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Relationship Between Mesozoic and Cenozoic Tectonic Features in West Central Arizona and Adjacent Southeastern California

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The Maria fold-and-thrust belt (MFTB) is a narrow belt of Mesozoic crustal shortening that trends east-west across west central Arizona and adjacent southeastern California. It is characterized by generally south vergent folds and thrusts that commonly displace Proterozoic crystalline rocks over deformed and metamorphosed Paleozoic and Mesozoic strata. The MFTB is cut by a south to southeast trending belt of mid-Tertiary extensional deformation. Extension was characterized by large displacements on low-angle normal faults, known as detachment faults, and by isostatic uplift of mylonitic midcrustal rocks now exposed in metamorphic core complexes. The geometry and style of extensional deformation change along the extensional belt and reveal the influence of the MFTB. Several extensional features are spatially coincident with the root zone of MFTB thrusts: (1) an areally extensive west-northwest trending belt of denuded Tertiary mylonitic fabrics in the Whipple and Harcuvar metamorphic core complexes, (2) a style of extension characterized by minimum extensional dismemberment of the upper plate and maximum denudation and uplift of deep-seated lower plate rocks, (3) an abrupt bend in the belt of arched, uplifted rocks below detachment faults, and (4) an abrupt bend in the trend of the breakaway zone of the detachment faults and an associated lateral ramp in the detachment fault system. The first two features may be the result of isostatic uplift of a crustal root (downward protruding Moho bulge) inherited from crustal thickening within the MFTB, and the other two features may reflect, at the time of detachment fault initiation, the influence of stresses in the crust associated with flexural support of the buoyant Mesozoic crustal root.

INTRODUCTION

Crustal extension within some large mountain belts reflects the inability of crustal rocks to maintain large topographic welts without spreading under their own weight. Potential energy stored in uplifted rocks in mountain belts and in underlying, downward protruding Moho bulges (Airy crustal roots) is available to drive extension [*England*, 1982; *Molnar and Lyon-Caen*, 1988]. Active extension in Tibet and the central Andes is occurring within greatly overthickened crust and is apparently driven by gravitational potential energy [*Molnar and Tapponnier*, 1978; *Dalmayrac and Molnar*, 1981]. A crustal welt produced by Mesozoic crustal thickening in western North America was greatly thinned by Tertiary extension [*Coney and Harms*, 1984; *Wernicke et al.*, 1988], although factors that determined the timing and magnitude of extension are not well understood (compare *Coney* [1987] and *Wernicke et al.* [1987]).

It is not known if a relationship between crustal thickening and extension applies to Cordilleran metamorphic core complexes [*Crittenden et al.*, 1980], which are much smaller than the width of the extended interior of the Cordilleran orogen. Mylonitic rocks in Cordilleran metamorphic core complexes represent areas where large displacement on gently to moderately dipping normal faults (detachment faults) has uncovered rocks that were below the crustal brittle-ductile transition before denudational faulting [e.g., *Wernicke*, 1981; *Davis et al.*, 1986]. Because of the large displacements necessary to uncover such deep seated rocks, these areas are thought to have undergone greater magnitudes of extension than areas where deep-seated rocks are not exposed [*Coney and Harms*, 1984; *Coney*, 1987]. Restoration of such large magnitudes of extension within metamorphic core complexes produces crustal welts directly beneath the complexes, leading to the inference that core complexes developed over local crustal welts [*Coney and Harms*, 1984]. This hypothesized relationship between crustal welts and metamorphic core complexes is appealing because it accounts for the general location of Cordilleran metamorphic core complexes within the interior of a broad belt of Mesozoic crustal thickening. It has not been established, however, that the crust beneath any particular metamorphic core complex underwent greater Mesozoic thickening than crust beneath adjacent areas where deep-seated rocks are not now exposed. This raises a fundamental question: Do the discontinuous exposures of Cordilleran metamorphic core complexes reflect short-wavelength variations in the magnitude of earlier crustal thickening or some other unrecognized factor in combination with only a general relationship to the belt of earlier crustal thickening?

Here we address possible relationships between Mesozoic shortening and Cenozoic extension by analyzing the tectonic history of west central Arizona and adjacent southeastern California. This area includes the anomalously oriented, east-west trending Maria fold-and-thrust belt (MFTB) [*Reynolds et al.*, 1986*b*] and a second belt of large-magnitude Tertiary extension that trends southward to southeastward down the lower Colorado River trough and across the east-west trending MFTB. Crosscutting relationships between belts of shortening and extension have not been recognized elsewhere in western North America; the study area thus offers an unusual opportunity to study relationships between crustal shortening and extension. Here we present evidence that the MFTB influenced the geometry and structural style of Tertiary extension and suggest that preextension variations in crustal thickness were the source of this influence.

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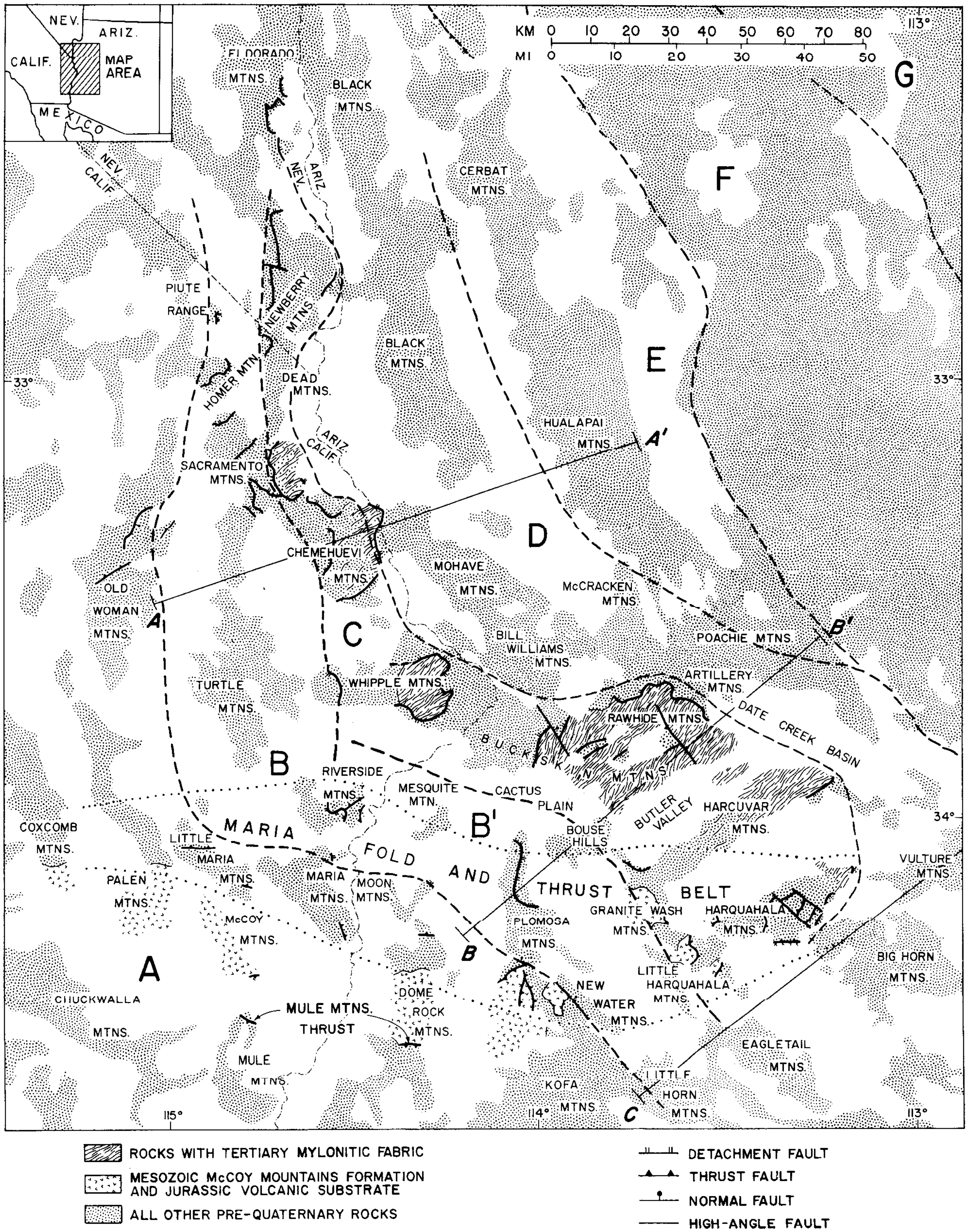
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THRUST FAULT
NORMAL FAULT
HIGH-ANGLE FAULT

MARIA FOLD-AND-THRUST BELT (MFTB)

In the Mohave and Sonoran Desert regions of southeastern California and southwestern Arizona, thrusts and folds accommodating Mesozoic crustal shortening formed within a region that had been part of the Paleozoic craton of North America [*Stone et al.*, 1983]. The thin, platformal Paleozoic sedimentary cover, approximately 1 km thick, did not influence regional geometries of Mesozoic structures, and thrust geometries are complex [*Burchfiel and Davis*, 1981; *Reynolds et al.*, 1986*b*]. An east-west trending basin in which the Jurassic(?) to Cretaceous McCoy Mountains Formation [*Harding and Coney*, 1985; *Stone et al.*, 1987] was deposited appears to have localized deformation in west central Arizona and adjacent southeastern California; thrusts verge inward toward the basin axis [*Tosdal*, 1982; *Harding and Coney*, 1985; *Reynolds et al.*, 1986*b*, 1987], and the MFTB lies along the northern flank of the basin. This complex style of deformation contrasts with that north of the Mojave Desert region where the Cordilleran fold-and-thrust belt is characterized by structures that accommodated eastward displacement, onto cratonic North America, of a westward thickening wedge of Paleozoic and upper Proterozoic continental margin sedimentary rocks. Gently dipping thrust faults in this northern area typically formed within regionally west dipping sedimentary units [*Armstrong*, 1968; *Burchfiel and Davis*, 1975, 1981].

