TECTONICS, VOL. 10, NO. 6, PAGES 1204-1221, DECEMBER 1991

# TECTONICS OF MID-TERTIARY EXTENSION ALONG A TRANSECT THROUGH WEST CENTRAL ARIZONA

Jon E. Spencer and Stephen J. Reynolds[1]
Arizona Geological Survey, Tucson

*Abstract.* Large-magnitude Miocene extension in west central Arizona occurred primarily along three imbricate, northeast dipping normal faults. The structurally highest of these faults, the gently dipping Buckskin-Rawhide detachment fault, accommodated approximately 66 km of crustal extension, whereas the two structurally lower faults accommodated a total of about 20 km extension. Due to this large-magnitude extension, an area at the Earth's surface that was 10 to 20 km wide is now over a 100 km wide, and crystalline rocks with mid-Tertiary mylonitic fabrics, uncovered by detachment faulting, are exposed over roughly 2000 km$^2$ in the Harcuvar metamorphic core complex. Most of the upper plate of the Buckskin-Rawhide detachment fault was largely undeformed by internal extension; only the thin, tapered end of the upper plate was highly extended. During extension the lower plate must have flexed to conform to the listric underside of the upper plate and to have flattened to its present subhorizontal form as it was uncovered. Grooves on the underside of the upper plate were apparently imposed on the pliable lower plate as it was denuded, forming extension-parallel folds in the lower plate. Low flexural strength characterized the lower plate during denudation, and a highly mobile, low-viscosity deeper crust must have effectively decoupled the upper crust from the mantle lithosphere.

## INTRODUCTION

The kinematics and dynamics of large-magnitude extension are a major focus of research in continental geodynamics. Cenozoic extensional strains of 100% or more are now recognized in some areas of the Basin and Range province, but in general it has been difficult to quantify such strains and to determine the kinematic evolution of rocks in affected areas. In this study we integrate data from previous studies in order to examine structural styles and magnitudes of extension along an extension-parallel transect in west central Arizona. Analysis of geologic maps, most of them recently published, reveals that extension in the study area was accommodated in the upper crust by displacement on three imbricate, regionally northeast dipping normal faults, the most important of which is the Buckskin-Rawhide detachment fault and its correlatives in the Harcuvar and Whipple mountains. Structural analysis and restoration of normal faults allow estimates of displacement on each of these faults and lead to a tectonic reconstruction that realigns Mesozoic structural features.

[1]Now at Department of Geology, Arizona State University, Tempe.



Paper number 91TC01160.
0278-7407/91/91TC-01160$10.00

Detachment faults have been considered to be the extensional analogs of thrust faults [Wernicke, 1981]. In detail, however, the mechanical behavior of the crust during large-magnitude extension may be quite different from that typically associated with crustal shortening. Specifically, the uplift and warping of large-displacement, low-angle normal faults (detachment faults) and their commonly mylonitic lower plates (metamorphic core complexes) during extension indicate that the flexural strength (resistance to bending) of detachment-fault lower plates was far less during extension than was the flexural strength of the lower plates of foreland fold and thrust belts during thrusting. Indeed, simplistic models of detachment faulting assuming essentially zero lower plate flexural strength yield fault geometries that are quite similar to some known geometries [Spencer, 1984].

Several types of evidence indicate that the Buckskin-Rawhide detachment fault and its downdip extension as a ductile (e.g., plastic [see Rutter, 1986]) shear zone had a broadly listric form and that the hanging wall largely maintained this form during extension. The lower plate therefore must have undergone major flexural deformation as it was displaced up and out from beneath the upper plate. A significant conclusion of this study is that, during extension, the low flexural strength of the lower plate of the Buckskin-Rawhide detachment fault and a highly mobile middle to lower crust allowed rapid warping and short-wavelength isostatic adjustment during extension. We thus support earlier proposals for styles of extensional deformation in which a migrating monocline in the lower plate follows the tapered end of the upper plate during extension [Buck, 1988; Hamilton, 1988; Wernicke and Axen, 1988]. In addition, we support previously proposed models for a highly mobile deeper crust [Gans, 1987; Spencer and Reynolds, 1989b; Wernicke, 1989; Block and Royden, 1990] that accommodated the migrating monoclinal flexure. Extension-parallel antiforms and synforms in the lower plates of the detachment faults, which are reflected by the physiography of the Buckskin, Rawhide, and Harcuvar mountains, are interpreted in part as folds that formed under conditions of low flexural strength.

## GEOLOGIC SETTING

The southwestern part of the Basin and Range province can be divided into Tertiary tilt-block domains within which normal-fault-bounded blocks are tilted in one dominant direction (Figure 1) [Spencer and Reynolds, 1989b]. Tertiary mylonitic fabrics in metamorphic core complexes have been interpreted as exhumed ductile shear zones that formed down dip from detachment faults (shear zone model of metamorphic core complexes) [Wernicke, 1981; Davis, 1983; Davis et al., 1986]. The Tertiary age of mylonitic fabrics in many metamorphic core complexes in the southwestern United States is indicated by geochronologic data from the Whipple [Wright et al., 1986], Buckskin [Bryant and Wooden, 1989], South [Reynolds et al., 1986b], and Tortolita [Keith et al., 1980] mountains. The sense of shear during mylonitization, as interpreted from mylonitic petrofabrics, was the same as the general sense of displacement on normal faults in the associated tilt-block domains [Davis et al., 1986; Reynolds and Lister, 1987; Spencer and Reynolds, 1989b]. This kinematic coordination supports the shear zone model for the origin of Tertiary mylonitic fabrics in Cordilleran metamorphic core

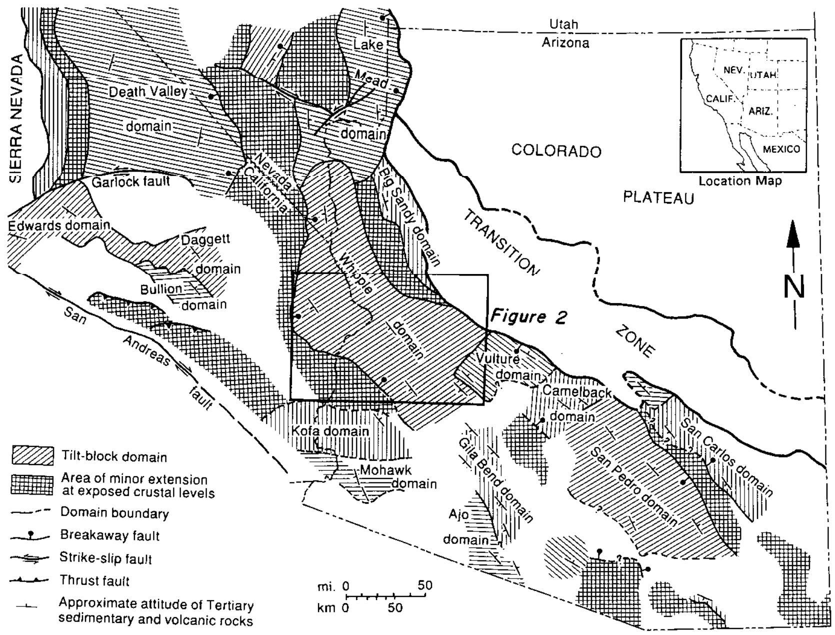


Fig. 1. Tilt-block domain map of the Mojave-Sonora desert area. Normal-fault-bounded blocks are tilted dominantly in one direction within each domain. Modified from Spencer and Reynolds [1989b] with additions from Dokka [1989]. It is not clear that the western part of the Edwards domain is extended [see Bartley et al., 1990].

complexes, and all of our data from the study are consistent with this interpretation.

The Whipple tilt-block domain in western Arizona, southeastern California, and southernmost Nevada (Figure 1) [Howard and John, 1987; Spencer and Reynolds, 1989b] contains some of the most areally extensive exposures of Tertiary mylonitic fabrics in North America [Davis et al., 1980; Davis and Lister, 1988; Spencer and Reynolds, 1989a]. The study area is a transect across the southern part of this tilt-block domain and includes areas at the ends of the transect that have undergone little or no Tertiary extension at exposed crustal levels.

The Transition Zone physiographic province of Arizona, which is at the northeastern end of the transect, separates the Basin and Range province from the Colorado Plateau. It is structurally continuous with the Colorado Plateau, but its Paleozoic and Mesozoic sedimentary cover has been largely removed by erosion. It has undergone little Tertiary extension at exposed structural levels. The southwestward regional slope of the Transition Zone reflects a decrease in crustal thickness from more than 40 km to the northeast to less than 30 km to the southwest [Warren, 1969; McCarthy et al., 1987; Hauser et al., 1987; Hauser and Lundy, 1989]. Before mid-Tertiary extension, the area that is now the Transition Zone sloped northeastward and sediments were shed onto the Colorado Plateau from what is now the Basin and Range province [Young and McKee, 1978; Peirce et al., 1979]. The mid-Tertiary reversal in drainage and sediment-transport direction is interpreted as a reflection of crustal thinning of the Basin and Range province from thicknesses greater than to thicknesses less than those of the Colorado Plateau. The reversal in the surface slope of the area that is now the Transition Zone was presumably caused by southwestward displacement and thinning of lower and middle crustal rocks, with progressively greater crustal thinning toward the southwest [Wernicke, 1985; Reynolds and Spencer, 1985; Spencer and Reynolds, 1989b].

Ranges at the southwestern end of the transect have undergone little extension at exposed crustal levels. These ranges include the southern Plomosa [Miller, 1970] and central Dome Rock (R. Tosdal, unpublished map, 1988) mountains in Arizona and the Big Maria [Hamilton, 1987], Little Maria [Emerson, 1982], and Palen [Stone and Kelley, 1989] mountains in California (Figure 2). This part of the Basin and Range province now has a crustal thickness of 22 to 28 km [Hearn, 1984; Hauser et al., 1987] but almost certainly had a much greater crustal thickness immediately after Mesozoic crustal shortening and granitoid plutonism [e.g., Hamilton, 1978].

## STRUCTURAL GEOLOGY AND ROCK TYPES ALONG THE TRANSECT

Structural styles of Miocene extension vary greatly across the southern part of the Whipple tilt-block domain (Figure 2). The southwestern part of the transect (Ranegras Plain area) crosses an area where displacement on initially steeply to moderately northeast dipping normal faults was associated with substantial rotation of faults and fault blocks. The middle part of the transect crosses the northern part of the Harcuvar metamorphic core complex (Buckskin and Rawhide mountains). The northeastern part of the transect crosses the boundary between the Basin and Range and Transition Zone physiographic provinces (Artillery and Poachie mountains).

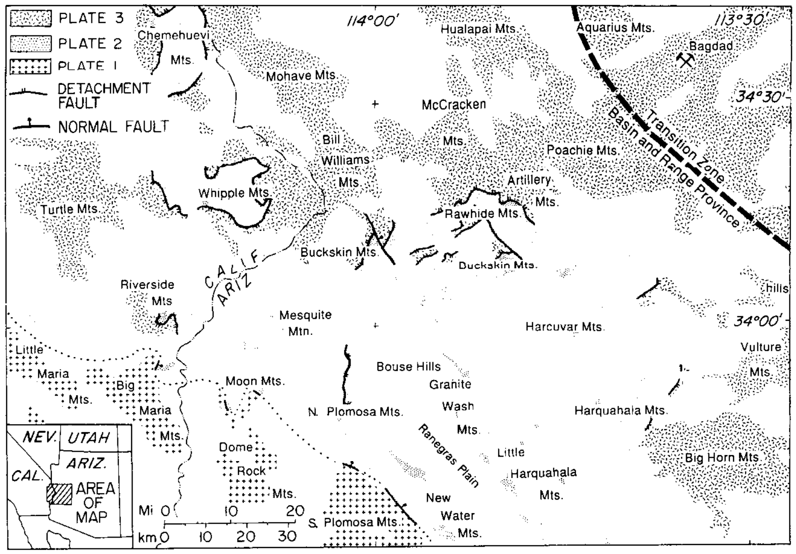


Fig. 2. Map showing locations of mountain ranges and regional structural plates. Plate 1 consists of rocks that form the footwall block of the southwesternmost northeast dipping normal fault (breakaway) within the Whipple tilt-block domain. Plate 2 consists of rocks that are structurally above the breakaway but are below the large detachment faults of the region. Rocks above the detachment faults comprise Plate 3 and extend northeastward to the Transition Zone physiographic province and Colorado Plateau. Some correlations are speculative; rocks shown as Plate 2 in California may actually be Plate 1 [e.g., Frost and Okaya, 1986].

*Ranegras Plain Area*

The southern Plomosa Mountains (southwest corner of Figure 3) consist largely of rocks that have not been significantly affected by Tertiary normal faulting [Miller, 1970; Sherrod and Koch, 1987]. These rocks are bounded to the northeast by a northeast-side-down normal fault (breakaway fault on Figure 3) that separates the largely unextended southern Plomosa Mountains from gently to steeply southwest tilted fault blocks bounded by normal faults in the Ranegras Plain area. Gently southwest dipping Tertiary mafic volcanic rocks that rest depositionally on pre-Tertiary rocks along the southwestern flank of the Little Harquahala Mountains [Spencer et al., 1985] are similar and probably coeval with southwest tilted mafic volcanic rocks in the New Water and central Plomosa Mountains [Sherrod et al., 1990]. Northeast dipping normal faults along the southwest side of Ranegras Plain are thus inferred to extend under the Little Harquahala and Granite Wash mountains.

