Geometry and evolution of a mid-crustal extensional fault system: Chemehuevi Mountains, southeastern California

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SUMMARY: The extensional fault system exposed in the Chemehuevi Mountains area of the southern Cordillera provides data on the mode of mid-crustal accommodation to continental extension. A stacked sequence of three mid-Tertiary low-angle normal faults cut gently down-section through deformed Proterozoic and Mesozoic crystalline basement below Cenozoic strata. Hanging wall blocks are consistently displaced relatively NE across these three detachment faults, recording unidirectional extension of quartzofeldspathic crust at palaeodepths of 6–10 km. The two structurally deepest faults in the sequence are exposed over 22 km in a down-dip direction, across a total area in excess of 350 km^2, and were initiated with a regional dip of less than 15° NE. Both of the structurally deepest faults are corrugated parallel to the direction of transport; wavelengths of the corrugations range between 200 m and 10 km, and amplitudes range from 30 to 400 m. These undulations are broad mullion structures that developed coeval with fault slip. Amplitude and wavelength vary with footwall rock type and pre-existing structural grain. Slip on the faults at the present level of exposure was accomplished by brittle deformation, with the generation of gouge, breccias, rocks of the cataclasite series, and rare pseudotachylites. Major mylonite zones in the Chemehuevi Mountains are older and unrelated to the extensional faulting. These data support the conclusion that mid-crustal extension in the Chemehuevi Mountains area was accommodated by an asymmetrical normal-slip shear system. Extension occurred along seismically active, gently NE-dipping, undulating surfaces. During their evolution they rose from middle- to upper-crustal depths.

Shallow-crustal structure associated with Cenozoic continental extension is relatively well documented from geological studies in the northern Basin and Range (Stewart 1980; Proffett 1977; Proffett & Dillas 1984). Knowledge of deeper-crustal structure, however, is based largely on geophysical studies and limited well data (Anderson *et al.* 1983; Smith & Bruhn 1984; Allmendinger *et al.* 1983). As most of these data represent an indirect observation of continental extension, the mode of mid-crustal accommodation to stretching remains poorly understood. Published studies on the geometry and kinematics of extensional regimes often present models that are confined to the geometry of deformation within the upper few kilometres of the Earth's surface and lose validity with greater structural depth, or are based on inadequate knowledge of the timing of structural events. This paper reports on a mid-crustal extensional fault system exposed in the Chemehuevi Mountains area of the southern Cordillera. Extension was accomplished here along a stacked sequence of very low-angle normal or detachment faults with unidirectional slip. Above the regionally developed Chemehuevi detachment fault, the hanging wall block is distended by innumerable high-angle faults. Structurally below the Chemehuevi detachment fault lies the smaller-displacment Mohave Wash fault. Little deformation occurred in the footwall to this fault system. Both the Mohave Wash and Chemehuevi faults are broadly corrugated parallel to the direction of transport, and were originally formed with regional dips of less than 15° NE. Slip on the faults at palaeodepths of 6–10 km, the present level of exposure, was accomplished by brittle deformation. This paper seeks to document the geometry and evolution of a mid-crustal continental extensional fault system in an exceptionally well-exposed area, in order to constrain better models of crustal extension.

Regional setting

Major zones of thrust faulting, folding, and metamorphism have been documented through the eastern Mojave and Sonoran Deserts of California and Arizona (Fig. 1). Thrust faults and folds of late-Mesozoic age, marked by deformed Palaeozoic and Mesozoic strata and crystalline basement (Howard *et al.* 1980; Miller *et al.* 1982; Hamilton 1982; Frost & Martin 1982a), can be traced into the region from the Sevier orogenic belt of Utah and Nevada (Armstrong 1968; Burchfiel & Davis 1981). Thick zones of mylonitic gneiss that outcrop in eastern California and western Arizona are believed to be of similar age to the Mesozoic thrusting (John 1982, 1986; Howard *et al.* 1982c; Shackelford 1980; Davis *et al.* 1982). In

From Coward, M.P., Dewey, J.F. & Hancock, P.L. (eds), 1987, *Continental Extensional Tectonics*, Geological Society Special Publication No. 28, pp. 313–335.

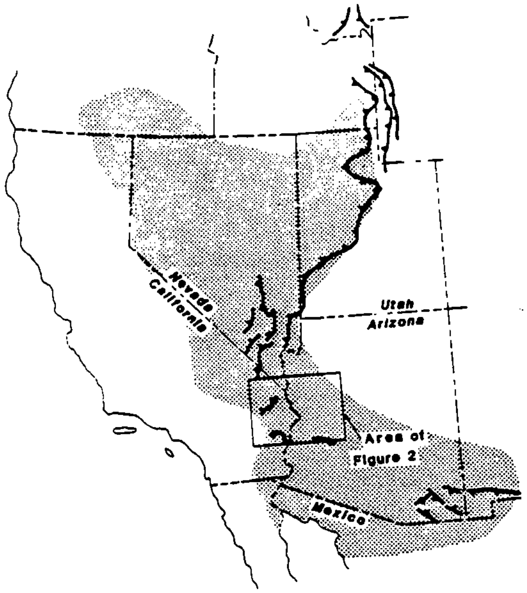


FIG. 1. Tertiary extension (shaded) overprints an area previously affected by Mesozoic compression in the North American Cordillera. The Colorado River extensional corridor lies between the central Mojave Desert in California, and the unbroken Colorado Plateau in Arizona.

the southern Cordillera, evidence of the thrust belt includes unroofed basement-involved ductile nappes, thrust faults and folds that are commonly associated with Cretaceous plutonic rocks (Davis *et al.* 1980; Howard *et al.* 1980; Coney & Harms 1984). Mid-Tertiary extension lay astride this belt and distended an already deformed or heterogeneous crust.

The Chemehuevi Mountains area lies in the central part of a 100-km wide zone of extension, termed the Colorado River extensional corridor, which is centred along the Colorado River trough (Fig. 2). Major mid-Tertiary extension involving the upper and middle crust was accomplished along brittle, E-dipping, low-angle normal or detachment faults (Howard & John, this volume). As a consequence of this deformation, crystalline rocks, including mylonites that resided at palaeodepths of at least 6–10 km in the crust, are juxtaposed against volcanic rocks erupted at the surface 18 Ma.

The western margin or breakaway zone of the Colorado River extensional corridor lies between the Turtle and Old Woman Mountains in California (John & Howard 1982) (Fig. 2). The breakaway exposes Tertiary faults that dip E into the corridor, and cut gently W-dipping Tertiary strata unconformably overlying Proterozoic granites and gneisses (Howard *et al.* 1982a). Offset structural and stratigraphic markers in the pre-Tertiary crystalline basement of the hanging wall and footwall indicate that down-to-the-E separation on the fault(s) was no more than 2–3 km either vertically or horizontally (Howard & John, this volume).

Low-angle normal or detachment faults are exposed around the domal metamorphic core complexes (Coney 1980) in the central part of the extensional corridor, including the Whipple and Rawhide Mountains (Davis *et al.* 1980; Frost & Martin 1982b), Chemehuevi Mountains (John 1982), Sacramento Mountains (McClelland 1982; Spencer 1985), and the Dead Mountains (Spencer 1985). These exposures apparently represent the sole fault(s) to the extensional fault system. Cumulative slip on this fault (or faults) increases northeastward across the extensional corridor, and totals an estimated 50 km, or 100% average extension regionally (Howard & John, this volume). The northeastward increase in cumulative slip results from displacement on numerous hanging wall faults that fed displacement into the detachment(s). Transport of the upper plate of each fault, where known, was to the NE (Davis *et al.* 1980; John & Howard 1982; Howard *et al.* 1982a; Spencer 1985). This transport direction holds even for the structurally deepest exposed faults in the system. Regional field relations indicate that the faults cut consistently down-section northeastwards, in the direction of tectonic transport (Howard & John, this volume). This relation implies that the fault system had a shallow NE dip away from the breakaway region.

The eastern limit of marked extension lies to the W of the Hualapai Mountains in Arizona, approximately 100 km NE of the breakaway. The Chemehuevi Mountains are in the central part of the corridor along the belt of metamorphic core complexes. The range is flanked by the regionally developed Chemehuevi detachment fault which projects at depth beneath the Hualapai Mountains and toward the Colorado Plateaus.

The Chemehuevi Mountains and nearby ranges are framed by the early-Miocene and Oligocene(?) low-angle extensional faults. In contrast, in the northern Basin and Range Province most ranges are fronted by younger high-angle faults (Stewart 1971; Eaton 1982).

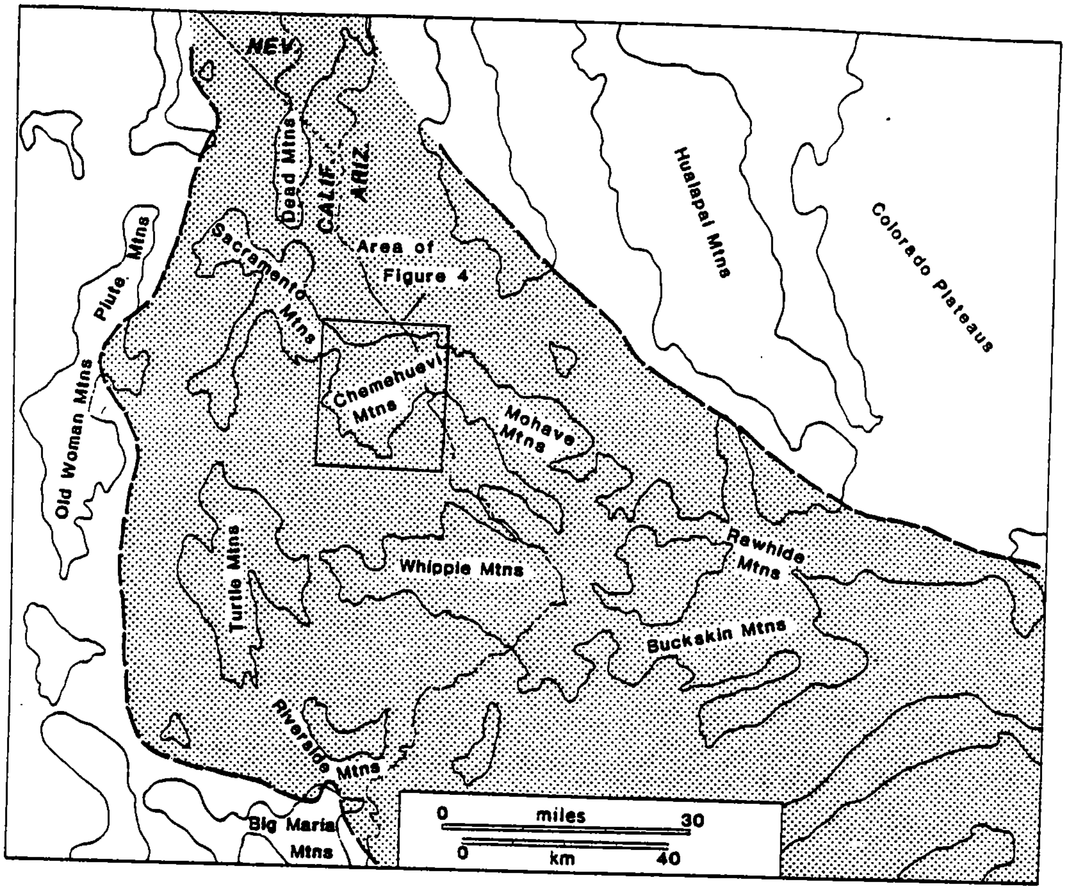


FIG. 2. Map of the Colorado River extensional corridor (shaded between the heavy dashed lines) in California and Arizona, as defined in Howard & John (this volume). The Chemehuevi Mountains (outlined in box) lie in the central belt of metamorphic core complexes that include from N to S, the Dead, Sacramento, Chemehuevi and Whipple Mountains. The eastern limit of extension marked by highly faulted and tilted blocks lies W of the Hualapai Mountains. Detachment faults exposed around the core complexes dip under the Hualapai Mountains and Colorado Plateau.

