gravel (Peirce and others, 1979), they contain similar clast types and reflect the same environment of northeastward sediment transport of arkosic material across the Transition Zone and possibly onto the Colorado Plateau. The age of these sedimentary units is not well constrained and could be any age between Eocene and early Miocene.

Initial formation of the geomorphic edge or rim of the Colorado Plateau in Arizona marks the beginning of a major tectonic event in which the edge of the Colorado Plateau became topographically higher than the Basin and Range and Transition Zone Provinces. This event was marked by formation of a drainage divide and erosional development of southwest-facing cliffs along the Plateau edge, with subsequent deposition of volcanic and conglomeratic sedimentary rocks on lower Paleozoic and Precambrian rocks in the Transition Zone. Volcanic rocks in several areas of the Transition Zone that postdate rim formation and drainage reversal yielded K-Ar ages of 8 to 14 Ma (Peirce and others, 1979). In northwestern Arizona, the 18-Ma Peach Springs Tuff accompanied or immediately preceded block faulting and regional tilting that resulted in drainage disruption and structural differentiation of the Basin and Range Province and the Hualapai Plateau (Young and Brennan, 1974). The age of geomorphic differentiation of the Hualapai Plateau and topographically higher Coconino Plateau, and associated rim formation, is not constrained, however. It thus appears that the reversal in the relative elevations of the Colorado Plateau and Basin and Range Provinces began no later than middle Miocene time and could have begun in the early Miocene or Oligocene (Peirce and others, 1979).

In the Fort Apache region of east-central Arizona, conglomerate and sandstone were deposited on a middle Tertiary or older erosion surface that gradually cuts downsection to the south across pre-Tertiary rock units (fig. 16; Wilson and others, 1969; Peirce and others, 1979). Northern exposures of these clastic sediments rest on Cretaceous and Permian strata along the edge of the Colorado Plateau, whereas more southwesterly exposures rest on progressively older Paleozoic units southward across the Transition Zone. Paleozoic rocks were completely removed by erosion in the southwesternmost areas where early(?) to middle Tertiary conglomerate and sandstone rest directly on Precambrian igneous and metamorphic rocks. The erosional surface that forms the base of these sediments now dips about one degree to the south (fig. 16). Limited paleocurrent data and clast compositions, however, indicate northeastward sediment transport on a northeast-sloping surface (Peirce, 1967, plate 13; Peirce and others, 1979, and references therein). It is uncertain whether all of the conglomeratic sedimentary rocks now resting on the south-sloping erosion surface are rim-gravel equivalents that were being transported toward the Colorado Plateau at the time of their deposition, or if the present distribution of Tertiary sediments and the slope of their basal contact is the result of more complex processes, possibly involving



EXPLANATION

- Upper Cenozoic volcanics.
- Eocene (?) to lower Miocene (?) conglomerate and sandstone.
- Pre-Cenozoic basement.
- —6000— Elevation (in feet) of base of Eocene (?) to lower Miocene (?) conglomerate and sandstone.
- –·–·–·–·– Southern limit of exposures of Permian Kaibab limestone.
- –··–··–··– Southern limit of exposures of Pennsylvanian-Permian Supai group.
- ·········· Southern limit of exposures of Paleozoic rocks.

Figure 16. Contour map of the base of early to middle Tertiary conglomerate and sandstone deposited across the Transition Zone and the edge of the Colorado Plateau in the Apache Junction area of east-central Arizona.

different-age sediments with different transport directions. If all of these conglomeratic rocks are rim-gravel equivalents, then the present southwest dip of the erosion surface is the result of middle to late Tertiary tectonic processes that lowered the Basin and Range Province relative to the Colorado Plateau and caused one to two degrees of regional southwestward tilting of the Transition Zone in the Fort Apache area.