Crystalline rocks that underlie the tilted Tertiary section in the central Plomosa Mountains continue unbroken for almost 20 km to the north where they form much of the northern Plomosa Mountains [Stoneman, 1985; Scarborough and Meader, 1989]. These crystalline rocks are bounded to the east and north by the Plomosa fault, a moderately to gently dipping normal fault that is overlain by an extended array of south to southwest tilted fault blocks. The Plomosa fault projects eastward beneath the western Bouse Hills, which consist of Proterozoic crystalline rocks that are depositionally overlain by moderately to steeply southwest dipping Tertiary volcanic and sedimentary rocks [Spencer and Reynolds, 1990a]. The tilted Miocene strata in the western Bouse Hills,

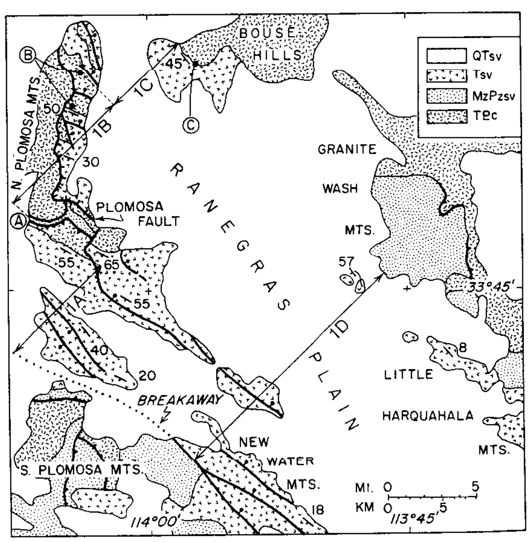


Fig. 3. Simplified geologic map of the Ranegras Plain area showing location of transects for which the magnitudes of extension have been estimated (estimates in Table 1 and Appendix). Abbreviations are QTsv, undeformed Quaternary and upper Tertiary sedimentary and volcanic deposits; Tsv, middle Tertiary sedimentary and volcanic rocks; MzPzsv, Mesozoic and Paleozoic sedimentary and volcanic rocks; and TPc, Tertiary to Proterozoic crystalline rocks.

including mafic volcanic rocks, are on strike with the tilted Miocene mafic volcanic rocks on the west flank of the Granite Wash and Little Harquahala mountains (Figure 3), and all three areas appear to be in the same basic mid-Tertiary structurally setting.

*Buckskin and Rawhide Mountains*

The undulating Buckskin-Rawhide detachment fault separates a variably mylonitic lower plate from highly faulted upper plate rocks that include Miocene volcanic and sedimentary rocks (Figure 4) [Rehrig and Reynolds, 1980; Spencer and Reynolds, 1989a]. The detachment fault has a corrugated form with corrugation axes trending approximately N55°E. Upper plate rocks are typically preserved in synforms, whereas resistant lower plate crystalline rocks make up the topographically higher antiforms.

Lower plate crystalline rocks in the Buckskin, Rawhide, and central and eastern Harcuvar mountains consist largely of amphibolite-grade gneisses intruded by granitic to dioritic sills and plutons of Proterozoic(?) to Tertiary age [Rehrig and Reynolds, 1980; Spencer and Reynolds, 1989a]. These

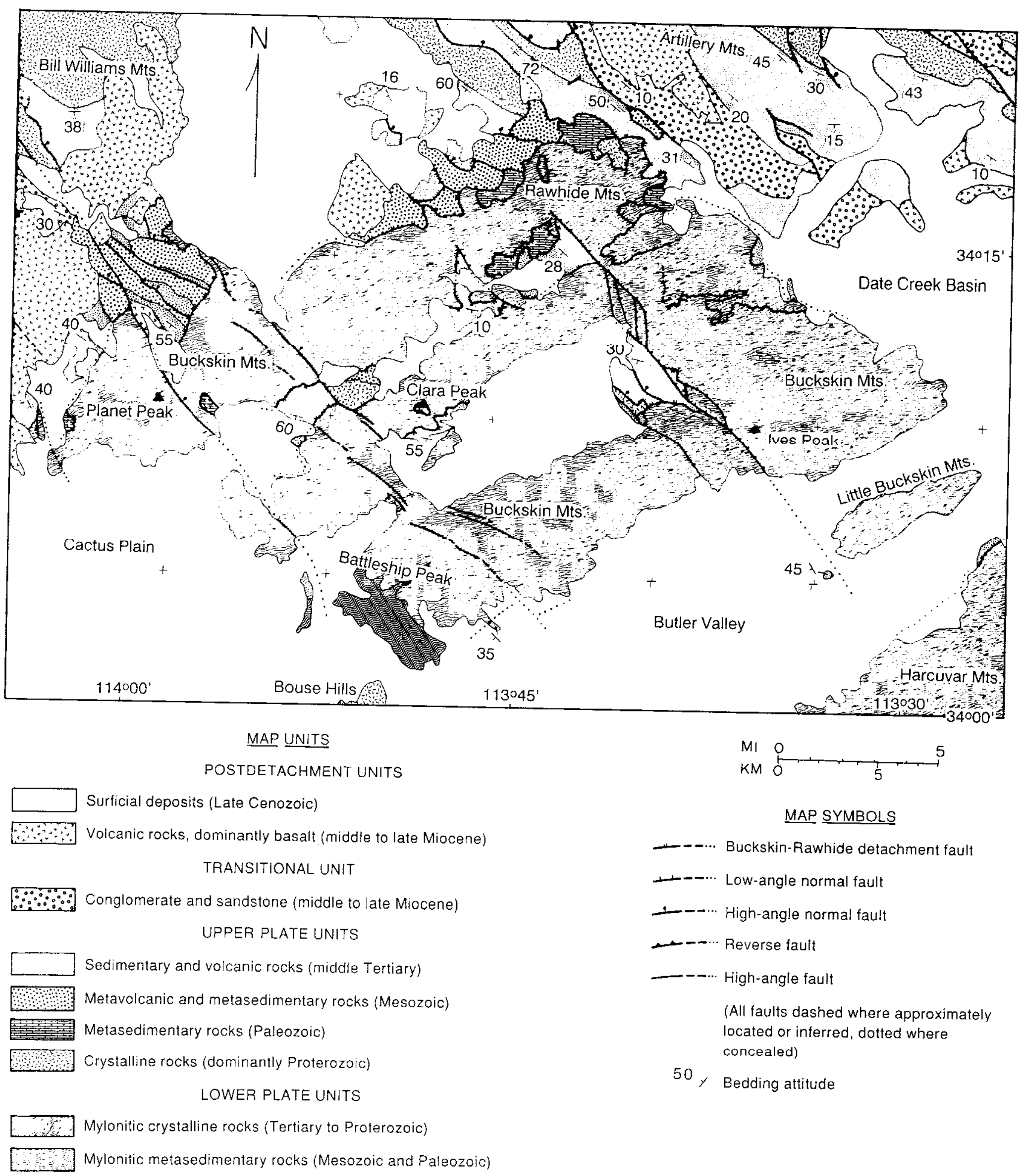


Fig. 4. Simplified geologic map of the Rawhide and central and eastern Buckskin mountains, and adjacent areas.

crystalline rocks are overprinted by a Tertiary mylonitic fabric that grades from well developed and penetrative in northeastern areas to weak and restricted to discrete shear zones in southwestern areas. The degree of mylonitic fabric development generally decreases structurally downward.

In the Rawhide and northern Buckskin mountains, the corrugated form of the Buckskin-Rawhide detachment fault is well constrained by numerous exposures of the fault. Farther south, the form of detachment faults is revealed primarily by the geomorphology of resistant lower plate rocks (Figure 5) [Pain, 1985]. Cretaceous sills within the lower plate appear to be arched in the eastern Harcuvar and eastern Buckskin mountains, which suggests that the corrugations partially reflect folds in lower plate rocks. The approximate parallelism of corrugation axes and mylonitic lineations suggests that folding and extension were related.

The Harcuvar, Little Buckskin, and Buckskin mountains are separated by intervening Quaternary surficial deposits in Butler Valley (Figure 4). Variably mylonitic, lower plate crystalline rocks are essentially identical in these ranges and the detachment fault corrugations defined by physiography are all parallel (Figure 5). The detachment fault at the east end of the Harcuvar Mountains, known as the Bullard fault (Figure 2) [Reynolds and Spencer, 1985], thus appears to be correlative with the Buckskin-Rawhide detachment fault; both faults form the upward bounding surface of what is probably a single areally extensive lower plate and both faults have the same sense and inferred age of displacement.

Lower plate rocks in the Buckskin and Rawhide mountains strongly resemble those in the eastern Whipple Mountains. Overlying detachment faults in the two areas have the same sense of displacement, and their upper plates appear to be part a single large area of tilt blocks and half grabens that includes the Bill Williams Mountains (Figure 2) [Sherrod, 1988; Spencer, 1989]. The two detachment faults are thus probably correlative [Davis et al., 1980; Spencer and Reynolds, 1990b].

### *Artillery and Poachie Mountains*

The northeastern part of the transect includes the area from the northeasternmost trace of the Buckskin-Rawhide detachment fault to the Transition Zone physiographic province (Figure 6). The detachment fault in the northeastern Rawhide Mountains dips gently northeastward beneath southwest-tilted Tertiary strata that overlie crystalline rocks in the Artillery and Poachie mountains [Lasky and Webber, 1949; Otton, 1982; Bryant, 1988; Spencer et al., 1989a]. Proterozoic crystalline rocks that underlie the tilted Tertiary strata include a variety of rock types, some of which form northeast trending belts that extend into the Transition Zone physiographic province of central Arizona [Bryant, 1988]. These belts are not significantly disrupted by Tertiary faults (locations A and B in Figure 6).

The base of mid-Tertiary strata in the Artillery Mountains and southern Poachie Mountains is tilted 30°-50° to the southwest. Farther northeast and east, similar-age strata are gently dipping and rest on an undulating subhorizontal to gently dipping disconformity [Bryant, 1988; Brooks, 1985] (volcanic rocks around location B in Figure 6). The magnitude of tilting of underlying pre-Tertiary rocks, which are not separated from the Transition Zone physiographic province by faults with large displacement, thus decreases to the northeast. Distributed brittle deformation within these

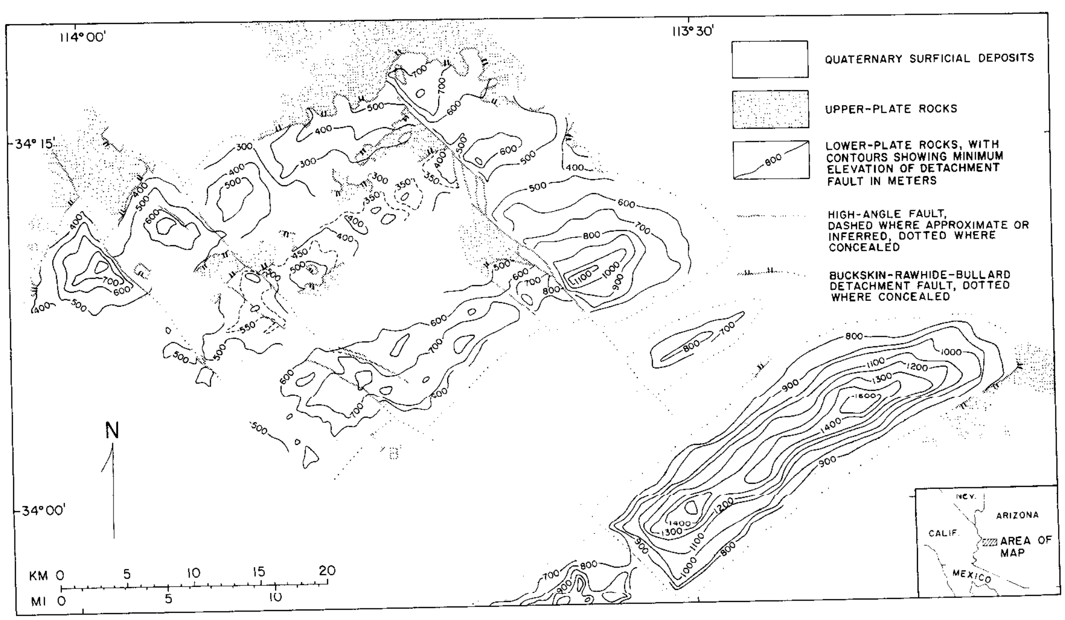


Fig. 5. Minimum-elevation contour map of the lower plate of the Buckskin-Rawhide-Bullard detachment fault showing fault-surface corrugations with axes parallel to fault-displacement direction. Contours are drawn to intersect topographically highest areas such as ridge crests and therefore to display the minimum elevation of the detachment fault over the lower plate.