Geology of the Chemehuevi Mountains

Three structural plates or allochthons, separated by three Tertiary low-angle normal or detachment faults, have been recognized in the Chemehuevi Mountains. The footwall or 'autochthon, A', of the Chemehuevi Mountains includes the structurally deepest exposed rocks in the range, below the deepest exposed detachment, the Mohave Wash fault (Fig. 3). Successively higher plates or allochthons are termed B, C and D (Figs 3 & 4a, b). Because the low-angle normal or detachment faults juxtapose mainly crystalline rocks of different structural levels from the upper and middle crust, usually with a gross lithological 'mis-match', it is necessary to separate rocks by their relative structural position. Rocks in the Chemehuevi Mountains are divided into two assemblages defined by their relative structural positions and lithology (Fig. 3). The structurally deeper rock assemblage (I) consists of a large, crudely zoned plutonic suite of probable Cretaceous age, that intrudes foliated mylonitic gneiss at least 1.5 km thick, and makes up most of the footwall, A, and lowest allochthon, B. These two plates are separated by the Mohave Wash fault (Figs 3 & 4). The higher rock assemblage (II) lies above the Chemehuevi detachment fault in allochthon C, and above the Devils Elbow fault in allochthon D. Assemblage (II) consists of Proterozoic igneous and metamorphic rocks, and an overlying Oligocene(?) and Miocene volcanic and sedimentary sequence. Locally, intrusive rocks of assemblage (I) are found above the Chemehuevi detachment fault, and some

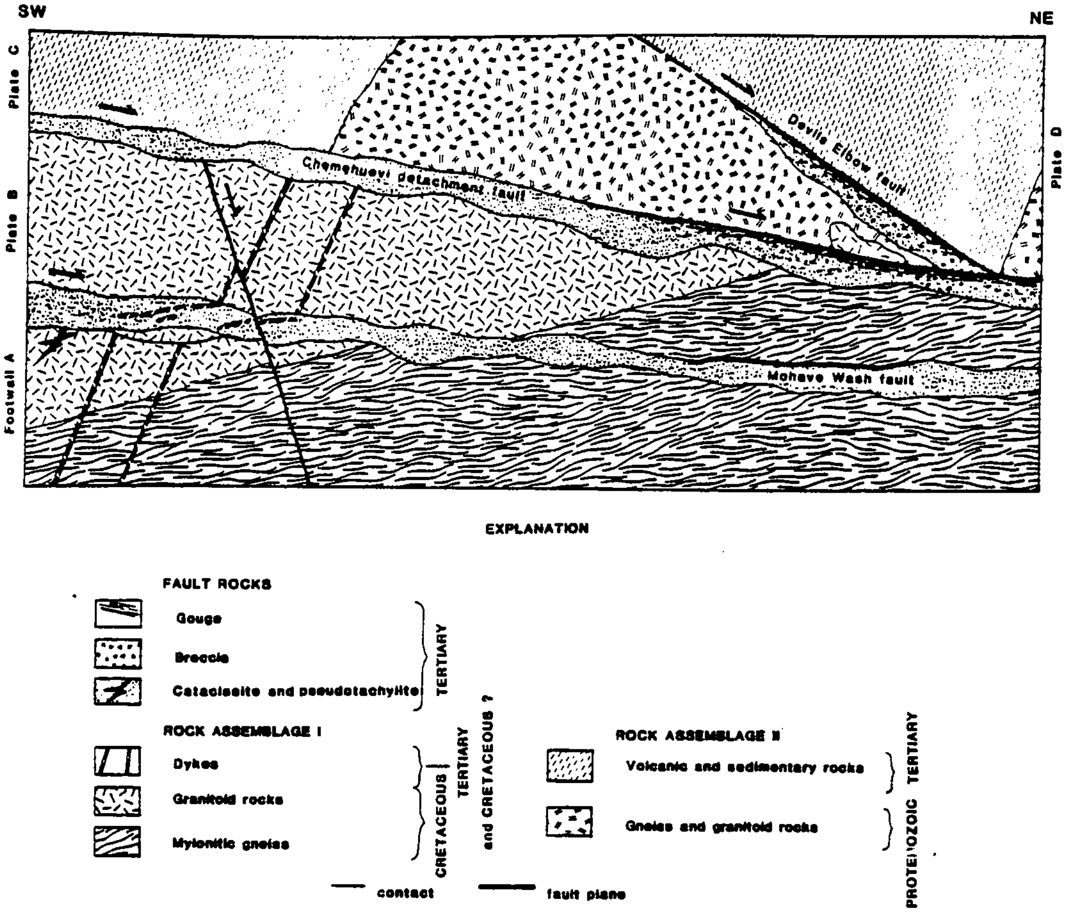


FIG. 3. Schematic composite section through the extensional fault system in the Chemehuevi Mountains. The range is cut by three low-angle normal or detachment faults—from structurally deepest to highest; the Mohave Wash, Chemehuevi and Devils Elbow faults. Each fault shows NE separation of its hanging wall. Variation in fault rock type and progressive reworking, from SW to NE, is shown diagramatically.

assemblage (II) rocks occur below the Chemehuevi fault (Fig. 4a). Each fault has normal-slip displacement shallow rocks against deeper-crustal rocks. This juxtaposition forms a distinctive tectonic layering (Fig. 3). Howard *et al.* (1982b) constructed a generalized crustal column for the extensional corridor. The reconstructed column indicates a gross 5–10 km scale layering of the crystalline upper and middle crust throughout the Colorado River area.

In this paper I use the terms low-angle normal and detachment fault interchangeably. The term low-angle normal fault implies knowledge of fault orientation and shear sense during slip, and conveys significant information about the geometry of the faults. Recognizing that the term detachment fault has been used without consistent meaning (cf. Pierce 1973; Carr & Dickey 1976; Reynolds & Spencer 1985), I will use it here for major unrotated, low-angle normal faults, to conform with previous usage in the region (Davis *et al.* 1980; Frost & Martin 1982a).

The time of initiation of extensional faulting is not well constrained, but is probably late Oligocene or early Miocene. In the nearby Whipple and Buckskin Mountains (Fig. 2), syntectonic sediments and interstratified volcanic rocks deposited in basins that developed during extension have been dated as early Miocene and late Oligocene (Davis *et al.* 1980, 1982). Cenozoic deformation in the Chemehuevi Mountains ended by the late Miocene; basalt plugs and local flows, dated at 11.6±1.2 Ma (K–Ar, whole rock—J. Nakata pers. comm., 1984), intrude or overlie and fuse cataclasites in the Chemehuevi detachment fault zone in the central part of the range. This relation indicates that movement had ceased on the Chemehuevi detachment fault by the late Miocene. Undeformed Pliocene sedimentary rocks and Quaternary deposits overlap the exposed fault system.

Rock assemblage (I)

Crystalline rocks of the footwall, A, and the lowest allochthon, B, outcrop in the central part of the range (Fig. 4a), and consist mostly of Proterozoic layered gneisses and migmatites, Cretaceous granitic rocks, and a dense swarm of younger Cretaceous(?) and Tertiary dykes.

The gneissic rocks of assemblage (I) consist of strongly foliated, variably mylonitized, layered orthogneisses and paragneisses of Proterozoic age. These upper greenschist- to lower amphibolite-facies rocks form a coherent gently (15°) SW-dipping sequence in the eastern part of the range, a steeply dipping (60–90°), NE-striking zone in the northern part of the range, and a long screen within the Cretaceous plutonic suite. The mylonitic gneisses outcrop beneath the detachment faults only in the northern and eastern parts of the range (Fig. 4a). Both the gently and steeply dipping mylonitic gneisses are *L–S* tectonites with a sub-horizontal NE–SW-trending mineral-elongation lineation which parallels the linear fabric component of other mylonites in the region (Coney 1980; Davis *et al.* 1980; Rehrig & Reynolds 1980).

Intruding the layered gneiss and migmatite complex and underlying most of the southern and central Chemehuevi Mountains is the plutonic suite of the Chemehuevi Mountains, of probable Late Cretaceous age (John 1982). The suite forms a concordant, irregularly zoned plutonic body, and comprises five phases, spanning a wide compositional range from hornblende- and sphene-rich quartz diorite and granodiorite, through biotite granodiorite, to leucocratic garnet-bearing, muscovite–biotite monzogranite. These intrusive phases are crudely concentric, the younger and more highly differentiated rocks occur towards the centre.

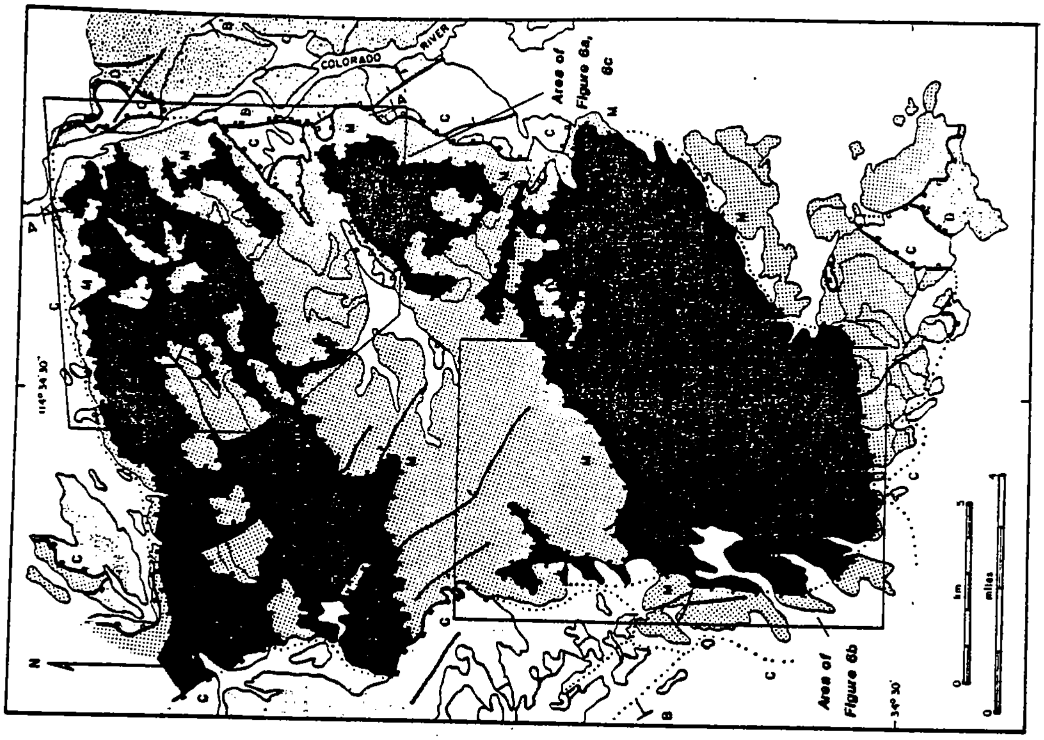
Foliated quartz diorite and granodiorite are the oldest phases of the suite. Locally these units are foliated and lineated with the same mylonitic fabric as the layered gneisses. A porphyritic granodiorite to monzogranite mass intrudes the older granodiorite. It is the most extensive phase of the suite. The eastern contact of this phase, against the base of mylonitic gneisses, is defined by fine- to medium-grained granitic sills in a *lit-par-lit* arrangement. The base dips gently southwestward under the pluton. The porphyritic granodiorite unit contains, and intrudes small enclaves, as well as a very large screen, of mylonitized layered gneiss, and is, therefore, post-mylonitic. Two-mica granodiorite to monzogranite form the youngest member of the suite. The distribution of distinctive compositional types and the attitudes of plutonic contacts are the main means for measuring the separation on the low-angle normal faults.

The porphyritic granodiorite yielded a 64 Ma K–Ar cooling age on biotite (John 1982). This date indicates that the mylonitic gneisses had acquired their fabric by the end of the Cretaceous. The mylonitic fabric is apparently unrelated to mid-Tertiary extensional faulting that coincidentally parallels the lineation direction. U–Pb dating of the plutonic suite is in progress to further constrain the timing. The consistent NE–SW lineation trend observed in the Chemehuevi Mountains and throughout the region implies, by analogy with other orogenic belts, that movement along mylonitic shear zones was either NE or southwestward (Escher & Watterson 1974).

The youngest intrusions recognized in the footwall, A, and the lowest allochthon, B, form dense swarms of mafic and silicic dykes in the western and central part of the range. The dykes are centred in the Cretaceous plutonic suite, and locally account for as much as 10% of the rock volume. They form two roughly orthogonal sets orientated ENE, and N to WNW. Intrusive relations between some of the NE-trending dykes and phases of the plutonic suite suggest that the dykes may be synplutonic, i.e. Late Cretaceous or older. The NW-trending dykes cut them and possibly are Miocene based on a K–Ar date (Frost *et al.* 1982). In the southern Chemehuevi Mountains is a second set of NE-trending mafic dykes, presumably Miocene, which intrude the Chemehuevi detachment fault, and exhibit substantial fracturing that resulted from subsequent fault movement. These dykes indicate that some intrusion was synchronous with detachment faulting.

