BLOOM

Uniform-sense normal simple shear of the continental lithosphere

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Geophysical studies suggest that the thin crust characteristic of the Basin and Range Province extends eastward beneath the west margin of the Colorado Plateau and Rocky Mountain regions. In Arizona and Utah, zones perhaps over 100 km wide may be defined, bounded on the west by the east limit of upper crustal normal faults that account for more than 10% extension and on the east by the east limit of thinning beneath the Colorado Plateau. A discrepancy exists within these zones between the negligible extension measurable in the upper crust and the substantial extension apparent from crustal thinning, assuming the "discrepant zone" crust was as thick as or thicker than the Colorado Plateau – Rocky Mountain crust prior to extensional tectonism.

If various theories appealing to crustal erosion are dismissed, mass balance problems evident in the discrepant zones are most easily resolved by down-to-the-east normal simple shear of the crust, moving lower and middle crustal rocks that initially were within the zones up-and-to-the-west to where they now are locally exposed in the Basin and Range Province. West of the discrepant zones in both Arizona and Utah, east-directed extensional allochthons with large displacement are exposed. These geophysical and geological observations complement one another if it is accepted that the entire crust in both Arizona and Utah failed during extension on gently east-dipping, east-directed, low-angle normal faults and shear zones over a region several hundred kilometres wide.

Large-scale, uniform-sense normal simple shear of the crust suggests the entire lithosphere may do the same. Such a hypothesis predicts major lithospheric thinning without crustal thinning will occur in plateau areas in the direction of crustal shear. In the case of the Arizona, Utah, and Red Sea extensional systems, and possibly the Death Valley extensional terrain, a broad topographic arch, typically 1500–2000 m higher than the extended terrain, is present, suggesting lithospheric thinning in areas predicted by the hypothesis.

Des études géophysiques révèlent que la croûte mince typique de la province de Bassin et Chaîne se prolonge en direction est sous la marge continentale des régions du plateau du Colorado et des montagnes Rocheuses. Dans l'Arizona et l'Utah, des zones possiblement plus larges que 100 km peuvent être délimitées du côté ouest par la limite est des failles normales de la croûte supérieure, lesquelles sont responsables de plus de 10% de l'extension, et du côté ouest par l'extrémité est de l'amincissement sous le plateau du Colorado. Un désaccord existe à l'intérieur de ces zones opposant une extension apparente substantielle résultant de l'amincissement de la croûte, en présumant que la "zone de désaccord" fut avant la distention tectonique de même épaisseur ou plus épaisse que celle du plateau du Colorado – montagnes Rocheuses.

Si on écarte les diverses théories invoquant une érosion de la croûte, les problèmes d'équilibre de masse dans les zones en désaccord sont plus facilement résolus par un cisaillement simple normal descendant vers l'est, déplaçant des roches de la croûte inférieure et moyenne, lesquelles se trouvaient originalement dans ces zones, vers le haut et en direction ouest jusqu'au l'endroit qu'elles occupent maintenant dans la province de Bassin et Chaîne. À l'ouest de ces zones de désaccord, tant dans l'Arizona que l'Utah, des roches allochtones d'extension de direction est sont exposées et elles exhibent un déplacement sur une grande distance. Ces observations géophysiques et géologiques se complètent les unes et les autres, si on accepte que la croûte entière dans l'Arizona et dans l'Utah fut brisée durant la distension sur un plan légèrement incliné vers l'est, le long de failles normales de direction est à angle faible et de zones de cisaillement sur une région large de plusieurs kilomètres.

Un cisaillement de la croûte normal, simple et de sens uniforme sur une grande échelle, semble pouvoir pénétrer toute la lithosphère. Une telle hypothèse dévoile un amincissement important de la lithosphère sans être accompagné d'un amincissement de la croûte dans les régions du plâteau situé dans la direction du cisaillement crustal. Dans le cas des systèmes de distension de l'Arizona, de l'Utah, de la mer Rouge et possiblement de la Vallée de la Mort, un grand arc topographique apparaît avec un soulèvement typique surmontant de 1500–2000 m les terrains de la zone de distension, suggérant alors un amincissement lithosphérique dans les régions où cette hypothèse peut s'appliquer.

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Introduction

With the proliferation of information on thin-skinned extensional tectonics and related phenomena in the Basin and Range Province, it is now possible to focus attention on the overall strain pattern during extension of at least the upper and middle crust and to some extent the lower crust and mantle lithosphere. In particular, much debate currently centers upon the relative importance of simple-shear and pure-shear strains, at scales ranging from that of a thin section up to that of the entire lithosphere (e.g., Armstrong 1982; Miller *et al.* 1983; Compton 1980; Bartley and Wernicke 1985; Davis *et al.* 1983).

In compressional mountain belts, simple shear with regionally uniform sense developed in the upper, middle, and lower crust is well known from field studies and seismic reflection profiling in areas such as the western Alps (Milnes and Pfiffner 1980), Canadian Rockies (Price 1981), Appalachians (Cook *et al.* 1979; Harris and Milici 1977), Wyoming Rockies (Smithson *et al.* 1978), and the Scandinavian Caledonides (Gee 1975; Hodges *et al.* 1982). Using thin-skinned compressional belts as an analogue, I have proposed (Wernicke 1981*a*) a large-scale simple-shear kinematic model in order to explain enigmatic relationships in the surface geology of the Basin and Range Province. Because the Basin and Range only exposes upper- and middle-crustal rocks, surface geology alone provides few clues to the nature of extension in the lower lithosphere. Since upper- and middle-crustal extension seemed to be adequately explained in many areas by large-scale, regionally uniform simple shear, I have speculated that these upper-

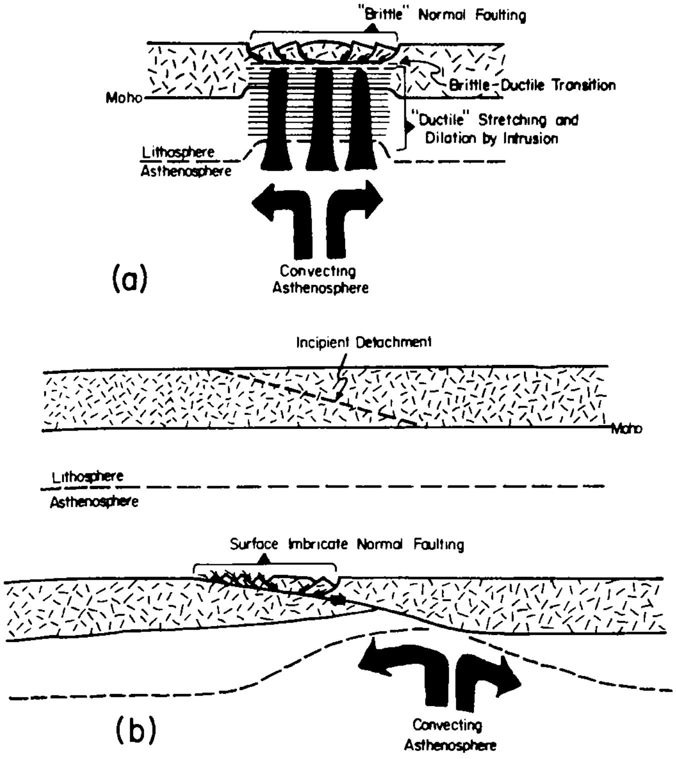

FIG. 1. End-member models of strain geometry in rifts. (*a*) "Pure-shear" model, in which crust and mantle lithosphere are attenuated uniformly along any given vertical reference line. (*b*) "Simple-shear" model, in which relative extension of crust and mantle lithosphere along any given vertical line is nonuniform. After Wernicke (1981*b*).