It is uncertain what the absolute elevations of the Colorado Plateau and Basin and Range Provinces were before reversal of their relative elevations. Absolute uplift of the Plateau is probably the result of regional uplift that affected the entire Rocky Mountain-western Great Plains region as well as the Plateau (Thompson and Zoback, 1979). The Basin and Range Province was almost certainly subjected to the same regional uplift-causing process, but crustal thinning due to extension counteracted regional uplift. Present regional elevations in Arizona are thus viewed as resulting from a combination of regional uplift that affected much of the western half of the United States and subsidence due to crustal thinning and extension. Present elevations were determined by the relative significance of the two processes in a given area (Thompson and Zoback, 1979).

CRUSTAL THICKNESS

Several seismic refraction surveys have determined approximate crustal thicknesses over much of Arizona (fig. 17). Most refraction profiles are unreversed, but overlapping and closely spaced profiles in central Arizona constitute a database of sufficient quality that definitive statements about crustal thickness can be made for this area. The crustal thickness in the Basin and Range Province of Arizona is in the range of 22-30 km, while that of the Colorado Plateau is in the range of 39-42 km. The crust in southeastern Arizona is thicker than that in the Basin and Range Province elsewhere in Arizona and reaches thicknesses of over 40 km (Wallace and others, 1986). Crustal thickness changes gradually across the Transition Zone, with a change of about 15 km in thickness over a lateral distance of 150 km in central Arizona (fig. 17).

The crust of the Basin and Range Province was almost certainly as thick or thicker than that of the Colorado Plateau after Mesozoic and early Tertiary crustal shortening and during rim-gravel deposition. Given present crustal thicknesses, this indicates that crustal thickness was reduced by approximately 15-20 km in the Basin and Range Province of Arizona in post-Eocene time (e.g., Wernicke, 1985). Low-angle extensional faulting was certainly a major cause of crustal thinning, but another cause may have been late Laramide (early Tertiary) "decretion," a process in which low-angle subduction of oceanic lithosphere under Arizona resulted in wholesale removal of lower crustal material that was carried eastward under the Colorado Plateau-Rocky Mountains-western Great Plains or

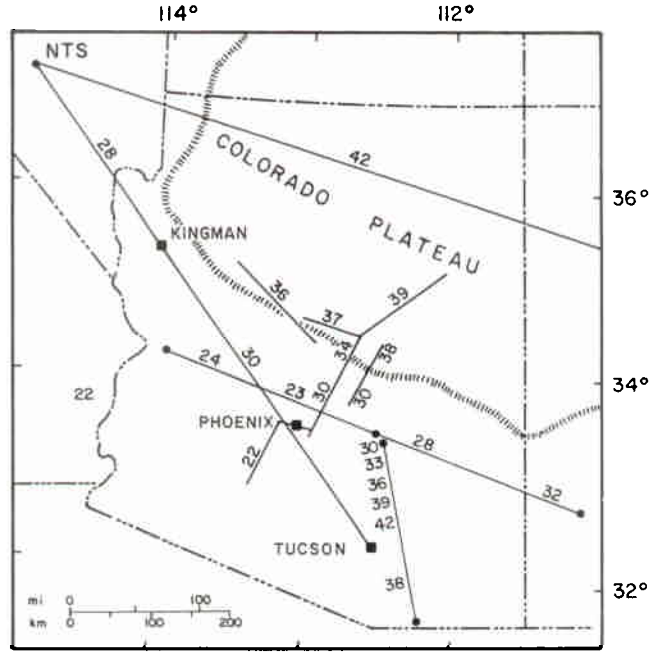


Figure 17. Location of seismic-refraction lines in Arizona and adjacent areas. Approximate depth to Moho is indicated by numbers adjacent to lines. Data sources: southeastern California (Hearn, 1984), northeast-southwest lines in central Arizona (Warren, 1969), eastern Arizona (Gish and others, 1981), southeastern Arizona (Wallace and others, 1986), west-central Arizona (Sinno and others, 1981), lines originating from the Nevada Test Site (NTS) from Diment and others (1961), Langston and Helmberger (1974), and Bache and others (1978).