Rock assemblage (II)

Crystalline rocks of assemblage (II) outcrop in allochthons C and D, above the Chemehuevi detachment fault in the western Chemehuevi Mountains and above the Chemehuevi and Devils Elbow faults in the eastern part of the area (Fig. 4a). Proterozoic granites and gneisses without a mylonitic fabric, and therefore texturally unlike those in rock assemblage (I), are the major crystalline rock types in assemblage (II).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RIVER
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FIG. 4(b)

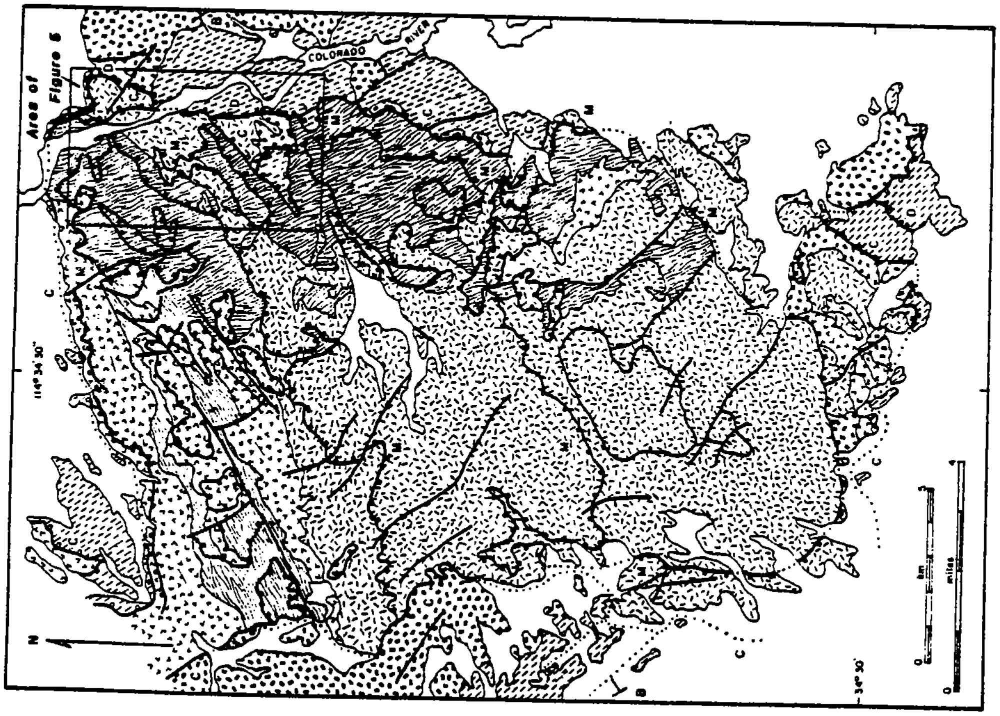
COLORADO
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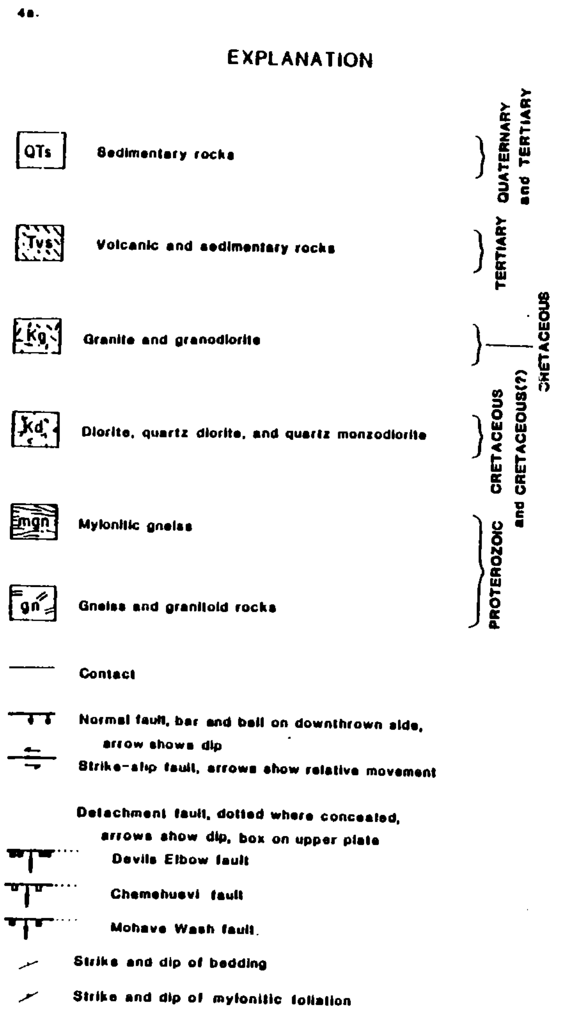
FIG. 4(a)



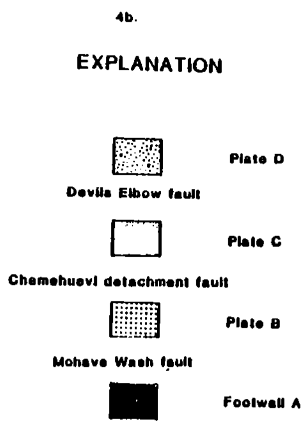


FIG. 4. (a) Generalized geological map of the Chemeheuvi Mountains area in California and Arizona. The three detachment faults are indicated by M = Mohave Wash fault; C = Chemehuevi fault; and D = Devils Elbow fault. (b) Tectonic map of the Chemehuevi Mountains portraying the Tertiary detachment faults and intervening plates. Unpatterned areas outline post-detachment deposits that are Pliocene and younger. The patterned areas outline plates discussed in the text. The footwall, A, is the structurally deepest plate exposed. Plate B lies above the Mohave Wash fault. Plate C lies above the regionally developed Chemehuevi detachment fault. The structurally highest plate, D, is above the Devils Elbow fault, in the southern and eastern part of the range. Plates C and D, both of which are broken and shingled by numerous E-dipping(?) normal faults, moved together during slip on the Chemehuevi detachment fault, after the Devils Elbow fault became inactive.

Distinctive Proterozoic ophitic diabase sheets, striking NW and dipping steeply, intrude the non-mylonitic gneisses and granites. Unlike rock assemblage (I), none of the crystalline rocks exposed in rock assemblage (II) exhibit a mylonitic fabric. Non-mylonitic gneisses assigned to assemblage (II) outcrop in plate B in the southern part of the range, and are inferred as lying above an unexposed upper-shear-zone margin or mylonite front.

Volcanic and sedimentary rocks of Tertiary age encircle the range above the Chemehuevi detachment fault and Devils Elbow fault, and lie both unconformably and in fault contact above the crystalline rocks just described. The deformed Tertiary rocks are divided into three major lithological sequences, from oldest to youngest, mafic and intermediate lavas, an ash-flow tuff considered to be the Peach Springs Tuff of Young & Brennan (1974), and a thick sequence of alluvial fan deposits and breccias with thin interbedded mafic and silicic flows and tuffs. An estimated thickness of the Tertiary section is of the order of 2–3 km. The age of the older sequence of volcanic rocks is not accurately known. Most of the faulted Tertiary rocks in the region around the Chemehuevi Mountains are between 17 and 22 Ma (Howard & John, this volume). In the Whipple Mountains, however, volcanic rocks have ages as old as 26 Ma. This age range suggests that the older sequence is of latest-Oligocene or early-Miocene age. The Peach Springs Tuff outcrops in both the eastern and western parts of the range, and has a K–Ar age of 18.1±0.6 Ma (Howard *et al.* 1982a).

Within the faulted Tertiary sedimentary sequence are large (up to 1 km in greatest dimension) lenses of monolithologic breccia. These megabreccia lenses are composed of shattered Proterozoic granites and gneisses of assemblage (II) and the Cretaceous granitic rocks and younger dykes of assemblage (I). Deposits of this type are characteristic of landslides in arid environments (Krieger 1978), and may represent seismically triggered debris derived from over-steepened or unstable fault scarps. The granitic megabreccia deposits and alluvial sediments lie within the tilted Tertiary sequence above the Chemehuevi fault in the eastern part of the range. Clast types match source regions of restricted outcrop in plates A and B less than 8 km away in the central Chemehuevi Mountains. Similarity in fracture intensity and alteration between exposed cataclasites and the granite megabreccias suggests that these syntectonic deposits may have resulted from the exhumation of the detachment faults during progressive extension. This is supported by the presence of clasts of chlorite-and epidote-altered cataclasite, elsewhere associated with the faults, in allochthonous alluvial fan deposits younger than the megabreccias.

Style and sequence of Tertiary deformation

All the rock types in assemblages (I) and (II) were mildly to intensely deformed during the mid- to late-Tertiary. The deformation produced a fault system comprised of at least three allochthons, separated by three brittle, low-angle normal faults (from structurally deepest to most shallow), the Mohave Wash, Chemehuevi Mountains and Devils Elbow detachment faults (Figs 3, 4 & 5). Criteria for the recognition of each fault, separating the allochthons, include types of rocks juxtaposed, style and intensity of the brittle deformation and related fault rocks, amount of reworking of fault rocks, and relative structural position and continuity of outcrop. Of the three faults, the Chemehuevi fault is of the greatest significance regionally and is the youngest. It is here equated with the Whipple Mountains detachment fault of Carr & Dickey (1976) and the Whipple detachment fault of Davis *et al.* (1980) exposed in the Whipple Mountains 20 km to the S, and with the Sacramento detachment fault of McClelland (1982) exposed just NW of the Chemehuevi Mountains in the Sacramento Mountains (Fig. 2).

From the evidence of offset markers, preserved striae, drag folds, minor faults within related cataclasites, and the SW dip of Tertiary strata in the Chemehuevi Mountains, it is estimated that slip on each of the low-angle normal faults resulted in northeastward (040–060°) transport of successively higher plates or allochthons. The detachment faults cut down-section in the direction of tectonic transport, and record unidirectional extension of the upper and middle crust. The upper and middle crust as a whole extended non-uniformally–rocks above the Chemehuevi detachment fault were extended along a series of steep normal faults, while the footwall apparently remained largely undeformed. Plutonic contacts in allochthon B are separated from the footwall, A, along the Mohave Wash fault by ~2 km. Separation of plate B from plate C along the Chemehuevi detachment fault is at least 8 km. Movement of the structurally highest plate, D, above plate C on the Devils Elbow fault is likewise believed to be many kilometres. Plates C and D behaved as a single plate during the most recent motion on the Chemehuevi detachment fault.

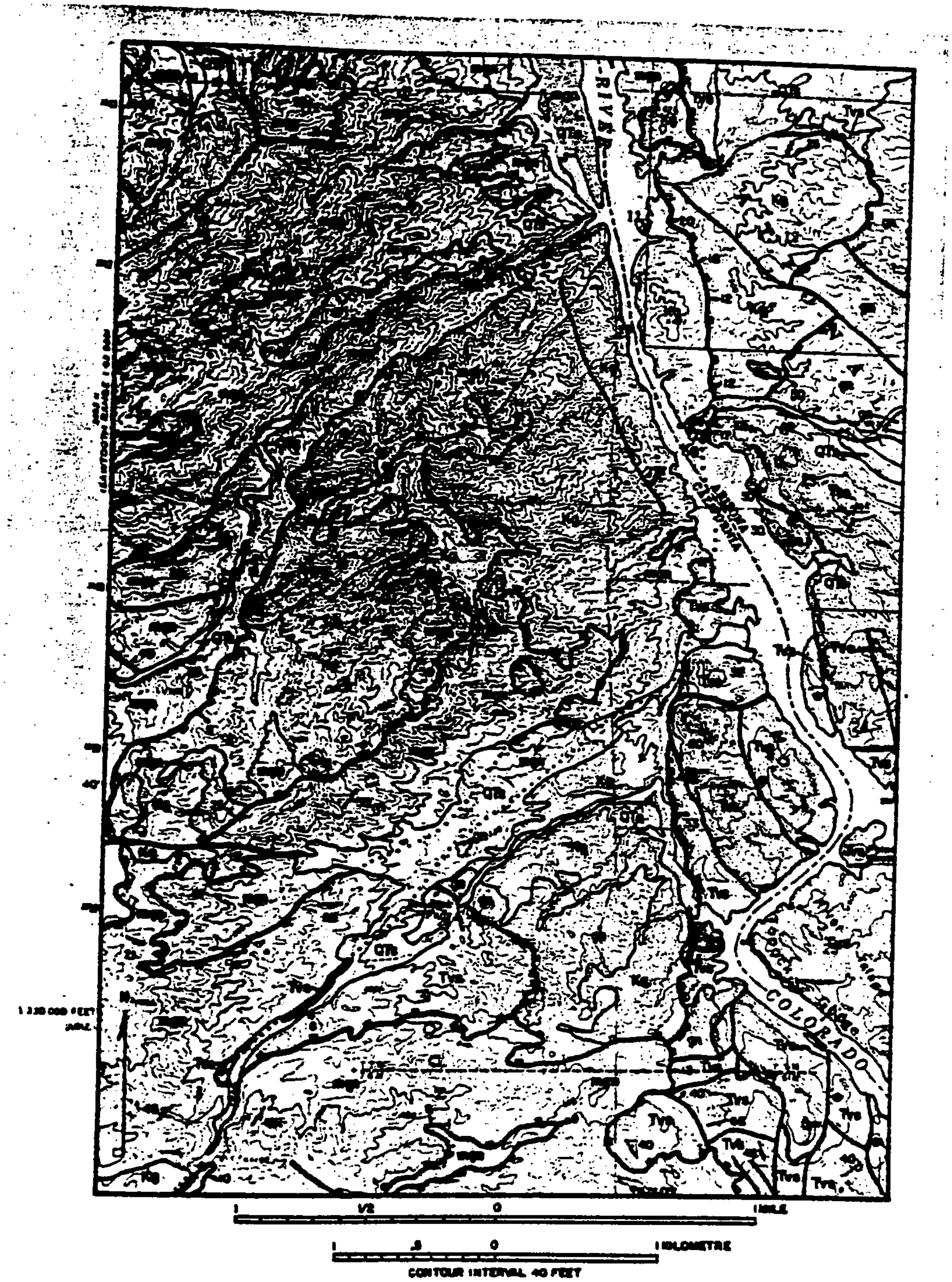


FIG. 5. Geological map of part of the eastern Chemehuevi Mountains (outlined in Fig. 4a), showing the stacked sequence of detachment faults. Symbols used are the same as those in Fig. 4.