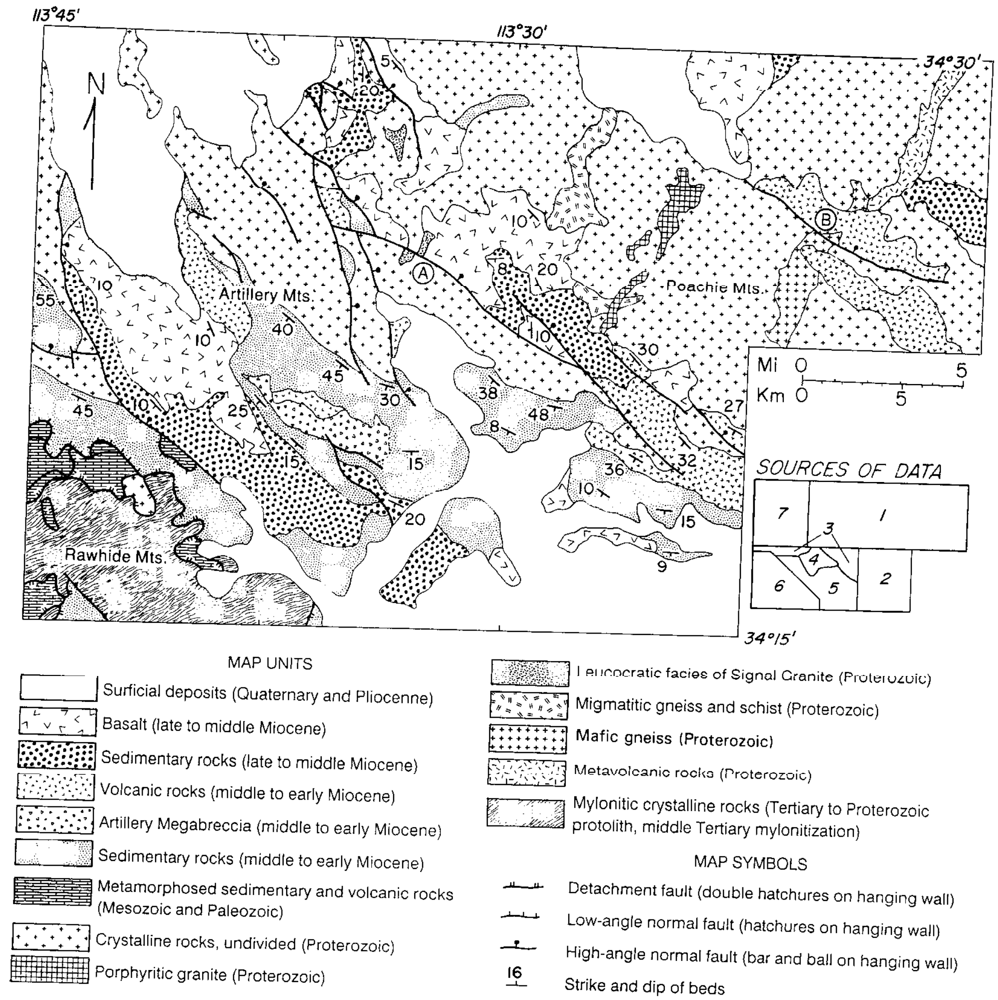


Fig. 6. Simplified geologic map of the Poachie, Artillery, and northeastern Rawhide mountains and adjacent areas. Tertiary normal faults at locations A and B only slightly offset Proterozoic rock units that form northeast trending belts. Sources of data are 1, Bryant [1988]; 2, J. Otton and J. Yarnold (unpublished map, 1989); 3, J. Otton and J. Yarnold (unpublished maps, 1989) and aerial photograph interpretation by J. Spencer; 4, Spencer et al., [1989a]; 5, Lasky and Webber [1949]; 6, Shackelford [1989a]; and 7, Lucchitta and Suneson [1985].

rocks appears to have at least partially accommodated progressively greater tilting toward the southwest.

## MAGNITUDE AND DIRECTION OF EXTENSION

Various geologic relationships allow fairly well constrained estimates of extension along four transects in the southern part of the Whipple tiltblock domain (Figures 3 and 7). Each of these transects is divided into segments; detailed analysis of each segment is given in the Appendix, and estimates of extension are in Table 1. The following summarizes the results of this analysis.

Transect 1 (Figure 3) crosses a belt of extension between the ranges directly southwest of the Whipple tilt-block domain and the lower plate rocks in the Harcuvar metamorphic core complex, whereas transects 2, 3, and 4 (Figure 7) cross an area of extension associated with movement on the Whipple-Buckskin-Rawhide-Harcuvar detachment system or within its upper plate. Lower plate rocks in the Harcuvar (excluding the Harquahala Mountains) and Whipple metamorphic core complexes can be treated as part of a single, structurally intact block that did not undergo significant dismemberment by normal faulting. The areally extensive exposures of crystalline rocks that make up the Transition Zone physiographic province northeast of the study area can also be treated as a single, unextended fault block. The Date Creek, Poachie, and Artillery mountains represent the tapered end of a largely unextended Transition Zone block. Thus estimates of extension along Transects 2, 3, and 4 should all be similar.

The direction of extension in the Harcuvar and Whipple metamorphic core complex is indicated by the N55°E±3° orientation of detachment-fault corrugation axes (Figure 5) and

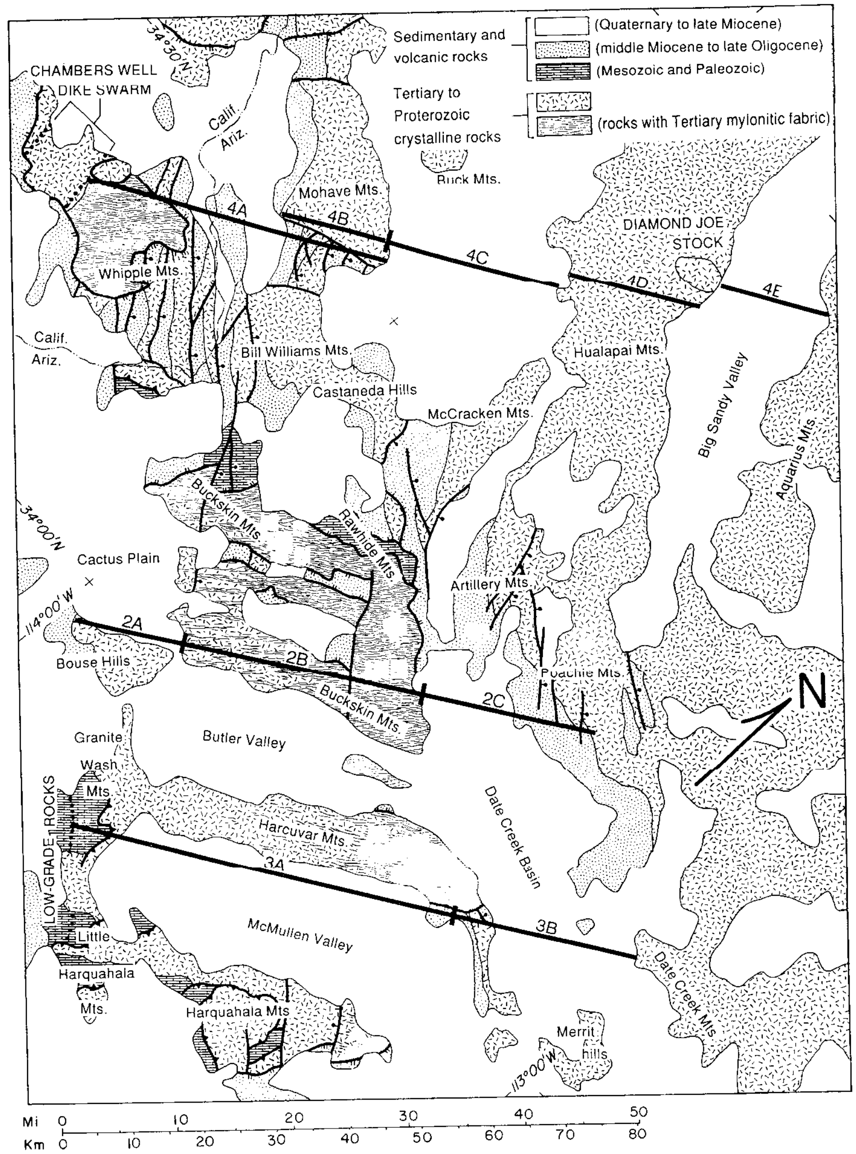


Fig. 7. Simplified geologic map of west central Arizona and adjacent southeastern California showing location of three transects for which the magnitude of extension has been estimated (see Table 1 and Appendix).

the N50°E$\pm$10° orientation of mylonitic lineations (average mylonitic-lineation trend from each of 10 studies falls within this range). Detachment-fault corrugation axes have a more narrowly constrained orientation than mylonitic lineations and are probably a better indicator of extension direction. Displacement oblique to the larger corrugations seems unlikely because of the large flexural strains that upper plate rocks would have to undergo during movement.

### *Ranegras Plain Transect (Transect 1)*

The direction of extension in the Ranegras Plain area is suggested by several features: (1) dip directions of tilt blocks, (2) slickenside striations on the Plomosa fault, and (3) mylonitic lineations in the footwall of the Plomosa fault. These features are all consistent with a N45°E$\pm$15° direction of extension.

In the northwestern Ranegras Plain area, total extension is estimated to be 23$\pm$8 km, which is the sum of estimates of extension along three segments of a transect from the southern Plomosa Mountains to the Bouse Hills (transect segments 1A, 1B, and 1C in Figure 3, Table 1, and Appendix). Most of this extension occurred by movement on the Plomosa fault, and is apparent in part because upper plate rocks include highly tectonized Paleozoic and Mesozoic strata (location B in Figure 3) that were displaced approximately 13 km to the

TABLE 1. Estimates of Extension

| Transect | Segment | Segment Length (km) | Magnitude of Extension (km) |
|---|---|---|---|
| 1 (Plomosa) | A (S. Plomosa) | 11 | 6±4 |
| | B (Cen. Plomosa) | 13 | 13±2 |
| | C (N. Plomosa) | 8 | 4±2 |
| | TOTAL | 32 | 23±8 |
| | D (Ranegras) | 25 | <25 |
| 2 (Buckskin) | A (Bouse Hills) | 16 | 15±1 |
| | B (Buckskin) | 34 | 33±1 |
| | C (Date Creek) | 24 | 18±6 |
| | TOTAL | 74 | 66±8 |
| 3 (Harcuvar) | A (Harcuvar) | 55 | 55±10 |
| | B (Date Creek) | 25 | 12±7 |
| | TOTAL | 80 | 67±17 |
| 4 (Whipple) | A (Whipple) | 45 | 45±5 |
| | B (Crossman) | 15 | 8±3 |
| | C (Sacramento) | 25 | 12±8 |
| | D (Hualapai) | 22 | 0±0 |
| | F (Big Sandy) | 14 | 6±3 |
| | TOTAL | 105* | 71±19 |

*Represents distance between endpoints of transect.

northeast from their lower plate equivalents in a Mesozoic thrust zone in the Plomosa Pass area (location A in Figure 3). In another transect to the southeast (segment 1D), extension must have been less than about 25 km because restoration of more than 25 km of extension along northeast dipping normal faults places weakly to moderately metamorphosed and deformed Paleozoic and Mesozoic strata in the western Granite Wash Mountains [Reynolds et al., 1989] on top of even less metamorphosed and deformed Paleozoic and Mesozoic strata in the New Water Mountains [Sherrod and Koch, 1987]. Although thrust juxtapositions of higher grade Mesozoic metamorphic supracrustal rocks over lower grade rocks are possible, such juxtapositions of Mesozoic strata have not been recognized in the region [Reynolds et al., 1986c, 1988]. Our estimate of 20±5 km of total Tertiary extension in the Ranegras Plain area represents the range of extension encompassed by estimates from both transects 1A-1C and 1D.

### *Buckskin and Rawhide Mountains Transect (Transect 2)*

Displacement on the Buckskin-Rawhide detachment fault resulted in virtually complete denudation of the lower plate. Upper plate rocks in much of the area consist of a thin, discontinuous veneer of klippen that are composed primarily of Miocene sedimentary and volcanic rocks and that include conglomerate with abundant clasts derived from the lower plate [Spencer and Reynolds, 1989c]. The general absence of pre-Tertiary rocks above the detachment fault indicates that minimum displacement on the detachment fault was comparable to the 34 km extension-parallel distance over which mylonitic lower plate rocks are exposed (transect segment 2B in Figure 7, Table 1, and Appendix).

The tilted Tertiary strata on the west side of the Bouse Hills represent the tilted and eroded footwall of the breakaway zone for the Buckskin-Rawhide detachment fault. Equivalent hanging wall rocks are now in the subsurface beneath Date Creek basin east of the eastern Buckskin Mountains and were originally separated from lower plate rocks in the Bouse Hills only by strata that are now preserved in klippen or were eroded away. South to southwest dipping Tertiary strata in the Artillery and Poachie mountains project downdip to the south beneath Date Creek basin and are inferred to be truncated in the subsurface by the northeast dipping Buckskin-Rawhide detachment fault. Total displacement of Tertiary strata and underlying crystalline rocks, originally close to each other in the breakaway zone, is estimated to be 66±8 km (sum of displacements along transect segments 2A, 2B, and 2C in Figure 7, Table 1, and the Appendix).

### *Harcuvar Transect (Transect 3)*

A southwest dipping sequence of Miocene volcanic and sedimentary rocks in the Bullard Peak area on the south flank of the eastern Harcuvar Mountains contains a conglomerate and sedimentary breccia unit that is interpreted to have been displaced 55±10 km northeastward relative to lower plate rocks (transect segment 3A, Figure 7; Table 1; Appendix) [Reynolds and Spencer, 1985]. The crystalline rocks of the eastern Date Creek Mountains represent the edge of the Transition Zone physiographic province and are approximately 25 km northeast of the Bullard Peak area. We estimate that 12±7 km of extension has occurred within this transect segment (transect 3B), for a total of 67±17 km of extension along transect 3.

### *Whipple Transect*

The major offset feature in the Whipple-Mohave mountains region to the northwest of the Harcuvar metamorphic core complex is a dike swarm in the lower plate of the Whipple detachment fault (Chambers Well dike swarm of Davis et al. [1980, 1982]) that is interpreted to be represented in the upper plate by a dike swarm in the Mohave Mountains (transect segment 4A in Figure 7) [Nakata, 1982; Howard et al., 1982]. Restoration of 43 km of displacement along a N55°E transport vector is necessary to bring the easternmost exposures of the Mohave Mountains dike swarm above the easternmost exposures of the Chambers Well dike swarm (Table 1; Appendix; see also Davis and Lister [1988]). The N55°E direction is based on the orientation of axes of corrugations in the Whipple Mountains [Frost, 1981]. If displacement was more northerly, as suggested by the N45E±10° mylonitic lineations in the Whipple Mountains [Davis and Lister, 1988], slightly greater minimum displacement would be indicated. Additional extension occurred at structurally higher levels in the Mohave Mountains [Howard et al., 1982] and areas farther east (Figure 7; Table 1; Appendix). Total extension along this transect is estimated at 71±19 km.

