Crustal extension along a rooted system of imbricate low-angle faults: Colorado River extensional corridor, California and Arizona

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SUMMARY: The upper 10 to 15 km of crystalline crust in the 100-km-wide Colorado River extensional corridor of mid-Tertiary age underwent extension along an imbricate system of gently dipping normal faults. Detachment faults cut gently down-section eastward in the direction of tectonic transport from a headwall breakaway, best expressed in the Old Woman Mountains, California. Successively higher and more distal allochthons are displaced farther from the headwall, some as much as tens of kilometres. The basal fault(s) cut initially to depths of 10 to 15 km, the palaeothickness of a tilted allochthonous slab of basement rocks above the Chemehuevi–Whipple Mountains detachment fault(s). Hanging wall blocks tilt consistently toward the headwall as shown by dips of capping Tertiary strata and of originally horizontal Proterozoic diabase dykes. Block tilts and the degree of extension increase northeastward across much of the corridor. The faults are interpreted as rooting under the unbroken Hualapai Mountains and Colorado Plateau on the down-dip side of the corridor in Arizona. Slip on faults at all exposed levels of the crust was unidirectional, and totals an estimated 50 km. These data and inferences support the concept that the crust in California moved out from under Arizona along a rooted, normal-slip shear system. Brittle thinning above the sole faults affected the entire upper crust, and in places wholly removed it along the central part of the corridor. Upwarp exposed metamorphic core complexes in footwall domes.

Studies of continental extension have increasingly focused on low-angle faulting as a major tectonic process. Extensional faults that dip at low angles in western North America are documented around metamorphic core complexes (Crittenden *et al.* 1980) and in seismic reflection profiles of the Basin and Range Province (Allmendinger *et al.* 1983; Smith & Bruhn 1984). Several possible models of structural geometry have been proposed for extensional fault systems (Fig. 1). These models include distension over ductilely thinned crust (Fig. 1a, Eaton 1982; Gans & Miller 1983), or over magmatic intrusions (Fig. 1b, cf. Thompson & Burke 1974), crustal-scale lenses or boudins (Fig. 1c, Davis 1980; Hamilton 1982), and crustal shear zones (Fig. 1d, Wernicke 1981, 1985). In this paper we summarize geometrical aspects of the 100-km-wide Colorado River extensional corridor that indicate uniform-sense extension on rooted detachment faults to palaeodepths of at least 10–15 km in the crust. We infer from these data that crustal shear zones are an important mode of extension.

Setting and framework

The Basin and Range Province contains numerous tilt domains, with dimensions of the order of 100 km, in which fault blocks all tilt in one direction as shown by stratal dips of Tertiary rocks (Stewart 1980). We define the Colorado River extensional corridor as the tilt domain in the southern Basin and Range Province along the Colorado River as shown in Fig. 2. In this corridor, almost all fault blocks produced during mid-Tertiary crustal extension tilt to the W or S. This tilt is shown by steep to gentle dips of Tertiary strata (Fig. 3) and originally horizontal Proterozoic diabase dykes. The corridor is 50–100 km wide. Partial transects of the northern, central, and southeastern parts of the corridor, as shown in Fig. 2, have been described, respectively, by Spencer (1985), Davis *et al.* (1980), G. A. Davis & G. S. Lister (unpublished work), and Reynolds & Spencer (1985). We have mapped in many of the ranges shown in Fig. 2, including the Calumet, Ship, Clipper, Granite, Iron, Arica, Old Woman, Piute, Little Piute, Stepladder, Turtle, Chemehuevi, Mohave, Bill Williams, Buck, and Hualapai Mountains. Other tilt domains lie to the NW, SW, and SE of the area shown in Fig. 2 (Stewart 1980).

The rocks involved in the extension are syntectonic volcanic and sedimentary rocks of latest Oligocene(?) and early Miocene age, about 1–3 km thick, and a thick metamorphic and plutonic basement of Proterozoic, Mesozoic and locally Palaeozoic rocks (Figs 4 & 5a). Tertiary and older dykes are abundant in places. Dating by the K–Ar method places most of the faulted

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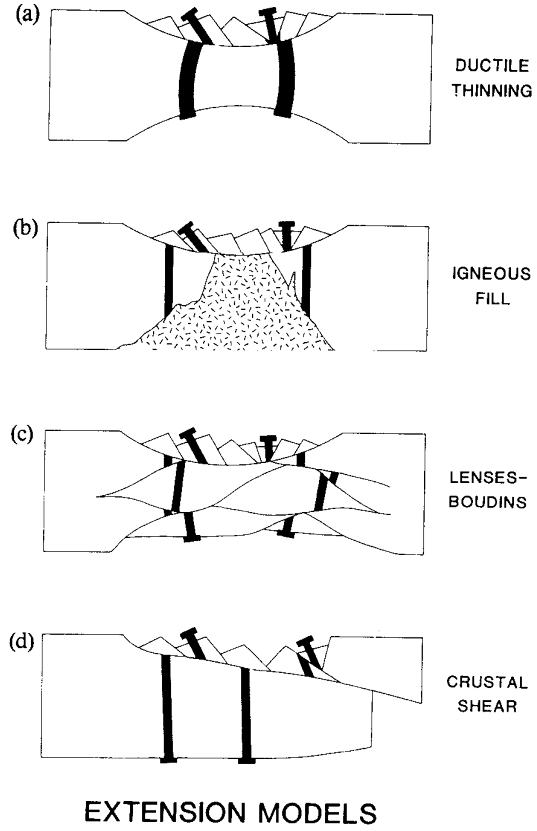

FIG. 1. Four major models for tectonic extension of continental crust. The fate of two initially vertical markers (black) illustrates different predictions of each model. The evidence presented in this paper favours model d, in which an inclined shear zone traverses much of the crust.

syntectonic rocks at between 17 and 22 Ma. Post-extensional fanglomerates and basalts dated at 10–15 Ma lap across the highly faulted rocks of the extensional corridor and cap the extensional episode (Dickey *et al.* 1980; Davis *et al.* 1980; Spencer 1985).