South, southwest, and southeast vergent folds and thrusts in the MFTB are exposed in approximately a dozen ranges [*Reynolds et al.*, 1986*b*] (Figures 1 and 2). Except for Mesozoic folds and thrusts in the Buckskin and Rawhide mountains, MFTB structures are exposed south of the large detachment faults in the northern Colorado River extensional corridor or are in their footwalls; as a result, the MFTB has not been severely dismembered or distorted by Tertiary extension at exposed crustal levels. Approximately 20 km of extension within a zone that passes through the Plomosa Mountains (Figure 1) [*Scarborough and Meader*, 1982; *Stoneman*, 1985] caused the only known significant Tertiary distortion of the MFTB outside of the Buckskin and Rawhide mountains. The two dotted lines in Figure 1 outline the largely undistorted form of the belt. The outline of the MFTB in Figure 2 includes the displaced fragments of the MFTB in the Buckskin and Rawhide mountains and reveals distortion of the belt caused by detachment faulting along its northern edge.

The structurally lowest thrusts of the MFTB displaced a variety of Proterozoic to early Mesozoic rock types approximately southward over the Jurassic(?) to Cretaceous McCoy Mountains Formation and its Jurassic volcanic substrate [*Miller*, 1970; *Spencer et al.*, 1985; *Richard et al.*, 1987; *Laubach et al.*, 1987]. Structurally higher thrusts interleaved Jurassic and older rocks [*Reynolds et al.*, 1980; *Carr and Dickey*, 1980; *Yeats*, 1985; *Stoneman*, 1985; *Cunningham*, 1986; *Richard*, 1988; *Knapp*, 1989]. Many thrust faults place Proterozoic crystalline rocks over upended to overturned, moderately to highly attenuated Mesozoic and Paleozoic sections [*Emerson*, 1982; *Reynolds et al.*, 1986*b*, 1987; *Reynolds and Spencer*, 1989; *Laubach et al.*, 1989]. Thrusts are absent in some ranges such as the Palen Mountains, where south vergent folding has upended and locally overturned Paleozoic and Mesozoic strata [*Stone and Kelly*, 1988], and the Big Maria Mountains, where complex folding and attenuation characterize deformation [*Ellis*, 1982; *Hamilton*, 1984, 1987].

Several types of evidence indicate that exposed Paleozoic and Mesozoic strata in the MFTB underwent tectonic burial and metamorphism followed by early Tertiary erosional denudation, uplift, and cooling: (1) Nearly all exposed Paleozoic and Mesozoic strata within the MFTB underwent greenschist- to local amphibolite-grade metamorphism [*Hamilton*, 1987; *Reynolds et al.*, 1988; *Hoisch et al.*, 1988]. (2) These strata are commonly foliated or contain one or more cleavages [*Reynolds et al.*, 1986*b*]. (3) K-Ar and $^{40}Ar/^{39}Ar$ dates from many ranges in the MFTB record early Tertiary cooling millions to tens of millions of years after Mesozoic magmatism had ended [*Martin et al.*, 1982; *Fryxell et al.*, 1987*a*; *Reynolds et al.*, 1986*a*, 1988; *Richard and Sutter*, 1988; *Knapp and Heizler*, 1988; *Hoisch et al.*, 1988]. (4) Early Tertiary strata are completely absent.

In contrast to widespread exposures of metamorphosed pre-Tertiary strata over a 10,000 km^2 area encompassing the MFTB, a 30,000 km^2 area directly north of the MFTB is completely devoid of exposed Paleozoic and Mesozoic strata (Figure 2). Unlike the MFTB, Proterozoic crystalline rocks at many locations in this northern area have yielded Proterozoic K-Ar mica dates [*Reynolds et al.*, 1986*a*]. Based on contrasting K-Ar dates between the two areas, we infer that the northern area underwent less uplift and erosional denudation than did the MFTB. In spite of greater uplift and erosional denudation in the MFTB, Paleozoic and Mesozoic strata were preserved because they were deeply buried by thrust faulting.

The structurally highest thrusts of the MFTB separate the MFTB from the large region to the north that is devoid of exposed Paleozoic and Mesozoic strata and apparently did not undergo significant Mesozoic deformation. This tectonic boundary is preserved as a fault contact in the Riverside and western Buckskin mountains. Elsewhere the boundary is either buried or dismembered by extensional faulting.

Fig. 1. Generalized tectonic domain map for mid-Tertiary structures in the Colorado River extensional corridor. Parts of the Maria fold-and-thrust belt (MFTB), displaced by Tertiary faulting and now in the Buckskin and Rawhide mountains, are not included here in the MFTB. The outline of the MFTB (two dotted lines) is thus restricted to rocks in the lower plate of the Whipple-Buckskin-Rawhide-Bullard detachment fault and is not significantly distorted by extensional faulting. Note that Tertiary mylonitic rocks parallel, and lie north of, the MFTB. Mid-Tertiary tectonic domains are as follows: A, area of minor extension at exposed surface levels; B, synformal keel of distended upper plate rocks above warped detachment fault system; C, belt of uplifted, commonly arched, mylonitic and nonmylonitic crystalline rocks below detachment faults; D, wedge-shaped (in cross section) extensional allochthon of moderately to highly extended upper plate rocks; E, area of slight to moderate extension characterized by large fault blocks generally with minor tilts; F, Transition Zone; and G, Colorado Plateau. Domain B' is extended by the Plomosa-Moon Mountains fault system that projects beneath domain C. Northwestern part of domain B' and southernmost part of domain B have probably been affected by both the Plomasa-Moon Mountains fault system and the Whipple-Buckskin-Rawhide detachment fault system. Breakaway faults are exposed or inferred to have been present at the western and southern edges of domains B and B' and along the east edge of the eastern part of domain B'. Note that the breakaway fault zones change trend at the intersection with the MFTB and mirror the change in trend of domain C. See Figure 7 for cross sections.

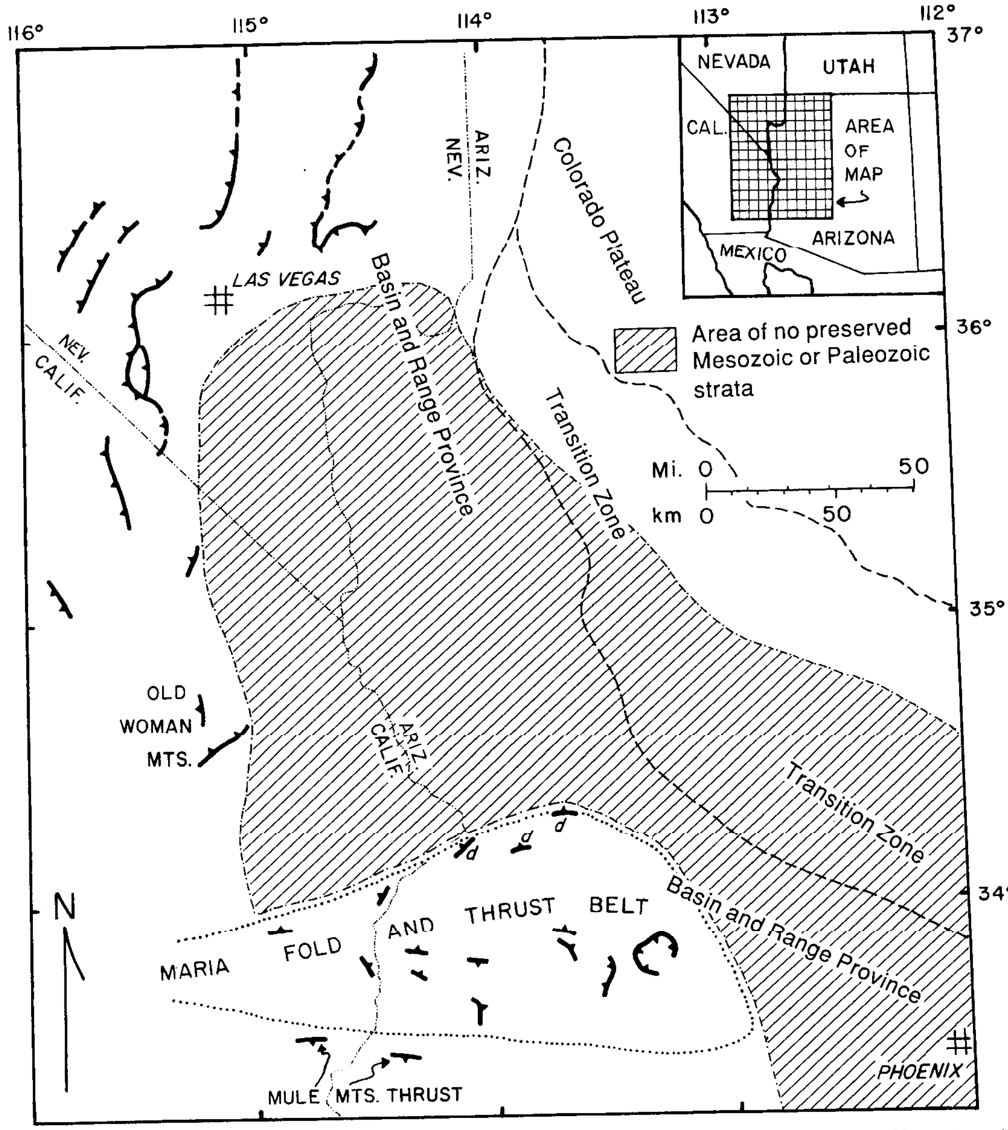


Fig. 2. Schematic map showing locations of major thrust faults in western Arizona and adjacent parts of California and Nevada. Ruled area contains no preserved Paleozoic or early to middle Mesozoic strata, which were apparently removed by erosion in Cretaceous and early Tertiary time. Paleozoic and Mesozoic strata are preserved beneath thrust faults in west central Arizona and southeastern California. The distribution of Paleozoic and Mesozoic strata reveals that the structurally highest thrust of the MFTB, which has been partially displaced and dismembered by detachment faulting, is a major tectonic feature in the Cordilleran fold-and-thrust belt. Outline of MFTB shown here includes displaced fragments of the MFTB, indicated by letter *d*, that are now exposed in the Buckskin and Rawhide Mountains.