crustal shear systems may penetrate the entire lithosphere as single entities (Fig. 1). This paper is intended to explore the feasibility of that hypothesis by integrating surface geology with geophysical and petrological observations in the Basin and Range Province and in the Red Sea region. The results suggest that large-scale uniform-sense simple shear of the lithosphere during extension not only is feasible but in some areas more adequately accounts for these observations than pure-shear theories of rifting do. More importantly, it provides a new hypothesis of rift tectonics that may be tested by many highly diverse forms of geoscientific data.

Middle- and upper-crustal extension

Early workers in thin-skinned extension, in concert with the widely held notion that the strain field of an intracontinental rift resembles a stretched piece of taffy, viewed the overall strain pattern as pure-shear flattening accompanied by igneous dilation, in which vertical reference lines through the lithosphere would not significantly rotate as a result of crustal extension (Proffett 1977; Wright and Troxel 1969, 1973; Anderson 1971; Armstrong 1968, 1972). These models generally assumed that thin-skinned normal faulting was accommodated in the middle and lower crust by stretching and igneous dilation, similar to ideas of early thinkers on the depth accommodation problem for widely spaced Basin and Range normal faults responsible for the modern topography (Thompson 1960; Hamilton and Myers 1966; Stewart 1971). The recent recognition of regional low-angle detachments beneath normal fault systems and, in many areas, a subjacent zone of ductile deformation whose maximum elongation direction is colinear with that inferred from normal faulting above the detachment (Compton *et al.* 1977; Davis and Coney 1979; Davis *et al.* 1980; Crittenden *et al.* 1980; Coney 1980; Compton 1980; Keith *et al.* 1980; Rehrig and Reynolds 1980; Reynolds and Rehrig 1980) led many geologists to the hypothesis that detachments represent the brittle–ductile transition zone thought to exist at depth by earlier workers. In this view, brittlely extended upper-crustal fault blocks "collapse" directly on top of a ductilely extended substratum (e.g., Rehrig and Reynolds 1980; Eaton 1979). A variation of this concept, intended to account for the domal form of the detachment terrains and the absence of severe ductile deformation at structurally deep levels, is the ingenious megaboudin concept (Davis and Coney 1979), in which the ductile extension at depth is modeled as being heterogeneous. This hypothesis views the extending crust as being composed of large bodies of relatively undeformed material set in a matrix of ductile tectonite, as in a row of boudins. Based on Davis and Coney's work and detailed observations of shear-zone processes in Hercynian basement rocks in the Pennine Zone in the western Alps, Ramsay (1980) suggested that systems of conjugate, shallowly inclined shear zones should be the norm in an extending middle crust, giving way upward to more steeply inclined brittle normal faults. Similar models have also been advocated by Kligfield *et al.* (1982) and Hamilton (1982). Inherent in Ramsay's model is a large amount of simple shear between lenses, but no more than a few tens of kilometres of horizontal translation of upper-crustal levels with respect to the lower crust is required to accommodate a net crustal extension many times the amount of these translations. In contrast, large-scale, uniform-sense simple shear of the crust (Wernicke 1981*a*) would produce translations of upper crust with respect to lower crust approximately equal to the net extension, a geometric attribute of fold–thrust belts such as the southern Canadian Rockies (Price 1981).

Recent field studies of tectonites beneath detachments suggest that both pure shear and simple shear exist in these terrains (e.g., Davis *et al.* 1983; Compton 1980), but that simple shear appears to be dominant and of consistent sense over very large areas (e.g., Snoke 1983; Lister and Davis 1983).

Of fundamental importance in evaluating these concepts is the *timing* of lower-plate ductile deformation relative to upper-plate events. In many detachment terrains, lower-plate tectonites cooled through the blocking temperature of argon in biotite 5–10 Ma *prior* to large amounts of extensional strain via imbricate normal faulting in the upper plate (Fig. 2). This observation, coupled with the fact that some lower plates are not ductilely strained (Spencer and Turner 1982; Wernicke 1982*b*), indicates that hypotheses of simple collapse of imbricate normal fault mosaics atop a ductilely stretching lower plate are inadequate because they require synchroneity between high-temperature deformation and *all* upper-plate extension. They do not account for the many examples of detachments and superjacent normal fault mosaics deformed and (or) emplaced upon rigid lower plates (e.g., Davis *et al.* 1979; Shackleford 1980; Wernicke 1981*a*, 1982*b*). It is precisely this diachroneity that makes a simple-shear explanation attractive. By this mechanism, most or all lower-plate ductile tectonism may substantially predate large amounts of upper-plate extension, or not be present at all if upper-plate translation and (or) distension are of insufficient magnitude to expose early formed tectonites.

The kinematic evolution of a "typical" Basin and Range detachment terrain is depicted in Fig. 3. Firstly, a shallowly inclined fault (or shear zone at depth) penetrating most of the