The extensional faults juxtapose shallow crustal rocks on rocks from deeper levels, forming a distinctive tectonic layering. Regional study both of this relationship and of tilted, obliquely eroded sections suggests a reconstructed crustal section that applies to much of the extensional corridor. This reconstruction is shown in Fig. 4.

Low-angle normal (detachment) faults are prominently exposed around the domal metamorphic core complexes in the central part of the corridor, including the Whipple and Rawhide Mountains (Davis *et al.* 1980; Frost & Martin 1982a), Chemehuevi Mountains (John 1982, this volume), Sacramento Mountains (McClelland 1982; Spencer & Turner 1982; Spencer 1985), and the Dead and Newberry Mountains (Mathis 1982; Spencer 1985). Numerous tilted blocks overlie the major low-angle faults and show NE upper-plate transport away from the tilt direction (Davis *et al.* 1980). Faults that we consider to be the sole faults of the extensional corridor (Fig. 5b, bottom) shoal along the W side of the corridor and cut down-section northeastward in the direction of tectonic transport, as indicated by evidence presented below. Higher and more distal allochthons are each displaced farther from the headwall breakaway. The major detachment faults root at a shallow angle in the NE transport direction under relatively unbroken rocks that merge with the undeformed Colorado Plateau (Lucchitta & Suneson 1981). Progressive normal faulting and subsequent doming of the sole faults from palaeodepths of 10–15 km have exposed them in the metamorphic core complexes along the central part of the Colorado River corridor (Howard *et al.* 1982a, b; Spencer 1984).

The extensional strain, as deduced from exposures in the ranges we have mapped in, was primarily by brittle slip with a uniform shear sense, even at the deepest exposed levels which represent mid-crustal palaeodepths in the fault system. Igneous dykes in rocks exposed from deep levels can account for a few percent of the extension. Small Tertiary ductile shear zones and local protomylonites, thinner than 1 m, demonstrate a small amount of syntectonic ductile deformation at the deepest exposed levels (John, this volume). Thick sections of pre-Tertiary mylonitic gneiss in the core complexes here appear to be unrelated to the Tertiary extension; their pre-Tertiary age is well documented where cut by granite with a minimum age of 64 Ma in the Chemehuevi Mountains (John 1982, this volume). Mylonitization in the Whipple Mountains, where we have not mapped, has been variously interpreted as pre-Tertiary (Davis *et al.* 1980; Anderson & Rowley 1981) or partly Tertiary (G. A. Davis pers. comm. 1985). In the Chemehuevi Mountains and other areas that we have mapped, we conclude that the mid-Tertiary crustal extension was not accommodated in a major way by either igneous intrusion or ductile distension at any crustal levels now exposed.

Detachment faults

Detachment fault, as used in this paper, applies to major low-angle normal faults that attenuate

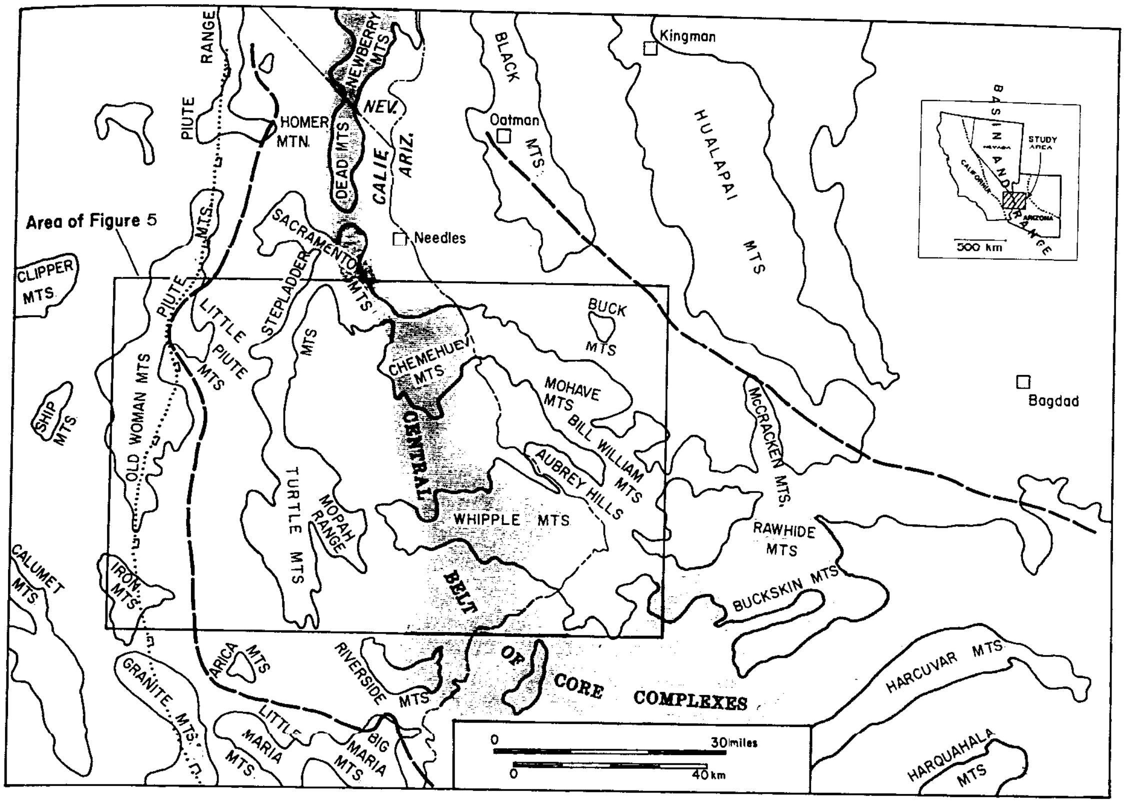

FIG. 2. Map of the Colorado River extensional corridor (between heavy dashed lines) in California, Arizona, and Nevada. Tertiary fault blocks within this corridor tilt to the W or SW. A central belt of metamorphic core complexes is shaded. Alluviated basins intervene between the named mountain ranges. The western dashed line indicates the position of westward-shoaling faults. The dotted line with teeth indicates the inferred breakaway line before erosion.