In the Riverside Mountains a thrust fault in the footwall of the Riverside Mountains detachment fault places Proterozoic crystalline rocks over highly faulted and deformed Paleozoic and Mesozoic strata [*Lyle*, 1982*a*, *b*; see also *Carr and Dickey*, 1980]. This thrust fault is the structurally highest exposed thrust in this part of the MFTB. Mylonitic fabrics within the thrust zone contain a moderately well-developed N5°E to N15°E lineation and locally well-developed S-C fabrics that indicate top-to-the-south shear (J. Spencer, unpublished data, 1987).

A segment of this thrust boundary, now displaced tens of kilometers to the northeast or east-northeast by detachment faulting, is exposed in the western Buckskin Mountains. The fault segment juxtaposes Proterozoic crystalline rocks to the north and west with highly slivered and sheared Paleozoic and Mesozoic metamorphic rocks to the south and east (Figures 3 and 4) [*Frost*, 1983; *Reynolds and Spencer*, 1989]. The fault is interpreted as a product of multiple deformations and is not a simple thrust fault. Crystalline rocks to the north and west are part of an extensive terrane of crystalline rocks in the western Buckskin, eastern Whipple, and southern Bill Williams mountains that form much of the upper plate of the Whipple detachment fault. This crystalline rock terrane is not known to have been affected by significant Mesozoic deformation [*Davis et al.*, 1980; *Frost*, 1983] except near the deformed Mesozoic and Paleozoic strata [*Reynolds and Spencer*, 1989].

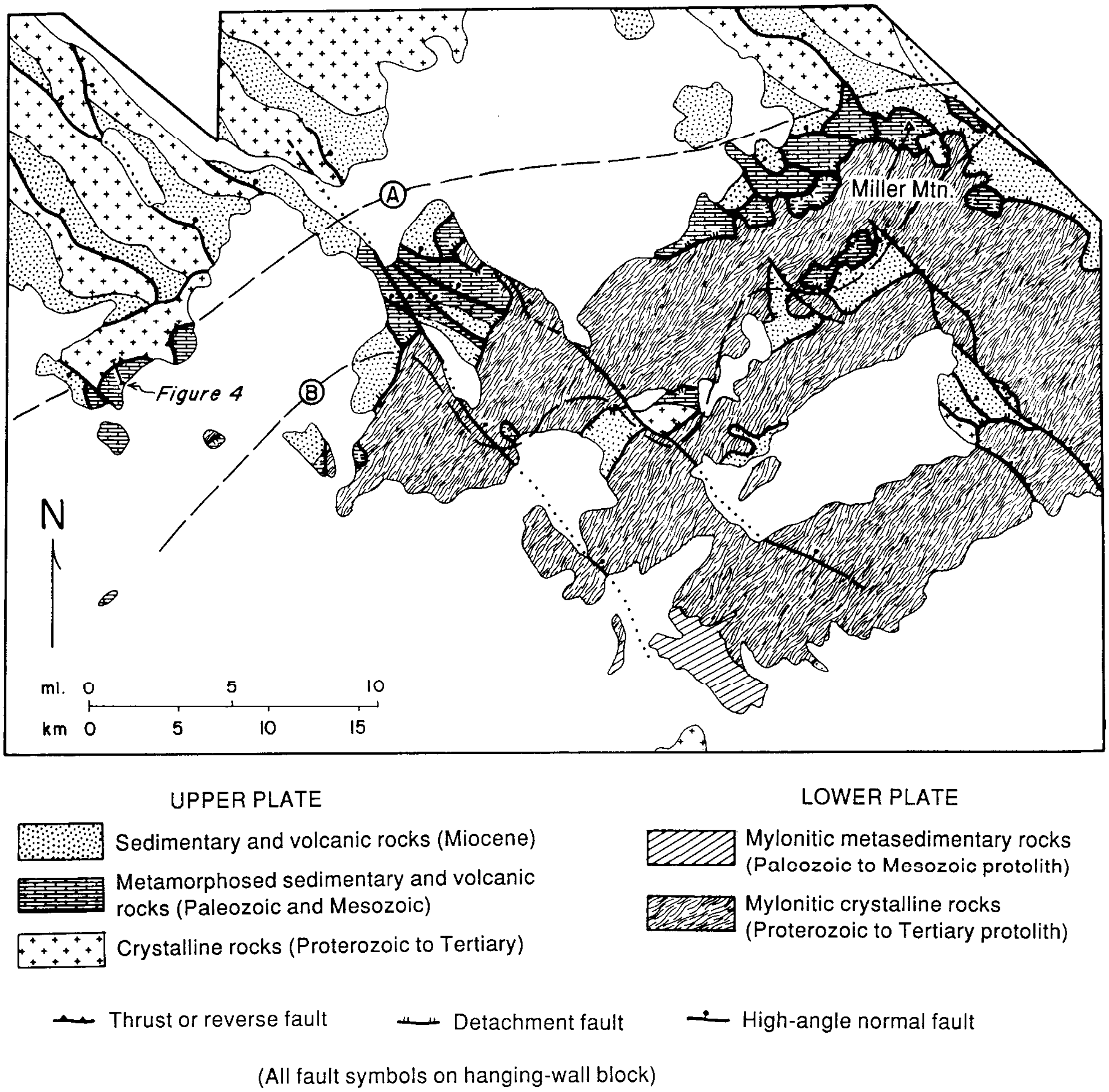
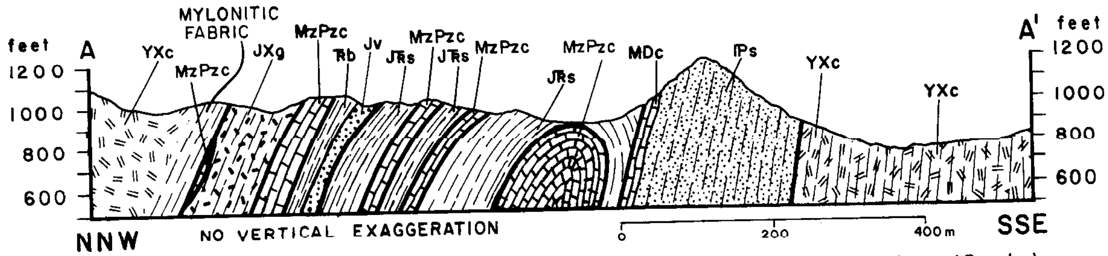


Fig. 3. Simplified geologic map of upper and lower plate rocks in the Buckskin and Rawhide Mountains and adjacent areas (modified from *Spencer* [1989]). Dashed line A represents dismembered, discontinuously exposed, structurally highest thrust of MFTB. Dashed line B represents approximate southward termination of pre-Tertiary upper plate rocks; primarily Tertiary rocks rest on detachment fault south of this line.

Farther northeast in the northern Buckskin and Rawhide mountains, the structurally highest thrust or thrust zone in the MFTB is concealed by younger deposits or is so dismembered by Tertiary faulting that thrust contacts are no longer preserved (Figure 3). Nevertheless, juxtapositions along some Tertiary faults in the Rawhide Mountains are reasonably interpreted as reflecting combined Mesozoic and Tertiary displacements, and Mesozoic and Paleozoic strata have undergone pervasive metamorphism, attenuation, and multiple deformation as is typical of similar age strata throughout the MFTB. North and northeast of the Rawhide Mountains an extensive terrane of dominantly Proterozoic crystalline rocks has yielded progressively older K-Ar mica and fission track dates at progressively greater distances from the Rawhide Mountains [*Reynolds et al.*, 1986*a*; *Bryant and Naeser*, 1987, 1988]. Metamorphosed Paleozoic and Mesozoic strata overlying the Rawhide detachment fault are separated from the Proterozoic rocks to the north and northeast by Tertiary faults and sedimentary and volcanic rocks [*Shackelford*, 1989*a*]. The metamorphosed strata were interpreted by *Shackelford* [1976, 1989*a*, *b*] to have been severely slivered by Tertiary low-angle faults. Our observations indicate that at least in the Miller Mountain area, Mesozoic and Paleozoic rocks are not strongly affected by Tertiary faulting but are highly attenuated and folded (Figure 5) in a manner similar to other areas affected by Mesozoic deformation but completely unlike deformation typically associated with crustal extension [*Wernicke and Burchfiel*, 1982].



Jv	Vampire Formation (Jurassic)	Ps	Supai Group (Pennsylvanian and Permian)
JŦs	Schist (Triassic or Jurassic)	MDc	Martin Formation (Devonian) and Redwall Limestone (Mississippian)
Ŧb	Buckskin Formation (Triassic)	JXg	Granitoid rocks (Proterozoic or Jurassic)
MzPzc	Carbonate rocks (Paleozoic or Mesozoic)	YXc	Crystalline rocks (Proterozoic)

Fig. 4. Cross section through structurally highest thrust zone of the MFTB at Billy Mack Mountain, westernmost Buckskin Mountains [from *Reynolds and Spencer*, 1989]. Styles of deformation are characteristic of deep seated crustal shortening. See Figure 3 for location.