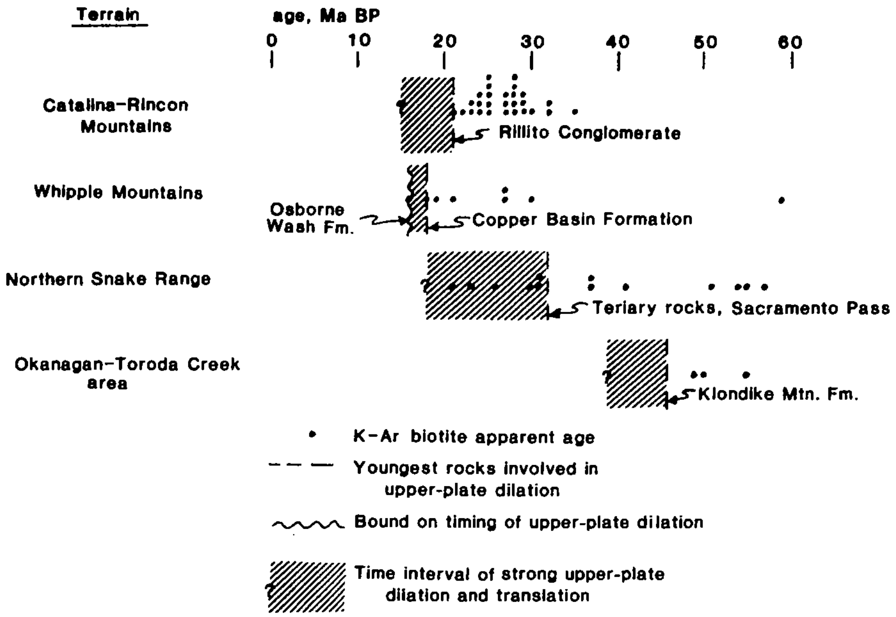

FIG. 2. Age relations between cooling of lower-plate tectonites and timing of latest upper-plate imbricate normal faulting and brittle detachment. Significant amounts of upper-plate dilation and translation probably occurred in all of these terrains prior to the deposition of the youngest rocks involved in the deformation; thus the shaded areas represent only the latest phase of significant upper-plate strain. Sources: Catalina–Rincon mountains, Keith *et al.* (1980) and M. Shafiqullah and H. W. Peirce (unpublished data); Whipple Mountains, Davis *et al.* (1982); northern Snake Range, Miller *et al.* (1983 and unpublished data) and Lee *et al.* (1980); Okanogan – Toroda Creek area, Fox *et al.* (1977) and Pearson and Obradovich (1977).

crust (and perhaps much of the mantle, as will be discussed below) forms, developing at the surface as a "breakaway fault" and an accompanying sedimentary basin. It is possible to envisage the fault–shear zone as having several kilometres of movement prior to the accumulation of coarse clastics, depending on local drainage conditions. As the fault moves and the basin grows, earliest formed ductile tectonite begins its ascent (Fig. 3 *a* and *b*). The early basins associated with extended terrains generally contain a large percentage of nonconglomeratic material deposited over wide areas. The Sevier Desert basin may be an active example of this type of setting. After a substantial amount of displacement on the fault, penetrative brittle deformation begins to affect the sedimentary basin and its basement as deformation continues (Fig. 3*c*). Closer fault spacing and growing relief cause coarsening of sedimentation. At this point, upper-plate thinning has been sufficient to move tectonites into brittle conditions. As shear continues, a portion of the upper plate may begin to preferentially extend relative to surrounding areas (Fig. 3*d*). If extension is large enough, folds in the detachment surface may develop as a result of isostatic rebound of the unloaded terrain, forming the familiar arched configuration of a mature detachment terrain, with old tectonite exposed in the core of the arch. No attempt has been made in Fig. 3 to specify the precise amount of isostatic rebound of the denuded terrain, other than keeping the top of the cross section approximately at the Earth's surface (the effect of extension on topography will be treated below). Internal distension of the upper plate thus completely postdates the formation of lower-plate tectonites. Upper-plate extension in the early stages is essentially accomplished by movement of a relatively coherent plate away from the breakaway zone with infilling of the void by sedimentary debris, whereas in later stages it is accomplished by upper-plate extensional strain and wholesale denudation of the lower plate (e.g., Spencer 1984).

If extension is accommodated on a number of regionally persistent, gently inclined shear zones that penetrate the crust deeply, early formed tectonite may be brought upward along the shear zone and cooled through geochronometric blocking temperatures long before extensional deformation is complete.

The geometry of Fig. 3 suggests a classification of ranges with respect to their tectonic affiliation with detachment systems. Although it has been widely held in the past that early thin-skinned extension is a separate phenomenon from widely spaced Basin and Range faulting (e.g., Zoback *et al.* 1981; Miller *et al.* 1983), I have argued based on seismic reflection data from the Sevier Desert area, Utah (McDonald 1976), that the development of detachment systems may control Basin and Range faulting (Wernicke 1981*a*).

Figure 3 depicts how classical Basin and Range topography may form in concert with large-scale, low-angle, normal fault systems. Breakaway ranges generally take on the appearance of an asymmetric horst and frequently display upward flexure toward the faulted side of the range (see discussion in next section). Imbricately extended ranges may have one fault-bounded margin, and their internal geology consists of a number of long, thin, highly rotated faults and fault blocks, but extension has not been great enough to expose a basal detachment. Core-complex ranges have highly extended upper plates that have passed through a phase of imbricate normal faulting before they are thinned sufficiently to expose the lower plate. They are veneered by their upper plates, and map traces of erosionally "stranded" detachments within these ranges feed into active, range-front, *low-angle* (0–30°) normal faults, accomplishing subaerial exposure of the lower plates in active extensional terrains such as the Death Valley region of eastern California (Wright *et al.* 1974). Adjacent to core-complex ranges, in addition to imbricately extended ranges, occur large fault-block ranges, characterized by comparatively little internal distension, riding passively in the upper plate.