dragged into the asthenosphere (Bird, 1984; Keith and Livaccari, 1985). That decretion played a significant role in reduction of crustal thickness is suggested by the fact that the thinnest crust does not appear to correspond to those areas that have undergone the most crustal extension. The greatest amount of Tertiary extension is inferred to have occurred along a northwest-trending belt through Arizona within which detachment faulting has unroofed mylonitic rocks of the metamorphic core complexes. Detachment faults southwest of this belt, in southwestern Arizona, do not appear to have displacements as large as those associated with metamorphic core complexes, yet southwestern Arizona and adjacent southeastern California have the thinnest crust. Significant crustal thinning in southwestern Arizona could have resulted from decretion, and minor decretion-related thinning possibly occurred under the belt of metamorphic core complexes. It is also possible that earlier crustal thickening was less significant in southwestern Arizona than in the areas of the metamorphic core complexes (e.g., Coney and Harms, 1984), and therefore decretion-related thinning may have been less significant. Another possibility is that extension at deeper crustal levels during opening of the Gulf of California and Salton Trough caused significant crustal thinning in southwestern Arizona, and that decretion did not occur at all.

Surficial manifestations of crustal extension are minor in the Transition Zone of Arizona, yet the crust has been thinned by as much as 50-100 percent along the southwestern edge of the Transition Zone, based on an assumed original thickness of 40-50 km. Thinning must have occurred at moderate to deep crustal levels where regionally northeast-dipping detachment faults project from the Basin and Range Province (Wernicke, 1985). Large displacement on such detachment faults resulted in withdrawal of crustal material up and out from beneath the Transition Zone, leaving it reduced in thickness, especially along its southwestern edge (Wernicke, 1985; Reynolds and Spencer, 1985). Such deep-level crustal thinning would result in a lowering of elevation in the Transition Zone without appreciable surficial manifestations such as normal faults, a process we term "deflation."

Crustal thinning due to deep-seated extension may explain the southwest dip of the erosion surface at the base of the Eocene-Oligocene(?) rim gravels and possible equivalents in the Fort Apache region (fig. 16). Tilting due to progressively greater thinning to the southwest would have occurred after deposition of the rim gravels and therefore is significantly younger than Laramide deformation in Arizona (Wernicke, 1985). This would rule out Laramide decretion as the primary cause of crustal thinning in the Transition Zone and adjacent parts of the Basin and Range Province.

Large displacement on detachment faults and associated distension of upper-plate rocks are the primary mechanisms of crustal extension at depths shallower than approximately 10-15 km. The mechanism of extension at deeper crustal levels where ductile conditions prevail is controversial. Three models have been proposed that might be applicable to Arizona: (1) detachment faults penetrate the entire lithosphere (Wernicke, 1981, 1985), (2) detachment faults die out into zones of ductile, coaxial extension (Rehrig and Reynolds, 1980; Miller and others, 1983), and (3) detachment faults die out into zones where extension is accommodated by magma intrusion (Anderson, 1971; Wright and Troxel, 1973). We believe that extension by magma emplacement occurred only locally in Arizona, as many areas of extreme extension lack large syntectonic plutons. Determining the relative significance of the other two processes has not generally been possible, except that the ductile, *in situ* extension model is not consistent with regionally consistent sense-of-shear indicators in lower-plate mylonitic rocks in metamorphic core complexes and with the downward decrease in intensity of lower-plate mylonitic fabrics (e.g., Davis, 1983; Davis and others, 1986).