We thus interpret the regional juxtaposition of dominantly Proterozoic crystalline rocks to the north with highly deformed and metamorphosed Paleozoic and Mesozoic strata to the south as the product of approximately south vergent thrusting along the structurally highest thrusts of the MFTB. Tertiary deformation in the Buckskin and Rawhide mountains has dismembered the thrust zone, but regional distributions of rock types, thermal histories, and styles of deformation and metamorphism support the interpretation that the contact was originally a Mesozoic thrust zone. Restoration of several tens of kilometers of Miocene displacement on the Buckskin-Rawhide detachment fault restores the thrust boundary in the Buckskin and Rawhide mountains to a position much closer to, or even on top of, the Riverside Mountains [*Spencer and Reynolds*, 1989]. Thus the segment of the thrust boundary that is now dismembered and spread out over almost 100 km was originally considerably shorter, perhaps 30-50 km in length.

GEOMETRY AND STRUCTURAL STYLE OF TERTIARY EXTENSION

The Colorado River extensional corridor (Figure 1) [*Howard and John*, 1987] contains one of the largest areas of exposed detachment faults and footwall mylonites in western North America. Lower plate (footwall) rocks have been displaced as much as several tens of kilometers southwestward relative to upper plate (hanging wall) rocks [*Reynolds and Spencer*, 1985; *Howard and John*, 1987; *Davis and Lister*, 1988; *Spencer and Reynolds*, 1989]. Upper plate rocks are typically broken by numerous, commonly northeast dipping normal faults [e.g., *Davis et al.*, 1980]. Synextension sedimentary and volcanic rocks fill half grabens above upper plate fault blocks and record early to middle Miocene tilting and footwall denudation [e.g., *Miller and John*, 1988].

Lower plate rocks in the Buckskin, Rawhide, and parts of the Whipple, Harcuvar, and Harquahala mountains contain a subhorizontal mylonitic foliation with a well-developed, northeast trending (N40°E to N60°E) lineation. Asymmetric petrofabrics, such as S-C structures, indicate that mylonitization occurred primarily during top-to-the-northeast shearing [*Reynolds and Lister*, 1987; *Davis and Lister*, 1988; *Spencer and Reynolds*, 1989; *Marshak and Vander Meulen*, 1989]. Mylonitization occurred after intrusion of mid-Tertiary igneous rocks in some areas [*Wright et al.*, 1986; *Bryant and Wooden*, 1989; *Spencer et al.*, 1989*b*] and before uplift, local subareal exposure, and burial by postdetachment, middle to upper Miocene basalts [*Davis et al.*, 1980, 1982; *Suneson and Lucchitta*, 1979; *Spencer and Reynolds*, 1989]. Numerous early to middle Miocene K-Ar and $^{40}Ar/^{39}Ar$ dates on mylonitic lower-plate rocks record rapid uplift and cooling to temperatures below those necessary for mylonitization [*Davis et al.*, 1982, 1987; *Fryxell et al.*, 1987*a*; *Bryant and Naeser*, 1988; *Spencer et al.*, 1989*c*]. The uplifted and arched lower plates of detachment faults north of the Whipple Mountains contain mylonitic fabrics of Cretaceous and possibly Tertiary age [*McClelland*, 1982; *John*, 1987] or entirely nonmylonitic crystalline rock [*Volborth*, 1973; *Mathis*, 1982; *Spencer*, 1985]. Detachment faulting in these northern areas did not uncover large areas of well-developed Tertiary mylonitic fabrics.

The progressive Tertiary ductile to brittle deformation of the lower plate, and juxtaposition of contrasting rock types across the detachment fault, is accounted for by the shear zone model for the origin of metamorphic core complexes [*Wernicke*, 1981, 1985; *Davis*, 1983; *Reynolds*, 1985; *Davis et al.*, 1986]. According to this model, rocks that were subjected to ductile shearing along the downdip projection of normal faults, and that were in the footwalls of the shear zones, cooled and underwent progressively more brittle deformation as they were displaced up and out from beneath hanging walls.

Here we outline evidence that the geometry of detachment faults and the structural style of extension change where the Colorado River extensional corridor crosses the root zone of MFTB thrusts. These changes include the following: (1) within the extensional corridor, a belt of uplifted, commonly arched, lower plate rocks, including mylonitic rocks in metamorphic core complexes, bends abruptly at the Whipple Mountains into parallelism with the MFTB (domain C in Figure 1), (2) the breakaway fault zone for detachment faults bends in a similar manner and forms an oblique breakaway zone across the MFTB (Figure 1), (3) a lateral ramp in the Buckskin-Rawhide detachment fault system, in which the detachment faults-ductile shear zones originally dipped in a more northerly direction than the direction of extension,

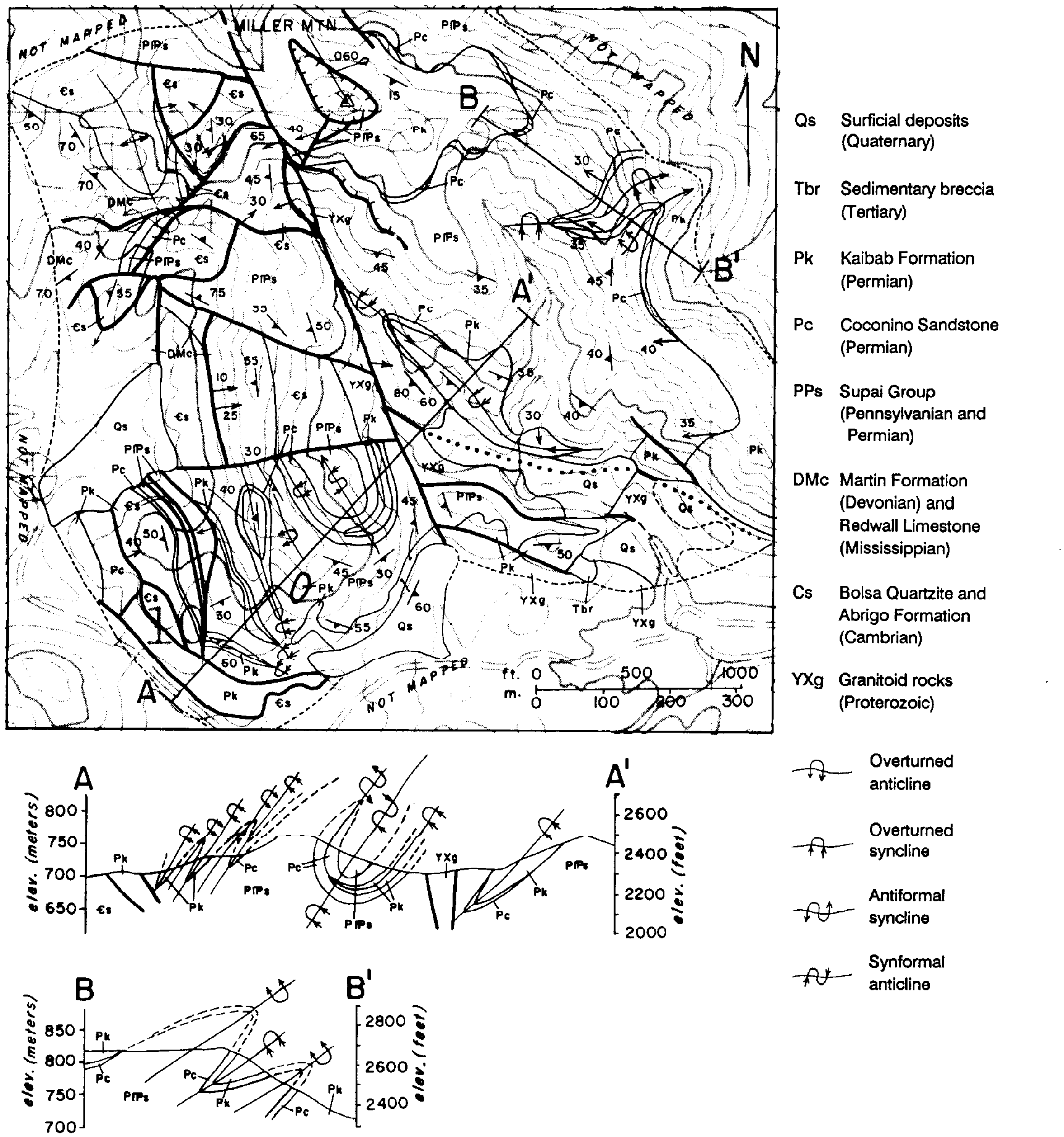


Fig. 5. Geologic map of Miller Mountain in the northern Rawhide Mountains. Tight to isoclinal folding and refolding are characteristic of deep-seated crustal shortening, not extension. These rocks are interpreted to have been deformed in the footwall of the structurally highest thrust of the MFTB. All heavy lines are faults. Hatchures on faults indicate probable Tertiary age based on brittle character of fault rocks. Most or all of the other faults are inferred to be Mesozoic. See Figure 3 for location.

characterized extension along the north flank of the MFTB, and (4) structural styles of extension change along strike; the greatest amount of Tertiary denudation and mylonite exposure occurred above the root zone of MFTB thrusts. We also outline evidence that (1) the Whipple and Buckskin detachment faults are correlative, which implies that the bend in the belt of uplifted lower plate rocks is original and does not reflect extensional distortion of an originally more linear belt, and (2) the east-west trend of the MFTB reflects its original geometry and is not the result of Tertiary extensional distortion.

Trend of Extensional Belts

Detachment faults in the Colorado River extensional corridor are interpreted to have originally dipped gently to moderately northeastward but are now warped into broadly undulating, subhorizontal surfaces [e.g., *Howard and John*, 1987]. Laterally varying tectonic denudation and associated laterally varying isostatic uplift was a major cause of warping of detachment fault footwalls [*Howard et al.*, 1982*b*; *Spencer*, 1984, 1985; *John*, 1987]. The warped form of detachment faults define subparallel belts that are crossed in extension-parallel transects across the Colorado River extensional corridor [*Spencer*, 1984]. In the northern part of the Colorado River extensional corridor these belts are (Figure 1): A, an area of little or no surficial manifestation of extension; B, a synformal keel of extended upper-plate rocks separated from the adjacent unextended area by a breakaway fault; C, an arched and uplifted lower plate; D, a wedge of extended upper plate rocks that is gradational into E, an area of large fault blocks and high-angle normal faults. Farther south, rocks of the synformal keel are either not present or, if present, are largely buried by younger deposits.