Figure 3 contains only basic geometric elements of detach-

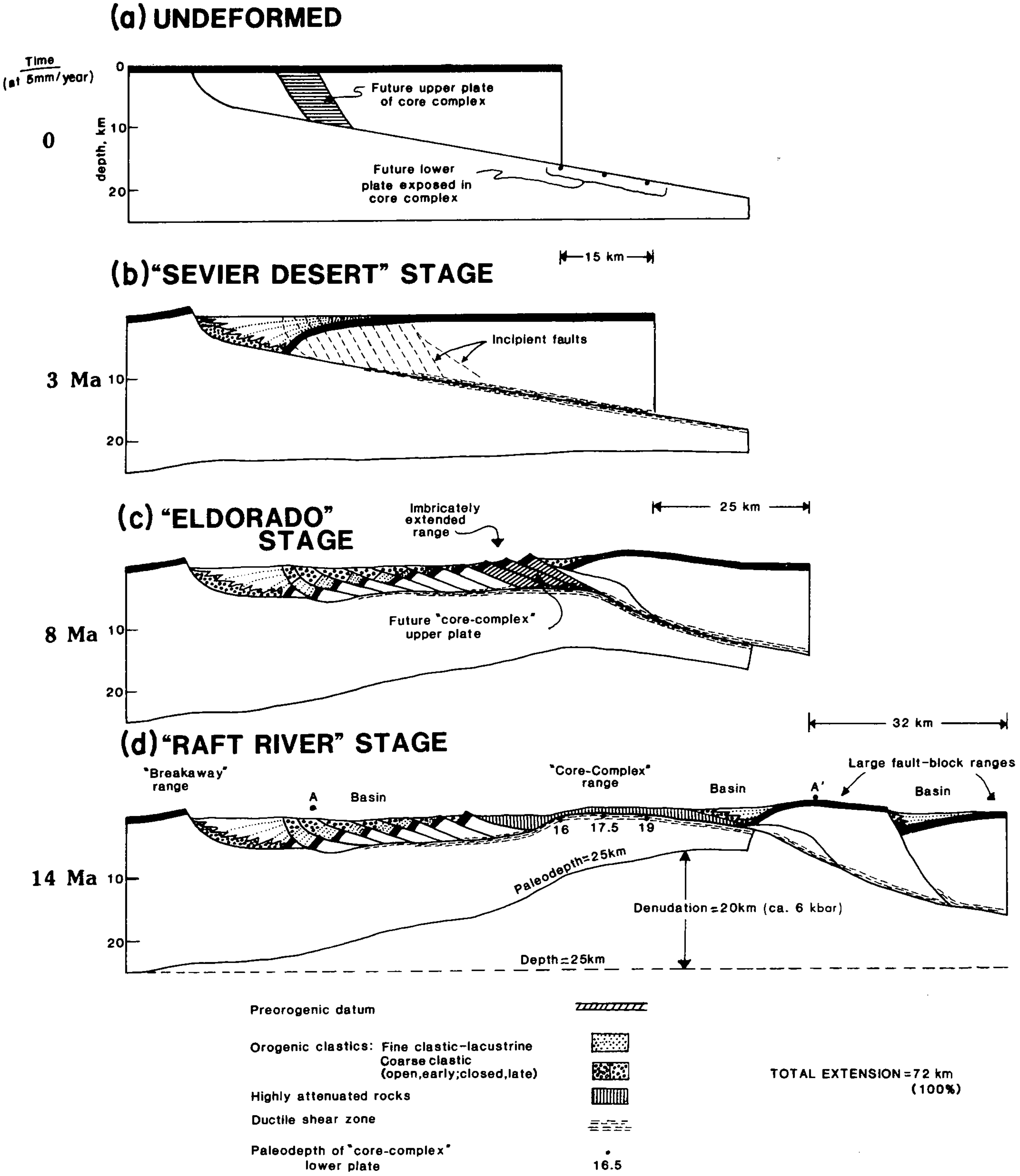

FIG. 3. Developmental model of an extensional shear system in the upper and middle continental crust, showing in particular how mid-crustal rocks may be reworked in an extensional shear zone under greenschist or amphibolite facies conditions (*b*), cool through geochronometric blocking temperatures (*c*), and be reworked under brittle conditions 5–10 Ma later, assuming probable strain rates and extension magnitudes. For simplicity, no attempt is made to palinspastically account for the volume of clastic detritus deposited during rifting. Mechanisms of upper-plate dilation include sedimentary infilling (*b*), imbricate distension (*c*), and wholesale subaerial denudation (*d*).

ment terrains, and it is emphasized that specific geometries of these shear systems and basin geometries are highly diverse. Although a typical detachment system may contain complex combinations of these elements (especially when the along-strike dimension is considered), Spencer (1984) has shown how the simple geometry of a breakaway, synformal upper plate, arched core complex, and wedge-shaped upper plate (shown in Fig. 3*d*) accounts for observed geometries in a num-

TABLE 1. Examples of range types and sedimentary basins associated with upper- and middle-crustal low-angle shear systems

BREAKAWAY RANGES	EARLY BASINS
Galiuro Mountains, Arizona Beaver Dam – north Virgin mountains, Nevada, Utah, and Arizona (see Fig. 14) Wasatch Range, Utah Pavant Range, Utah Wasatch Plateau, Utah Spring Mountains, Nevada (see Fig. 15)	Sheep Pass, Nevada (Eocene (?)–Oligocene) Horse Spring, Nevada (Late Oligocene – Miocene) Titus Canyon – Artist Drive, California (Late Oligocene – Miocene) Coal Valley, Nevada (Miocene) Sevier Desert, Utah (Miocene–Recent) Gene Canyon – Artillery, California and Arizona (Mid-Oligocene–Miocene) Pantano–Mineta, Arizona (Late Eocene – Miocene)
IMBRICATELY EXTENDED RANGES	"CORE-COMPLEX" RANGES
Eldorado and Black mountains, Nevada and Arizona Singatse and Buckskin ranges, Nevada Southern Black Mountains, California Resting Spring and Greenwater ranges, California Desert Range, Nevada South Virgin Mountains, Nevada	Catalina–Rincon mountains, Arizona Whipple–Buckskin–Rawhide mountains, California and Arizona Newberry Mountains, California and Nevada Mormon Mountains, Nevada Snake Range, Nevada Raft River Mountains, Utah
LARGE FAULT-BLOCK RANGES	
Gila Mountains, Arizona Artillery and Aquarius mountains, Arizona McCollough Range, Nevada Argus Range, California	Meadow Valley Mountains, Nevada Confusion Range, Utah Adobe Range, Nevada Sublette Range, Idaho

ber of detachment systems. Table 1 gives specific examples of range types according to the classification scheme in Fig. 3, as well as specific sedimentary basins that are related to early extensional tectonism.

It thus seems that in many areas the range-forming process is an integral part of the detachment process. Overprinting of several major shear systems may account for observations of detachment terrains overprinted by large fault-block ranges. It is noteworthy that the only direct information revealing the process of formation of at least some of the classical basin ranges comes from Consortium for Continental Reflection Profiling (COCORP) data in the Sevier Desert area (Allmendinger *et al.* 1983). These data demonstrate that the Pavant, Crickett, and House ranges, all excellent examples of classical basin ranges in west-central Utah, are an integral part of a large-scale system of down-to-the-west shear on low-angle normal faults. This particular system of detachments is probably still active (Wernicke 1981*a*). Nowhere have any geophysical or geological data conclusively documented that actively forming basin ranges are accommodated *in situ* at depth by ductile stretching and igneous dilation.

The model for upper and middle crustal extension presented in Fig. 3 suggests that detachments are major, crustally penetrating normal faults or shear zones that form with shallow, regional initial dip (10–30°) and progressively flatten and flex as a result of either the upper plate being unloaded from the lower plate or later events (such as reverse-drag flexing) deforming the fault surface. Thus, arches with axes perpendicular to transport direction are not products of the initial geometry of boudins or lenses, nor are detachments regional subhorizontal boundaries between crustal layers of contrasting rheological properties.

The validity of regional initial dip and the existence of a single shear surface penetrating rheological boundaries have recently been dramatically confirmed by the COCORP data in the Sevier Desert area (Allmendinger *et al.* 1983). In the profile, a single low-angle (ca. 12°) reflector with unequivocal normal offset can be traced from near the Earth's surface to 12–15 km depth. The fault may penetrate to as much as 20 km depth, as supported by a weaker band of reflectors that continue down-dip from the more obvious ones (down to about 7 s two-way travel time). Reasonable estimates for the displacement on the fault are about 30–60 km. If so, restorations of the deeper parts of the hanging wall indicate that it initiated as a single shear zone from the surface to a depth of at least 21 km (30 km offset restored over a 12 km deep footwall) and possibly as much as 30 km (60 km offset, as shown in Fig. 4). The large depth range over which the detachment is present (at the very minimum 12 km) suggests rocks along it are shearing under conditions in excess of 360°C and 3.5 kbar (350 MPa), assuming Lachenbruch and Sass's (1979) standard Basin and Range geotherm of 30°C/km. If the deeper estimates of detachment – shear zone initiation are considered (for example, 20 km with a 30°C/km geotherm), then shear along the deeper parts would have taken place at 600°C (mid-amphibolite facies) and 6 kbar (600 MPa). Both estimates are well within the ductile field of deformation for granitic rocks (Tullis and Yund 1977). Kinematically, the large-scale, uniform-sense simple shear of the upper and middle crust evidenced by the profile is difficult to interpret in terms of various models advocating rheological layering as the primary control of extensional strain geometry.