### *Summary*

Of the three estimates of total extension between the Transition Zone and the lower plate rocks on the western flanks of the Harcuvar and Whipple metamorphic core complexes, the estimate for the Buckskin transect (66±8 km) is the best constrained and is entirely within the uncertainties in estimated extension for the other two transects. An additional 20±5 km of extension occurred in the Ranegras Plain area. If this amount is added to the estimate for extension along the Buckskin transect, extension between the southern Plomosa Mountains and the Transition Zone totals 86±13 km. The belt of extension through the Ranegras Plain area may die out northwestward west of the Turtle and Whipple mountains. If it does, then the unextended area along the southwest flank of the Whipple tilt-block domain must have undergone 10°-15° of clockwise rotation.

## TECTONIC RECONSTRUCTION

Major pre-Tertiary geologic features in west central Arizona and adjacent southeastern California include the Maria fold and thrust belt, which is an east-west trending belt of generally south-vergent folds and thrusts [Reynolds et al., 1986c; Laubach et al., 1989; Spencer and Reynolds, 1990b], and the thick sequence of Jurassic(?) and Cretaceous clastic sedimentary rocks (McCoy Mountains Formation of Harding and Coney [1985]; see also Stone et al. [1987]) that form the structurally lowest levels of the Maria fold and thrust belt. Restoration of Tertiary extension in the Ranegras Plain area brings exposures of the McCoy Mountains Formation in the Granite Wash Mountains [Reynolds et al., 1989] to a position adjacent to similar rocks in the New Water Mountains [Sherrod and Koch, 1987], and thus increases the linearity of the belt of outcrops of the McCoy Mountains Formation (compare Figures 8 and 9). The reconstructed Maria fold and thrust belt (Figure 9) is more linear and narrow than it is today (Figure 8) partly because thrust-fault segments in Tertiary fault blocks that are now above the Buckskin-Rawhide detachment fault were restored to their pre-Tertiary position [Spencer and Reynolds, 1990b]. In addition, the mylonitic lower plate of the Harcuvar metamorphic core complex is restored to beneath the Transition Zone or beneath the slightly faulted rocks of the eastern Poachie Mountains (see also Reynolds and Spencer [1985] and Wernicke [1985]).

## CROSS-SECTION EVOLUTION

### *Initial Shear Zone Geometry*

Southwest tilted Tertiary strata in the western Bouse Hills are interpreted as the tilted footwall block of the Buckskin-Rawhide detachment fault adjacent to the point where the fault initially reached the Earth's surface (initial breakaway region). Lower plate rocks in the Buckskin Mountains contain Tertiary mylonitic fabrics approximately 16 km to the east of the tilted strata. The initial Buckskin-Rawhide detachment fault must have cut downward from the Earth's surface to depths of mylonitization over this 16 km distance, which is measured across the now rotated and flattened lower plate but represents original downdip distance along the fault.

Tertiary mylonitic fabrics below the Buckskin-Rawhide detachment fault are not restricted to areas of Tertiary

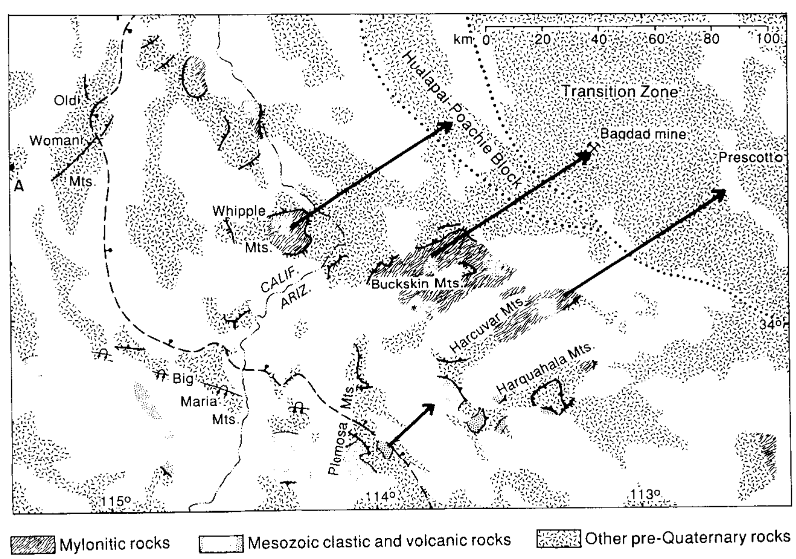


Fig. 8. Map showing major tectonic features of study area. Dashed line with bar and ball is southwesternmost normal fault of Whipple tilt-block domain. Restoration of Cenozoic extension shown in Figure 9 was done by restoring 66 km of N55°E extension (represented by three long arrows) between the Transition Zone and mylonitic rocks below detachment faults. All structures and rocks that are to the southwest of the mylonitic rocks in Figure 9 were also restored this amount except for two segments of thrust faults in the upper plate of the detachment fault in the Buckskin and Rawhide mountains which were restored smaller amounts relative to the Transition Zone. Additional restoration of rocks southwest of the normal fault that marks the southwest boundary of the Whipple tilt-block domain was done by moving the southern area 20 km to the northeast (short arrow) with rotation about point A.

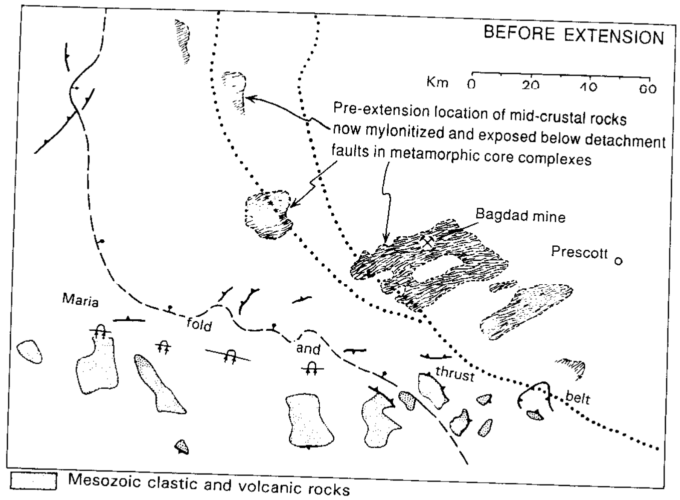


Fig. 9. Reconstructed tectonic map showing tectonic features, displayed in Figure 8, before extension.

magmatism but must have formed at depths where regional temperatures were sufficient for plastic deformation of quartz. Lower plate rocks in the Buckskin and Rawhide mountains have consistently yielded Miocene K-Ar and $^{40}Ar/^{39}Ar$ dates on biotite [Spencer et al., 1989b; Richard et al., 1990] and Miocene fission track dates on apatite and zircon [Bryant and Naeser, 1987]. The association of young thermochronometric dates with mylonitic rocks suggests that mylonitization occurred at temperatures above approximately 300°C. The 300°C isotherm would be at a depth of approximately 15 km in a low geothermal gradient of 20°C/km and at approximately 6 km depth in a high geothermal gradient of 50°C/km. For a planar fault to reach these depths over a downdip distance of 16 km would require fault dips of 69° to 22°. Average dip of the initial Buckskin-Rawhide detachment fault was probably within this range.

The lack of major changes in rock type or metamorphic grade from southwest to northeast across the mylonitic lower plate in the Buckskin and Rawhide mountains suggests that the ductile shear zone that was the precursor to the Buckskin-Rawhide detachment fault had a gentle dip. If the shear zone had a steep initial dip, lower crustal granulites or even mantle peridotites would presumably be exposed in the eastern part of the lower plate. The increasing intensity of mylonitization toward the northeast is the only presently known lithologic indication of greater structural depths toward the northeast. Late Cretaceous and early Tertiary K-Ar and $^{40}Ar/^{39}Ar$ hornblende dates from the Rawhide and eastern Harcuvar mountains indicate that the eastern part of the lower plate was above the 450°C-500°C isotherm during the mid-Tertiary [Shackelford, 1980; DeWitt and Reynolds, 1990; Richard et al., 1990]. A maximum temperature difference at opposite ends of the Buckskin-Rawhide mountains of 150°-200°C within a geothermal gradient of 20°-50°C/km corresponds to a 3-10 km maximum difference in pre-extension depth across the ranges and indicates that initial, average, shear zone dip was not more than about 16°.

The initial cross-sectional form of the Buckskin-Rawhide detachment fault and its downdip continuation as a ductile shear zone is thus constrained by the following: (1) the average dip of the brittle, upper crustal part of the shear zone was between approximately 22° to 69°, and (2) below the brittle-ductile transition the ductile shear zone dipped less than about 16°. A broadly listric shear zone form seems virtually certain (Figure 10). These geometric constraints allow a fault dip of greater than 30° where the fault intersects the brittle-ductile transition, which is consistent with seismological studies of normal-fault dips at depths of earthquake nucleation [Jackson, 1987].

An alternative interpretation is that the lower plate was derived from a reservoir of highly mobile deep crust, and extrusion of low-viscosity crust from this reservoir was accommodated above by slip on a moderately to steeply dipping mylonitic shear zone. Major penetrative strain would accompany such an extrusion process. Leucocratic granitoid sills are present in many areas of the Harcuvar metamorphic core complex, including a single sill-like intrusion that extends over much of the central and eastern Harcuvar Mountains [Drewes et al., 1990]. In the Harcuvar Mountains, the granitoids are interpreted as a single comagmatic intrusive suite that includes the 78 Ma [DeWitt and Reynolds, 1990] Tank Pass granite in the western Harcuvar and Granite Wash mountains. Host rocks have yielded pre-Tertiary hornblende $^{40}Ar/^{39}Ar$ plateau dates [DeWitt and Reynolds, 1990]. Unlike their highly foliated Proterozoic host rocks, the granitoids in the central and eastern Harcuvar Mountains are typically undeformed except for mylonitization at their upper and lower margins. The lack of evidence of penetrative deformation in these Cretaceous granitoids and their moderate mid-Tertiary temperature probably precludes this alternative extrusion model.

The initial cross-section geometry of the two major normal shear zones in the Plomosa Mountains (Plomosa fault and breakaway fault in Figure 3) is not as well constrained as for the Buckskin-Rawhide detachment fault. The 45°-60° southwestward dip of Tertiary strata in the Plomosa Pass area [Stoneman, 1985] suggests that the Plomosa fault and breakaway fault have been similarly rotated and thus formed as high-angle normal faults. Initially, the two major normal faults in the Plomosa Mountains could have been

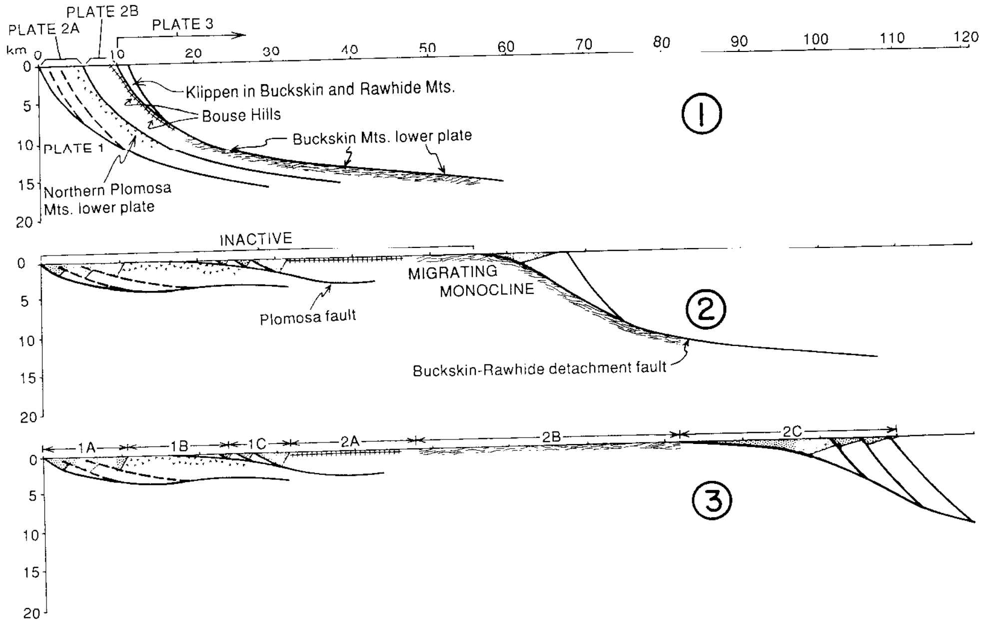


Fig. 10. Cross-section evolution diagram along transects 1A-1C (Figure 3) and 2 (Figure 7).

approximately parallel to the listric Buckskin-Rawhide detachment zone (Figure 10), but it is also possible that they had significantly different geometry, either dipping more shallowly and merging with the mylonite zone exposed in the Buckskin and Rawhide mountains or dipping more steeply and diverging with depth from the Buckskin-Rawhide detachment zone.

### *Incisement and Excisement*

Detailed geologic studies in the nearby Whipple Mountains and ranges farther north have led to recognition of two processes that played a significant role in the evolution of some detachment faults. Incisement is the process whereby a new splay of a detachment fault cuts downward through the lower plate and transfers a slab of lower plate rock to the upper plate. Excisement is the process whereby a new splay of a detachment fault cuts upward through the upper plate and transfers a slab of upper plate rocks to the lower plate [Davis and Lister, 1988; see also John, 1987]. In both processes, the old splay of the detachment fault becomes largely or entirely inactive. Although both processes were inferred to be important in the Tertiary structural evolution of the Whipple Mountains, we infer that incisement was not important in the Harcuvar complex.