One striking feature of the lower Colorado River extensional corridor is the abrupt change in trend of the belt of arched lower plate rocks at the Whipple Mountains (belt C in Figure 1). This belt trends southward from the Newberry Mountains in southernmost Nevada, through the Dead, Sacramento, and Chemehuevi mountains to the Whipple Mountains where it turns abruptly and trends eastward to southeastward to encompass mylonitic crystalline rocks in the Buckskin, Rawhide, eastern Harcuvar mountains and easternmost Harquahala Mountains. The S75°E-trending belt of mylonitic crystalline rocks that extend for over 100 km from the central Whipple Mountains to the eastern Harcuvar Mountains is one of the largest areas (>1000 km^2) of exposed mylonitic crystalline rocks in western North America.

Oblique Breakaway and Lateral Ramp

The breakaway zone for detachment faults along the north flank of the MFTB apparently was not perpendicular to the extension direction, but instead had a more east-west trend that was oblique to extension direction. Available data also suggest that a lateral ramp in the detachment fault system paralleled the oblique breakaway. The existence of an oblique breakaway and lateral ramp is indicated by four types of evidence, as follows:

1. As presently exposed, the breakaway zone of the extensional faults of the Colorado River extensional corridor (boundary between domains A and B in Figure 1) roughly parallels the belt of uplifted lower plate rocks. The breakaway zone trends southward for 160 km from north of the Piute Range to north of the Little Maria Mountains where it turns eastward and continues east-southeastward within the MFTB for over 100 km.

2. The pervasiveness of lower plate mylonitic fabrics in the Buckskin and Rawhide mountains increases in a direction that is more northerly than the northeastward direction of extension. This suggests that the ductile shear zone that was downdip from the precursor to the Buckskin-Rawhide detachment fault dipped in a more northerly direction than the direction of displacement and that it formed an oblique, lateral ramp in the detachment fault system.

3. Upper plate tilt blocks thin southeastward along strike toward the northern flank of the Buckskin and Rawhide Mountains [e.g., *Spencer et al.*, 1989*b*]. This thinning is further reflected by thin sheets and slivers of Tertiary sedimentary and volcanic rocks that are the primary rock type above the detachment fault in the southern and eastern Buckskin Mountains (Figure 3) and are the only upper plate rock type exposed in Butler Valley. Complete denudation of some of the mylonitic lower plate in the Buckskin and Rawhide mountains, indicated by a substantial proportion of mylonitic clasts in late syntectonic conglomerates, is also evidence of southeastward thinning of the upper plate [*Spencer and Reynolds*, 1989].

4. Reverse drag above a listric breakaway fault should result in approximate parallelism between the strike of upper plate strata and the breakaway (Figure 6). Areas where strata do not strike perpendicular to extension direction, but instead have a more east-west strike that possibly reflects the orientation of an oblique breakaway, include the Artillery Mountains [*Lasky and Webber*, 1949; *Spencer et al.*, 1989*a*], north flank of Date Creek basin [*Otton*, 1982], easternmost Harcuvar Mountains [*Reynolds and Spencer*, 1985], the Swansea Mine area in the Buckskin Mountains [*Spencer and Reynolds*, 1989] and possibly the southern Riverside Mountains [*Hamilton*, 1964].

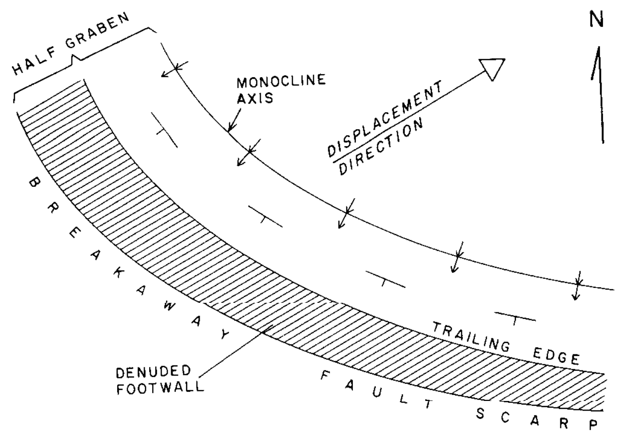


Fig. 6. Schematic diagram of structural relationships along an oblique breakaway zone. Illustrated case is for listric fault with the same curvature for all cross sections perpendicular to the top of the breakaway fault scarp. Modified from Figure 16 of *Dokka* [1986].

Variations in Structural Styles Along Strike

Tertiary extensional faulting along an extension-parallel transect through the Buckskin, Rawhide, and Artillery mountains was characterized by displacement and uplift of lower plate rocks up and out from beneath an upper plate that largely retained its original wedge-shaped form and was not highly distended by faulting (Figure 7) [*Bryant*, 1988; *Spencer and Reynolds*, 1989; *Spencer et al.*, 1989*a*]. Upper plate rocks in the Buckskin and Rawhide mountains are highly extended, but these rocks represent a tiny fraction of the total volume of the upper plate. In contrast, extension within the upper plate in adjacent areas to the north, exemplified by the Turtle, Mopah, Whipple, Chemehuevi, Bill Williams, and Mohave mountains, was characterized by moderate to extreme structural dismemberment and extension of a large volume of upper plate rocks and by preservation of a substantial synformal keel of upper plate rocks (Figure 7) [*Davis et al.*, 1980; *Howard et al.*, 1982*a, b*; *Frost and Okaya*, 1986; *John*, 1987; *Howard and John*, 1987; *Davis and Lister*, 1988]. South of the Harcuvar metamorphic core complex, extension produced complexly faulted, moderately to highly tilted fault-block arrays without exposures of deep crustal levels [e.g., *Richard et al.*, 1988]. Ranges characterized by this structural style include (Figure 7), from west to east, the Bighorn [*Capps et*

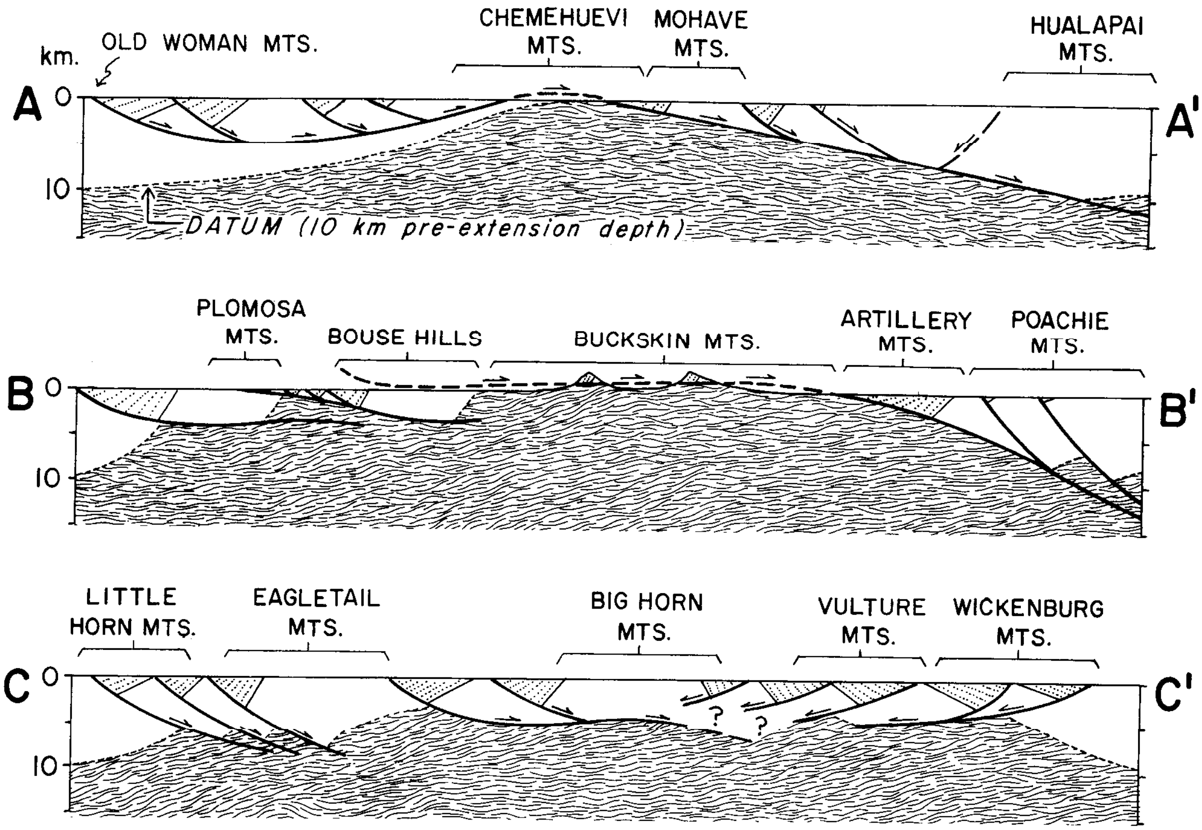


Fig. 7. Schematic cross sections illustrating different structural styles of extension along the Colorado River extensional corridor. Wavy line pattern indicates rocks that were below the brittle-ductile transition zone before extension. See Figure 1 for location of cross sections (east end of cross section C-C' is off map).

al., 1985], Vulture [*Grubensky et al.*, 1987; *Grubensky and Reynolds*, 1988], Wickenburg [*Fryxell et al.*, 1987*b*], and Heiroglyphic mountains [*Capps et al.*, 1986; *Stimac et al.*, 1987]. Thus the style of extensional faulting along an extension-parallel transect that crosses the Buckskin and Rawhide mountains favored exposure of midcrustal mylonitic rocks by large displacement of a mylonitic lower plate from beneath a largely unextended upper plate. In contrast, areas farther north and south were characterized by greater upper plate dismemberment and less exposure of denuded midcrustal mylonitic rock.