Consideration of experimental rock mechanics and thermal modeling argues strongly against the discrete brittle–ductile transition suggested by many of the pure-shear scenarios for detachment genesis (most recently Miller *et al.* 1983). Experimental deformation of dry quartzo-feldspathic rocks by Tullis and Yund (1977) indicates that such a transition takes place

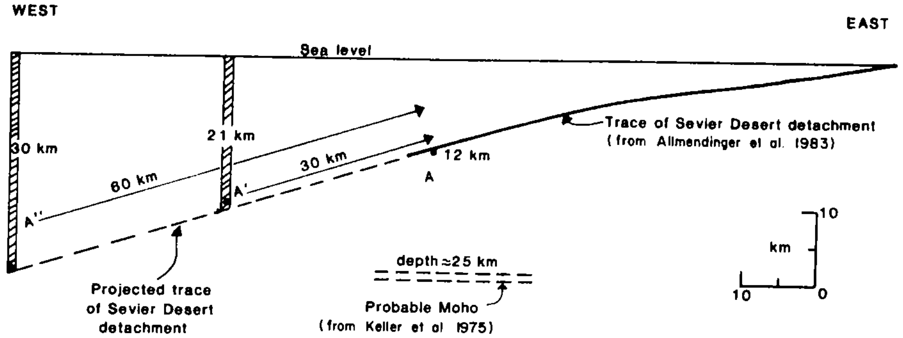

FIG. 4. Diagram showing possible initial overburden on the deepest clearly visible part of the Sevier Desert detachment.

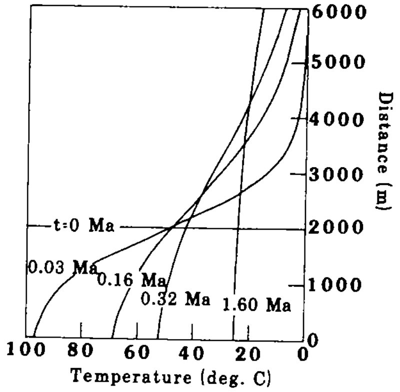

FIG. 5. Time versus temperature profile for conductive decay of a 100°C temperature step in rocks with thermal diffusivity of 1.3×10^{-6} $m^2 s^{-1}$, adapted from Carslaw and Jaeger (1959).

gradually over a temperature range of 300–500°C. This approximate range of transition is consistent with phase equilibrium studies of mylonitic rocks in which quartz is ductilely strained (e.g., Anderson *et al.* 1979; Davis *et al.* 1979). For this type of deformation to occur within a few tens of metres of unrecrystallized, brittlely shattering upper-plate rocks would require the maintenance of a thermal gradient of 100°C km or more across the detachments for long periods of time, at least several million years. Figure 5 shows the decay by thermal conduction of a 100°C temperature step in rocks of typical crustal conductivity. If significant hydrothermal circulation were present in the system, the decay times would be substantially reduced. The extremely short lifespan of sharp thermal gradients in the crust indicated by these calculations (particularly over distances of a few hundred metres or less) is a serious problem with hypotheses that require the close juxtaposition of brittlely shattered materials and dynamically recrystallizing quartzo-feldspathic rocks over long periods of time (e.g., Miller *et al.* 1983). Even if heat were continuously infused into the lower plate by some mechanism, it is still virtually impossible to keep the upper plate from heating up to a similar temperature.

In addition to the large spatial separation of brittle and ductile deformation indicated, Fig. 2 underscores the temporal separation between ductile deformation and the final emplacement of the upper plates in most detachment terrains. To a large degree, mylonitization takes place under conditions in which (1) quartz is ductile in quartzo-feldspathic rocks and (2) middle and even upper greenschist facies metamorphism takes place. Figure 6 outlines the likely temperature range for this type of deformation in comparison with the range of argon closure temperatures in biotite derived by Wagner *et al.* (1977). The likely temperature range of deformation of dynamically recrystallizing quartzose rocks is generally above these closure temperatures.

The geometry and kinematics of these regionally persistent upper- and middle-crustal shear systems are highly analogous to those of fold–thrust belt systems, and detachment-bounded, transported plates are thus termed extensional allochthons (Wernicke and Burchfiel 1982). These systems form elongate belts within the Basin and Range Province, and it is the large-scale, regionally uniform sense of shear within two of these belts that will be discussed below in the context of geophysical observations of nearby areas.

Lower-crust and mantle lithospheric extension

A possible means of placing constraints on deep-lithosphere strain geometry is to compare deep geophysical data with strain geometry observed from geological mapping at the surface. In particular, the relationship between an observed crustal thickness and that expected from the geologic history of an area should indicate whether or not the crust extends strictly by pure shear.

Segments of the Basin and Range – Colorado Plateau (or Rocky Mountain) transition zone, including the Wasatch Front region in Utah and the Mogollon Rim vicinity in Arizona, are well suited for this type of comparison. The geology of both areas is known well enough to make reasonable assumptions about their crustal thickness histories, and both areas have been surveyed using the seismic refraction technique, permitting comparison of the two sets of data. The transition zones in Utah and Arizona also approximately coincide with the westernmost front of large-scale crustal shortening during Mesozoic time. In orogenic belts that have not experienced major postcompressional extension, such as the Helvetic Zone in the Swiss Alps and the foreland fold and thrust belt in Canada, crustal thickening is evident as one moves from the cratonal foreland into the compressional belt. In both areas (and as was emphasized by Monger and Price (1979) for the Canadian Rockies), thin platform sediments and their cratonic basement are present across most of the width of the thrust belt. Assuming the uniform, thin stratigraphy characteristic of the platform sediments indicates that, prior to nappe emplacement, the crust was of relatively uniform thickness, the thickening must be accomplished largely by top-loading the craton with basinal nappes. Monger and Price (1979) argued that the amount of crustal thickening observed in the Canadian Rockies as one moves from the foreland into the orogenic belt (from 45 to over 50 km) agrees rather closely with the structural thickness of basinal sediments emplaced onto the craton.