crustal section. The term detachment fault was coined to avoid the connotation of compressional thrusting on a low-angle fault along which strata were detached and moved (Pierce 1963; Campbell *et al.* 1966). Carr & Dickey (1976) broadened the term when they applied it to the Whipple Mountains fault in non-stratified crystalline rocks. Later authors have since widely used the term detachment fault for low-angle normal faults in the Colorado River region and elsewhere, whether in stratified rocks or not (e.g. Davis *et al.* 1980; papers in Frost & Martin 1982b; Davis 1984; Wernicke *et al.* 1985a). Such faults have also been called denudational faults (Armstrong 1972), decollements (Coney 1974, 1979), lag faults (Dennis *et al.* 1983) or by the acronym LANF (Brun & Choukroune 1983) for low-angle normal faults. The current widespread use of detachment fault deviates from the original meaning in that commonly no stratified rocks are involved. Furthermore, some low-angle faults may have rotated from initially much steeper dips during progressive extension (Proffett 1977); Gans & Miller 1983; Colletta & Angelier 1982), and yet closely resemble others (e.g. Wernicke *et al.* 1985a, b) that were low-angle initially. The primary dip of low-angle normal faults is commonly difficult to establish, and we suspect that faults labelled detachments in the literature embrace a wide variety of primary dips. Further, slip at low dips undoubtedly continues on some faults that have rotated from initially steep dips. Considering these difficulties, we here use the term detachment fault in its broadest sense, in order both to conform to popular use and to avoid genetic interpretations of primary dip where evidence for possible rotation is inconclusive. We emphasize that most of the faults termed detachments truncate discordantly the rock fabrics of both hanging walls and footwalls. In that sense, they cut across, rather than detach. In addition, some faults termed detachments were possibly initially steep faults now rotated to sub-horizontal.

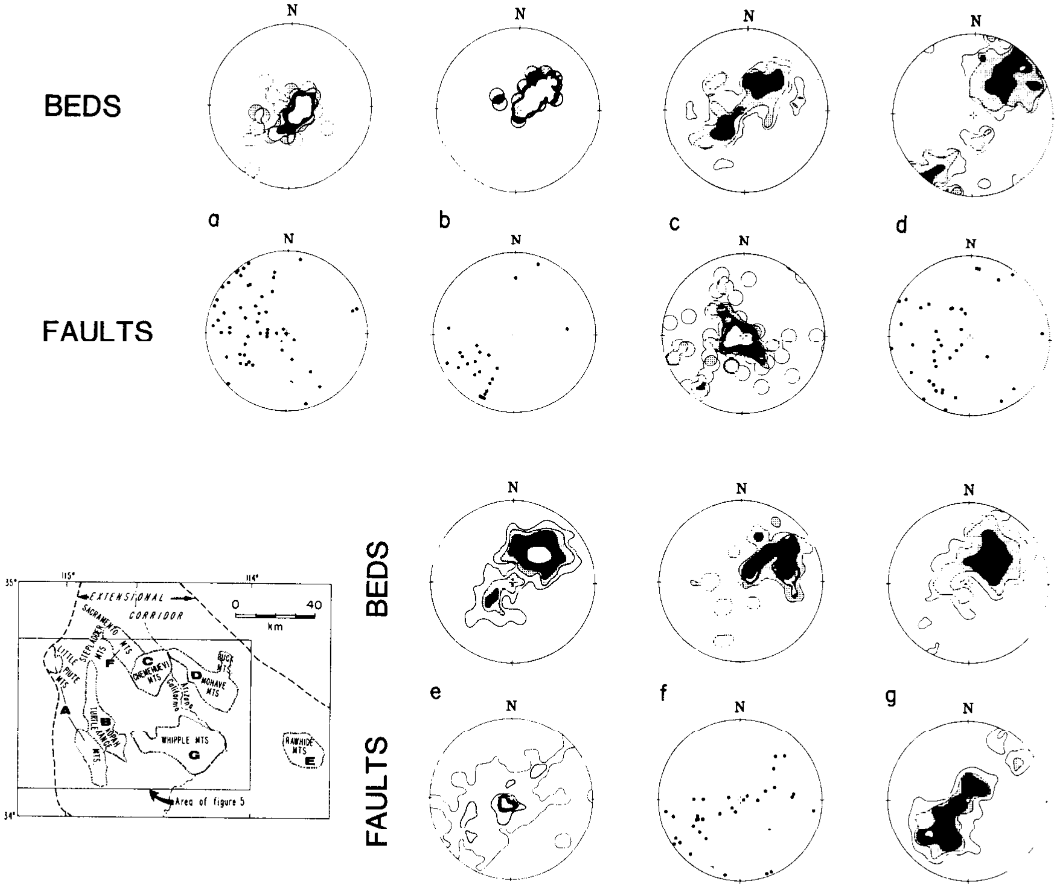

FIG. 3. Orientation of faults and of lower-Miocene and Oligocene(?) strata. Diagrams are lower-hemisphere, equal-area projection. Average stratal dips increase W to E through areas a, b, c, and d, then decrease in eastern area e. Areas f and g are similar to c in the central belt of metamorphic core complexes. Diagrams e are from Shackelford (1976); others are compiled from published and unpublished sources. Number of bedding measurements: (a) 49, (b) 34, (c) 148, (d) 149, (e) 328, (f) 88, (g) 219. Number of fault measurements: (a) 55, (b) 23, (c) 79, (d) 38, (e) 170, (f) 35, (g) 176. Contoured maxima are 6 to 9% per 1% area.