Inferences about the nature of lower crustal extensional deformation can be made for southeastern Arizona. Detachment faults and associated low- to moderate-angle normal faults dip in opposite directions away from the Galiuro Mountains and do not appear to project beneath the range. Movement on these faults and on their downdip continuation as normal-slip ductile shear zones that transect the entire lower crust (e.g., Wernicke, 1981, 1985) would cause no crustal thinning beneath the Galiuro Mountains. Thus, if crustal thinning occurred entirely by displacement on detachment faults and their down-dip ductile continuations, the thickness of the crust beneath the Galiuro Mountains should be the same as the pre-extension crustal thickness, which is estimated to be 40 to 50 km. Sparse seismic refraction data indicate that the regional crustal thickness ranges from about 30 to 42 km in southeastern Arizona (fig. 17). If crustal thickness beneath the Galiuro Mountains is 10 kilometers greater than that in surrounding areas, the Galiuro Mountains should be approximately two kilometers higher in elevation than surrounding regions, assuming local isostatic rebound. This elevation anomaly should be broader than the mountain range itself, including the flanking basins. In addition, the deep crustal root should be associated with a negative Bouguer gravity anomaly. Neither anomalously high elevations nor negative gravity anomalies are observed (Lysonski and others, 1980), which suggests that the crust beneath the Galiuro Mountains is not appreciably thicker than that beneath surrounding areas. We note that inferences about the form of the Moho and associated lateral crustal-thickness changes based on gravity and topography are only suggestive. If correct, however, the only likely mechanism for thinning of the crust beneath the Galiuro Mountains is deep crustal flow and extension in which ductile, lower-crustal rocks flow laterally away from the Galiuro Mountains, resulting in flattening of the Moho (fig. 18, see also Gans, 1987). The sense of shear at the top of this deep crustal-flow zone would be opposite to the sense of shear on structurally higher detachment faults. Rocks with Tertiary fabrics formed by this style of deep-seated ductile flow have not been recognized in Arizona and the Southwest and probably are not exposed.

DISCUSSION

Causes of Extension

The ultimate cause of mid-Tertiary magmatism and extension is controversial. Magmatism has generally been considered to have resulted from subduction of oceanic lithosphere beneath western North America, and space-time patterns of magmatism have been viewed as the result of the changing dip and configuration of the subducted lithosphere (e.g., Christiansen and Lipman, 1972; Lipman and others, 1972; Snyder and others, 1976; Coney and Reynolds, 1977). In contrast, Glazner and Bartley (1985) suggested that gradual warming of the overthickened Laramide-Sevier compressional orogenic belt led to melting of the deepest part of the lower crust without any influence from a subducted slab. Crustal thickening, which occurred in Arizona during Mesozoic and early Tertiary time, would have depressed isotherms initially as rocks below thrust and reverse faults underwent tectonic burial (e.g., Haxel and others, 1984). Re-establishment of normal geothermal gradients, or elevated geothermal gradients due to the greater content of radioactive elements in a vertical section