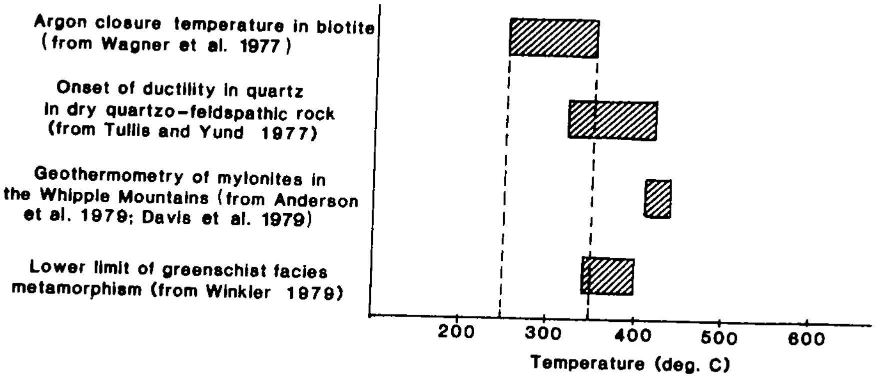

FIG. 6. Comparison of temperature ranges between some "core-complex" lower-plate tectonite lithologies and closure temperature of argon in biotite.

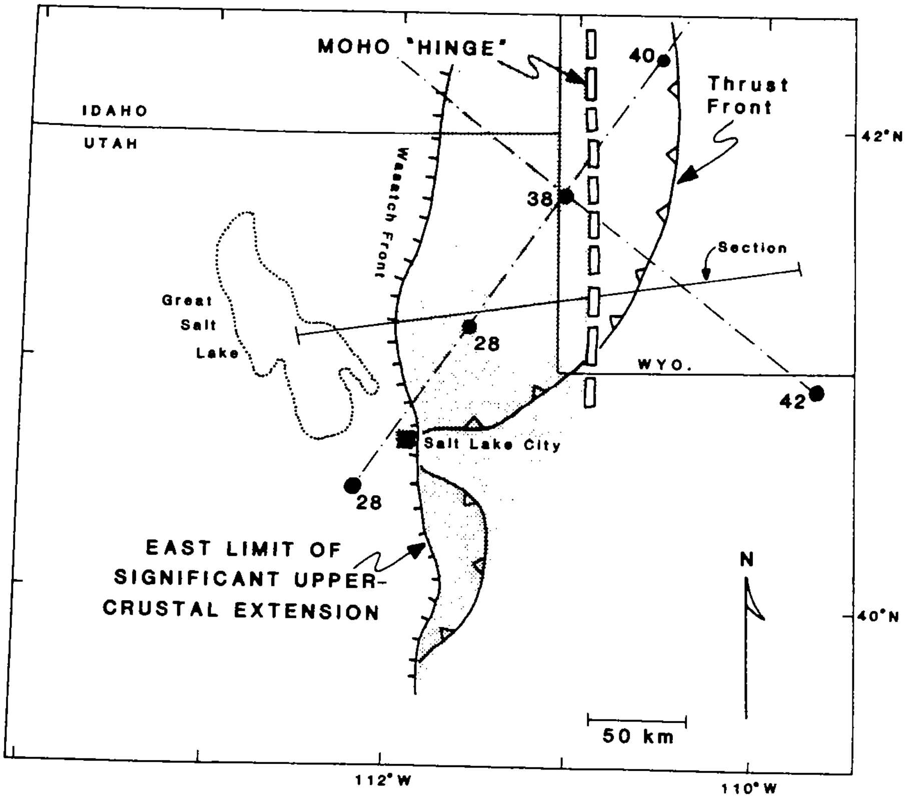

FIG. 7. Map showing positions of tectonic elements and refraction lines, which may indicate a discrepancy between crustal thickness deduced from surface faulting and that actually measured. Refraction lines and interpretatons from Braile *et al.* (1974). Section line refers to Fig. 8.

Discrepant Moho depths in Utah and Arizona

Unlike their unextended counterparts, the crust in Utah and Arizona thins from foreland into the craton-margin (Utah) or intracratonic (Arizona) orogenic belt.

In Utah (and part of Wyoming) (Fig. 7), the expected Mohorovičić discontinuity (Moho) configuration would be a Plateau – Rocky Mountain crustal thickness of about 40–45 km increasing up to 50–55 km in the area just east of the Wasatch Front, where thick late Precambrian and Paleozoic basinal sediments have been emplaced atop the cratonal margin. Instead, the refraction data and interpretations of Braile *et al.* (1974), although not completely unambiguous, suggest that westward thinning of the crust begins at or just west of the thrust front. So at precisely the location east of the Wasatch Front where the Mesozoic geology predicts a ≥50 km thick crust, a thickness of only 28 km is observed, suggesting that the crust has been thinned by nearly a factor of two since Mesozoic time. Royse (1983) has shown that extensional faulting in the region between the Wasatch Front and the thrust front, a distance of over 100 km, accounts for less than 10 km of extension. Further, this extension consists only of back-slipped thrust faults and does not involve the autochthonous cratonic block. Thus, the maximum thinning of the crust across the interval in question deduced from surface geology is no more than several kilometres. This is so little that one might still expect the thrust belt to be a locus of thickening had surface normal faulting been the sole crustal thinning process. The discrepancy between crustal thinning deduced from Moho depths and that deduced from surface faulting is depicted in Fig. 8, across the section line shown in Fig. 7.

The area between the onset of thinning and the first significant upper-crustal extension is here termed a *discrepant zone*; in Utah and Wyoming it appears to have a width of about 100 km. The eastern margin of the discrepant zone, or Moho

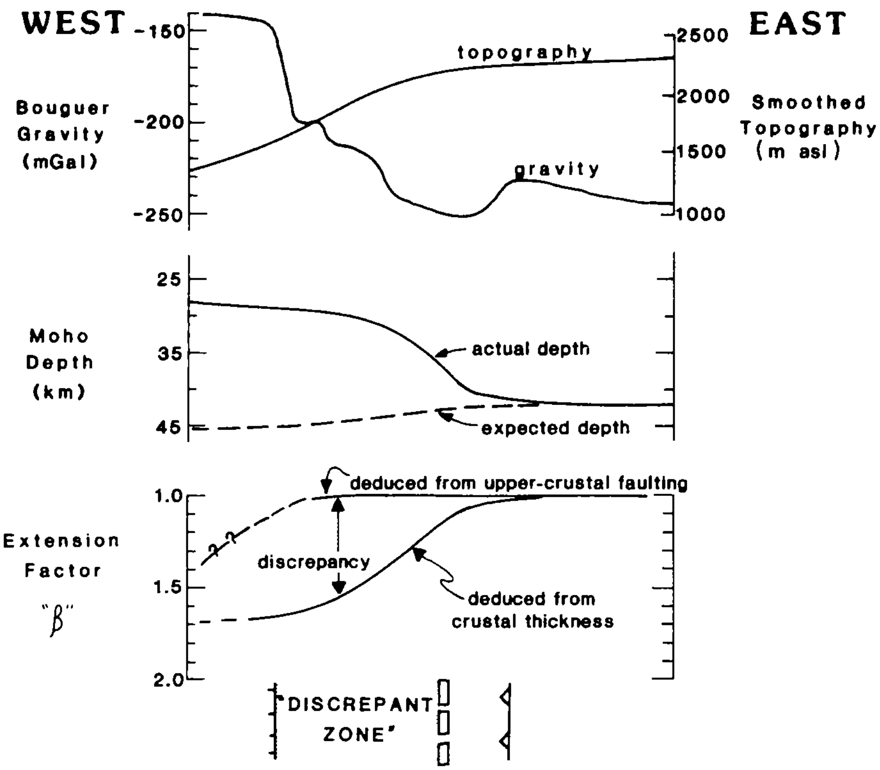

FIG. 8. Data along section line in Fig. 7 showing discrepant zone defined by crustal thickness deduced assuming pure-shear crustal necking and that deduced from refraction experiments. Line marked "expected depth" is the probable Moho configuration before extension. Gravity and smoothed topography from Eaton *et al.* (1979).