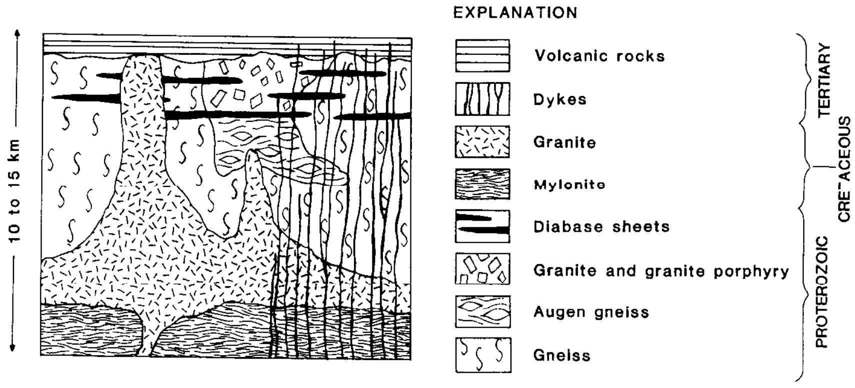

FIG. 4. A reconstructed generalized crustal section before extension schematically shows Proterozoic batholiths and sub-horizontal dykes near the surface, Cretaceous batholiths at depth, and mylonites beneath (modified slightly from Howard *et al.* 1982a). The mid-Tertiary extensional fault system transected this heterogeneous crystalline crust and exposed dismembered parts of it.

Shoaling faults on the west side of the corridor

The western margin of the extensional corridor traces Tertiary faults that dip E at low angles into the corridor, above footwalls of crystalline basement rocks (Fig. 5b). In contrast to the extensional corridor, areas 10–40 km W of these faults are relatively unbroken, contain no recognized large detachment faults and Tertiary tilting is either inconspicuous or variable in direction. The western dashed line in Fig. 2 outlines the inferred trace of westward-shoaling faults. The shoaling fault system where exposed in the Old Woman and Piute Mountains was initially shallow, barely into basement rocks; it juxtaposes two plates, each consisting of pre-Tertiary rocks and overlying lower Miocene strata and including an ignimbrite 18–19 My old that we consider to be the distinctive Peach Springs Tuff of Young (1966). The low-angle fault in the Old Woman and Piute Mountains was originally mapped by Cooksley (1960a) (BR in Fig. 5b). The fault dips 5 to 35° SE in the Piute Mountains and truncates Miocene fanglomerates that dip 20 to 30° into a footwall of crystalline rocks. Along part of its trace in the Old Woman Mountains the fault is steep, locally vertical. The hanging wall block contains a N-trending asymmetric syncline with a narrow W limb due to drag and a broad E limb resulting from block tilt, or 'reverse drag' in the sense of Hamblin (1965). Structural and stratigraphic markers in the pre-Tertiary crystalline basement of the hanging wall block (the Little Piute Mountains) demonstrate, when compared to the footwall block, that down-to-the-E displacement on the shoaling fault was no more than two or three kilometres either vertically or horizontally. The markers are narrow belts of attenuated and metamorphosed Palaeozoic strata along a system of Mesozoic thrust faults (Miller *et al.* 1982).

During extensional faulting, coarse detritus and landslides were shed eastward from the Old Woman and Iron Mountains breakaway area, as shown by distinctive clasts in lower Miocene deposits in the Turtle Mountains area. We therefore view the breakaway as a headwall scarp having substantial topographic relief. A young analog may be the Turtleback area in Death Valley (Wright *et al.* 1974).

In the Big Maria Mountains and Homer Mountain (Fig. 2) the exposed shoaling faults juxtapose contrasting suites of crystalline rocks that imply substantial excision of crustal section (Fig. 4) and suggest horizontal separation of many kilometres. Spencer & Turner (1982) and Spencer (1985) infer that the exposed detachment faults at Homer Mountain represent an eroded breakaway along which at least several kilometres of top-to-the E horizontal separation occurred. We interpret the faults of the northern Big Maria Mountains (Hamilton 1982; Martin *et al.* 1982), as analogous.

Crystalline rocks in the lower plate of the Big Maria Mountains contrast with those in the upper plate both in rock type and thermal history and no detachment faults are known throughout 30 to 40 km of virtually continuous exposure to the W. The Big Maria area then, like the Homer Mountain area, can be interpreted as deeply eroded footwall exposures, located many kilometres E of the original headwall region, where the faults surfaced. Displacement is larger on the faults in the Big Maria Mountains and at Homer Mountain than for the shoaling fault in the Old Woman–Piute range probably because cumulative displacement on the basal fault(s) increases eastward in the transport direction from the breakaway. This increase in fault displacement results from numerous upper-plate faults that each contribute displacement to the basal fault(s) (Fig. 5b, bottom). This type of geometry is described on the Crossman Peak fault in the Mohave Mountains (Fig. 5b, Howard *et al.* 1982a) as well as in other extensional terranes (Gans & Miller 1983).

The regional trace of gently dipping basal faults, which shoal to the W over a footwall of denuded crystalline rocks, forms the western margin of the detached and tilted terrane. We consider that the original position of the headwall breakaway is approximated by the exposure in the Old Woman Mountains, and that exposures in the Big Maria Mountains, as at Homer Mountain, are eroded remnants that lie many kilometres E of where the fault system initially surfaced (Fig. 2). Seismic reflection data (Frost & Okaya 1985) and regional map patterns of crystalline rock units (Howard *et al.* 1982b, unpub. data) both suggest that the breakaway fault system in the Old Woman Mountains connects at depth beneath the Turtle Mountains with the now-updomed detachment faults in the Chemehuevi Mountains.

Eastward from the headwall across much of the extensional corridor (as far as the Buck Mountains, Figs 2 & 5), block tilts generally steepen (Fig. 3). Many sub-vertical to overturned Tertiary stratal dips are measured in the Mohave and Buck Mountains, indicative of a high degree of upper-plate extension there (cf. Wernicke & Burchfiel 1982; Gans & Miller 1983).