At outcrop scale, each fault is approximately planar, but when viewed at map scale, the two structurally deepest faults are corrugated parallel to the NE transport direction. Orthogonal to these are broad NNW-trending antiformal and synformal undulations of the fault surfaces (Cameron & Frost 1981; John 1982, 1984; Spencer 1984).

Dips on each detachment fault vary from horizontal or very gently inclined along the troughs or crests of the mullion structures, to as much as 40° on the steeper flanks or strike-slip portions of the faults.

Mohave Wash fault

The lowest detachment fault, the Mohave Wash fault, occurs wholly within the crystalline rocks of assemblage (I), except in the very southernmost part of the range (Fig. 4a). The fault is exposed as a sinuous trace over more than 350 km^2 in the Chemehuevi Mountains (Fig. 4). An initial NE dip of the fault, in the transport direction, is suggested by several lines of evidence (Howard & John, this volume). An initial average dip of the Mohave Wash fault of 15°NE, which implies cutting through nearly 6 km of crustal section over 22 km, is considered to be the maximum possible, based on the lack of significant chemical, textural and mineralogical variations within the porphyritic granodiorite phase of the plutonic suite across 15 km of strike (John 1982, and unpublished work). Therefore the original dip of the faults was probably less than 15°NE, and could have been as low as 5° regionally. This corroborates data from the fault zone, which indicate relatively little changes in fault rock type, deformation mechanism and metamorphic grade in the footwall.

Correlation of a moderately dipping, roughly N-trending internal contact within the plutonic suite in the footwall, A, and in the lowest allochthon, B, and numerous truncated screens of older wall-rocks within the plutonic suite, indicate ~2 km ENE–WSW separation on the Mohave Wash fault. Sub-horizontal striae preserved along the fault trend 040–060°, and indicate the direction of most recent movement.

Deformation within autochthon A and plate B

Autochthon A and lowest allochton B, as exposed in the Chemehuevi Mountains, are largely undeformed internally. Sparse, discontinuous ductile shear zones or mylonites (up to 1 m thick) cut all rock types in assemblage (I). These are concentrated zones of high strain, locally with variably orientated foliation and mineral-elongation lineations. Stereo-plots of the foliation and lineations show no consistent orientation. Where dykes or compositional layering in the crystalline rocks are cut by these shear zones, separations up to tens of centimetres have been measured. Numerous small microfaults and vein-like intrusions are common throughout the autochthon and lowest allochthon, and are concentrated near both the Mohave Wash and Chemehuevi detachment faults.

Moderate to steeply dipping (50–80°) normal faults with strikes ranging from 110 to 170° cut autochthon A and allochthon B, some truncating and others truncated by the Mohave Wash fault (Figs 3, 4 & 5). These faults have tens to hundreds of metres of separation, and are nowhere known to cut the structurally higher Chemehuevi detachment fault. Locally preserved striae indicate nearly pure dip-slip movement. Because slip occurred on the steep normal faults both before and after movement on the Mohave Wash fault, it is reasonable to conclude that these steeper faults were active concurrent with faulting along the Chemehuevi detachment.

Several NE-trending (050–060°) strike-slip faults truncate the Mohave Wash fault, and are older than the latest movement on the Chemehuevi detachment. Dip of the faults is between 40 and 80°, but tends to mimic the foliation in the steeply dipping mylonitic gneisses in the northern Chemehuevi Mountains. Left-lateral separation on the northern strike-slip fault (Fig. 4) may be as much as several hundred metres.

One klippe of a small displacement low-angle fault, mapped as part of the footwall, A, outcrops in the southwestern part of the range (Figs 3 & 4a, b). Irregular plutonic contacts cut by the fault are not significantly offset, indicating probably less than one hundred metres separation.

Both the normal and strike-slip faults, are planar discontinuities marked by coherent breccias and cataclasites. Locally, a microbreccia layer one millimetre to several centimetres thick marks the most recent fault trace. The cataclasites are composed primarily of quartz, plagioclase and potassium-feldspar, the milled-down equivalent of the wall-rock, in a matrix of hematite (or specular hematite) ±calcite ±quartz±azurite±malachite±barite. In contrast, the low-angle fault is marked by coherent cataclasites composed of quartz, plagioclase and potassium-feldspar, with the retrograde mineral assemblage of chlorite±albite±epidote±clinozoisite±sericite and rare calcite.

Taken as a group the normal and strike-slip faults, and microfaults cutting the footwall, A, and allochthon B, can account for a few percent extension, below the regionally developed Chemehuevi detachment fault. Displacement within the thin ductile shear zones can account for even less extension. Dyke rocks, only some of which are coeval with the extension, intrude the footwall, A, and allochthon B and constitute up to 10% of the rock volume in the western half of the Chemehuevi Mountains. Dyke intrusion therefore accounts for no more than 5% extension overall in the footwall of the regionally developed Chemehuevi detachment fault. Footwall accommodation to movement on the regionally developed Chemehuevi detachment fault was therefore small.

Chemehuevi detachment fault

The Chemehuevi detachment fault lies 0–750 m above the older Mohave Wash fault, and generally separates rock assemblage (I) of the footwall, A, and plate B, from rock assemblage (II) and plate C. The fault juxtaposes Miocene ash-flow tuffs and lavas directly on the plutonic suite and underlying mylonitized gneisses. The depth at which the fault was initiated is estimated as at least 6 km, because structurally intact blocks above the Chemehuevi detachment fault in the western Chemehuevi Mountains and along the Colorado River have minimum palaeothicknesses (measured perpendicular to the Tertiary unconformity) up to 6 km (Fig. 4). The 'toes' of these blocks have either been eroded, or are covered by structurally higher blocks; the palaeothickness of the blocks provides a minimum estimate of crustal thickness above the fault prior to their detachment, rotation and northeastward translation. From regional arguments put forward by Howard & John (this volume), it can be inferred that the easternmost exposures of the Chemehuevi and Whipple detachment fault(s) were initiated at depths of 10 and 15 km. Juxtaposition of Tertiary strata down against plate B implies that the Chemehuevi detachment fault has at least 6 km and perhaps 10–15 km of crustal excision and vertical displacement. A more detailed discussion of initial dip will further constrain this estimate.

Horizontal separation of crystalline rocks on the Chemehuevi detachment fault is a minimum of 8 km NE, and displacement is probably on the order of 20–40 km. Broad areas of slickensides occur along the fault. The striae are sub-horizontal, and regionally trend 220–240° parallel to the dip direction of the overlying rotated Tertiary strata. Assuming that the Tertiary succession was horizontal prior to detachment faulting, NE upper-plate slip can be inferred from the direction of tilted strata, the orientation of striae, observed offset on minor normal faults within related cataclasites, and the geometry of drag folds in plates C and D. Intrusive rocks of the plutonic suite crop out just E of the Colorado River above the Chemehuevi fault (Figs 3 & 4). The restored position of these rocks in the footwall, A, suggests a minimum of 8 km northeastward horizontal separation of plate C along the Chemehuevi detachment fault, from what is now the N-central part of the range. This estimate is based on the location of the northeastern limit of the Cretaceous granite and granodiorite phases of the plutonic suite in the footwall, A, and plate B (Fig. 4). A reasonable estimate of slip on the Chemehuevi fault in the Chemehuevi Mountains would be on the order of 20–40 km, based on the overall increase in displacement noted regionally by Howard & John (this volume) across the extensional corridor. Estimates of 30–40 km separation have been suggested for the Whipple detachment fault by G. A. Davis (pers. comm. 1981) and Howard *et al.* (1982a). To the W, in the headwall region of the extensional corridor, displacement is significantly less (Howard & John, this volume). The youngest deformed Miocene rocks show separation on the fault of 8 km or less, based on the presence of garnet-bearing, muscovite-biotite monzogranite clasts in the syntectonic deposits, that are areally restricted within the footwall (A).

Both the Chemehuevi and Mohave Wash faults are corrugated parallel to the NE transport direction, but are not everywhere parallel to each other. Locally plate B is cut out, and plate C lies in direct tectonic contact with plate A along the Chemehuevi fault. This relationship suggests that movement had ceased on the Mohave Wash fault, while the Chemehuevi detachment fault was still active. The Mohave fault may have been an early splay that became inactive, and was cut by the new Chemehuevi detachment fault which was more favourable for slip during the evolution of the fault system.

Unlike the deeper Mohave Wash fault, the Chemehuevi fault is not cut by younger high-angle normal faults. Numerous high-angle faults cut rocks above the Chemehuevi detachment fault (Figs 4a, b & 5), and account for extreme extension of the hanging wall. For simplicity only a few of the largest faults are shown in Fig. 4; I have mapped many others (John, unpublished work; Miller *et al.* 1983). None of these faults, however, can be traced across the detachment into plate B. The Chemehuevi detachment fault is preserved within a few degrees of the initial orientation, and is not a steep normal fault that has been rotated during progressive extension. As with the Mohave Wash fault, exposure of the Chemehuevi detachment fault over an area in excess of 350 km^2 and 22 km across strike, with only small changes in crustal level and nature of related fault rocks, limits the initial dip of the fault to a very low angle in this region. Deepening of the Chemehuevi fault by 2–4 km across the range (SW–NE) is inferred, compatible with an initial regional dip of 5–15° NE as described for the structurally deeper Mohave Wash fault.

Devils Elbow fault

The Devils Elbow fault, the structurally highest exposed detachment fault, can be traced along-strike for roughly 6 km along both sides of the Colorado River. This limited exposure precludes detailed analysis of the geometry. In excellent exposures along the W side of the river (Fig. 5), the fault juxtaposes Tertiary fanglomerates and crystalline-clast megabreccias in plate D, against granites of the plutonic suite in plate C. The fault is marked by a moderately E-dipping (34°) planar surface, on which striae plunge 30–060°. Based on the orientation of preserved striae, SW dip of the overlying Tertiary strata, and observed offsets on minor normal faults within the related breccias and cataclasites, the hanging wall of the Devils Elbow fault is inferred to have moved NE. It is truncated in at least two places by the structurally deeper Chemehuevi fault. Separation of plate D from plate C on the Devils Elbow fault is estimated as 3–8 km, using the base of the Tertiary section as a datum (John, unpublished work). No source of the rocks above the fault has been recognized in the footwall, A.

Cumulative separation of plate D from the footwall, A, is the combined displacement of the Mohave Wash fault (~ 2 km), the Chemehuevi detachment fault (>8 km), and earlier slip on the Devils Elbow fault (~ 4–8 km). Estimated minimum horizontal slip on the composite fault system exceeds 22 km, the present width of the Chemehuevi detachment fault exposure around the range.