"hinge," coincides with other hinges, most notably a westward decrease in smoothed topography and an increase in Bouguer gravity (Fig. 8). Other anomalous geophysical aspects of the discrepant zone are summarized in Smith (1979) and Thompson and Zoback (1979).

A situation analogous to that in Utah also seems to be present in Arizona (Fig. 9). In early Mesozoic time, thin cratonal sediments blanketed the region shown in Fig. 9, suggesting that the Moho depth at that time over the entire area was approximately 40–42 km, similar to the untectonized, modern interior of the Colorado Plateau. Intracratonic compression and uplift of the Plateau – Basin and Range transition zone (southwest of the Mogollon Rim, Fig. 9) in late Mesozoic and early Tertiary time caused erosion of the Phanerozoic section and the northeastward flow of rivers toward the plateau, which during the Late Cretaceous (Turonian?) was still at sea level (Peirce *et al.* 1979). The crust in the Basin and Range and transition zone was therefore as thick as or thicker than the Colorado Plateau crust in Eocene time, prior to the onset of extensional deformation. The transition zone has experienced only minor extensional strain during the Tertiary, occurring on high-angle normal faults that only mildly rotate mid-Oligocene and younger volcanics blanketing large areas of the transition zone. Although precise estimates of surface dilation cannot yet be made between the Mogollon Rim and Phoenix, the total extension is probably no more than a few kilometres across an area nearly 100 km wide. These observations predict a transition zone crustal thickness of about 40–42 km or greater, assuming surface extensional faulting is held strictly accountable for the amount of crustal thinning. Instead, refraction data from Warren (1969) and Sinno *et al.* (1981) indicate that southwestward thinning of normal Colorado Plateau crust (40–42 km thick) may begin on or even northwest of the Mogollon Rim (at the Moho hinge, Fig. 9) and thins to less than 30 km thick about 50 km northeast of Phoenix, where surface normal faulting becomes significant enough to expect crustal thinning. These data may define a discrepant zone some 125 km wide in which crustal thinning is not accounted for by surface normal faulting. As shown in Fig. 10, the Moho hinge also corresponds to a change in gradient of regional topography and Bouguer gravity, as was the case in the Utah transition zone.

Evolution of discrepant zones

Although some workers still advocate chemical processes by which crustal-velocity materials may be transformed into mantle-velocity materials, thereby thinning the crust (e.g., Chenet and Montadert 1981), such models are improbable because (1) a chemical process that could transform even a dominantly gabbroic lower crust into mantle-velocity materials at less than 20 kbar (2000 MPa) confining stress has not been demonstrable experimentally, and (2) deeply eroded portions of continental crust (shield areas, the Ivrea zone, etc.) contain no evidence that such a process occurs. The general correspondence between thin crust in rifts (0–30 km), intermediate thickness crust in shield areas (30–45 km), and thick crust in compressional areas (45–70 km) also argues that changes in crustal thickness result predominantly from strain rather than mobile chemical reaction fronts.

Using this assumption, the geometry of the discrepant zones in Arizona and Utah requires removal of crustal material from beneath them. Assuming the missing lower crust was not mechanically digested to great depth by the mantle lithosphere, this material must have been normally sheared up-to-the-west toward the Basin and Range Province (normal simple shear,

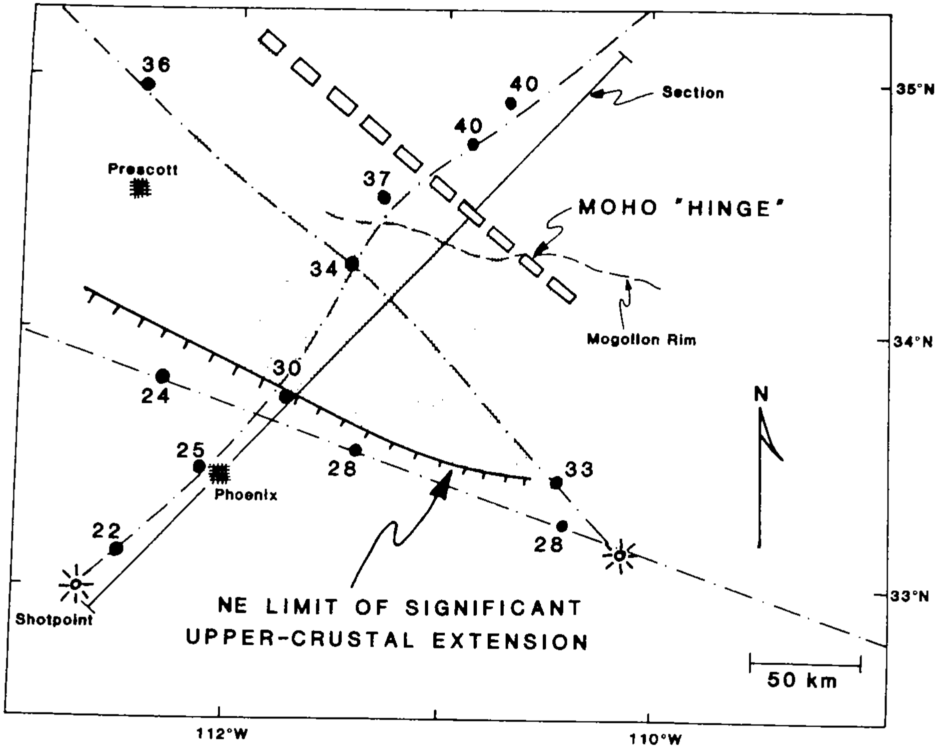

FIG. 9. Map showing positions of tectonic elements and refraction lines defining a discrepant zone northeast of Phoenix, Arizona. Northeast- and northwest-trending lines from Warren (1969); west-northwest-trending line from Sinno *et al.* (1981). Section line refers to Fig. 10.