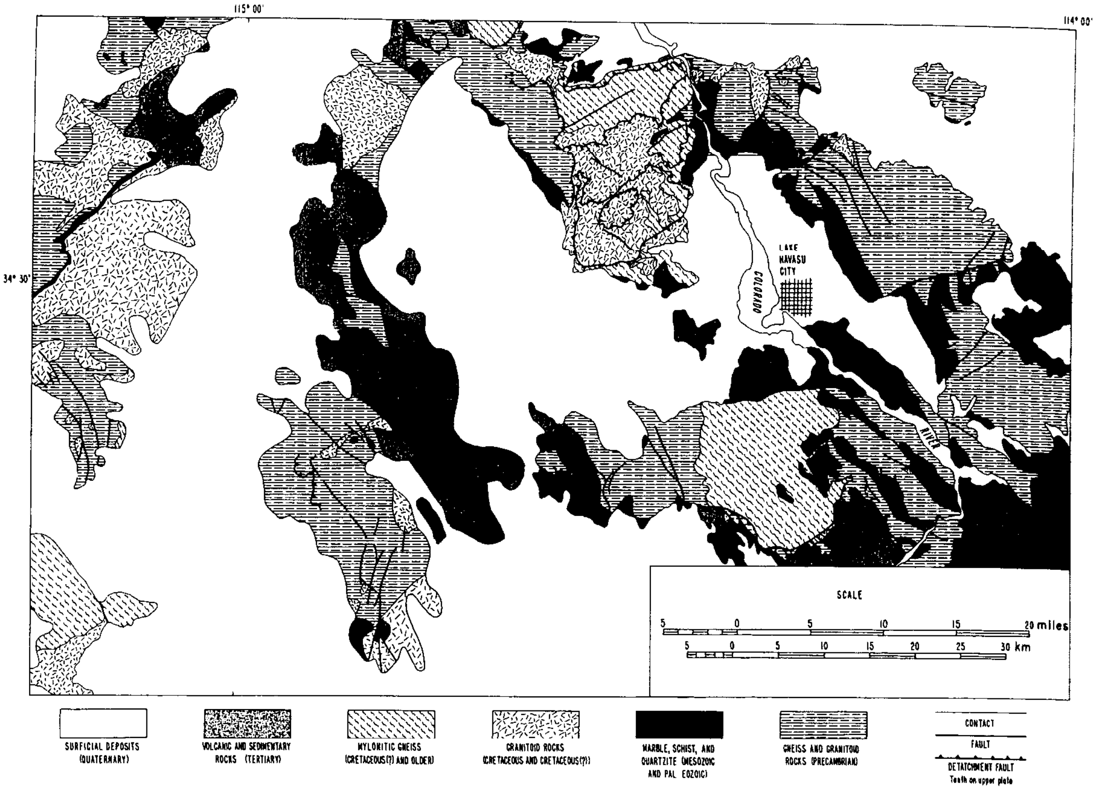

FIG. 5. (a) Generalized geological map of part of the Colorado River extensional corridor showing major Tertiary faults. The location of this map is shown in Fig. 2. Compiled from Cooksley (1960a, b), Collier (1960a, b), Miller *et al.* (1982), Howard *et al.* (1982a, b), John (this volume), Stone *et al.* (1983), Light *et al.* (1983), Miller & Howard (1985), W.J. Carr's mapping as compiled by Stone & Howard (1979), and unpublished mapping by the authors and P. Stone, J.E. Nielson, J.W. Goodge, and V.L. Hansen.
(b) Top: Tectonic map of the area shown in Fig. 5(a). Low-angle faults are designated as follows: BR = breakaway fault in Old Woman–Piute range; CH = Chemehuevi fault; MW = Mohave Wash fault; DE = Devils Elbow fault; WM = Whipple Mountains fault; CP = Crossman Peak fault. Unpatterned areas show post-extension deposits (mid-Miocene and younger). The patterns show structural zones of rocks involved in the extension (see Fig. 4). Zone I (grey) is headwall and footwall terranes below the deepest known faults. IA (dark grey) is allochthons in the Chemehuevi Mountains above the Mohave Wash and another small-displacement fault. IIA (stipple) is gently tilted large blocks near the headwall breakaway. IIB (dots) is smaller, moderately tilted blocks. III is numerous mostly small blocks allochthonous over the central belt of metamorphic core complexes. IV is a large allochthon in the Mohave Mountains area, representing a thick upended crustal section. V is higher allochthons above the Crossman Peak fault. Bottom: Conceptual section across the width of the map at about 34° 30′ latitude. Patterns match the map patterns. Capping strata on tilt blocks diagrammatically indicate a Tertiary layer. The section is greatly simplified and does not indicate exact scale or angular relations.

Lithological match in allochthons

Normal faults, commonly spaced 1 to 3 km apart, separate allochthonous tilted blocks above the detachment faults (Fig. 5, Dickey *et al.* 1980; Carr *et al.* 1980). Tertiary volcanic and sedimentary strata and plutonic and metamorphic rock units of Proterozoic and Mesozoic age can be correlated in a general way from one allochthonous block to the next (Davis *et al.* 1980; Howard *et al.* (1982a, b), and to the relatively undeformed terrane NE of the extensional corridor (Lucchitta & Suneson 1981). This match supports the concept that allochthons were initially contiguous. Lower plates below the detachment faults generally expose different crystalline rocks than those of the allochthons. Davis *et al.* (1982) point out that Proterozoic diabase and coarse-grained granite, typically present in the allochthons, crop out in the westernmost exposures of the lower plate in the Whipple Mountains. Consequently a palinspastic reconstruction would compress the allochthons