Fault blocks and slivers incised from the lower plate should be present above the Buckskin-Rawhide detachment fault if incisement had been an important process during detachment faulting. Low-angle faults in the lower plate in the eastern Buckskin and Rawhide mountains are discontinuous, do not juxtapose highly contrasting rock types, and do not have significant displacement compared to the detachment fault [Shackelford, 1989a; Bryant and Wooden, 1989]. Similar lower plate faults have been recognized in the Whipple Mountains [Davis et al., 1980]. The Buckskin-Rawhide detachment fault is discontinuously exposed for approximately 34 km in the direction of displacement, yet upper plate fault blocks and slivers of lower plate rock types have not been recognized. Upper plate crystalline rocks in the Buckskin and Rawhide mountains are composed primarily of reddish brown granitoid rocks that do not resemble the commonly epidote- and chlorite-bearing, gneissic and mylonitic lower plate rocks. In addition, the upper plate crystalline rocks commonly are depositionally overlain by sedimentary and volcanic rocks deposited during early detachment faulting [Spencer and Reynolds, 1989c]. These upper plate crystalline rocks were thus at the Earth's surface early in the history of detachment faulting and represent shallow crustal levels characteristic of the top of the upper plate rather than the mid-crustal levels where lower plate rocks underwent plastic deformation and, during uplift, retrograde metamorphism. Incisement was thus not an important process during much or all of the history of detachment faulting in the Buckskin and Rawhide mountains. In contrast to Davis and Lister's [1988] interpretation that the Whipple detachment fault is only the youngest manifestation of a complex, evolving detachment system, the Buckskin-Rawhide detachment fault was a long-lived feature, during extensional faulting, with respect to the lower plate.

Upper plate normal faults that are truncated downward by the Buckskin-Rawhide and Whipple detachment faults indicate that excisement was an important process in both areas [Davis and Lister, 1988; Lister and Davis, 1989; Spencer and Reynolds, 1989c]. The excised slabs that contain the presumably listric, downdip continuations of the upper plate normal faults are not presently exposed and are presumably in the subsurface to the southwest. Stepwise migration of the breakaway fault to previously active upper plate normal faults is similar to excisement because it transfers upper plate rocks to the lower plate, but unlike excisement, it is not accompanied by formation of new faults. In both processes, upper plate fault blocks can be left stranded on a progressively lengthening, inactive segment of the detachment fault [Buck, 1988; Hamilton, 1988; Wernicke and Axen, 1988].

The hanging walls of listric or low-angle normal faults within the upper plates of detachment faults may be displaced down and onto the footwalls of detachment faults. Such a process could occur during extension within the upper plate or during stepwise breakaway migration. In the Buckskin and Rawhide mountains, much of the upper plate is composed of synextension sedimentary and volcanic rocks that did not even exist when detachment faulting began. The detachment fault, with respect to the upper plate, is thus a young structural feature in the history of detachment faulting. This is similar to the interpretation of the Whipple detachment fault by Davis and Lister [1988], although they emphasize low-angle excisement, rather than extension of the upper plate and stepwise breakaway migration, as the primary causative process.

The process of excisement appears to have affected only the tapered end of the upper plate, and to have affected primarily Tertiary strata deposited in an extensional basin above this tapered end. In other words, only a small but now well-exposed volume of the total upper plate was affected by excisement tectonics. It is possible that a larger volume of rock, including a substantial component of crystalline rock, was transferred from the upper plate to the lower plate near the breakaway but is now concealed by surficial deposits southwest of the Buckskin Mountains [Spencer and Reynolds, 1989c], but there is no trace of such an excised sliver in the Bouse Hills. We conclude that neither incisement nor excisement was very significant in terms of volume of rock affected, and these processes can be largely ignored in constructing regional evolutionary cross sections of the Buckskin-Rawhide detachment system (Figure 10).

*Monoclinal Flexure*

The lack of significant extension within the Artillery and Poachie mountains and the absence of an extensive array of crystalline fault blocks above the Buckskin-Rawhide detachment fault, especially in the eastern and central Buckskin Mountains, indicate that the upper plate did not undergo major changes in form during displacement. The only significant modification occurred at the tapered end of the upper plate which was affected by southwest tilting and, for a fairly small volume of rock, extreme extension. Displacement of the largely rigid upper plate of the Buckskin-Rawhide detachment shear zone, with its broadly listric underside, thus requires major flexural deformation of the lower plate (Figure 10). A monoclinal flexure of the lower plate must have followed the tapered end of the upper plate as the upper plate was displaced (relatively) to the northeast. Following uplift and flexural deformation, the lower plate formed a regionally subhorizontal, generally low-relief surface. This migrating monocline style of deformation has been proposed elsewhere [Buck, 1988; Hamilton, 1988; Wernicke and Axen, 1988].

*Timing of Extension*

The Plomosa fault and the structurally lower normal fault that underlies all of the northern Plomosa Mountains were rotated to gentle dips and probably became inactive before much or most of the movement on the Buckskin-Rawhide detachment fault. Basin formation had begun in the northern Plomosa Mountains, Bouse Hills, Buckskin Mountains, and the Artillery Mountains by about 24 Ma (K-Ar data from Eberly and Stanley [1978] and R. Miller, written communication, 1987, 1990), probably as a result of initial movement on the Plomosa and Buckskin-Rawhide detachment faults. Tilting had largely ended in the Bouse Hills by the time 20 Ma volcanics were erupted [Eberly and Stanley, 1978; Spencer and Reynolds, 1990a], but continued in the southernmost Bill Williams and, presumably, Buckskin and Rawhide mountains until after deposition of a 16 Ma basalt [Spencer et al., 1989b]. Lower plate rocks in the Buckskin Mountains cooled through the approximately 300° C argon blocking temperature of biotite at 13 to 15 Ma [Spencer et al., 1989b; Richard et al., 1990] and were presumably undergoing rapid uplift and denudation at this time. On the basis of these data, we infer that extensional faulting began at about 23-25 Ma in the Plomosa Mountains and Bouse Hills and on the Buckskin-Rawhide detachment system, ended in the Plomosa Mountains and Bouse Hills by about 20 Ma, and continued until after 15 Ma in the Buckskin and Rawhide mountains. Approximately 80 to 90 km of extension occurred at an average rate of 8 to 9 mm per year over the approximately 10 m.y. period of extensional deformation in the study area.

The Plomosa detachment fault and structurally lower faults, and their down dip continuations as ductile shear zones, have been warped and rotated in part by isostatic uplift associated with displacement on the structurally higher Buckskin-Rawhide and correlative detachment faults. Warping and rotation may have been so severe that the normal shear zones were tilted over large areas back toward their breakaways and their movement was terminated. Sequential termination of movement on imbricate detachment faults, with structurally highest faults remaining active longest, is thus indicated.

*Postdetachment Geomorphology*

Basaltic volcanic rocks and locally occurring felsic volcanic and clastic sedimentary rocks, dated at 9-15 Ma and deposited in and around the northern Rawhide and western Buckskin mountains, buried and partially preserved the immediately postdetachment landscape (Figure 11). The crests of lower plate anticlines are commonly at greater elevations than the base of preserved postdetachment strata. This is not due to warping after deposition of postdetachment strata because these strata are not warped, but was an original feature of the immediately postdetachment landscape that is consistent with evidence for subareal exposure of the lower plate late during detachment faulting. The level of structural exposure represented by the surface upon which Miocene postdetachment strata were deposited is similar to present levels of exposure, a conclusion reached earlier by Davis et al. [1980, p. 122].

Elevations in the Whipple-Buckskin-Rawhide region range between about 200 and 800 m above sea level over an area of greater than 2000 km$^2$ and are similar to those of surrounding parts of the Basin and Range province. In contrast to tectonically active parts of the Basin and Range province, the geomorphic maturity of the study area is indicated by gentle slopes of alluvial fans, pediments above some granitoid rocks, and the absence of internal drainages. Incised drainages are

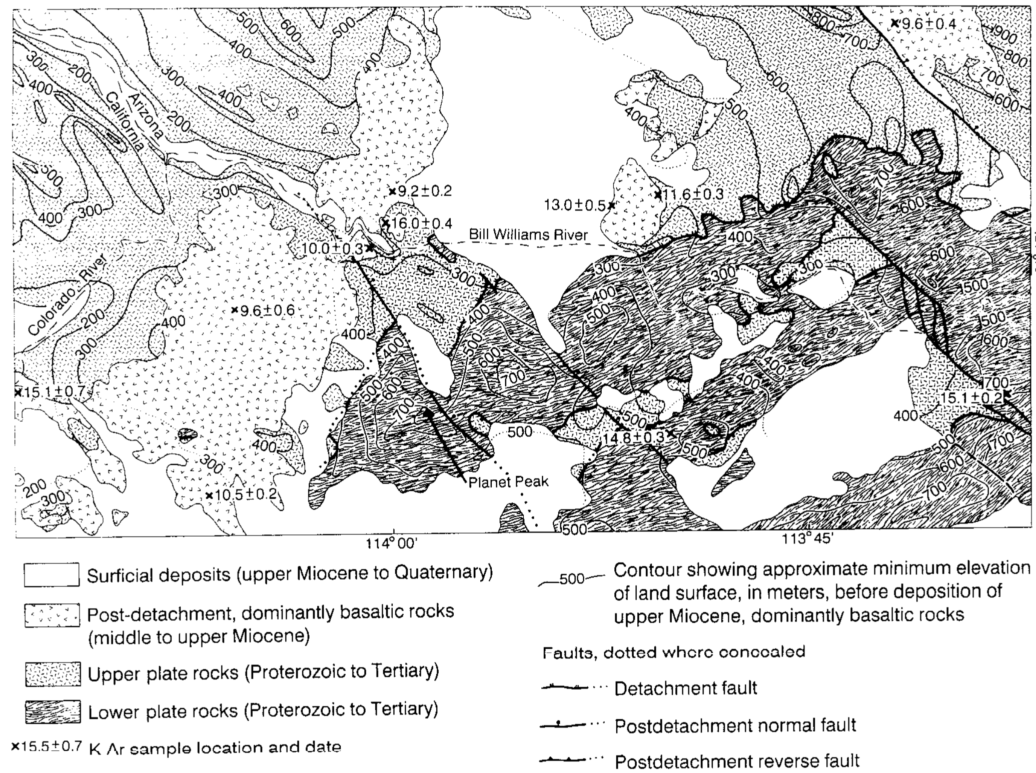


Fig. 11. Simplified geologic map of the central and western Buckskin Mountains and adjacent areas showing smoothed contours of the minimum elevation of the surface upon which postdetachment basalts and clastic sediments were deposited. Contours intersect topographically highest areas such as ridge crests and therefore display the minimum elevation of the postdetachment surface. K-Ar dates indicate the age of postdetachment deposits (9-15 Ma), tilted upper plate volcanic rocks (one date at 16 Ma), and cooling of lower plate crystalline rocks (two biotite dates at approximately 15 Ma). K-Ar data are from Armstrong et al., [1976], Suneson and Lucchitta [1979], Shackelford [1980], Davis et al., [1982], Reynolds et al., [1986a], and Spencer et al., [1989b]. The 15.1 Ma date from the western edge of the map is a weighted mean average of three dates (see Long and Rippeteau [1974] for weighting method).

present only along the Colorado and Bill Williams rivers where downcutting is associated with regional tilting and post-Miocene opening of the Gulf of California [Lucchitta, 1979]. Depth to bedrock beneath basins is rarely greater than 1 km [Oppenheimer and Sumner, 1980]. The regional low relief of the modern landscape and the apparent regional low relief of the immediately postdetachment landscape indicate that large-magnitude intracontinental extension involving many kilometers of uplift over thousands of square kilometers may not produce significant mountain ranges or sedimentary basins. Significant relief did develop early during detachment faulting, as indicated by numerous catastrophic debris avalanche deposits in the lower parts of tilted Tertiary sections [e.g., Spencer and Reynolds, 1989c], but this relief was apparently a transient feature during early extension.

## SPECULATIONS ON CRUSTAL MECHANICS

### *Migrating Monocline and Flexural Strength*

The migrating monocline style of deformation in the lower plate requires that the lower plate have low flexural strength. If the lower plate had a tectonically significant flexural strength, it would first have resisted concave upward bending as it was drawn upward beneath the upper plate, and then would have resisted concave downward bending and later flattening to its present subhorizontal form. The result of significant resistance to bending would be to retard lower plate uplift, thereby forming a deep basin at the tapered end of the upper plate that could be filled by sediments or by a distended fault-block array derived from the upper plate. However, the thickness of upper plate sediments and distended fault blocks in the Buckskin and Rawhide mountains is trivial compared to the magnitude of footwall uplift. Significant resistance to bending of the lower plate in the breakaway region would tend to preserve a large mountain front adjacent to the trace of the breakaway fault, but a mountain front at the breakaway zone has not been preserved. The presence of abundant catastrophic debris-avalanche deposits in the lower parts of many Tertiary sedimentary sequences in the study area is probably due to substantial relief produced during early normal faulting and may reflect high lower plate flexural strength that characterized only the earliest phase of extension.

The low flexural strength of the lower plate probably had several causes. High lower plate temperatures during uplift would result in low flexural strength by allowing ductile creep at shallow crustal depths [Brace and Kohlstedt, 1980]. Mylonitic lower plate rocks were initially at midcrustal temperatures and would retain some of their heat during uplift, especially if uplift was rapid [England and Jackson, 1987]. Magmatism further elevated temperatures and reduced flexural strength. Flexural slip along weak zones within lithologically layered lower plate rocks may have accommodated flexure and further reduced flexural strength. Flexural strength reduction by these mechanisms is supported by Miocene K-Ar, $^{40}Ar/^{39}Ar$, and fission track cooling ages from the lower plate, and by the presence of mid-Tertiary intrusions and subhorizontal faults within the lower plate [Shackelford, 1989a; Bryant and Wooden, 1989; Spencer, 1989]. Flexural slip on normal faults, exposed in the Plomosa Mountains, that dip beneath the Buckskin-Rawhide detachment fault possibly reduced the flexural strength of the lower plate of the Buckskin-Rawhide detachment fault in its breakaway region. Such a strength reduction may have been necessary for complete denudation in the breakaway region; upper plate synformal keels and sedimentary basins cover lower plates in most other breakaway regions [e.g., Spencer, 1984; John, 1987] where lower plates may not have been underlain by deeper active normal faults that could have accommodated flexural slip.