Deformation within plates C and D

Deformation above the regionally developed Chemehuevi detachment fault accounts for the extreme extension of the upper crust above the largely undeformed footwall. Plates C and D were extended along innumerable steeply dipping (60–80°) normal faults with strikes ranging from 135 to 160°, and oblique-slip faults trending 045–090° (Figs 4 & 5). These faults have tens of metres to over one kilometre of separation, and are never seen to cut the Chemehuevi detachment fault.

Both the normal and oblique-slip faults, where well exposed, are irregular planar discontinuities characterized by thin zones of hematite-rich gouge and breccia, commonly with calcite vein-fill.

Structures in the hanging wall of the Chemehuevi detachment fault are best preserved in the E-central part of the range (Fig. 4). There cross-cutting relationships between faults suggest a complex history of repeated high-angle faulting (normal and oblique-slip), to produce both the steeply and gently dipping faults exposed.

Fault corrugation: mullion structures

The synchronous development of Tertiary low-angle normal faults and broad undulations in these faults is well documented along the Colorado River trough (Wilkens & Heidrick 1982; Cameron & Frost 1981; Frost *et al.* 1982; John 1984). The undulations form generally orthogonal sets that trend NE and NNW. The origin of these undulations is currently a topic of interest among numerous geologists in the region (Rehrig & Reynolds 1980; Frost 1981; Spencer 1982; John 1984; Spencer 1984).

The two structurally deepest detachments in the Chemehuevi Mountains, the Chemehuevi and Mohave Wash faults, are corrugated parallel to the NE direction of transport during fault slip. Other, broader undulations trending N-NW perpendicular to the slip direction, with wavelengths of 10–50 km, are discussed later. It is thought that the corrugations along the slip direction developed during fault movement as primary mullion structures based on the detailed analysis that follows. The amplitude and wavelength of the corrugations vary with footwall rock type and pre-existing structural grain, and also differ between the two faults.

Minimum-relief contour maps have been constructed from 1:24,000 scale mapping for both the Mohave Wash and Chemehuevi detachment faults (Fig. 6a–c) in areas where the faults are best preserved (Fig. 4). The maps (Fig. 6) were constructed in a manner similar to that used by Spencer (1985). From these maps comparisons are made regarding the influence of footwall rock type and fabric on the fault shape, relative amplitude and wavelength of corrugations associated with the two faults, and down-dip

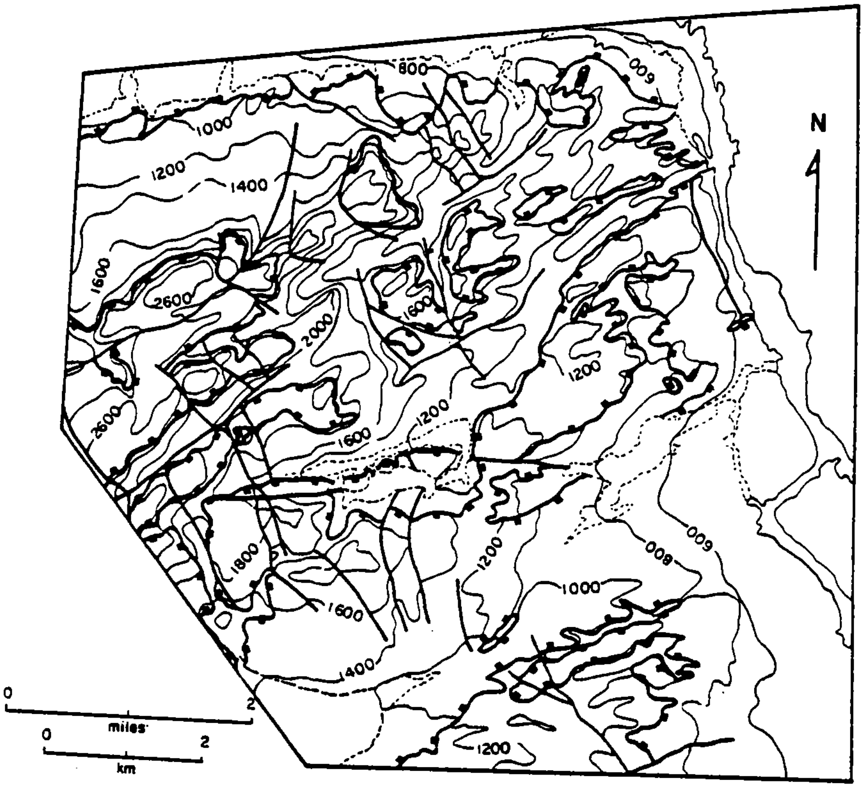

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FIG. 6(a)

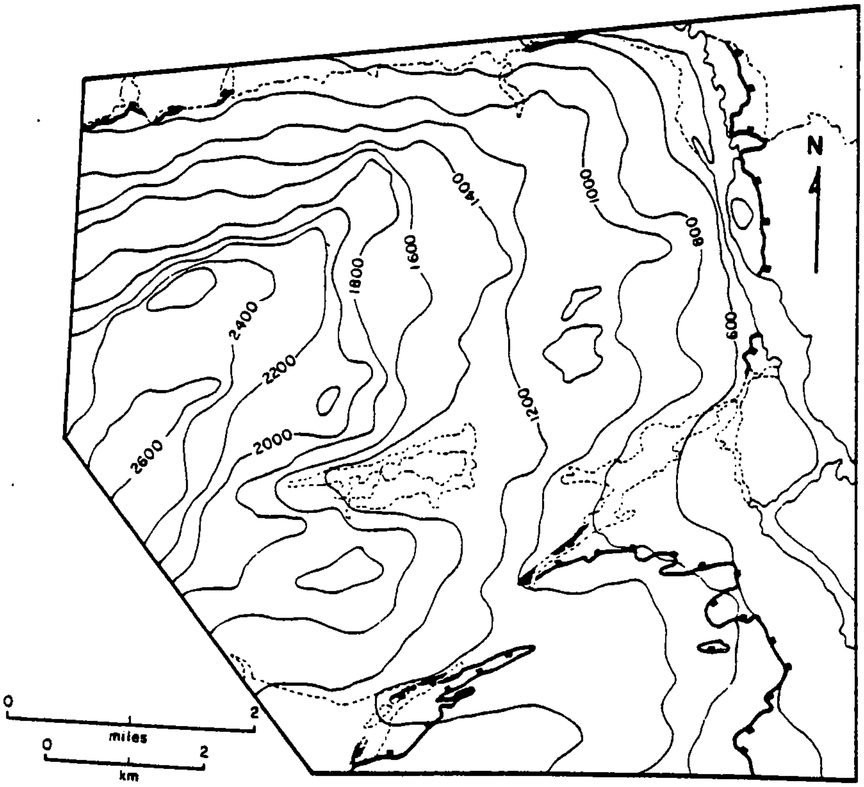
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FIG. 6(b)

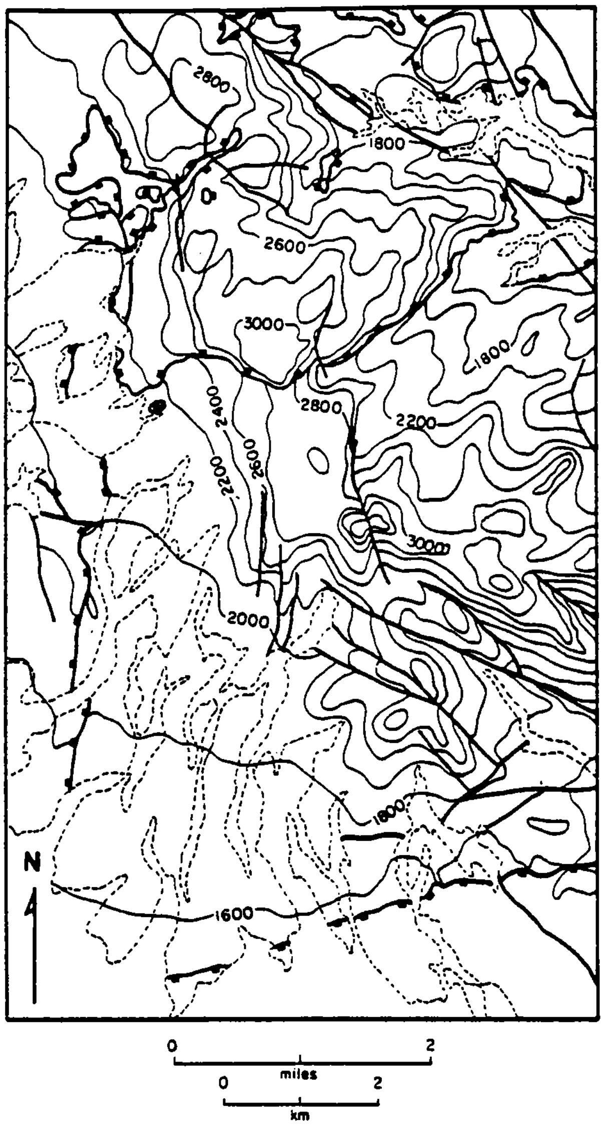

FIG. 6(c)

FIG. 6. Minimum-relief contour maps of the Mohave Wash and Chemehuevi faults in the areas outlined in Fig. 4(b). Contour interval for each map 200ft. (a) Structure contour map of the Mohave Wash fault in the northeastern part of the Chemehuevi Mountains. Footwall rocks are both sub-horizontally and sub-vertically foliated mylonitic gneiss. (b) Structure contour map of the Chemehuevi detachment fault in the same area as Fig. 6(a). The footwall of the fault consists of sub-horizontally and sub-vertically foliated mylonitic gneiss. (c) Structure contour map of the Mohave Wash fault in the southwestern part of the Chemehuevi Mountains. Footwall rocks are isotropic Cretaceous granitic rocks.

irregularities of the fault surfaces. Differences in form between the Mohave Wash and Chemehuevi detachment faults may be attributed in part to the high-angle faults that cut the Mohave Wash, but not the Chemehuevi fault. Of the three detachment faults exposed in the Chemehuevi Mountains, the geometry of the Mohave Wash fault is best characterized.

Mohave Wash fault

The geometry of the Mohave Wash fault is dominated by a series of NE-trending mullion structures. They are corrugations having wavelengths of 200 m to 1 km and amplitudes of up to 150 m where the fault cuts sub-horizontally foliated mylonitic gneisses (Fig. 6a). Locally the fault has small parasitic undulations with amplitudes as low as 30 m. Where the Mohave Wash fault cuts homogeneous granite, the wavelengths are up to 3 km and the amplitudes as much as 390 m (Fig. 6c). Antiformal corrugations commonly project along their lengths into synformal corrugations in a down-dip direction along the fault. In addition, the non-cylindrical appearance of the corrugations seen in the structure contour maps probably reflects, in part, unrecognized younger normal and strike-slip faults that cut the Mohave Wash fault.

The long dimensions of the mullion structures are oriented 055±5°. Inasmuch as slickensides on the fault surfaces are orientated 040–060°, the latest fault movement roughly paralleled the axes of the mullion structures.

Along the strike-slip segments or lateral walls of the corrugations, crystalline rocks of the two adjacent plates have been dragged past each other. Originally steep NE- and NW-striking dykes of the Cretaceous(?) and/or Tertiary dyke swarms are fractured and rotated into subparallelism with the gentle dipping fault zone. Throughout the zone of cataclasis the dykes are clearly recognizable, as shown in Fig. 3, but fracture intensity and rotation increase near the upper margin where offset is greatest. This relationship of increased fracture intensity and dyke rotation within the fault zone is consistent enough to be used to estimate the original position of eroded parts of either the Mohave Wash or Chemehuevi detachment faults, and help constrain the contour maps.

Chemehuevi detachment fault

The Chemehuevi detachment fault surface has broader NE-trending corrugations than the Mohave Wash fault. Where the Chemehuevi fault truncates sub-horizontally foliated gneisses in the footwall (Fig. 6b), the fault is corrugated with wavelengths of 1.5–3 km and amplitudes of only 50–100 m. Above undeformed granites in the western part of the range, the wavelengths vary up to 8–10 km and the amplitudes vary between 150 and 300 m. In the northernmost part of the range, where vertically foliated mylonitic gneisses make up the footwalls of both the Mohave Wash and Chemehuevi faults (Fig. 4), the amplitude of corrugations on each of the two faults increases to nearly 400 m, and the wavelength is approximately the same as elsewhere. As with the Mohave Wash fault, corrugations of the Chemehuevi detachment fault apparently porpoise from antiformal to synformal, in the transport direction.