Correlation of Detachment Faults

The abrupt bend in the belt of uplifted, lower plate rocks could be the result of large displacement on a detachment fault that cut across the belt between the Whipple and Buckskin mountains and distorted an originally more linear belt. The Whipple detachment fault is the only candidate for such a fault and could have caused such distortion only if it extends below the mylonitic rocks that underlie the Buckskin detachment fault. However, available data support correlation of the Whipple and Buckskin-Rawhide detachment faults, as originally proposed by *Davis et al.* [1980]. Evidence supporting correlation includes the following: (1) Tertiary strata deposited during extension in the easternmost Whipple and western Buckskin mountains are correlative and, at least during the later part of their period of deposition, were probably deposited in the same sedimentary basin above a single detachment fault [*Spencer and Reynolds*, 1989]. (2) There is no evidence for major mid-Tertiary normal faulting in the lower plate in the Buckskin and Rawhide mountains [*Osborne*, 1981; *Woodward*, 1981; *Bryant and Wooden*, 1989; *Spencer et al.*, 1989*b*; *Spencer and Reynolds*, 1989]; normal faulting would be expected if this area were above the gently to moderately dipping Whipple detachment fault. (3) There is no evidence that the western continuation of the Buckskin-Rawhide detachment fault is within the upper plate of the Whipple detachment fault in the Whipple, westernmost Buckskin, or southern Bill Williams mountains (Figure 8) [*Davis et al.*, 1980; *Frost*, 1983, and unpublished map, 1988; *Sherrod*, 1988; *Spencer and Reynolds*, 1989], which would be expected if the Whipple and Buckskin-Rawhide detachment faults were imbricate detachment faults. This last constraint is especially significant. If the mylonitic rocks at Mammon mine (Figure 8), which underlie the Buckskin-Rawhide detachment fault, are part of the upper plate of the Whipple detachment fault, then a southeast facing, oblique breakaway fault for the Buckskin-Rawhide detachment fault must have originally cut downward from the Earth's surface (location A on Figure 8) to depths of mylonitization (probably 10-15 km) within a 5-km-wide zone that is now concealed by postdetachment basalt west of Mammon mine. This zone is not wide enough to include such a large range of paleodepths. Mylonitic rocks exposed in the Buckskin and Whipple mountains are

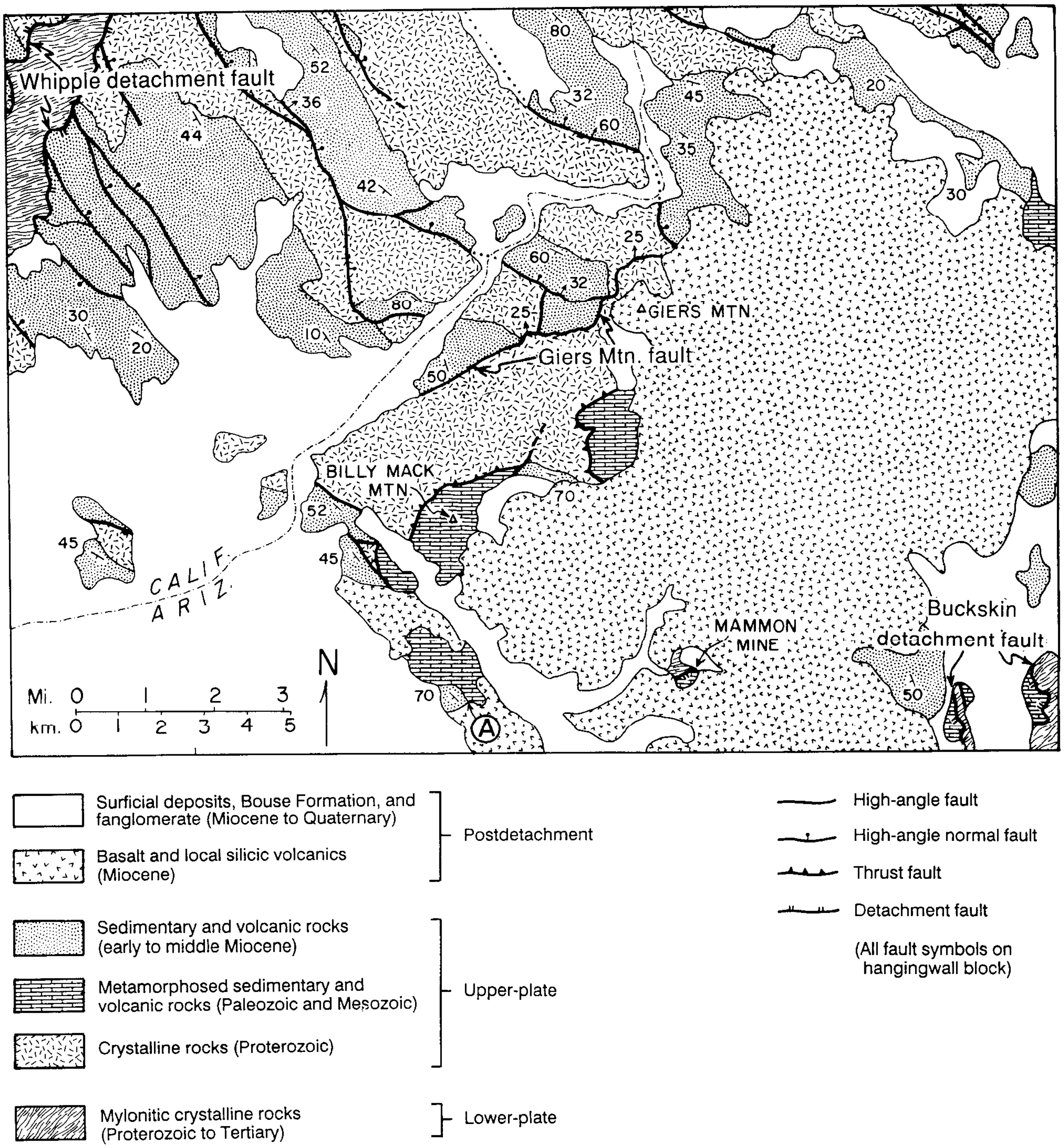


Fig. 8. Simplified geologic map of westernmost Buckskin and southeastern Whipple mountains. Giers Mountain fault is a tear fault in the upper plate of the Whipple detachment fault. Rocks that are structurally part of the footwall of the Giers Mountain fault are exposed as far south as location "A." Rocks at location "A" were at the Earth's surface when the oldest, regionally exposed mid-Tertiary strata were deposited [*Spencer and Reynolds*, 1989]. If the Buckskin detachment fault is structurally higher than the Whipple detachment fault, then the breakaway fault for the Buckskin detachment fault must have reached the Earth's surface between location "A" and the Mammon Mine area where the mylonitic lower plate of the Buckskin detachment fault is exposed. Furthermore, the breakaway fault must have cut downward from the Earth's surface to depths of mylonitization in the 5-km-wide covered region between location "A" and Mammon Mine. This seems unlikely because mylonitization probably occurred at depths much greater than 5 km, and there is not enough room in the 5-km-wide covered region for a greater range of paleodepths. Correlation of the Whipple and Buckskin detachment faults is the only reasonable alternative. Sources of data are *Dickey et al.* [1980], *Spencer and Reynolds* [1989], *Spencer* [1989], E. Frost (unpublished map, 1988) and G.A. Davis et al. (unpublished map, 1982).

thus interpreted as exposures of a single, structurally continuous mylonitic lower plate.

Extensional Distortion of the MFTB

Moderate distortion of the MFTB was caused by extensional faulting within a northeast trending zone between the Harcuvar metamorphic core complex and the southern Plomosa Mountains. Movement on northeast dipping normal faults exposed in the New Water and central and northern Plomosa mountains caused moderate to steep southwest tilting of fault blocks [*Miller*, 1970; *Stoneman*, 1985]. Normal faults in the Plomosa Mountains strike northwestward toward Mesquite Mountain and the Moon Mountains. The Moon Mountains detachment fault at the northern tip of the Moon Mountains represents the structurally lowest fault in the array of extensional faults in this area. Mesquite Mountain is composed of weakly mylonitic gneiss and granitic rocks that have yielded mid-Tertiary $^{40}Ar/^{39}Ar$ biotite dates [*Knapp*, 1988; *Knapp and Heizler*, 1988] and that closely resemble the weakly mylonitic parts of the lower plate in the Buckskin Mountains. The moderate to steep southwest dip of mylonitic fabric and gneissic layering at Mesquite Mountain, unlike the generally gentle dips of such layering in the Whipple and Harcuvar metamorphic core complexes, is possibly the result of rotation above the Moon Mountains detachment fault. The denuded and tilted crystalline rocks at Mesquite Mountain could be structurally correlative with tilted and denuded crystalline rocks in the northern Plomosa Mountains [*Scarborough and Meader*, 1983; *Stoneman*, 1985] and those below the Riverside Mountains detachment fault in California [*Hamilton*, 1964; *Carr and Dickey*, 1980; *Lyle*, 1982*a, b*].

Normal faulting in the New Water, Plomosa, and Moon mountains and tilting of Mesquite Mountain and possibly the Riverside Mountains occurred within an extensional fault system (here referred to as the Plomosa-Moon mountains fault system) that projects beneath the lower plate of the Whipple-Buckskin-Rawhide-Bullard detachment system. Approximately 20 km of extension that resulted from movement on this fault system is recorded by normal faults and moderate to steep tilts of fault blocks within a 25- to 30-km-wide corridor between the breakaway fault for the Plomosa-Moon mountains fault system and the largely unbroken exposed bedrock in the Little Harquahala and Granite Wash mountains. Thus the Whipple and Harcuvar metamorphic core complexes and the eastern part of the MFTB have been displaced northeastward relative to the central and western part of the MFTB. This displacement was not sufficient, however, to substantially distort the MFTB or alter its spatial relationship to mylonitic detachment-fault footwalls.