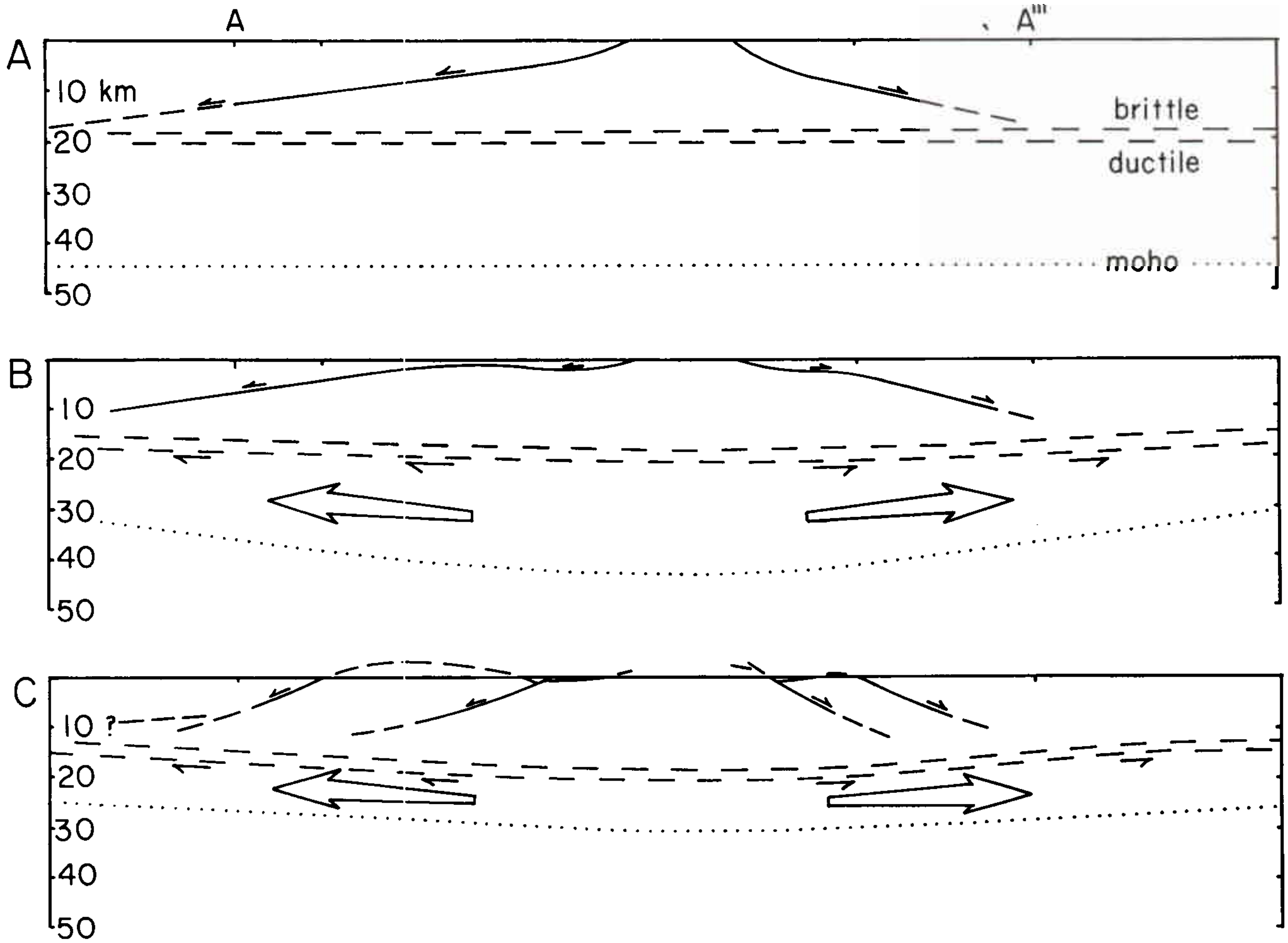


Figure 18. Sequential evolutionary cross section from Tucson Mountains through Galiuro Mountains to Gila Mountains (see fig. 9 for location of cross section) showing hypothesized flow of deep-crustal rocks out from beneath the Galiuro Mountains and associated flattening of the Moho during mid-Tertiary time.

through the crust after thickening, could have led to melting of deep crustal rocks. Glazner and Bartley raised the possibility that complexities in migration patterns of magmatism during mid-Tertiary time resulted from lateral variations in ages of crustal thickening and in radioactive element content of the middle and lower crust. Their hypothesis fails, however, to account for the general east-to-west sweep of magmatism across Arizona in the mid-Tertiary, and it is not consistent with the composition of mid-Tertiary igneous rocks, which are chemically and isotopically distinct from late Laramide muscovite granites that are almost certainly lower-crustal melts. Nd-Sm and Rb-Sr isotopes suggest that mid-Tertiary igneous rocks contain a significant mantle component (Farmer and DePaolo, 1984), which would be unaccounted for by Glazner and Bartley's model. In addition, Mesozoic thrusting occurred over a broad time range in the southwest, beginning in the Triassic in some areas (Burchfiel and Davis, 1981) and continuing until early Tertiary in others. Magmatism due to crustal thickening, as envisioned by Bartley and Glazner, presumably should have begun in the late Mesozoic in some areas following early Mesozoic crustal thickening. The complete absence of magmatism during the late Eocene-early Oligocene magmatic hiatus in most of the Southwest, followed by sudden regional onset of magmatism in mid-Tertiary time (Coney and Reynolds, 1977), is not consistent with Glazner and Bartley's hypothesis, and another mechanism for triggering mid-Tertiary magmatism is required.