A section (Fig. 7) drawn perpendicular to the corrugations (Fig. 4b) illustrates differences in relative amplitude and wavelength between the two faults where they cut the same footwall rock type. The section emphasizes the cross-cutting nature of the faulting with respect to the pre-existing mylonitic fabric. The two faults anastomose both along strike (NW-trend) and down-dip (NE-trend) (Fig. 8). In places the faults are separated by nearly 1 km of coherent rock. Elsewhere the two faults are separated by hundreds of metres of altered cataclasites; locally, the Chemehuevi detachment fault truncates the Mohave Wash fault (Figs 4 & 9).

Devils Elbow fault

Throughout its relatively limited exposure, the Devils Elbow fault is apparently either very broadly warped or uncorrugated in the slip direction. The structurally deeper Chemehuevi detachment fault is corrugated in a broad antiform–synform mullion pair where it truncates a NW-trending warp in the Devils Elbow fault in the eastern part of the range (Fig. 4).

Northwest-trending fault undulations

Broad undulations of the two structurally deepest fault zones, with wavelengths of 10–50 km, trend NNW, orthogonal to the mullion structures. These larger undulations combine with the NE-trending mullion structures to produce the domal topography characteristic of the metamorphic core complexes W of the Colorado River in California (Cameron & Frost 1981; Spencer 1984). Possible origins of these features are discussed in a later section.

Evidence for a syntectonic origin of the corrugations

Warps of the detachment faults along the Colorado River trough have been attributed to folding of the faults by Cameron & Frost (1981), Davis *et al.* (1982), and Spencer (1982, 1984), whereas Woodward & Osborn (1980) and Wilkens & Heidrick (1982) described some as primary megagrooves. The wave-like pattern of parallel NE-trending undulations formed along the Mohave Wash and Chemehuevi fault zones are not folds, but primary grooves or syntectonic corrugations. Amplitude and wavelength of the corrugations differ along the three main faults. The corrugated Chemehuevi fault cuts the more planar Devils Elbow fault (Fig. 5). Both the Mohave Wash and Chemehuevi detachment faults truncate pre-existing gently W-dipping mylonitic foliation in the eastern part of the range (Figs 7 & 9). This fabric is cut by the undulating faults, and not folded into

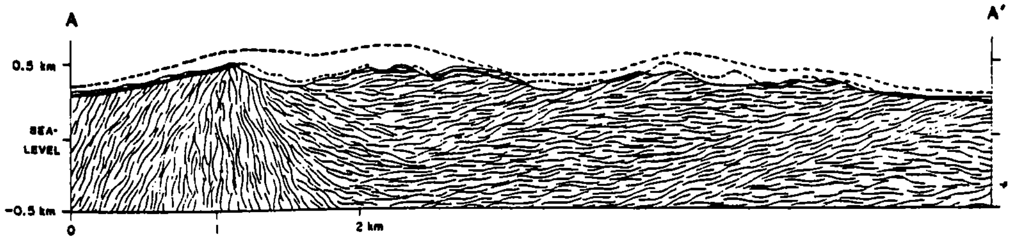

FIG. 7. Geological section along the line A–A′ (Fig. 4b), drawn NW–SE normal to the corrugation axes. Corrugations of the Mohave Wash fault cut the mylonitic foliation.

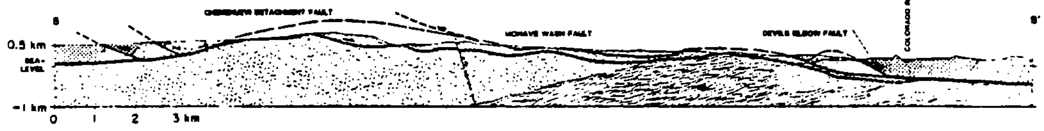

FIG. 8. Geological section along B–B′ (Fig. 4a), drawn SW–NE parallel to the corrugation axes. The Tertiary section is repeated by numerous faults above the regionally developed Chemehuevi detachment fault. The Mohave Wash fault is truncated by the structurally higher Chemehuevi fault in the W, and inferred to be cut in the E. Patterns shown are the same as in Fig. 4.

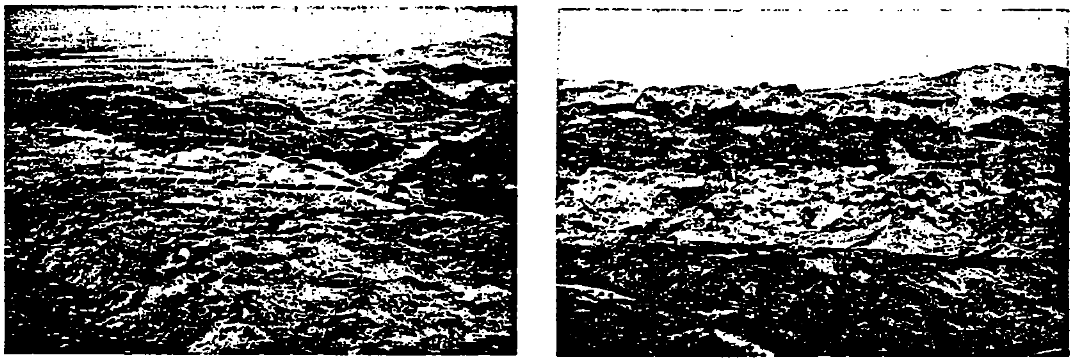

FIG. 9. Left: view NE from the central part of the Chemehuevi Mountains showing the stacked sequence of Tertiary detachment faults. The Mohave Wash fault (M) separates gently dipping mylonitic gneisses in the footwall from equivalent rocks in plate B. Rocks above the Chemehuevi detachment fault (C) across the Colorado River in Arizona, are Cretaceous granitic rocks. Rocks above the Devils Elbow fault (D) are Proterozoic gneisses and granites, and unconformable Tertiary strata.
Right: view SE from the northeastern part of the Chemehuevi Mountains showing the discordance between gently SW-dipping mylonitic foliation, and the E-dipping Mohave Wash fault.

concordance with them. The thickness of cataclasites and breccias associated with the two faults varies with relative position on the corrugations. The corrugation axes and lateral walls parallel the 040–060° slip on the faults. In the northern part of the range where steeply dipping mylonites make up the footwall (Fig. 4), extension was apparently more easily accommodated by broad, high-amplitude undulations and tear faults. This contrasts with the high-frequency, low-amplitude corrugations that formed where the faults cut sub-horizontally foliated mylonites in the eastern part of the range.

Fault rocks

Rocks produced by slip on the detachment faults in the Chemehuevi Mountains include incoherent gouge, breccia, rocks of the cataclasite series, and rare protomylonite and pseudotachylite.

Following the conceptual model of Sibson (1977, 1983), these fault rocks can be interpreted as a depth series formed roughly at crustal depths from 0 to 5 km (gouge and breccia), 5 to 10 km (breccia and cataclasite) and >10 km (protomylonite). Thin mylonites 0.01–1 m thick are present, but no major zones of mylonite can be related to the detachment faulting in the Chemehuevi Mountains. Fluids associated with the faulting hydrothermally altered intrafault cataclasites and breccias. From SW to NE in the transport direction across the range, fault rocks associated with detachment faulting change progressively in alteration mineral assemblages, in nature of active deformation mechanism, and in amount of reworking of the fault rocks.

Rocks produced by slip on the Mohave Wash fault include crush breccias, cataclasites and locally pseudotachylite. Thickness of these fault rocks varies from less than 2 m to more than 100 m. The retrograde mineral assemblage associated with the fault zone is consistently lower greenschist facies (e.g. chlorite±epidote±albite±clinozoisite±sericite±actinolite±calcite). The northeasternmost exposures show evidence of reworking of these rocks at shallower structural levels to form gouge and breccia, rich in hematite and calcite, that overprint earlier cataclasites. A general lack of reworking of fault rocks elsewhere along the fault, and its small displacement, suggests that the Mohave Wash fault was active for a relatively short time; the cataclasites suggest generation at intermediate crustal depths (Sibson 1977).

Fault rocks associated with the Chemehuevi fault include gouge, crush breccias and cataclasites. Thick zones of altered cataclasite are reworked into thinner zones of breccia. This sequence of cross-cutting or reworked fault rocks suggests that the depth of faulting became progressively shallower during fault evolution owing to progressive normal faulting and tectonic unroofing. The most recently active fault surface outcrops as planar zones, typical of shallow-level faults, marked in eastern exposures by the juxtaposition of hematite-rich breccias against chlorite- and epidote-rich cataclasites (Fig. 3). These relations suggest that the Chemehuevi detachment fault evolved from a wide zone of cataclasite at mid-crustal depths, to a narrower zone of breccia within the upper crust, to a sharp planar discontinuity marked by breccia and gouge locally at shallow-crustal depths of 0–5 km. Cataclasites beneath the fault are typically tens of metres thick. Locally, flow-laminated breccias as thick as 1 m are preserved in the synformal hinges. In western exposures, the Chemehuevi fault juxtaposes Proterozoic granites and gneisses of assemblage (II) down on Cretaceous granites from assemblage (I). Rocks of both the hanging wall and footwall are intensely fractured, and show limonitic alteration apparently superimposed on pervasive chlorite and epidote mineralization. In these western exposures, the fault is marked by breccia and cataclasite, lacking any throughgoing planar surface. The absence of gouge and of a planar fault surface in western exposures of the Chemehuevi detachment fault suggests that slip there may have ceased at some intermediate depth in the upper crust (>5 km). If so, movement on the eastern portion of the fault may have continued after the western portion locked.

The Devils Elbow fault is marked by a gouge and breccia zone less than 2 m thick beneath an extremely planar fault surface. Footwall granitic rocks are highly fractured crush breccias and cataclasites, which contain chlorite- and epidote-alteration mineral assemblages. The cataclasites are reworked as clasts in younger scaly gouge, reflecting continued faulting. The gouge, planar fault surface, and thinness of the fault zone suggest that the most recent movement on the Devils Elbow fault was at a shallow crustal level, probably less than 5 km.

Cataclastic rocks along the detachment fault zones in the Chemehuevi Mountains provide evidence of either high strain rates or temperatures low enough for frictional processes (cataclastic flow and frictional sliding) to have dominated deformation at the present level of exposure. Elongate quartz and alkali feldspar suggests that in the structurally deepest exposures of the Mohave Wash fault incipient crystal plastic behaviour in quartz and pressure solution apparently became important deformation mechanisms.

Rare cross-cutting veins of pseudotachylite a few millimetres to centimetres thick and as much as 0.5 m long occur in and adjacent to the Mohave Wash fault zone in the southwestern part of the area. The pseudotachylite, identified microscopically by R. H. Sibson (1984, pers. comm.), resulted from frictional melting during faulting. Its presence in the Mohave Wash fault zone suggests that the fault was seismically active during at least part of its movement history as a low-angle normal fault. Similar veins are found along the Chemehuevi detachment fault, although none are unambiguously pseudotachylite. The Mohave Wash and Chemehuevi detachment faults are also characterized by a high concentration of cross-cutting mineralized veins and fractures. The veins are host to chlorite and epidote and/or calcite and hematite vein-fill.

Cross-cutting relationships between the veins and fractures, and their proximity to the faults, imply episodic fracturing and fluid flow associated with detachment faulting.

Along both the Mohave Wash and Chemehuevi detachment faults cataclasites are thickest on the lateral walls of the mullion structures, and thinnest on the crests and troughs. Along the Mohave Wash fault cataclasites vary in thickness from less than 2 m over an antiformal crest, to greater than 100 m locally across the lateral wall of one of the mullion structures. Thickness variations along the Chemehuevi detachment fault are less well documented but apparently similar. Other properties being equal (slip, strain rate, thermal gradient, etc.) cataclasis was apparently more widespread along the sides, or strike-slip portions, of the mullion structures.

Fault-zone evolution

The fault system in the Chemehuevi Mountains evolved over roughly 5–10 My. Initial extension was accommodated at palaeodepths of greater than 6–10 km by the gently NE-dipping Mohave Wash fault. The upper crust was apparently being pulled apart simultaneously along steeply dipping normal faults. The small-displacement Mohave Wash fault is interpreted as representing an early stage of the regionally extensive Chemehuevi detachment fault which became active with continued extension at upper mid-crustal levels. Footwall accommodation (within the autochthon, A, and plate B) to movement on the Chemehuevi fault was minor, but included the development of normal and strike-slip faults, microfaults, local ductile shear zones and dyke emplacement. With continued extension upper-crustal volcanic and sedimentary rocks were rotated along high-angle normal faults above the Chemehuevi detachment fault, to a position against the mid-crustal footwall rocks. Examination of fault rocks associated with the Chemehuevi fault, and syntectonic alluvial fan deposits suggests that movement on the detachment continued up to very shallow crustal levels (0–5 km), and locally breached the surface leading to wholesale denudation of the fault zone.