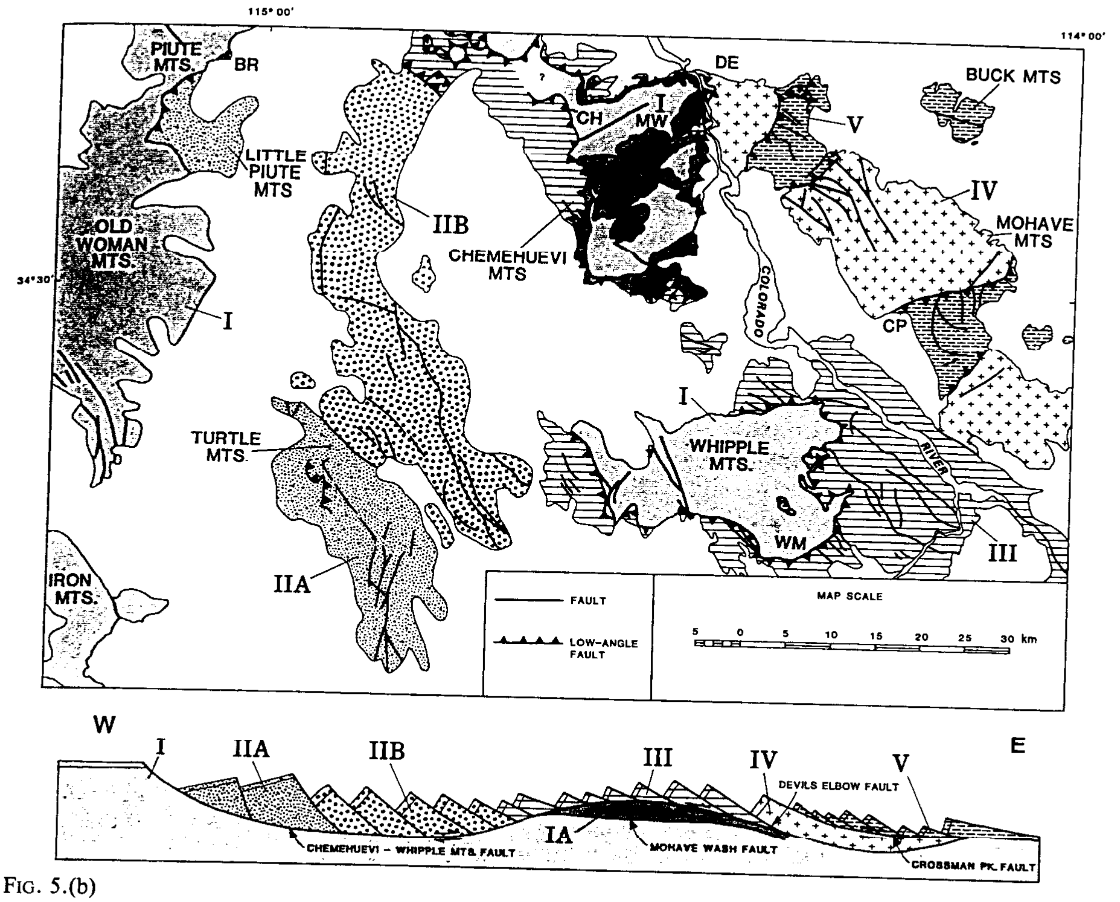

FIG. 5.(b)

together so that they overlay western parts of the lower plate (Davis *et al.* 1982; Howard *et al.* 1982a, b). Only in the Old Woman–Piute breakaway area are Tertiary volcanic rocks found in lower-plate position.

Unidirectional slip of imbricate allochthons

Upper-plate transport sense on each fault, where known, was to the NE (Davis *et al.* 1980; John & Howard 1982; Howard *et al.* 1982a; John this volume). Stratal tilts (Fig. 3), slickensides, offset plutonic contacts, and a coarse sedimentary breccia that is offset from unique source rocks all confirm this transport. The transport direction holds even for the structurally deepest faults and allochthons.

Detachment faults define a series of stacked allochthons in the central part of the extensional corridor. Each of the metamorphic core complexes exposes at least two stacked low-angle faults (Shackelford 1976; Frost 1981; Adams *et al.* 1982; Frost & Martin 1982a; John 1982; Mathis 1982; Spencer & Turner 1982; Wilkens & Heidrick 1982; Spencer 1985).

In the Chemehuevi Mountains (John 1982, this volume), the deepest exposed detachment fault, the Mohave Wash fault, offset plutonic contacts in its allochthon 1–2 km NE (Fig. 5a & b). The allochthon is 0 to 800 m thick and it is roofed by the younger Chemehuevi detachment fault, with probably tens of kilometres displacement. The structurally higher and older low-angle Devils Elbow fault also has large separation; it is truncated to the E by the lower Chemehuevi fault. These three faults project down-dip to the E under a large allochthon or allochthons in the Mohave Mountains (Fig. 5a & b) at least 1 km thick, and 15 by 25 km wide in map view. This large allochthon in turn is overlain by higher, smaller allochthons above the low-angle Crossman Peak fault (Howard *et al.* 1982a). The allochthons above the Crossman Peak fault each show top-to-the-NE separation.

The allochthons in the extensional corridor are shingled, many are tilted, and some of them are upended so that SW-facing Miocene strata that cap crystalline basement rocks are steeply dipping or even overturned. The tilted blocks, now slices of upended crust, must thin and terminate down-section between faults, in the NE transport direction. The allochthons are viewed as imbricated in a manner analogous to major thrust fault systems. Commonly imbricate thrust allochthons thicken away from the transport direction (Boyer & Elliott 1982), whereas imbricate extensional allochthons are inferred to thin in the transport direction (Fig. 5b, bottom).

The palaeodepth of the easternmost exposures of the sole faults in the Chemehuevi and Whipple Mountains at the time of fault initiation is inferred to have been at least 10–15 km in places. This inference derives from the structural interpretation that an intact allochthon in the Mohave Mountains above these faults (IV in Fig. 5b) exposes 10–15 km of crustal section that was detached, upended and moved off the core complexes during faulting (Howard *et al.* 1982a). This tilted section consists mostly of Proterozoic gneiss, cut by unbroken early Miocene dykes (now gentle dipping), and capped by lower Miocene volcanic strata (now sub-vertical) (see Fig. 4). Its palaeothickness is indicated by the stratal and dyke orientations and by its structural integrity for 15 km across-strike (Howard *et al.* 1982a). Proterozoic gneiss is granulite-textured only in the structurally deeper part, consistent with inferred crustal position. Likewise, medium-grained Tertiary dyke rocks are found only in the deeper part, whereas all Tertiary dykes in the shallower part are fine-grained. The faults and lower plate that underlie this block, in the area from which it slid and rotated, must have initiated at depths as great or greater than the palaeothickness of the block. Based on a 10- to 15-km palaeodepth of the sole faults in the core complexes, the stacked low-angle faults formed at various levels throughout the upper crust.