Gradual warming of an overthickened crust should result in reduction of lithospheric strength to less than the prethickened strength, leading to the inference that extensional deformation is localized in areas of previous crustal shortening (Glazner and Bartley, 1985). Heating of lithosphere due to magmatism, as occurred in the Basin and Range Province during mid-Tertiary time, also should cause strength reduction. Crustal thickening imparts significant gravitational potential energy to the overthickened crust, as represented by the high elevation of mountain belts and the downward-projecting bulge of the Moho beneath mountain belts. Release of this potential energy is an important driving force for extension (Dalmayrac and Molnar, 1981; Molnar and Chen, 1983; Coney and Harms, 1984). Large-magnitude crustal extension in the southwestern

U.S. was apparently triggered by reduced lateral compression associated with, or as a result of, steepening of the mid-Tertiary subduction zone beneath the southwestern United States (Coney and Harms, 1984). We conclude that Laramide and older crustal thickening ultimately weakened the Basin and Range lithosphere and gave it potential energy to help drive extension. Mid-Tertiary magmatism, and reduced lateral confining stress due to changes in plate-tectonic interactions, ultimately triggered large-magnitude mid-Tertiary extension.

Relationship of Metamorphic Core Complexes to Older Structures

Large displacement on detachment faults resulted in unroofing of rocks that underwent mylonitization along the down-dip projection of detachment faults during the earliest increments of movement. Mylonitic and nonmylonitic rocks exposed in uplifted lower plates also include structures and fabrics that record earlier, dominantly Mesozoic or early Tertiary deformation and metamorphism. Mylonite zones associated with mid-Tertiary extensional versus older compressional deformations have a generally different character. For example, Mesozoic thrust faults exposed in west-central Arizona are locally associated with weakly lineated, weakly to moderately developed mylonitic schists, in contrast to the strongly lineated, typically well developed, penetrative mylonitic fabric developed during mid-Tertiary extension. These contrasts in deformation styles are apparent elsewhere as well, and mylonitic deformations associated with each are generally distinguishable. Although Tertiary detachment faults and mylonite zones may have locally formed near or along older thrust faults and ductile shear zones (e.g., Haxel and Grubensky, 1984), this appears to be the exception rather than the rule (e.g., Wernicke and others, 1985).

Large-scale geometric relationships between detachment faults and thrust faults suggest that some genetic relationship exist between the two, at least in some areas. The belt of exposed, uplifted, lower-plate crystalline rocks, including mylonites, in the Whipple tilt-block domain (zone C in fig. 11) extends southward along the west side of the Colorado River trough to the Whipple Mountains where it abruptly swings eastward to the Buckskin and Rawhide Mountains. Mylonitic rocks of the Whipple, Buckskin, Rawhide, Harcuvar, and Harquahala Mountains lie in a west-northwest—east-southeast-trending belt that approximately parallels the east-west-trending, south-vergent Maria fold and thrust belt located 10-70 km to the south (fig. 11; Reynolds, Spencer, and others, 1986). Thus, the crust beneath the metamorphic core-complex mylonites should have been thickened during Mesozoic crustal shortening and formation of the Maria fold-and-thrust belt. The east-west-trending, elongate, overthickened crustal welt lying along and north of the Maria fold-and-thrust belt prior to mid-Tertiary extension could have produced stresses in the crust that influenced the geometry of later detachment faults and were responsible for the change in trend of the zone of uplifted, mylonitic, lower-plate crystalline rocks in the Whipple-Buckskin-Rawhide Mountain area (Spencer and Reynolds, 1986b). The exact nature of these stresses is presently unclear, but could have been related to lack of isostatic equilibrium of the overthickened, E-W-trending crustal welt. This welt probably underwent significant early Tertiary erosional denudation, but possibly without sufficient isostatic rebound for complete isostatic reequilibration until mid-Tertiary extensional faulting and isostatic uplift of lower-plate rocks (see also Holt and others, 1986).

Warping of Detachment Faults

Laterally varying tectonic denudation during detachment faulting resulted in laterally variable isostatic rebound, which in turn resulted in crustal flexure. Concave-upward flexure produced subhorizontal compression at shallow crustal levels that locally overwhelmed regional extensional stresses and led to local development of structures indicating compression parallel to the direction of regional extension (Spencer, 1982, 1984, 1985a, 1985b). For example, local anomalous dike orientations are apparently the product of stresses associated with crustal flexure (Spencer, 1985a). The Lincoln Ranch reverse fault in the Buckskin and Rawhide Mountains of west-central Arizona cuts the Buckskin-Rawhide detachment fault (Shackelford 1976, 1980; Spencer and Reynolds, 1986a) and could have formed in response to concave-upward flexure during late, one-sided denudation of the east flank of the Buckskin and Rawhide Mountains (e.g., Spencer, 1985a), or it could be younger and unrelated to mid-Tertiary tectonism.