Discussion

The tendency for the crust to extend in one particular mode is influenced by thermal gradient, and to a lesser extent, strain rate, depth, rock type, asssociated fluids and pre-existing structures or crustal heterogeneity. The Chemehuevi Mountains provide an example of mid-crustal accommodation to continental stretching, in which some of the effects of these variables can be evaluated. Deformation in the Chemehuevi Mountains took place along gently NE-dipping detachment fault zones that cut discordantly across heterogeneous crystalline rocks. The faults had low initial dips, and accommodated up to 100% extension. Above the regionally developed detachment faults, extension took place along a system of steeper normal faults which probably fed displacement into the detachment(s) (Davis *et al.* 1980; Howard *et al.* 1982a). The mapped fault geometry and inferred evolution of the fault system, place certain constraints on models of continental extension.

Detachment faults within the Chemehuevi Mountains area were initiated with a regional dip of 5–15° NE. Minor pseudotachylite associated with the low-angle normal faults suggests that they were seismically active during at least part of their movement history. The presence of cataclasites but absence of thick zones of associated mylonite indicate that the faults were active at a low angle within the brittle regime, at crustal depths of 6–10 km. Seismologists have yet to find earthquake evidence for seismic slip on low-angle normal faults. Fault-plane solutions of large normal-faulting earthquakes throughout the world appear at the time of movement to have dips of 30–60° throughout the 'brittle' upper crust (Eyidogan & Jackson 1985; Jackson & McKenzie 1983). The Chemehuevi Mountains are therefore particularly significant, emphasizing the paradox that needs to be resolved between field evidence and seismic data concerning the nature of crustal accommodation to continental extension.

The field evidence from the Chemehuevi Mountains also challenges the common assumption that low-angle normal faults theoretically cannot move in that orientation. Jackson & McKenzie (1983) suggest that new generations of high-angle faults are required during progressive extensional deformation, because of the decrease in effectiveness of gravity to overcome friction on a fault plane, as the dip of a fault decreases. I suggest that movement may have been aided in the Chemehuevi Mountains area by intermittent high(?) fluid pressure. Altered intrafault cataclasites and breccias, and associated veins showing repeated fracturing, fluid flow and mineralization, suggest that detachment faulting may have been accompanied by episodic high fluid pressure. A similar relationship has been documented by Power (unpubl. work) along detachment faults in the

Riverside Mountains approximately 50 km to the S. He suggests that intermittent high fluid pressure may have diminished the frictional resistance, and effective normal stress along the fault(s), and allowed movement at a low dip. As in the Chemehuevi Mountains, extensional deformation in the Riverside Mountains was confined to the brittle regime. Bartley & Glazner (1985) have gone a step further in proposing a model for the initiation of low-angle normal faults, through the reorientation of stress trajectories by periodic sealing of a geothermal system.

The NE-trending corrugations on the Chemehuevi and Mohave Wash fault developed coeval with slip. Shovel or scoop-shaped faults present in the Chemehuevi Mountains resulted where antiformal crests were eroded or else truncated by a later detachment fault, and are not the original fault geometry. I suspect that most scalloped or cuspate-shaped faults commonly described in other areas of continental extension may be characteristic of high structural levels in the crust. Quaternary normal-fault scarps along the Wasatch front, Utah, (Smith & Bruhn 1984), the Pearce and Tobin scarps associated with the 1915 Pleasant Valley earthquake in Nevada (Wallace 1984) and scarps from the 1969–70 Gediz earthquakes in Turkey (Ambraseys & Tchalenko 1972) all have cuspate forms at the surface. Each of these faults dips steeply (50–70°), with scallops measuring from hundreds of metres to several kilometres. The more continuous sub-horizontal mullion structures described in this paper may represent the downward continuations of cuspate fault scarps.

The detachment faults in the Chemehuevi Mountains are shown to be initially continuous sub-horizontal surfaces that are corrugated parallel to the NE transport direction. Orthogonal to these are broad NNW-trending undulations of the fault surfaces. These undulations may be the result of crustal flexing due to isostatic rebound following denudation (Howard *et al.* 1982a; Spencer 1984), reverse drag above a young high-angle normal fault (Gibbs 1984; Gans *et al.* 1985; Wernicke *et al.* 1985), ramping of the faults 'down' in the direction of transport (John 1984; Coward 1984), or some combination of the above. Spencer (1984) argues that the broad NNW-trending undulations of the detachment surfaces along the Colorado River trough and in southern Arizona are a product of isostatic uplift following tectonic denudation. Wernicke *et al.* (1985) suggest that the folding of detachments along axes perpendicular to the transport direction occurs as a result of reverse drag along younger, deeper faults. However, inasmuch as no younger faults have been recognized cutting the Chemehuevi fault, arching of the range orthogonal to the transport direction is unlikely to be the result of reverse drag.

An alternative, perhaps complementary explanation of the undulations with axes perpendicular to the transport direction is a ramp–flat pair in the detachment fault system (Fig. 10). This geometry has been inferred by Gibbs (1984) in interpretations of seismic sections from the North Sea, and may account for some of the irregularities in reflectors on the COCORP Sevier Desert line (Allmendinger *et al.* 1983).

With specific reference to the Chemehuevi Mountains area, this fault geometry could provide a mechanism for continued movement on different parts of the once continuous Chemehuevi detachment fault, at different times. Figure 10 outlines the schematic evolution of the fault system across the extensional corridor and the Chemehuevi Mountains. In this model, the extensional fault system initially cut steeply down-section from the headwall region in the Old Woman–Piute Mountains area, and flattened at a depth of ~6 km. The small-separation Mohave Wash fault is portrayed as an early ramp splay that is cut off by younger movement along the Chemehuevi detachment fault, as the fault cut into the hanging wall with progressive extension. With continued extensional deformation, the ramp is domed causing cessation of slip on the structural flat to the W. Continued down-slope movement on the eastern portion of the fault would thin and eventually denude the ramp, reworking structurally deeper cataclasites into gouge and breccia. Isostatic rise, as outlined by Spencer (1984) would enhance the already domal form of the detachment fault system, and produce the subdued arch of the fault surface we see today.

This model allows for local exhumation of the detachment fault(s), to provide detritus including altered lower-plate cataclasites that were shed into basin(s) in the eastern part of the range. A cross-section drawn parallel to the slip direction on the detachment faults (Fig. 8) requires a major displacement fault repeating the Tertiary section near what is now the inflection point of the dome. This fault may be a 'young' fault feeding slip into the eastern part of the Chemehuevi detachment fault. As the western segment of the Chemehuevi detachment fault became inactive due to doming the eastern portion moved down-slope under the influence of gravity to produce the very shallow fault rocks associated with the latest movement on the faults in the eastern part of the range (Fig. 10).

There appears to be some influence of pre-existing structures on the overall geometry of the

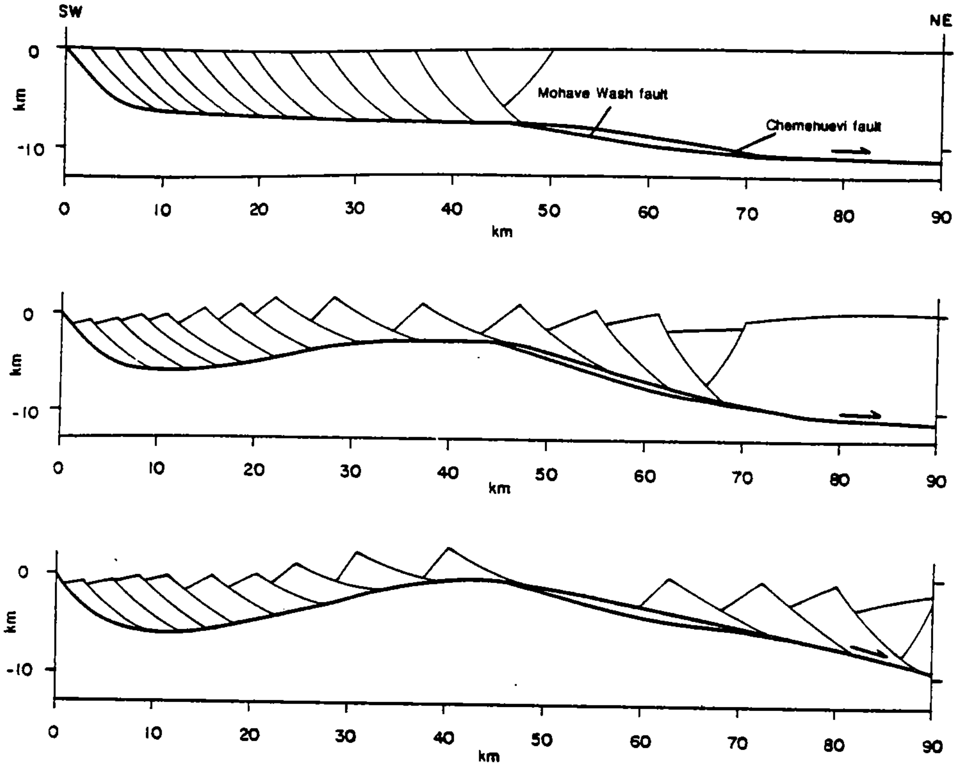

FIG. 10. Schematic evolution of the extensional fault system in the Chemehuevi Mountains area, outlined in the text and modified after Spencer 1984. The top diagram shows the initial trajectory of the fault system, from the breakaway in the Old Woman–Piute Mountains area, NE across the extensional corridor. With continued extensional deformation, the ramp is domed and progressively denuded. Final slip on the Chemehuevi fault along the eastern slope of the dome is gravity driven, at very shallow crustal levels. Implied in this model is a transition from brittle to ductile deformation associated with extension at greater structural depths, under what is now Arizona.

fault system. Undeformed granitoids, sub-horizontally foliated gneiss, and sub-vertically foliated gneiss in the footwalls of the two lower detachment faults are each associated with different scales in amplitude and wavelength of the syntectonic corrugations and apparently influenced their shapes. Steep strike-slip faults are most common within the sub-vertically foliated gneisses, paralleling the foliation. Corrugation amplitudes and wavelengths are greater in sub-vertical than in sub-horizontal gneisses.

On a crustal scale, the fault system may have ramped down through the undeformed granitoids and flattened within the sub-horizontal gneisses. In the Chemehuevi Mountains (Fig. 9), the angular discordance between the sub-horizontal foliation and detachment faults is ~20°, and very little slip was accommodated by movement parallel to foliation. These earlier structures apparently influenced but did not overwhelmingly control the position and geometry of the extensional faults.

Concluding remarks

This paper documents the geometric evolution of an extensional fault system in an area of heterogeneous continental crust. The geometry and evolution of the extensional fault system exposed in the Chemehuevi Mountains area has basic similarities with those documented for classic fold and thrust belts (Boyer & Elliot 1982; Bally *et al.* 1966), but opposite in sense of movement. Thrust systems have two possible propagation sequences. Piggy-back thrust propagation arises if a younger thrust develops in the footwall of an older thrust. The sequence of fault generation in the Chemehuevi Mountains is analogous but opposite to that outlined above, as the Chemehuevi fault developed in the hanging wall of the earlier Mohave Wash fault. This relationship implies that extensional fault systems may propagate towards the hanging wall, in the direction of transport.

Acknowledgments: Thanks are due to K. A. Howard, W. L. Power, G. A. Davis, E. G. Frost, J. L. Anderson and D. M. Miller for countless discussions and field trips pertaining to detachment faulting. R. H. Sibson and R. E. Anderson provided much needed tutoring on the nature of continental fault zones. Special thanks are due to my field assistants, in particular V. L. Hansen and L. L. Glick for their time, energy and sweat. Without them this study would not have been possible. Financial support from the U.S. Geological Survey Graduate Intern Program is gratefully acknowledged. Finally, I thank R. H. Sibson, M. W. Reynolds, K. A. Howard and an anonymous reviewer for helpful, critical reviews of the manuscript.

References

Allmendinger, R.W., Sharp, J.W., von Tisch, P., Serpa, L., Brown, L., Kaufman, S., Oliver, J. & Smith, R.B. 1983. Cenozoic and Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic reflection data. *Geology*, 11, 532–36.

Ambraseys, N.N. & Tchalenko, J.S. 1972. Seismotectonic aspects of the Gediz Turkey, earthquake of March 1970. *Geophys. J. R. astron. Soc.*, 30, 229–52.

Anderson, R.E., Zoback, M.L. & Thompson, G. 1983. Implications of selected subsurface data on the structural form and evolution of some basins in the northern Basin and Range Province, Nevada and Utah. *Bull. geol. Soc. Am.* 94, 1055–72

Armstrong, R.L. 1968. Sevier orogenic belt in Nevada and Utah. *Bull. geol. Soc. Am.* 79, 429–58.