The shingled allochthons, representing many kilometres of original crustal section, now total a structural thickness less than 2 km thick over the core complexes. In places the allochthons were completely removed before post-extensional fanglomerates and basalts lapped across denuded mid-crustal rocks 10–15 Ma (e.g. Dickey *et al.* 1980; Davis *et al.* 1980). It is thought that erosion contributed little to this denudation, based on field relations and on the short time interval between tectonism and overlap (Davis *et al.* 1980). The denudation is considerably greater than the average thickness of erosional debris represented by syntectonic clastic deposits and can be attributed primarily to tectonic thinning. We conclude therefore that tectonic thinning and extension of the upper crust above the sole faults locally amounted to several hundred percent or more in order to account for the thinning. Extension of this order is also suggested by the steep to overturned stratal tilts within allochthons (Fig. 3) (cf. Wernicke & Burchfiel 1982; Gans & Miller 1983). Across the width of the extensional corridor the extension amounted to at least 50 km, or about 100 percent average extension. This estimate is based on 30–40 km separation between footwalls and hanging walls, suggested to match; (i) belts of metamorphosed Palaeozoic strata from the Riverside to the Buckskin Mountains (W. J. Carr pers. comm. 1977); (ii) Proterozoic granite and diabase from the western to the eastern Whipple Mountains (Davis *et al.* 1982); and (iii) a dyke swarm from the Whipple to the Mohave Mountains (G. A. Davis pers. comm. 1981; Howard *et al.* 1982a). These ranges are in the central part of the corridor; if displacement increases cumulatively northeastward as expected, a separation of at least 50 km is predicted at the NE margin of the corridor. This analysis concurs with a 50-km separation farther to the SE, in the Harcuvar Mountains area (Fig. 2), suggested by Reynolds & Spencer (1985).

Initial dip of faults

The detachment faults are now domed around the metamorphic core complexes, but were originally probably more planar and dipped gently northeastward in the direction of transport. Evidence outlined below suggests that the faults cut consistently down crustal section to the NE.

In western exposures the lower plates expose initially shallower crustal rocks than in eastern exposures. The Crossman Peak fault in the Mohave Mountains cuts across the thick, upended crustal section in the footwall (IV in Fig. 5b), from vertical Tertiary strata in the SW to basement rocks that were initially 10–15 km deeper, measured perpendicular to the Proterozoic–Tertiary unconformity, in the NE (Howard *et al.* 1982a). In lower plates in the Chemehuevi, Sacramento, and Whipple Mountains core complexes, deeper level rocks lie to the E of initially shallower rocks. Before extension, the middle Proterozoic granites and diabases that occur only in westernmost exposures of the footwall of the Whipple Mountains detachment fault, typically lay only within the top 5 km of the crust, as measured orthogonally below lower Miocene strata in upper-plate tilt blocks in several ranges

(Fig. 4). Deeper level rocks including Cretaceous plutonic rocks and mylonitic gneisses lie in central and eastern exposures of core-complex footwalls (Davis *et al.* 1980, 1982; John 1982). Mesozoic mylonitic gneisses in the Chemehuevi, Whipple, Sacramento, and Rawhide Mountains core complexes dip gently westward under higher level footwall rocks (Davis *et al.* 1980; McClelland 1982; John, this volume); a geometry consistent with deeper structural levels to the E. A zoned Cretaceous pluton below the Chemehuevi detachment fault contains quartz veins and sparsely mineralized joints suggestive of moderate to high plutonic levels in the western exposures of the Chemehuevi Mountains. In the eastern exposures the pluton floor grades structurally downward *lit-par-lit* with older gneiss below, suggesting greater palaeodepth to the E.

K–Ar biotite dates of pre-Tertiary rocks are Miocene in the central and eastern parts of the lower plates in the Whipple and Chemehuevi Mountains, but are Mesozoic in western parts of the lower plates in these ranges (Davis *et al.* 1982; John 1982; Martin *et al.* 1981; M. A. Pernokas, pers. comm. 1982; D. L. Martin, pers. comm. 1981). This eastward decrease of K–Ar dates with greater inferred palaeodepth is consistent with greater Miocene extensional unroofing and thermal quenching of deeper, hotter rocks to the E. Other factors that probably affect K–Ar dates in the area include strain or heating near the major faults (Martin *et al.* 1981), and extension-related intrusions. These factors do not explain eastward younging. Dyke swarms that may be extension-related are concentrated in the western parts of the Chemehuevi and Whipple Mountains lower plates (Carr *et al.* 1980; Davis *et al.* 1980, 1982; John 1982), and therefore do not explain the young K–Ar dates from the E.

Fault rocks also suggest eastward-increased palaeodepth. Eastern exposures of the Chemehuevi detachment fault include deep-formed cataclasites (John, this volume), whereas western exposures show breccias and minor cataclasites inferred to have formed at lesser depth. Gouge overprints both, and can be ascribed to faulting at shallow levels (Sibson 1977) as tectonic unloading progressed and the overburden thinned. Fault zones tend to widen with depth according to Sibson (1977), a relation that may be reflected in eastward-increased thickness of chlorite breccia as mapped below detachment faults in both the Whipple and Sacramento Mountains by Davis *et al.* (1982) and McClelland (1982).