The migrating monocline style of deformation depicted in Figure 10 requires not only low flexural strength of the footwall, but also that the deeper middle to lower crust behaved as a low-viscosity fluid that flowed into the area beneath the migrating monocline and mechanically decoupled the upper crust from the stronger mantle lithosphere [Block and Royden, 1990]. The low viscosity of the deeper crust either was caused by heating of pre-existing crustal rocks by mid-Tertiary magmas [e.g., Gans, 1987; Spencer and Reynolds, 1989b] or reflects voluminous magmatic underplating and deep intrusion [Thompson and McCarthy, 1990].

*Regional Elevations and Isostasy*

The areally extensive Tertiary mylonitic rocks in the Harcuvar and Whipple metamorphic core complexes overlie the root zone of thrusts in the east-west trending Cretaceous Maria fold and thrust belt to the south. This spatial relationship suggests that isostatic uplift of the buoyant crustal root (downward protruding Moho bulge) of the Maria fold and thrust belt was responsible for the widespread exposures of Tertiary midcrustal mylonitic fabrics [Spencer and Reynolds, 1990b]. The apparent influence of an inherited crustal root on vertical movements in the upper crust requires that deep-crustal viscosity be high enough to support tectonically significant horizontal pressure gradients throughout most or all of the 10 m.y. period of detachment faulting and magmatism. If lower crustal viscosity was too low, uplift of a Moho root would cause rapid lateral flow in the deep crust with rapidly diminishing influence on the upper crust.

In contrast to the above inference of a tectonically significant, moderate deep-crustal viscosity, migration of short-wavelength monoclinal flexures of lower plates requires a highly mobile, low-viscosity substrate. These contrasting inferences about deep crustal behavior may be consistent with each other because of the different length scales of deep-crustal flow for each process. The low viscosity of the deep crust during extension may have allowed rapid isostatic equilibration at horizontal length scales of 5 to 15 km, but this viscosity may have been sufficient to support regional horizontal pressure gradients that were significant at length scales of >50 km. The viability of this mechanism is supported by numerical analysis that indicates that the time period for equilibration of horizontal pressure gradients by horizontal channelized flow is proportional to the square of the length scale of equilibration [Kruse et al., 1991].

*Detachment-Fault Corrugations*

Extension-parallel corrugations of detachment faults have been recognized for many years [e.g., Rehrig and Reynolds, 1980], but there has been controversy regarding their origin. Corrugations above largely nonmylonitic crystalline rocks farther north in the lower Colorado River trough have been interpreted as reflecting original fault geometry and not folding of a planar fault [Spencer, 1985; John, 1987]. This interpretation is based in part on the irregular, nonsinusoidal form of the detachment faults in these areas. Field relationships in the Whipple Mountains suggest that corrugations of the detachment fault formed after arching of lower plate mylonitic foliation and lithologic layering and that the corrugated form of the detachment fault was somewhat discordantly superimposed upon the arched lower plate fabric but crudely mimics its form [Davis and Lister, 1988].

The arched form of Cretaceous sills in the eastern Harcuvar and eastern Buckskin mountains, which is mimicked by the form of mylonitic foliation and the detachment faults, may be the result of folding during the period of rapid lower plate uplift and low flexural strength. Folding apparently occurred without corresponding folding of adjacent nonmylonitic lower plate rocks in the Granite Wash and western Harcuvar mountains [Reynolds et al., 1989]. The Granite Wash and western Harcuvar mountains had greater flexural strength during mid-Tertiary extension because they had cooled through K-Ar mica blocking temperatures tens of millions of years before extension [Rehrig and Reynolds, 1980] and were thus within the strong, brittle upper crust at the time of extension.

Folding of only the initially deep, low flexural strength part of the lower plate can be accounted for by the following model: The listric normal fault that became the Buckskin-Rawhide-Bullard detachment fault system had an original trace at the Earth's surface that was characterized by segmentation and irregularity, as do modern normal faults [e.g., Jackson and White, 1989]. The irregular fault passed downward through the brittle-ductile transition into a more planar, gently dipping ductile shear zone. As ductile middle-crustal rocks, initially beneath or within a planar ductile shear zone, were displaced from beneath the upper plate, they deformed to conform to the irregularities at shallower crustal levels on the underside of the relatively rigid upper plate. Neither the upper plate nor shallow and cool lower plate rocks were folded, but lower plate rocks at depths and temperatures sufficient for mylonitization were folded to conform to irregularities in the fault surface beneath the tapered end of the upper plate. Thus the corrugations of mylonitic lower plate rocks reflect the type of irregularities and segmentation that characterize active normal faults [John, 1987; Jackson and

White, 1989], but the corrugations are folds that formed during extension and are not original features of the lower plate. Folding was not accomplished by shortening perpendicular to fold axes; rather, it represents an increase in the surface area of the top of the lower plate as it was stretched to conform to an irregular surface.

An implication of this model is that the lower plate folds are a kind of tape recorder of extension direction. As each part of the ductile lower plate is drawn up beneath the grooved, tapered end of the upper plate, the extension direction is recorded by the orientation of fold axes in that part of the lower plate as it cools and becomes stronger. If this interpretation is correct, the N55°E$\pm$3° orientation of corrugation axes in the Harcuvar metamorphic core complex accurately represents the direction of extension. The greater range of mylonitic lineation orientations (N50°E$\pm$10°) is possibly due to nonrigid ductile deformation before or during folding that reflects the influence of other unknown processes.

## CONCLUSION

Miocene extension along a transect through the Whipple tilt-block domain in west central Arizona was accommodated at upper crustal levels by movement on three imbricate normal faults, the structurally highest of which evolved into the Buckskin-Rawhide detachment fault. Most of the extension was accommodated by movement on the Buckskin-Rawhide detachment fault, and this movement uncovered extensive areas of crystalline rocks with Tertiary mylonitic fabrics. Estimates of displacement on the three faults indicate that an area at the Earth's surface that was originally only 10 to 20 km wide is now approximately 100 km wide. Restoration of fault movement realigns Mesozoic tectonic features.

The hanging wall of the Buckskin-Rawhide detachment fault and its downdip continuation as a ductile shear zone had an original, broadly listric form that does not appear to have changed significantly during extension. Various types of constraints on the cross-sectional evolution of the Buckskin-Rawhide detachment fault require that, as the lower plate was displaced from beneath the upper plate, it flexed to conform to the curved underside of relatively rigid upper plate and flattened at near-surface levels as it was uncovered. The low regional surface relief of the denuded lower plate apparently reflects short-wavelength isostatic equilibration that occurred during extension. Folds below the Buckskin-Rawhide-Bullard detachment fault system have axes parallel to extension direction and are interpreted to have formed during extension as weak lower plate rocks conformed to the irregularities along the tapered end of the strong upper plate.

The inferred structural evolution of the study area requires very low flexural strength of the lower plates of detachment faults and low viscosity of the deeper crust during extension. Such crustal mechanical characteristics may be restricted to areas of high heat flow. Thrust belts, in contrast, are typically supported by the substantial flexural strength of underthrust lithosphere [e.g., McNutt et al., 1988]. Horst and graben topography with large range fronts and deep basins may characterize areas of extension where flexural strength and deep-crustal viscosity were greater than they were during mid-Tertiary extension in west central Arizona. Even in west central Arizona, the deep crust apparently had sufficient viscosity to support horizontal pressure gradients over distances of 50-100 km that promoted regional uplift of overlying metamorphic core complexes. We conclude, however, that structural styles of Miocene extension in west central Arizona may be an example of extensional deformation in a crustal mechanical environment of unusually low crustal flexural strength and low-viscosity deep crust.

## APPENDIX: MAGNITUDES OF EXTENSION

### *Ranegras Plain Transect (Transect 1, Figure 3)*

*Segment 1A.* Strata at the base of the tilted Tertiary section in the lower plate of the Plomosa detachment fault dip 55°-65° to the southwest and project downdip into a northeast dipping normal fault. The exposed basal depositional contact is now approximately 11 km from the buried trace of the underlying fault to the southwest. A major, poorly constrained variable relevant to extension estimates concerns the amount of concealed pre-Tertiary rock beneath volcanic rock in tilt blocks along this 11-km-wide transect segment. If there is much concealed pre-Tertiary rock in tilt blocks, extension may not have been great. The absence of a negative residual Bouguer gravity anomaly over the half graben [Lysonski et al., 1980], which contains primarily silicic volcanic and clastic sedimentary rock at exposed levels, suggests that underlying crystalline rocks are not at great depth, but it is not known if underlying crystalline rocks are below or above the master normal fault. In addition, the location of the buried trace of the breakaway fault is not well constrained but is projected into the transect from the southeast where it is exposed. On the basis of these considerations, we estimate 6$\pm$4 km total extension for this segment. The estimated range of 2 to 10 km of extension encompasses virtually all of the uncertainties outlined above.

*Segment 1B.* Two fault blocks above the Plomosa detachment fault contain multiply deformed and metamorphosed Paleozoic and Mesozoic strata (locations B in Figure 3) that strongly resemble tectonized rocks along a steeply dipping thrust zone in the Plomosa Pass area (location A in Figure 3) [Stoneman, 1985; Scarborough and Meader, 1989; Duncan, 1990]. The 13 km distance between the northern of the two fault blocks and the thrust fault (both projected laterally to the transect) is interpreted to represent normal displacement on the Plomosa detachment fault. Uncertainties in projecting the thrust under alluvium lead to an estimated magnitude of extension along this segment of the transect of 13$\pm$3km.

*Segment 1C.* Normal faults exposed in the northern Plomosa Mountains [Scarborough and Meader, 1989; Duncan, 1990] that project beneath the western Bouse Hills are estimated to have accommodated 4$\pm$2 km of extension.

*Segment 1D.* See text.

### *Buckskin Transect (Transect 2, Figure 7)*

*Segment 2A.* The base of the steeply tilted Tertiary section in the western Bouse Hills (location C in Figure 3) is an eroded segment of the breakaway of the Buckskin-Rawhide detachment fault. Mylonitic crystalline rocks in the southern Buckskin Mountains are exposed 16 km northeast of this contact, and no klippen are preserved between these two points. The absence of klippen indicates that the lower plate was completely uncovered by 16 km of displacement on the detachment fault or that thin klippen were left behind but are now eroded away or assimilated by a Miocene pluton in the eastern Bouse Hills. We estimate that now-eroded or assimilated klippen could have been derived from a sliver at the trailing edge of the upper plate that was as much as 2 km thick and that detachment-fault displacement necessary to initiate uncovering of the mylonites could have been 2 km less than 16 km. Total displacement on this segment is thus estimated at 15$\pm$1 km.

*Segment 2B.* Lower plate rocks are exposed over a distance of 34 km along this segment of the transect in the southern Buckskin and Rawhide Mountains. We estimate that slivers of pre-Tertiary rock comprising up to 2 km of the tapered end of the upper plate could have been left stranded on the lower plate (but are now largely eroded away). This yields an estimate of 33$\pm$1 km as the displacement necessary to uncover the mylonitic lower plate.

*Segment 2C.* Along this transect segment the Buckskin-Rawhide detachment fault dips northeastward beneath the northwest end of Date Creek Basin and the southern edge of the Poachie Mountains. The south to southwest dipping base of the Tertiary stratigraphic sequence in the Poachie and Artillery Mountains projects downdip into the detachment fault. The point where the transect crosses the truncated contact at the base of the Tertiary section is interpreted to mark the offset, upper plate equivalent of the basal Tertiary contact in the western Bouse Hills. The transect-parallel distance (approximately downdip) along the detachment fault from the edge of exposed lower plate rocks in the eastern Buckskin Mountains to this point of intersection is estimated at 14±4 km and represents extension due to detachment-fault displacement. An additional 4±2 km of extension occurred along normal faults in the southern Poachie Mountains. Total extension on this segment of the transect is thus estimated at 18±6 km.

*Harcuvar Transect (Transect 3, Figure 7)*

*Segment 3A.* Sedimentary breccias in a tilted Tertiary stratigraphic sequence above the Bullard detachment fault in the Bullard Peak area were derived from an area of weakly metamorphosed Mesozoic sandstone. The nearest exposed potential source areas for these breccias are in the western Granite Wash and Little Harquahala mountains (west of dotted line on Figure 7), which is at least 55 km away from the breccias. The coarse breccias were presumably deposited by catastrophic debris avalanches and were probably not deposited more than 10 km from their source area. The Bullard detachment is thus estimated to have displaced the breccias at least 45 km [Reynolds and Spencer, 1985]. The breccia clasts most strongly resemble the Mesozoic clastic sedimentary rocks of the New Water Mountains southwest of the Granite Wash Mountains and could have been derived from that area when the bedrock of the New Water Mountains was much closer to the Granite Wash and Little Harquahala mountains (before major extension in the Ranegras Plain area). On the basis of these considerations we estimate that displacement of the breccias has been 55±10 km, which is consistent with a previous estimate [Reynolds and Spencer, 1985].

*Segment 3B.* The Bullard fault dips beneath southeastern Date Creek Basin where it and most of its upper plate are concealed. Two to four kilometers of displacement occurred on a low-angle normal fault within the upper plate of the Bullard detachment fault at the east end of the Harcuvar Mountains [Reynolds and Spencer, 1984]. The amount of extension that has occurred on other faults, if they exist, that are completely concealed beneath Date Creek basin east of the Harcuvar Mountains is poorly constrained. The Vulture and Wickenburg mountains to the southeast are highly extended by Miocene faults which strike northwestward toward southeastern Date Creek Basin [Stimac et al., 1987; Fryxell et al., 1987; Grubensky et al., 1987; Grubensky, 1989]. The Merrit hills, which lie between the two areas, may be significantly extended although this is not readily apparent because the hills are composed of Proterozoic crystalline rock that lacks clear marker units. We estimate that extension on hypothetical faults within a 20 km wide swath of completely concealed basement in the southeastern Date Creek Basin is 3 to 15 km. Total extension along transect segment 3C is thus estimated at 12±7 km.