RELATIONSHIP BETWEEN CENOZOIC AND MESOZOIC TECTONIC FEATURES

With restoration of Tertiary extension, all of the thrust faults in the Maria fold-and-thrust belt are restricted to an east trending belt approximately 50 km wide and located directly south of the east to east-southeast trending belt of Tertiary mylonitic fabrics in the Whipple and Harcuvar metamorphic core complexes. Thrust faults of the MFTB dip regionally northward beneath these mylonitic rocks. A relationship between Mesozoic and mid-Tertiary tectonism is suggested by the spatial coincidence of the root zone of MFTB thrusts with (1) the belt of denuded Tertiary mylonitic fabrics, (2) the abrupt eastward bend, at the Whipple Mountains, of the belt of arched, uplifted rocks below detachment faults, (3) an abrupt eastward bend, north of the Little Maria Mountains, in the trend of the breakaway zone of extensional faults of the Colorado River extensional corridor, (4) a lateral ramp in the Whipple-Buckskin-Rawhide detachment fault, and (5) a structural style of extension characterized by minimum extension within the upper plate and maximum denudation of deep seated lower plate rocks.

We consider two hypotheses for the origin of relationships between Mesozoic and Cenozoic tectonic features in west central Arizona and adjacent southeastern California. According to the crustal welt hypothesis, the geometry and style of extensional tectonism was influenced by isostatic forces associated with thickened crust in the root zone of MFTB thrusts. According to the weak zone hypothesis, MFTB thrust zones and fabrics localized deformation and became nucleation sites for north dipping detachment faults, producing the oblique breakaway and lateral ramp in the detachment fault system. Neither of these hypotheses can be completely eliminated, and both may have exerted some influence on detachment fault geometry. Only the crustal welt hypothesis, however, can account for all of the various geometric and kinematic features that indicate the existence of a relationship between Mesozoic and Cenozoic tectonism.

Crustal Welt Hypothesis

Substantial early Tertiary erosional denudation of the MFTB is indicated by widespread early Tertiary K-Ar and $^{40}Ar/^{39}Ar$ cooling dates [*Rehrig and Reynolds*, 1980; *Martin et al.*, 1982; *Reynolds et al.*, 1986*a*; *Fryxell et al.*, 1987*a*; *Knapp and Heizler*, 1988] and widespread exposure of rocks that underwent greenschist-grade metamorphism in the Cretaceous [*Reynolds et al.*, 1988; *Hoisch et al.*, 1988]. Adjacent areas north of the MFTB have yielded older dates [*Davis et al.*, 1982; *Reynolds et al.*, 1986*a*; *Bryant and Naeser*, 1987], indicating less uplift. Greater erosional denudation was presumably due to greater elevations associated with Cretaceous crustal thickening and greater isostatic uplift during erosion. Isostatic uplift of the MFTB accompanying erosional denudation would be associated with flexural stresses in the crust. These flexural stresses possibly influenced the geometry of detachment faults during mid-Tertiary fault initiation [*Spencer and Chase*, 1989] and produced a regional lateral ramp and oblique breakaway in the detachment-fault system. In addition, uplift of that part of the crustal welt that remained after early Tertiary uplift and erosion could account for the widespread exposure of mid-crustal crystalline rocks that underwent Tertiary mylonitization [*Spencer and Reynolds*, 1986].

Weak Zone Hypothesis

The brittle-ductile transition zone, which is located at a depth of approximately 8-15 km in quartzofeldspathic crustal rocks, is the strongest part of the crust [*Brace and Kohlstedt*, 1980; *Sibson*, 1982]. A weak zone within the brittle-ductile transition zone can provide greater strength reduction than at any other crustal level and therefore should be able to significantly influence the initial geometry of faults and ductile shear zones. We consider two sources of weakness within the brittle-ductile transition: lithologic layering in quartzofeldspathic crystalline rocks and intercalated slivers and sheets of carbonate rocks. The lateral ramp in the detachment fault system and the bend in extensional belts could have resulted from initiation of mid-Tertiary detachment faults-ductile shear zones along north dipping planes of weakness.

Lower plate rocks in the Buckskin and Rawhide Mountains are composed of amphibolite-grade mafic and felsic gneisses intruded by granitoid sills and stocks. The age of the gneissic layering is not known, but the sills and stocks are known or suspected to be Tertiary and Cretaceous [*Bryant and Wooden*, 1989; *Spencer et al.*, 1989*b*]. A COCORP seismic reflection profile that crosses the southern Buckskin Mountains and the adjacent, sediment covered Cactus Plain reveals numerous reflectors in the upper 15-17 km of crust that dip 25°-30° to the southwest [*Hauser et al.*, 1987]. Lithologic layering like that of exposed lower-plate rocks [e.g., *Marshak and Vander Meulen*, 1989] is the likely source of the dipping seismic reflections. The detachment fault cuts across lower plate lithologic layering in the weakly mylonitized southern Buckskin Mountains but is roughly concordant in areas of more pervasive mylonitization farther north. Thus the initial detachment fault-ductile shear zone (precursor to the Buckskin-Rawhide detachment fault) appears to have cut downward across lithologic layering to a depth of several kilometers below the brittle-ductile transition zone and was roughly concordant to lithologic layering at greater depth. We conclude that lithologic layering exerted little control over the geometry of the detachment fault-ductile shear zone within or above the brittle-ductile transition zone but was important at greater depths.

Carbonate rocks are weak and highly ductile at typical temperatures within the brittle-ductile transition zone and where surrounded by quartzofeldspathic crystalline rocks would be especially likely to localize deformation. Lower plate rocks in the Buckskin and Rawhide mountains contain sparse but widely scattered carbonate sheets and slivers that are typically a few meters thick and concordant to mylonitic and gneissic layering [*Bryant and Wooden*, 1989; *Spencer and Welty*, 1989; *Shackelford*, 1989*b*]. The carbonate slivers were possibly originally intercalated with lower plate crystalline rocks during shearing along Mesozoic thrust faults [*Bryant and Naeser*, 1988]. There are very few locations in the Buckskin and Rawhide mountains where rocks directly below the detachment fault are composed of carbonate rock. Almost all of the known slivers of carbonate rock are completely enclosed within lower plate quartzofeldspathic crystalline rock [*Spencer and Welty*, 1989]. Metasedimentary rocks, including calcite and dolomite marble, form large (several square kilometer) areas of the lower plate in the southern [*Marshak and Vander Meulen*, 1989] and southeastern [*Spencer and Reynolds*, 1989] Buckskin Mountains. Even in these areas, the detachment fault cuts across layering at a low angle and is not preferentially located atop carbonate lithologies. Field relationships thus suggest that the detachment fault was not associated with weak carbonate rocks.

At Mesquite Mountain west of the Buckskin Mountains, carbonate slivers like those in the Buckskin and Rawhide mountains are present within mylonitic shear zones of probable mid-Tertiary age that cut discordantly across an older, probably mid-Tertiary mylonitic fabric [*Knapp*, 1988]. This relationship indicates that such slivering and intercalation occurred in the mid-Tertiary and suggests that intercalation of metasedimentary slivers was a mid-Tertiary event in the Buckskin and Rawhide mountains as well.

Finally, Mesozoic structures in the MFTB are typically highly complex and commonly include folded thrusts [e.g., *Reynolds et al.*, 1987]. Reactivation of Mesozoic thrusts as planar detachment faults generally was not possible.

Discussion

Two basic Tertiary features, which are geometrically related to the MFTB, must be accounted for by models that relate Mesozoic and Cenozoic tectonic features in west central Arizona and adjacent southeastern California. These two features are the 45°-75° bend in extensional belts and structures (the oblique breakaway and lateral ramp are manifestations of this bend), and the change in structural styles along the belts. Available geologic and geophysical evidence from the Buckskin and Rawhide mountains does not support the hypothesis that the bend of structural belts is related to initiation of detachment faults-ductile shear zones along north dipping zones of weakness that transect the brittle-ductle transition zone. In addition, the weak zone hypothesis can not account for the change in structural styles along the belts. In contrast, the crustal welt hypothesis possibly accounts for both features.

According to the crustal welt hypothesis, uplift of mylonitic lower plate rocks in the Whipple and Harcuvar metamorphic core complexes was driven by isostatic forces associated with a downward protruding Moho bulge inherited from the MFTB. Rapid and forceful isostatic uplift of mylonitic rocks above the Moho bulge is thus inferred to have prevented collapse and distention of upper plate rocks into an extensional basin (Figure 9). The corollary of this inference is that in the absence of a Moho bulge or zone of low-density crust in the lower plate, the upper plate will form a distended tilt-block array and little or no lower plate mylonitic rock will be exposed (unless mylonitization occurred at shallow crustal levels because of heating from magmatism). If this analysis is correct, first-order changes in structural style along extensional belts in detachment systems are influenced by lateral variations in magnitudes of isostatic uplift, which are in turn influenced by preexisting lateral variations in crustal thickness and density [e.g., *Holt et al.*, 1986]. Isostatic uplift of Moho bulges was facilitated by reduction of the flexural strength of the upper crust due to elevated geothermal gradients that caused weakening of the upper crust and to flexural slip along detachment faults [*Spencer*, 1982, 1984, 1987].