Subhorizontal mylonitic foliation in metamorphic core complexes of Arizona and adjacent southeastern California typically forms large-scale corrugations with axes oriented east-northeast—west-southwest, parallel to the direction of extension. These corrugations are best developed in the Whipple-Buckskin-Rawhide-Harcuvar Mountains area, but are also clearly present in the Santa Catalina-Rincon and South Mountain areas as well. The form of overlying detachment faults also reflects the undulations. If the corrugations are folds, as suggested by their fairly regular spacing, approximate sinusoidal form, and form of older fabrics and sills, they represent about 1 percent shortening in a north-northwest—south-southeast direction in the Whipple-Buckskin-Rawhide-Harcuvar area, where they are exposed over the largest area. The origin of these folds or foldlike features is unclear; possibly they were produced by stresses related to isostatic uplift and decompression of footwall rocks (Spencer, 1982).

Origin of High Geothermal Gradients

High geothermal gradients during middle Tertiary extension have been inferred based on the widespread presence of middle Tertiary volcanic rocks and numerous middle Tertiary K-Ar ages on crystalline rocks below detachment faults. The cause of high thermal gradients is generally assumed to be mid-Tertiary magmatism. It seems likely, however, that in some areas extension, rather than magmatism, was the major cause of high geothermal gradients. Magma intrusion effectively transmits heat to the crust and was locally important in raising geothermal gradients, but large regions of pre-Tertiary basement in Arizona contain no large Tertiary intrusions. Elevated geotherms are a consequence of extension (e.g., McKenzie, 1978; Lachenbruch and Sass, 1978; England and Jackson, 1987) and must have been high in the Basin and Range Province during and immediately after extension.

Relative Significance of Middle and Late Tertiary Extension

The relative significance of mid-Tertiary low-angle normal faulting versus late Tertiary high-angle normal faulting in accommodating lithospheric extension at upper-crustal levels has been controversial. Coney and Harms (1984), for example, attributed approximately equal significance to each. Most evidence, however, indicates that late Tertiary high-angle normal faulting in Arizona represents only a minor amount of extension compared to earlier, dominantly low-angle normal faulting. High-angle normal faults, other than those related to movement on deeper detachment faults, are not present in many parts of western Arizona, and where present, accommodated only a minor amount of extension. In west-central Arizona, for example, bedrock is exposed continuously in east-northeast-trending ranges for as much as 60 km and is broken by only sparse high-angle faults of small displacement. Late Cenozoic high-angle normal faulting probably accommodated only 5-15% extension of the upper crust in Arizona, with a much greater proportion of the total Tertiary crustal extension occurring during earlier low-angle normal faulting.

Physiography

Mid-Tertiary tectonism drastically altered the surface morphology of what is now Arizona and adjacent areas. Immediately prior to this time, what is now the Basin and Range Province must have been a broad highland devoid of sedimentary basins, with many streams flowing northeastward onto the Colorado Plateau. Extensional faulting changed the highland to an area of numerous sedimentary basins and complex morphology. Many of the modern basins and ranges of the Basin and Range Province formed in the mid-Tertiary, with little or no modification by late Tertiary high-angle normal faulting (e.g., Dickinson and others, 1987). Volcanism further modified the landscape, and several sizeable calderas were formed. Mid-Tertiary extension in the Basin and Range Province was accompanied by a drainage reversal along the edge of the Colorado Plateau, so that streams began flowing southwestward away from the Plateau and toward the Basin and Range Province. Thus, the mid-Tertiary period of major extension and magmatism greatly altered surface morphology and drainage patterns and was responsible for much of the present-day physiography of Arizona and the Southwest.

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