*Whipple Transect (Transect 4, Figure 7)*

*Segment 4A.* A dike swarm in the Mohave Mountains in the upper plate of the Whipple detachment fault is the probable offset equivalent of the lower plate Chambers Well dike swarm in the western Whipple Mountains [Howard et al., 1982; Nakata, 1982; Davis and Lister, 1988]. Restoration of 43 km of displacement on the detachment fault places the eastern edge of the exposed part of the Mohave Mountains dike swarm above the eastern edge of the Chambers Well dike swarm. Concealed dikes to the east of the Mohave Mountains would require greater displacement. Precise realignment is not possible because of the following: (1) the base of the Mohave Mountains dike swarm, where it is truncated by the detachment fault, is not exposed, (2) the eastern edge of the Mohave Mountains dike swarm is not exposed, and (3) the Chambers Well dike swarm fans upward and therefore does not have vertical sides. An estimate of 45±5 km probably encompasses the range of likely offsets.

*Segment 4B.* Additional extension is represented by displacement on low-angle normal faults that are structurally higher than the Whipple detachment fault (but may merge with it in the subsurface). The Crossman Peak low-angle normal fault, exposed as a tear fault on the south side of the Mohave Mountains [Howard et al., 1990], has 8±3 km of displacement [Howard et al., 1982].

*Segment 4C.* Bedrock is concealed beneath Quaternary surficial deposits between the Mohave and Hualapai mountains, but is moderately to highly extended where it is exposed along strike to the southeast between the Bill Williams and McCracken mountains [Suneson, 1980; Lucchitta and Suneson, 1989] and on the north flank of the Buckskin and Rawhide Mountains [Shackelford, 1989a, b; Spencer and Reynolds, 1989c]. Along strike to the northwest in the Buck Mountains, middle Tertiary units and underlying Proterozoic basement are tilted approximately 80° to the west [Howard et al., 1982]. Extension in both of these areas could be the lateral equivalent of extension above the Crossman Peak fault and need not entirely represent additional extension. Considering these uncertainties we estimate that 4 to 20 km of extension has occurred within the approximately 25 km wide swath of concealed bedrock between the Mohave and Hualapai mountains.

*Segment 4D.* There are no known Tertiary normal faults within the south central Hualapai Mountains (zero extension).

*Segment 4F.* The Hualapai Mountains are separated from the Transition Zone by the Big Sandy Valley, which formed by Tertiary extension (the timing of extension is not well constrained) [Scarborough and Wilt, 1979]. Reconnaissance geologic mapping has not revealed any normal faults on the flanks of Big Sandy Valley, presumably because they have been buried. Drilling and modeling of gravity data indicate that bedrock is greater than 1500 m deep (maximum depth of drill holes) in some of the valley [Lease, 1981; Oppenheimer and Sumner, 1980]. Contrasting Proterozoic bedrock on opposite sides of the valley, and the Cretaceous(?) Diamond Joe stock at the east edge of the west side of the valley that has no offset equivalent on the east side, indicates that total extension was significantly less than the 12 to 16 km width of the sediment-covered valley floor. Three kilometers of extension is the minimum extension needed (for a 45° fault dip) to produce the greater than 3 km difference in elevation between the crest of Hualapai Mountains and the minimum depth to bedrock beneath the Big Sandy Valley. If fault dip is more gentle or there are faults on both sides of the valley, extension could be much more, perhaps as much as 9 km. We thus estimate that extension has been 6±3 km.

*Acknowledgments.* We thank Bruce Bryant and Steve Richard for discussions in the field and elsewhere that improved our understanding of the geology of west central Arizona. We also thank Bruce Bryant, Bill Dickinson, and Phil Pearthree for comments on an earlier manuscript, and John Bartley and Simon Hanmer for constructive reviews.

## REFERENCES

Armstrong, R.L., R.C. Speed, W.C. Graustein, and A.Y. Young, K-Ar dates from Arizona, Montana, Nevada, Utah, and Wyoming, *Isochron West*, 16, 1-6, 1976.

Bartley, J.M., A.F. Glazner, and E.R. Schermer, North-south contraction of the Mojave block and strike-slip tectonics in southern California, *Science, 248*, 1398-1401, 1990.

Block, L., and L.H. Royden, Core complex geometries and regional scale flow in the lower crust, *Tectonics, 9*, 557-568, 1990.

Brace, W.F., and D.L. Kohlstedt, Limits on lithospheric stress imposed by laboratory experiments, *J. Geophys. Res., 85*, 6248-6252, 1980.

Brooks, W.E., Reconnaissance geologic map of part of McLendon volcano, Yavapai County, Arizona, scale 1:24,000, *U.S. Geol. Surv. Misc. Field Stud. Map MF-1783*, 1985.

Bryant, B., Map of the Poachie Range, Yavapai and Mohave Counties, Arizona, scale 1:50,000, *U.S. Geol. Surv. Open File Rep., 88-390*, 20 pp., 1988.

Bryant, B., and C.W. Naeser, Fission-track dating across the transition between the Basin and Range Province and the Colorado Plateau, west-central Arizona, *Geol. Soc. Am. Abstr. Programs, 19*, 604, 1987.

Bryant, B., and J.L. Wooden, Lower plate rocks of the Buckskin Mountains, Arizona: A progress report, in Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona, edited by J.E. Spencer and S.J. Reynolds, *Bull. 198*, pp. 47-50, Ariz. Geol. Surv., Tucson, 1989.

Buck, W.R., Flexural rotation of normal faults, *Tectonics, 7*, 959-974, 1988.

Davis, G.A., and G.S. Lister, Detachment faulting in continental extension; Perspectives from the southwestern U.S. Cordillera, *Spec. Pap., Geol. Soc. Am., 218*, 133-160, 1988.

Davis, G.A., J.L. Anderson, E.G. Frost, and T.J. Shackelford, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona, *Mem. Geol. Soc. Am., 153*, 79-129, 1980.

Davis, G.A., J.L. Anderson, D.L. Martin, D. Krummenacher, E.G. Frost, and R.L. Armstrong, Geologic and geochronologic relations in the lower plate of the Whipple detachment fault, Whipple Mountains, southeastern California: A progress report, in *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada*, edited by E.G. Frost and D.L. Martin, pp. 408-432, Cordilleran Publishers, San Diego, Calif., 1982.

Davis, G.A., G.S. Lister, and S.J. Reynolds, Structural evolution of the Whipple and South Mountains shear zones, southwestern United States, *Geology, 14*, 7-10, 1986.

Davis, G.H., Shear-zone model for the origin of metamorphic core complexes, *Geology, 11*, 342-347, 1983.

DeWitt, E., and S.J. Reynolds, Late Cretaceous plutonism and cooling in the Maria fold and thrust belt, west-central Arizona, *Geol. Soc. Am. Abstr. Programs, 22*, 18, 1990.

Dokka, R.K., The Mojave extensional belt of southern California, *Tectonics, 8*, 363-390, 1989.

Drewes, H., et al., Mineral resources of the Harcuvar Mountains wilderness study area, La Paz County, Arizona, *U.S. Geol. Surv. Bull., 1701-F*, 29 pp., 1990.

Duncan, J.T., The geology and mineral deposits of the Northern Plomosa mineral district, La Paz County, Arizona, 55 pp., *Ariz. Geol. Surv., Open File Rep. 90-10*, Tucson, 1990.

Eberly, L.D., and T.B. Stanley, Jr., Cenozoic stratigraphy and geologic history of southwestern Arizona, *Geol. Soc. Am. Bull., 89*, 921-940, 1978.

Emerson, W.S., Geologic development and late Mesozoic deformation of the Little Maria Mountains, Riverside County, California, in *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada*, edited by E.G. Frost and D.L. Martin, pp. 245-255, Cordilleran Publishers, San Diego, Calif., 1982.

England, P., and J. Jackson, Migration of the seismic-aseismic transition during uniform and nonuniform extension of the continental lithosphere, *Geology, 15*, 291-294, 1987.

Frost, E.G., Structural style of detachment faulting in the Whipple Mountains, California and Buckskin Mountains, Arizona, *Ariz. Geol. Soc. Dig., 13*, 25-29, 1981.

Frost, E.G., and D.A. Okaya, Application of seismic reflection profiles to tectonic analysis in mineral exploration, Frontiers in Geology and Ore Deposits of Arizona and the Southwest, edited by B. Beatty and P.A.K. Wilkinson, *Ariz. Geol. Soc. Dig. 16*, 137-152, 1986.

Fryxell, J.E., J.A. Stimac, and S.J. Reynolds, Superimposed domino-style normal faults in a Tertiary bimodal volcanic complex, Wickenburg Mountains and vicinity, central Arizona, *Geol. Soc. Am. Abstr. Programs, 19*, 670, 1987.

Gans, P.B., An open system, two layer crustal stretching model for the eastern Great Basin, *Tectonics, 6*, 1-12, 1987.

Grubensky, M.J., Geologic map of the Vulture Mountains, scale 1:24,000, *Map 27, Ariz. Geol. Surv.*, Tucson, 1989.

Grubensky, M.J., J.A. Stimac, S.J. Reynolds, and S.M. Richard, Geologic map of the northeastern Vulture Mountains and vicinity, central Arizona, scale 1:24,000, *Ariz. Bur. of Geol. and Mineral Tech., Open File Rep. 87-10*, Tucson, 1987.

Hamilton, W., Mesozoic tectonics of the western United States, in Mesozoic Paleogeography of the Western United States, edited by D.G. Howell and K.A. McDougall, pp. 33-70, Society of Economic Palentologists and Mineralogists, Pacific Section, Los Angeles, Calif., 1978.

Hamilton, W., Mesozoic geology and tectonics of the Big Maria Mountians region, southeastern California, in Mesozoic Rocks of Southern Arizona and Adjacent Regions, edited by W.R. Dickinson and M.A. Klute, *Ariz. Geol. Soc. Dig., 18*, 33-48, 1987.

Hamilton, W., Detachment faulting in the Death Valley region, California and Nevada, in Geologic and Hydrologic Investigations of a Potential Nuclear Waste Disposal Site at Yucca Mountain, Southern Nevada, edited by M.D. Carr and J.D. Yount, *U.S. Geol. Surv. Bull., 1790*, 51-86, 1988.

Harding, L.E., and P.J. Coney, The geology of the McCoy Mountains Formation, southeastern California and southwestern Arizona, *Geol. Soc. Am. Bull., 96*, 755-769, 1985.

Hauser, E.C., and J. Lundy, COCORP deep reflections: Moho at 50 km (16 s) beneath the Colorado Plateau: *J. Geophys. Res., 94*, 7071-7082, 1989.

Hauser, E.C., J. Gephart, T. Latham, J. Oliver, S. Kaufman, L. Brown, and I. Lucchitta, COCORP Arizona transect: Strong crustal reflections and offset Moho beneath the transition zone, *Geology, 15*, 1103-1106, 1987.

Hearn, T.M., Pn travel times in southern California, *J. Geophys. Res., 89*, 1843-1855, 1984.

Howard, K.A., and B.E. John, Crustal extension along a rooted system of imbricate low-angle faults: Colorado River extensional corridor, California and Arizona, *Spec. Pub., Geol. Soc. London, 28*, 299-312, 1987.

Howard, K.A., J.W. Goodge, and B.E. John, Detached crystalline rocks of the Mohave, Buck, and Bill Williams Mountains, western Arizona, in Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada, edited by E.G. Frost and D.L. Martin, pp. 377-390, Cordilleran Publishers, San Diego, Calif., 1982.

Howard, K.A., J.E. Nielson, H.G. Wilshire, J.K. Nakata, J.W. Goodge, S.L. Reneau, B.E. John, and V.L. Hansen, Preliminary geologic map of the western Mohave Mountains area, Mohave County, western Arizona, scale 1:48,000, *U.S. Geol. Surv. Open File Rep., 90-684*, 56 pp., 1990.

Jackson, J.A., Active normal faulting and crustal extension, *Continental extensional tectonics*, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, pp. 3-18, *Geol. Soc. London, Spec. Pub., 28*, 1987.

Jackson, J.A., and N.J. White, Normal faulting in the upper continental crust: observations from regions of active extension, *J. Struct. Geol., 11*, 15-36, 1989.

John, B.E., Geometry and evolution of a mid-crustal extensional fault system: Chemehuevi Mountains, southeastern California, *Geol. Soc. London, Spec. Pub., 28*, 313-335, 1987.

Keith, S.B., S.J. Reynolds, P.E. Damon, M. Shafiqullah, D.E. Livingston, and P.D. Pushkar, Evidence for multiple intrusion and deformation within the Santa Catalina-Rincon-Tortolita crystalline complex, southeastern Arizona, *Mem. Geol. Soc. Am., 153*, 217-268, 1980.

Kruse, S., M. McNutt, J. Phipps-Morgan, L. Royden, and B. Wernicke, Lithospheric extension near Lake Mead, Nevada: A model for ductile flow in the lower crust, *J. Geophys. Res., 96*, 4435-4456, 1991.

Lasky, S.G., and B.N. Webber, Manganese resources of the Artillery Mountains region, Mohave County, Arizona, *U.S. Geol. Surv. Bull., 961*, 86 pp., 1949.

Laubach, S.E., S.J. Reynolds, J.E. Spencer, and S. Marshak, Progressive deformation and superposed fabrics related to Cretaceous crustal underthrusting in western Arizona, U.S.A., *J. Struct. Geol., 11*, 735-750, 1989.

Lease, L.W., Summary geologic report on drilling in western Prescott and Williams quadrangles, Mohave, Yavapai, and Yuma Counties, Arizona, *U.S. Dep. Energy Open File Rep. GJBX-293(81)*, 82 pp., Grand Junction, Colorado, 1981.

Lister, G.S., and G.A. Davis, The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A., *J. Struct. Geol., 11*, 65-94, 1989.

Long, A., and B. Rippeteau, Testing contemporaneity and averaging radiocarbon dates, *American Antiq., 39*, 205-215, 1974.