Bally, A.W., Gordy, P.L. & Stewart, G.A. 1966. Structure, seismic data and orogenic evolution of the southern Canadian Rocky Mountains. *Bull. Can. Pet. Geol.* 14, 337–81.

Bartley, J.M. & Glazner, A.F. 1985. Hydrothermal systems and Tertiary low-angle normal faulting in the southwestern United States. *Geology*, 13, 562–4.

Boyer, S.E. & Elliot, D. 1982. Thrust systems. *Bull. Am. Ass. Pet. Geol.* 66, 1196–230.

Burchfiel, B.C. & Davis, G.A. 1981. Mojave Desert and Environs. *In*: Ernst, W.G. (ed.) *The Geotectonic Development of California*, pp. 217–52. Prentice-Hall Inc., New Jersey.

Cameron, T.E. & Frost, E.G. 1981. Regional development of major antiforms and synforms with detachment faulting in California, Arizona, Nevada and Sonora. *Abstr. with Programs geol. Soc. Am.* 13, 421–2.

Carr, W.J. & Dickey, D.D. 1976. Cenozoic tectonics of the eastern Mojave Desert. *U.S. geol. Surv. Prof. Pap. 1000*, 75 pp.

Coney, P.J. 1980. Cordilleran metamorphic core complexes: an overview. *In*: Crittenden, M.D., Coney, P.J. & Davis, G.H. (eds) *Cordilleran Metamorphic Core Complexes Mem. geol. Soc. Am.* 153, 7–31.

—— & Harms, T.A. 1984. Cordilleran metamorphic core complexes: Cenozoic extensional relicts of Mesozoic compression. *Geology*, 12, 550–4.

Coward, M.D. 1984. Major shear zones in the Precambrian crust; examples from NW Scotland and southern Africa and their significance. *In*: Kroner, A. & Greiling, R. (eds) *Precambrian Tectonics Illustrated*, pp. 207–35. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Davis, G.A., Anderson, J.L., Frost, E.G. & Shackelford, T.J. 1980. Mylonitization and detachment faulting in the Whipple–Buckskin–Rawhide Mountains terrane, southeastern California and western Arizona. *In*: Crittenden, M.D., Coney, P.J. & Davis, G.H. (eds) *Cordilleran Metamorphic Core Complexes, Mem. geol. Soc. Am.* 153, 79–129.

——, Anderson, J.L., Martin, D.L., Krummenacher, D., Frost, E.G. & Armstrong, R.L. 1982. Geologic and geochronologic relations in the lower plate of the Whipple detachment fault, Whipple Mountains, southeastern California: a progress report. *In*: Frost, E.G. & Martin, D.L. (eds) *Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region California, Arizona and Nevada (Anderson-Hamilton volume)*, pp. 409–32. Cordilleran Publishers, San Diego.

Eaton, G.P. 1982. The Basin and Range province: origin and tectonic significance. *Ann. Rev. Earth planet. Sci.* 10, 409–40.

Escher, A. & Watterson, J. 1974. Stretching fabrics, folds and crustal shortening. *Tectonophysics*, 22, 223–31.

Eyidogan, H. & Jackson, J. 1985. A seismological study of normal faulting in the Demirci, Alasehir and Gediz Earthquakes of 1969–70 in western Turkey: implications for the nature and geometry of deformation in the continental crust. *Geophys. J. R. astron. Soc.* 81, 569–607.

Frost, E.G. 1981. Structural style of detachment faulting in the Whipple Mountains, California, and Buckskin Mountains, Arizona. *In*: Stone, C. & Jenny, J.P. (eds) *Az. geol. Soc. Dig.* XIII, 25–9.

—— & Martin, D.L. (eds) 1982a. *Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada (Anderson-Hamilton volume)*, 608 pp. Cordilleran Publishers, San Diego.

—— & Martin, D.L. 1982b. Comparison of Mesozoic compressional tectonics with mid-Tertiary detachment faulting in the Colorado River area, California, Arizona and Nevada. *In*:

Cooper, J.D. (ed.) *Geologic Excursions in the California Desert, geol. Soc. Am. Field Trip Volume and Guide*, pp. 111-59.

—— , Cameron, T.G. & Krummenacher, D. 1982. Mid-Tertiary detachment related deformation in the Chemehuevi Mountains, and its implications for regional crustal extension. *Abstr. with Programs geol. Soc. Am.* **14**, pp. 164.

Gans, P.B., Miller, E.L., McCarthy, J. & Ouldcott, M.L. 1985. Tertiary extensional faulting and evolving ductile-brittle transition zone in the northern Snake Range and vicinity: New insight from seismic data. *Geology*, **13**, 189–93.

Gibbs, A.D. 1984. Structural evolution of extensional basin margins. *J. geol. Soc. London*, **141**, 609–20.

Hamilton, W. 1982. Structural evolution of the Big Maria Mountains, southeastern Riverside County, southeastern California. *In*: Frost, E.G. & Martin, D.L. (eds) *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 1-27. Cordilleran Publishers, San Diego.

Howard, K.A. & John, B.E. This volume. Crustal extension along a rooted system of low-angle normal faults: Colorado River extensional corridor, California and Arizona.

—— , Miller, C.F. & Stone, P. 1980. Mesozoic thrusting in the eastern Mojave Desert, California. *Abstr. with Programs geol. Soc. Am.* **12**, pp. 112.

—— , Stone, P., Pernokas, M.A. & Marvin, R.F. 1982a. Geologic and geochronologic reconnaissance of the Turtle Mountains area, California: west border of the Whipple detachment terrane. *In*: Frost, E.G. & Martin, D.L. (eds) *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 341-54. Cordilleran Publishers, San Diego.

—— , Goodge, J.W. & John, B.E. 1982b. Detached crystalline rocks of the Mohave, Buck and Bill Williams Mountains, western Arizona. *In*: Frost, E.G. & Martin, D.L. (eds) *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 377–90. Cordilleran Publishers, San Diego.

—— , Miller, D.M. & John, B.E. 1982c. Regional character of mylonitic gneiss in the Cadiz Valley area, southeastern California. *In*: Frost, E.G. & Martin, D.L. (eds) *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 441-7. Cordilleran Publishers, San Diego.

Jackson, J. & McKenzie, D. 1983. Geometrical evolution of normal fault systems. *J. struct. geol.* **5**, 471–82.

John, B.E. 1982. Geologic framework of the Chemehuevi Mountains, southeastern California. *In*: Frost, E.G. & Martin, D.L. (eds) *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 317-25. Cordilleran Publishers, San Diego.

—— 1984. Primary corrugations in Tertiary low-angle normal faults, SE California: Porpoising mullion structures? *Abstr. with Programs geol. Soc. Am.* **16**, pp. 291.

—— 1986. Evidence for late Mesozoic thrusting in the Chemehuevi Mountains area, southeastern California. *Abstr. with Programs geol. Soc. Am.* **18**, pp. 122.

—— & Howard, K.A. 1982. Multiple low-angle Tertiary faults in the Chemehuevi and Mohave Mountains, California and Arizona. *Abstr. with Programs geol. Soc. Am.* **14**, pp. 175.

Krieger, M.L. 1978. Large landslides composed of megabreccia interbedded in Miocene basin deposits, southeastern Arizona. *U.S. geol. Surv. Prof. Pap. 1008*, 25 pp.

McClelland, W.C. 1982. Structural geology of the central Sacramento Mountains, San Bernardino Country, California. *In*: Frost, E.G. & Martin, D.L. (eds) *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 401–6. Cordilleran Publishers, San Diego.

Miller, C.F., Howard, K.A. & Hoisch, T.D. 1982. Mesozoic thrusting, metamorphism, and plutonism, Old Woman-Piute Range, southeastern California. *In*: Frost, E.G. & Martin, D.L. (eds) *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 561-81. Cordilleran Publishers, San Diego.

Miller, D.M., John, B.E., Antweiler, J.C., Simpson, R.W., Hoover, D.B., Raines, G.L. & Kreidler, T.J. 1983. Mineral Resource Potential Map of the Chemehuevi Mountains Wilderness Study Area (CDCA-310), San Bernardino County, California. *U.S. geol. Surv. Misc. Field Studies Map MF-1584-A*, 1:48,000.

Pierce, W.G. 1973. Principle features of the Heart Mountain fault and the mechanism problem. *In*: DeJong, K.A. & Scholten, R. (eds) *Gravity and Tectonics*, pp. 457-71. John Wiley & Sons Inc., New York.

Power, W.L. 1986. Mechanics of low-angle extensional faulting in the Riverside Mountains, southeastern California. Unpubl. M.A. Thesis, U.C. Santa Barbara.

Proffett, J.M., jr 1977. Cenozoic geology of the Yerington District Nevada, and implications for the nature and origin of Basin and Range faulting. *Bull. geol. Soc. Am.* **88**, 247–66.

Proffett, J.M. jr & Dillas, J.H. 1984. Geologic map of the Yerington District, Nevada. *Nev. Bur. Mines and Geol. Map* 77, 1:24,000.

Rehrig, W.A. & Reynolds, S.J. 1980. Geologic and geochronologic reconnaissance of a northwest-trending zone of metamorphic complexes in southern Arizona. *In*: Crittenden, M.D., Coney, P.J. & Davis, G.H. (eds) *Cordilleran Metamorphic Core Complexes. Mem. geol. Soc. Am.* **153**, 131–58.

REYNOLDS, S.J. & SPENCER, J.E. 1985. Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona. *Geology*, **13**, 353–6.

SHACKELFORD, T.J. 1980. Tertiary tectonic denudation of a Mesozoic–early Tertiary(?) gneiss complex, Rawhide Mountains, western Arizona. *Geology*, **8**, 190–4.

SIBSON, R.H. 1977. Fault rocks and fault mechanisms. *J. geol. Soc. London*, **133**, 191-213.

—— 1983. Continental fault structure and the shallow earthquake source. *J. geol. Soc. London*, **140**, 741–67.

SMITH, R.B. & BRUHN, R.L. 1984. Intraplate extensional tectonics from the eastern Basin–Range: inference from seismic reflection data, regional tectonics, and thermal–mechanical models of brittle–ductile deformation. *J. geophys. Res.* **89**, 5733–62.

SPENCER, J.E. 1982. Origin of folds of Tertiary low-angle fault surfaces, southeastern California and western Arizona. *In*: FROST, E.G. & MARTIN, D.L. (eds) *Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 123-34. Cordilleran Publishers, San Diego.

—— 1984. Role of tectonic denudation in warping and uplift of low-angle normal faults. *Geology*, **12**, 95–8.

—— 1985. Miocene low-angle normal faulting and dike emplacement, Homer Mountain and surrounding areas, southeastern California and southernmost Nevada. *Bull. geol. Soc. Am.* **96**, 1140–55.

STEWART, J.H. 1971. Basin and Range structure: A system of horsts and grabens produced by deep-seated extension. *Bull. geol. Soc. Am.* **82**, 1019–44.

—— 1980. Regional tilt patterns of late Cenozoic basin-range fault blocks, western United States. *Bull. geol. Soc. Am.* 91, 460–4.

WALLACE, R.E. 1984. Faulting related to 1915 Earthquake in Pleasant Valley, Nevada. *U.S. geol. Surv. Prof. Pap. 1274A*, pp. A1-A33.

WERNICKE, B. 1985. Uniform-sense normal simple shear of the continental lithosphere. *Can. J. Earth Sci.* **22**, 108–25.

——, WALKER, J.D. & BEUFAIT, M.S. 1985. Structural discordance between Neogene detachments and frontal Sevier thrusts, central Morman Mountains, southern Nevada. *Tectonics*, 4, 213–46.

WILKENS, J. JR & HEIDRICK, T.L. 1982. Base and precious metal mineralization related to low-angle tectonic features in the Whipple Mountains, California and Buckskin Mountains, Arizona. *In*: FROST, E.G. & MARTIN, D.L. (eds) *Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada* (*Anderson-Hamilton volume*), pp. 182-209. Cordilleran Publishers, San Diego.

WOODWARD, R.J. & OSBORN, G.M. 1980. Low-angle detachment faulting and multiple deformation of the central Buckskin Mountains, Yuma County, Arizona. *Abstr. with Programs geol. Soc. Am.* **12**, pp. 245.

YOUNG, R.A. & BRENNAN, W.J. 1974. Peach Springs Tuff: It's bearing on the structural evolution of the Colorado Plateau and development of Cenozoic drainage in Mohave County, Arizona. *Bull. geol. Soc. Am.* **85**, 83-90.

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