We conclude that the faults initially cut down crustal section in the NE direction of transport. The present domal geometry in the core complexes resulted, in part, from upwarping (Howard *et al.* 1982b; Spencer 1982, 1984). Because the faults nowhere expose granulite facies or other lower-crustal rocks of Tertiary age, despite tens of kilometres of continuous exposure down-dip, the basal faults in the core complexes initially must have dipped no more than a few degrees. Palaeodepth comparisons of footwall plutonic rocks from up-dip and down-dip exposures suggest that the Chemehuevi and Mohave Wash faults dipped initially between about 5° and 15° (John, this volume).

Both steep and gentle initial dips can be inferred for upper-plate faults above the major detachment faults in the core complexes. An originally sub-horizontal orientation can be inferred for a shallow upper-plate detachment fault within the Tertiary stratigraphic section in the Sacramento Mountains, for it follows footwall bedding throughout many kilometres of exposure (McClelland 1982; Spencer & Turner 1982, 1983). Original orientations are likewise inferred for a pair of sub-horizontal faults in the Turtle Mountains, where Proterozoic diabase dykes are little rotated from their regionally consistent pre-Tertiary orientation. Many upper-plate faults initiated at steep dips, based on high angles between faults and bedding. A 90° average angle between upper-plate faults and beds, suggestive of initially vertical faults, was estimated for the Rawhide Mountains (Shackleford 1976) and Turtle Mountains (Howard *et al.* 1982b). Using data shown in Fig. 3, we now estimate that fault-bedding angles average about 60° in the Turtle Mountains and about 90° throughout the core complexes and the Mohave Mountains area. These values suggest that the initial dip of many of the faults, where they came to the surface, was in this range. Such estimates must be used with caution, because dip patterns (Fig. 3) are complicated by the effects of overturned beds, fault drag, antithetic faults, multi-stage faulting and rotation (cf. Gans & Miller 1983), and deposition during growth faulting (Frost 1981). The primary dip of the major Crossman Peak fault in the Mohave Mountains could have been any angle from horizontal to vertical, depending on its age relative to tilting of its footwall block. If bedding in the footwall, which is at 90° to the fault, was only marginally tilted when the fault formed, the fault originally could have been steep and only later rotated to the sub-horizontal, in the same way as faults at Yerington, Nevada and in the Egan Range, Nevada, have (Proffett 1977; Gans & Miller 1983).

Most of the faults in the extensional corridor cut indiscriminately across crystalline and stratified rocks. These faults were not guided by stratigraphic layering or older faults which elsewhere have guided some low-angle normal faults (e.g. Royse *et al.* 1975).

The faults in the core complexes and the Mohave Mountains project eastward under the relatively unbroken Hualapai Mountains along the E side of the corridor (Fig. 2). Lucchitta & Suneson (1981) reported that the major detachment fault in the Rawhide Mountains dips at a gentle inclination to the NE under rocks that are continuous with undeformed rocks of the Colorado Plateau. The fault there juxtaposes upper-crustal rocks—Tertiary strata and their basement of coarse-grained Proterozoic granite —upon mid-crustal mylonitic gneiss (Shackelford 1976; Suneson 1980). This juxtaposition suggests that substantial crustal section was cut out where the exposed fault system roots.

Conclusions

The fault system in the Colorado River extensional corridor accommodated at least 50 km of shear down to the E, along which the crust extended, to palaeodepths of at least 10 to 15 km. We find little evidence in ranges we have studied of ductile strain or magmatic inflation sufficient in magnitude to accommodate more than a small fraction of the extension, even at the mid-crustal levels now exposed. We are led, therefore, to favour a model in which the crust in California moved southwestward out from under the crust in Arizona on this fault system (Shackelford 1981; Reynolds & Spencer 1985; Wernicke 1985), as indicated in Figs 5(b) (bottom) and 1(d). An alternative model where the crust extends by the formation of giant lenses or boudins (Davis 1980; Hamilton 1982; Adams *et al.* 1982) seems applicable to this extensional corridor only if the lenses are part of a unidirectional simple-shear system. No known complementary slip system at any exposed level is opposite in sense and could allow a symmetrical lense or boudin mechanism such as depicted in Fig. 1(c). Other tilt domains in regions to the S and W of this extensional corridor may reflect intersecting shear zones that alternate in shear sense. Most importantly, however, there is no evidence known in the relatively unbroken terrane to the NE of the extensional corridor of major down-to-the-W extensional faults that could balance the shear and provide symmetry.

The rooted fault model of Wernicke (1981, 1985; see also Coward 1984), appears applicable in explaining the unidirectional slip in this area. In terms of this model, the crust in California and W-central Arizona moved out southwestward from under the Colorado Plateau (Fig. 1d). This model can be tested by geophysical experiments now in progress or planned by three groups: CALCRUST (a consortium of California university scientists); COCORP (the Consortium for Continental Reflection Profiling), and PACE (Pacific to Arizona Crustal Experiment of the USGS). Together they are studying a crustal transect across the southwestern United States that crosses the Colorado River extensional corridor.

Crustal thinning normally results in rise of the Moho and net subsidence of the ground surface (Le Pichon & Sibuet 1982). In the Colorado River region, middle-crustal rocks in the core complexes rose 10–15 km, and now stand higher than their surroundings. Unloading, leading to the isostatic rise of the denuded core complexes, undoubtedly accounts for part of the uplift along the relatively narrow belt of core complexes. Simple unloading seems unlikely to account for all of the uplift, however, for there is neither evidence nor likelihood that the base of the crust is similarly domed along this narrow belt. Even if the doming were related to flexing above unseen or unsuspected deeper extensional faults (e.g. Bartley & Wernicke 1984; Wernicke *et al.* 1985b), the uplift of middle-crustal rocks to the surface would still have required major updoming deeper in the crust. Thermal history studies of the Old Woman–Piute range, in the headwall area, show that Tertiary uplift and denudation there were relatively minor (Knoll *et al.* 1985), in contrast to the complete removal of the Tertiary upper crust in the central belt of the metamorphic core complexes. If there is no corresponding dome on the Moho under the core complexes, then evidence should be sought to establish whether the lower crust was ductilely redistributed or else inflated by magmatic additions at depth under the core complexes.

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