Lucchitta, I., Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region, *Tectonophysics, 61*, 63-95, 1979.

Lucchitta, I., and N. Suneson, Geologic map of the Artillery Peak northwest quadrangle, Mohave County, Arizona, scale 1:24,000, *U.S. Geol. Surv., Open File Rep. 85-277*, 1985.

Lucchitta, I., and N. Suneson, Geologic map of the Planet 2 NW quadrangle, Mohave County, Arizona, scale 1:24,000, *U.S. Geol. Surv., Open File Rep. 89-673*, 1989.

Lysonski, J.C., J.S. Sumner, C. Aiken, and J.S. Schmidt, Residual Bouguer gravity anomaly map of Arizona, scale 1:1,000,000, Lab. of Geophys., Dep. of Geosci., Univ. of Ariz., Tucson, 1980.

Marshak, S., and M. Vander Meulen, Geology of the Battleship Peak area, southern Buckskin Mountains Arizona: Structural style below the Buckskin detachment fault, in Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona, edited by J.E. Spencer and S.J. Reynolds, *Bull. 198*, pp. 51-66, Ariz. Geol. Surv., Tucson, 1989.

McCarthy, J., G.S. Fuis, and J. Wilson, Crustal structure in the region of the Whipple Mountains metamorphic core complex, from seismic refraction results, *Geol. Soc. Am. Abstr. Programs, 19*, 763, 1987.

McNutt, M.K., M. Diament, and M.G. Kogan, Variations in elastic plate thickness at continental thrust belts, J. Geophys. Res., 93, 8825-8838, 1988.

Miller, F.K., Geologic map of the Quartzsite quadrangle, Yuma County, Arizona, scale 1:62,500, *U.S. Geol. Surv. Geol. Quad. Map, GQ-841*, 1970.

Nakata, J.K., Preliminary report on diking events in the Mohave Mountains, Arizona, in *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada*, edited by E.G. Frost and D.L. Martin, pp. 85-89, Cordilleran Publishers, San Diego, Calif., 1982.

Oppenheimer, J.M., and J.S. Sumner, Depth-to-bedrock map, Basin and Range Province, Arizona, scale 1:1,000,000 Lab. of Geophys., Dept. of Geosci., Univ. of Ariz., Tucson, 1980.

Otton, J.K., Tertiary extensional tectonics and associated volcanism in west-central Arizona, in *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada*, edited by E.G. Frost and D.L. Martin, pp. 143-157, Cordilleran Publishers, San Diego, Calif., 1982.

Pain, C.F., Cordilleran metamorphic core complexes in Arizona: a contribution from geomorphology, *Geology, 13*, 871-874, 1985.

Peirce, H.W., P.E. Damon, and M. Shafiqullah, An Oligocene(?) Colorado Plateau edge in Arizona, *Tectonophysics, 61*, 1-24, 1979.

Rehrig, W.A., and S.J. Reynolds, Geologic and geochronologic reconnaissance of a northwest-trending zone of metamorphic core complexes in southern and western Arizona, *Mem. Geol. Soc: Am., 153*, 131-157, 1980.

Reynolds, S.J., and G.S. Lister, Kinematics of mylonitic rocks in metamorphic core complexes in Arizona - origin of the mylonitic front, *Geol. Soc. Am. Abstr. Programs, 19*, 443, 1987.

Reynolds, S.J., and J.E. Spencer, Geologic map of the Aguila Ridge-Bullard Peak area, eastern Harcuvar Mountains, west-central Arizona, scale 1:24,000, *Ariz. Bur. of Geol. and Mineral Tech., Open File Rep. 84-4*, Tucson, 1984.

Reynolds, S.J., and J.E. Spencer, Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona, *Geology, 13*, 353-356, 1985.

Reynolds, S.J., F.P. Florence, J.W. Welty, M.S. Roddy, D.A. Currier, A.V. Anderson, and S.B. Keith, Compilation of radiometric age determinations in Arizona, *Ariz. Bur. of Geol. and Mineral Tech., Bull. 197*, 258 pp., Tucson, 1986a.

Reynolds, S.J., M. Shafiqullah, P.E. Damon, and E. DeWitt, Early Miocene mylonitization and detachment faulting, South Mountains, central Arizona, *Geology, 14*, 283-286, 1986b.

Reynolds, S.J., J.E. Spencer, S.M. Richard, and S.E. Laubach, S.E., Mesozoic structures in west-central Arizona, in Frontiers in Geology and Ore Deposits of Arizona and the Southwest, edited by B. Beatty and P.A.K. Wilkinson, *Ariz. Geol. Soc., Dig. 16*, 35-51, 1986c.

Reynolds, S.J., S.M. Richard, G.M. Haxel, R.M. Tosdal, and S.E. Laubach, Geologic setting of Mesozoic and Cenozoic metamorphism in Arizona, *Metamorphism and Crustal Evolution of the Conterminous Western United States*, edited by W.G. Ernst, pp. 467-501, Prentice-Hall, Englewood Cliffs, N.J., 1988.

Reynolds, S.J., J.E. Spencer, S.E. Laubach, D. Cunningham, and S.M. Richard, Geologic map, geologic evolution, and mineral deposits of the Granite Wash Mountains, west-central Arizona, scale 1:24,000, *Open File Rep. 89-4*, Ariz. Geol. Surv., Tucson, 1989.

Richard, S.M., J.E. Fryxell, and J.F. Sutter, Tertiary structure and thermal history of the Harquahala and Buckskin mountains, west-central Arizona: Implications for denudation by a major detachment fault system, *J. Geophys. Res., 95*, 19,973-19,988, 1990.

Rutter, E.H., On the nomenclature of mode of failure transitions in rocks, *Tectonophysics, 122*, 381-387, 1986.

Scarborough, R., and N. Meader, Geologic map of the northern Plomosa Mountains, Yuma [La Paz] County, Arizona, scale 1:24,000, *Contrib. Map CM-89-D*, Ariz. Geol. Surv., Tucson, 1989.

Scarborough, R.B., and J.C. Wilt, A study of uranium favorability of Cenozoic sedimentary rocks, Basin and Range province, Arizona: Part I, general geology and chronology of pre-late Miocene Cenozoic sedimentary rocks, *Open File Rep. 79-1*, 101 pp., Ariz. Bur. of Geol. and Mineral Tech., Tucson, 1979.

Shackelford, T.J., Tertiary tectonic denudation of a Mesozoic-early Tertiary(?) gneiss complex, Rawhide Mountains, western Arizona, *Geology, 8*, 190-194, 1980.

Shackelford, T.J., Geologic map of the Rawhide Mountains, Mohave County, Arizona, Plate 1, scale 1:42,850, in Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona, edited by J.E. Spencer and S.J. Reynolds, *Bull. 198*, Ariz. Geol. Surv., Tucson, 1989a.

Shackelford, T.J., Structural geology of the Rawhide Mountains, Mohave County, Arizona, in Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona, edited by J.E. Spencer and S.J. Reynolds, *Bull. 198*, pp. 15-46, Ariz. Geol. Surv., Tucson, 1989b.

Sherrod, D.R., Preliminary geologic map of the Monkeys Head quadrangle, Mohave and La Paz Counties, Arizona, scale 1:24,000, *U.S. Geol. Surv. Open File Rep., 88-597*, 1988.

Sherrod, D.R., and R.D. Koch, Structure and stratigraphy of Mesozoic sedimentary and volcanic rocks in the New Water Mountains, southwestern Arizona, in Mesozoic Rocks of Southern Arizona and Adjacent Areas, edited by W.R. Dickinson and M.A. Klute, *Ariz. Geol. Soc. Dig., 18*, 81-90, 1987.

Sherrod, D.R., R.D. Koch, and M.J. Grubensky, Geologic map of the Vicksburg quadrangle, La Paz County, Arizona, scale 1:62,500, *U.S. Geol. Surv. Geol. Quad. Map, GQ-1684*, 1990.

Spencer, J.E., Role of tectonic denudation in warping and uplift of low-angle normal faults, *Geology, 12*, 95-98, 1984.

Spencer, J.E., Miocene low-angle normal faulting and dike emplacement, Homer Mountain and surrounding areas, southeastern California and southernmost Nevada, *Geol. Soc. Am. Bull., 96*, 1140-1155, 1985.

Spencer, J.E., Compilation geologic map of the Buckskin and Rawhide Mountains, west-central Arizona, Plate 3, scale 1:100,000, in Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona, edited by J.E. Spencer and S.J. Reynolds, *Bull. 198*, Ariz. Geol. Surv., Tucson, 1989.

Spencer, J.E., and S.J. Reynolds (Eds.), Geology and mineral resources of the Buckskin and Rawhide Mountains, west-central Arizona, *Bull. 198*, 279 pp., Ariz. Geol. Surv., Tucson, 1989a.

Spencer, J.E., and S.J. Reynolds, Middle Tertiary tectonics of Arizona and adjacent areas, in Geologic Evolution of Arizona, edited by J.P. Jenny and S.J. Reynolds, *Ariz. Geol. Soc. Dig., 17*, 539-574, 1989b.

Spencer, J.E., and S.J. Reynolds, Tertiary structure, stratigraphy, and tectonics of the Buckskin Mountains, in Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona, edited by J.E. Spencer and S.J. Reynolds, *Bull. 198*, pp. 103-167, Ariz. Geol. Surv., Tucson, 1989c.

Spencer, J.E., and S.J. Reynolds, Geology and mineral resources of the Bouse Hills, west-central Arizona, scale 1:24,000, *Open File Rep., 90-9*, Ariz. Geol. Surv., Tucson, 1990a.

Spencer, J.E., and S.J. Reynolds, Relationship between Mesozoic and Cenozoic tectonic features in west-central Arizona and adjacent southeastern California, *J. Geophys. Res., 95*, 539-555, 1990b.

Spencer, J.E., S.M. Richard, and S.J. Reynolds, Geologic map of the Little Harquahala Mountains, west-central Arizona, scale 1:24,000, *Open File Rep., 85-9*, Ariz. Bur. of Geol. and Mineral Tech., Tucson, 1985.

Spencer, J.E., M.J. Grubensky, J.T. Duncan, J.D. Shenk, J.C. Yarnold, and J.P. Lombard, Geology and mineral deposits of the central Artillery Mountains, in Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona, edited by J.E. Spencer and S.J. Reynolds, *Bull. 198*, pp. 168-183, Ariz. Geol. Surv., Tucson, 1989a.

Spencer, J.E., M. Shafiqullah, R.J. Miller, and L.G. Pickthorn, K-Ar geochronologyof Miocene extensional tectonism, volcanism, and potassium metasomatism in the Buckskin and Rawhide Mountains, in Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona, edited by J.E. Spencer and S.J. Reynolds, *Bull. 198*, pp. 184-189, Ariz. Geol. Surv., Tucson, 1989b.

Stimac, J.A., J.E. Fryxell, S.J. Reynolds, S.M. Richard, M.J. Grubensky, and E.A. Scott, Geologic map of the Wickenburg, southern Buckhorn, and northwestern Hieroglyphic Mountains, central Arizona, scale 1:24,000, *Open File Rep., 87-9*, Ariz. Bur. of Geol. and Mineral Tech., Tucson, 1987.

Stone, P., and M.M. Kelley, Geologic map of the Palen Pass quadrangle, Riverside County, California, scale 1:24,000, *U.S. Geol. Surv. Misc. Field Stud. Map, MF-2070*, 1989.

Stone, P., V.M. Page, W. Hamilton, and K.A. Howard, Cretaceous age of the upper part of the McCoy Mountains Formation, southeastern California and southwestern Arizona, and its tectonic significance: Reconciliation of paleobotanical and paleomagnetic evidence, *Geology, 15*, 561-564, 1987.

Stoneman, D.A., Geologic map of the Plomosa Pass area, northern Plomosa Mountains, La Paz County, Arizona, scale 12,000, *Misc. Map MM-85-B*, Ariz. Bur. Geol. Mineral Tech., Tucson, 1985.

Suneson, N.H., The origin of bimodal volcanism, west-central Arizona, Ph.D. thesis, 293 pp., Univ. of California, Santa Barbara, 1980.

Suneson, N.H., and I. Lucchitta, K/Ar ages of Cenozoic volcanic rocks, west-central Arizona, *Isochron West*, 24, 25-29, 1979.

Thompson, G.A., and J. McCarthy, A gravity constraint on the origin of highly extended terranes, *Tectonophysics, 174*, 197-206, 1990.

Warren, D.H., A seismic refraction survey of crustal structure in central Arizona, *Geol. Soc. Am. Bull., 80*, 257-282, 1969.

Wernicke, B., Low-angle normal faults in the Basin and Range Province: Nappe tectonics in an extending orogen, *Nature, 291*, 645-648, 1981.

Wernicke, B., Uniform-sense normal simple shear of the continental lithosphere, *Can. J. Earth Sci., 22*, 108-125, 1985.

Wernicke, B., The fluid crustal layer and its implications for continental dynamics, *Geol. Soc. Am. Abstr. Programs, 21*, 81, 1989.

Wernicke, B., and G.J. Axen, On the role of isostasy in the evolution of normal fault systems, *Geology, 16*, 848-851, 1988.

Wright, J.E., J.L. Anderson, and G.A. Davis, Timing of plutonism, mylonitization, and decompression in a metamorphic core complex, Whipple Mountains, CA, *Geol. Soc. Am. Abstr. Programs, 18*, 201, 1986.

Young, R.A., and E.H. McKee, Early and middle Cenozoic drainage and erosion in west-central Arizona, *Geol. Soc. Am. Bull., 89*, 1745-1750, 1978.



S.J. Reynolds, Department of Geology, Arizona State University, Tempe, AZ 85287.
J.E. Spencer, Arizona Geological Survey, 845 N. Park Avenue, Tucson, AZ 85719.



(Received November 7, 1990;
revised April 17, 1991;
accepted April 22, 1991.)