Elliott [1976] emphasized surface slope as a determinant of styles of deformation during crustal shortening and proposed that thrust sheets always move in the direction of the surface slope, regardless of the dip direction of the underlying thrust fault. We suggest that surface slope is a major control over the style of deformation in the upper plates of detachment faults. Where surface slope in the upper plate is toward the breakaway, the upper plate will undergo internal extension (Figure 9A). Gravitational potential energy is released by internal extension of the upper plate. Where surface slope is away from the breakaway, the upper plate will remain largely intact and unextended during detachment faulting (Figure 9B). Gravitational potential energy is available in this case to cause shortening within the upper plate (which is generally not observed) or wholesale displacement of the upper plate down the detachment ramp, but can not drive internal extension of the upper plate. Extension would possibly occur at the tapered end of the upper plate where reverse drag

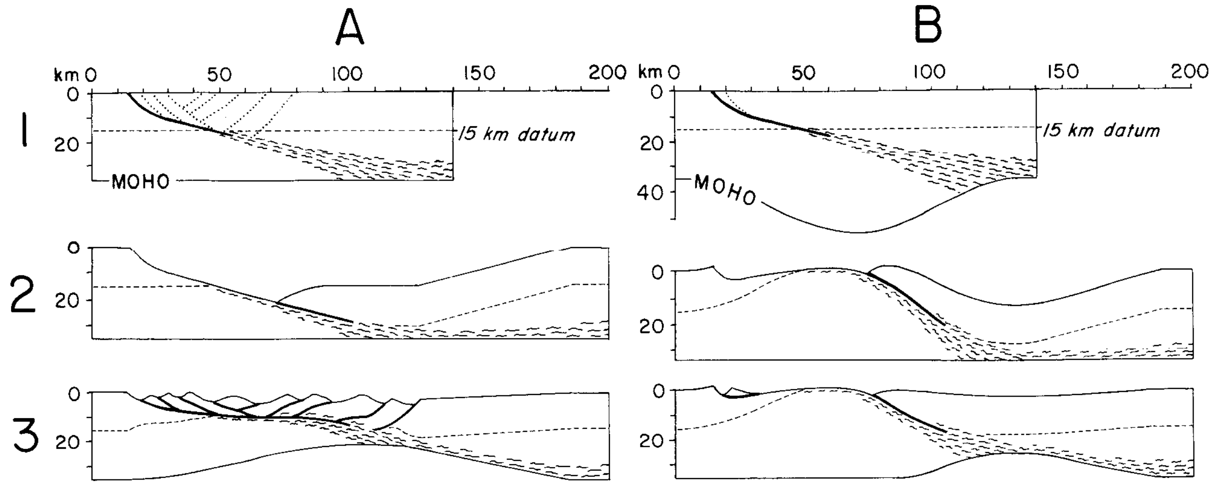


Fig. 9. Schematic diagrams of contrasting styles of extensional deformation for (*A*) initially flat Moho and (*B*) downward protruding Moho bulge. 1, Initial detachment fault geometry and down-dip continuation as ductile shear zone; 2, configuration after 60 km of extension with flat Moho, without isostatic equilibrium, and without internal extension of upper plate, and 3, configuration with isostatic equilibrium and internal extension of upper plate. The necked crust on the right side of cross section 3B is not characteristic of the crust northeast of the Harcuvar metamorphic core complex; the Moho is flat to gently east dipping (to the right) in this area [*McCarthy et al.*, 1987; *Hauser et al.*, 1987]. Flattening of the Moho during and after detachment faulting was presumably the result of ductile flow in the lower crust during elevated thermal gradients associated with Tertiary magmatism [e.g., *Bird and Kemp*, 1987].

[e.g., *Hamblin*, 1965] may cause the surface to slope toward the breakaway.

The Moho beneath west-central Arizona and adjacent southeastern California is presently nearly flat [*Hauser et al.*, 1987; *McCarthy et al.*, 1987]; any crustal welt originally associated with the MFTB has been completely eliminated. Substantial Moho relief can apparently survive in an amagmatic continental setting for hundreds of millions of years [*Goleby et al.*, 1989], but may not survive elevated temperatures associated with magmatism [*Bird and Kemp*, 1987]. Three processes probably contributed to the destruction of the welt in the study area: (1) isostatic uplift of the welt associated with latest Cretaceous and early Tertiary erosional denudation, (2) isostatic uplift of the welt associated with mid-Tertiary denudational faulting, and (3) lateral flow of lower crustal rocks away from the root during middle to late Cenozoic magmatism and increased lower crustal temperatures. We do not know the relative significance of each of these processes in flattening the Moho beneath the study area, but we suspect that all three were important.

Numerical analysis of bending stresses in the crust related to flexural support of Moho and surface relief suggest that low-angle normal faults will form if the ratio of bending stress to extensional stress is sufficiently high [*Spencer and Chase*, 1989]. Two tectonic configurations were considered by Spencer and Chase that are possibly applicable to the study area: (1) A solitary, downward protruding, flexurally supported Moho bulge without associated surface relief, and (2) a Moho bulge related to deep-seated crustal thickening that is laterally offset from a flexurally supported mountain belt related to thrusting. We consider these two tectonic configurations in three manifestations at the beginning of mid-Tertiary extension: (1) a solitary Moho bulge beneath the MFTB, (2) a solitary Moho bulge beneath the root zone of MFTB thrusts, and (3) a Moho bulge beneath the root zone of MFTB thrusts and a mountain belt along the MFTB.

Numerical analysis based on Airy stress functions for an elastic medium [*Spencer and Chase*, 1989] suggest that north dipping low-angle normal faults would develop on the north flank of the MFTB in configurations 1 and 3, but such faults would be south dipping in 2. Configuration 1 would be expected to promote formation of a symmetrical array of normal faults dipping outward from the axis of the welt, and the greatest amount of preextension uplift and cooling, leading to the youngest cooling ages, would be expected along the axis of the MFTB. A few southwest dipping normal faults are present south of the MFTB in the Trigo, southern Kofa, and Castle Dome Mountains [*Reynolds*, 1988; M. Grubensky, oral communication, 1989], but many northeast dipping normal faults are present as well [e.g., *Pridmore and Craig*, 1982]. Early Tertiary K-Ar and $^{40}Ar/^{39}Ar$ cooling dates characterize rocks within the MFTB, and those to the north that were above the root zone of MFTB thrusts have yielded older ages [e.g., *Davis et al.*, 1982; *Bryant and Naeser*, 1987]. However, some rocks to the south have yielded K-Ar cooling ages similar to those from the MFTB [*Tosdal*, 1988]. The lack of clear symmetry about the MFTB of Tertiary structures and cooling ages is more consistent with configuration 3 than 1, but 3 does not account for the greater early Tertiary uplift and cooling of the frontal part, and not the root zone, of the MFTB. Possibly the root zone was held down by the flexural strength of the adjacent Colorado Plateau. Constraining these various configurations is further complicated by possible major modification of the Moho during low-angle early Tertiary subduction [*Burchfiel and Davis*, 1981; *Bird*, 1984, 1988].

Thermochronologic studies indicate that substantial early Tertiary cooling occurred during erosional denudation and uplift of the MFTB and that less uplift occurred in areas to the north. Flexural stresses must have developed in the crust due to laterally varying uplift. We suggest that, at the beginning of Tertiary extension, a crustal root was supported by these flexural stresses and the strike of extensional faults was influenced by these stresses. Lack of knowledge of mid-Tertiary Moho and surface configuration does not allow well-constrained modeling of stress conditions during extensional-fault initiation. However, two of three reasonable approximations of tectonic setting and associated stress conditions are consistent with the northward dip of normal faults along the north flank of the MFTB. It is not clear, however, if less uplift occurred to the south of the MFTB than within it, if the axis of a Moho bulge was beneath the MFTB or beneath its root zone to the north, or if early Tertiary low-angle subduction modified the Moho.

CONCLUSION

Patterns of Mesozoic and Cenozoic tectonism in west central Arizona and adjacent southeastern California reveal a geometric relationship between Mesozoic and Cenozoic structures. Tertiary structural belts within the Colorado River extensional corridor trend southward and then bend abruptly eastward along the north flank of the MFTB. Relative to adjacent areas, extensional faulting along the north flank of the MFTB was characterized by maximum denudation and uplift of lower plate rocks and minimum extensional dismemberment of the upper plate. Available geological and geophysical data do not support the interpretation that north dipping thrusts and fabrics inherited from the MFTB were reactivated as extensional structures within and above the mid-Tertiary brittle-ductile transition zone; these thrusts and fabrics do not appear to have influenced the initial geometry of Tertiary structures in the upper crust.

Our interpretation of the geometric relationship between Mesozoic and Cenozoic tectonic features is as follows: Mesozoic crustal shortening and thickening within the MFTB produced a crustal welt. Early Tertiary erosion of surface relief associated with the MFTB was not accompanied by sufficient isostatic uplift to eliminate the downward protruding Moho bulge beneath the MFTB or its root zone. At the beginning of mid-Tertiary extension, the Moho bulge was partially supported by the flexural stresses in the lithosphere. These flexural stresses influenced initial detachment fault geometry and resulted in a bend in extensional belts and a major lateral ramp in the detachment fault system. Isostatic uplift of the Moho bulge carried midcrustal mylonitic rocks to surface levels. Forceful uplift of the lower plate prevented formation of a deep basin and extensional collapse of the hanging wall into the basin; the upper plate thus largely avoided internal extension.

Our conclusions support several previous concepts applied to Cordilleran orogenesis: (1) Tertiary uplift of metamorphic core complexes occurred in areas of anomalous Mesozoic crustal thickening [*Coney and Harms*, 1984; *Coney*, 1987], (2) lithospheric flexural strength can prevent isostatic uplift of downward-protruding Moho bulges after compensating mountain ranges have been largely removed by erosion [*Holt et al.*, 1986; *Chase and Wallace*, 1986, 1988], and (3) stresses resulting from flexural support of crustal welts can influence the geometry of detachment faults [*Spencer and Chase*, 1989].

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