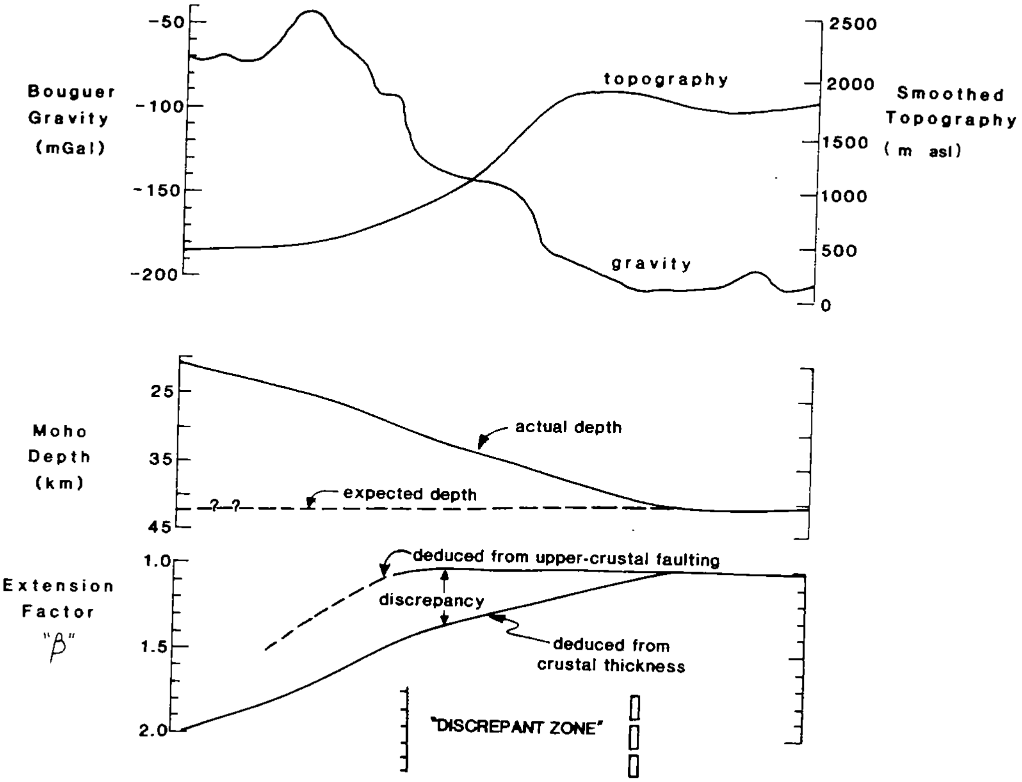

FIG. 10. Data along section line in Fig. 9 showing position of discrepant zone. Line marked "expected depth" is the probable Moho configuration before extension. Gravity and topography from Eaton *et al.* (1979).

Fig. 11). It cannot be discerned from these data whether or not the shear is localized in a single narrow zone, a number of narrow zones bounding undeformed slices, or a very wide zone of relatively uniform shear (end-member cases shown in Fig. 11), but the overall geometry must be one of large-scale, down-to-the-east normal simple shear if rocks at the surface in the discrepant zones are to remain relatively undeformed.

In and of itself this hypothesis is not especially compelling in view of the uncertainties in the refraction method (in particular the delay-time method) in determining Moho depths.

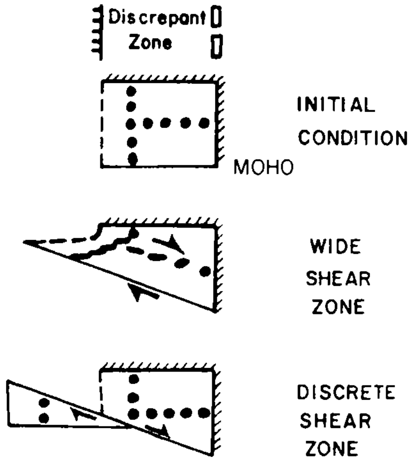

FIG. 11. Diagram showing end-member processes responsible for the development of discrepant zones.

However, to the west of both discrepant zones lie belts of extensional allochthons involving upper- and middle-crustal rocks with a down-to-the-east sense of simple shear. In Utah, the terrain of interest is the Raft River – Grouse Creek – Albion terrain (Compton 1972, 1975, 1980, 1983; Compton *et al.* 1977; Armstrong 1982), which involves at least 60 km of eastward translation of extensional allochthons involving the upper and middle crust (Compton and Todd 1979; Wernicke 1982*a*; Covington 1983). In Arizona, the northwest-trending belt of extensional terrains, including the South Mountains terrain near Phoenix (Reynolds and Rehrig 1980; Reynolds 1983; Davis *et al.* 1983), appears to represent at least several tens of kilometres of down-to-the-northeast simple shear of upper- and middle-crustal rocks.

Hypothesis of a normally sheared lithosphere

The geophysical data and recent interpretations of surface data discussed above together raise the possibility that the entire crust failed in down-to-the-east normal simple shear in mid-Tertiary time. This in turn leads to the hypothesis that the entire lithosphere failed by down-to-the-east simple shear and that such a strain pattern typifies rift tectonics. It is therefore necessary to qualitatively model normal shear of the entire lithosphere in order to devise potential tests for the hypothesis.

A hypothetical normal shear zone through the lithosphere is shown in Fig. 12. Although possible geometries are quite variable, any normally sheared lithosphere may be divided into five zones, corresponding to the amount of thinning experienced by the crust relative to the mantle lithosphere. Following the usage of Dokka (1983), the relative positions of rift elements will be referred to as "proximal" and "distal" with respect to the upper crustal breakaway and its adjacent unextended terrain.

According to the analysis of McKenzie (1978) and Royden and Keen (1980), net uplift or subsidence resulting from rifting involves an interplay between relative thinning of the mantle lithosphere and the crust. Since mantle lithosphere is more dense than asthenosphere, thinning it will cause uplift. The opposite is true of crustal thinning. Initial subsidence or uplift resulting from extensional strain (the initial condition of an instantaneously extended lithosphere) is termed the *tectonic subsidence* by Royden and Keen (1980), and subsidence related to later conductive cooling of the mantle lithosphere is termed the *thermal subsidence*.

Unstrained lithosphere toward the "breakaway" side of the rift, here termed zone A, may experience a small amount of uplift adjacent to the breakaway if the breakaway cuts steeply enough into the crust to cause an isostatic "edge effect" (e.g., Hellinger and Sclater 1983). Abrupt unloading of several kilometres of crust by the breakaway fault will cause substantial rebound of the crust there, which, if firmly enough coupled to unstrained crust in zone A, will produce uplift. Lateral conduction of heat from the rift could also serve to uplift zone A. If substantial erosion of uplifted zone A crust occurs, it may then experience an amount of thermal subsidence greater than its uplift during extension.

Zone B, defined as the region over which crust but not mantle lithosphere is extended, should experience subsidence both during and after the rifting event, since both processes add mass to the isostatic column. The point at which the shear system cuts into the mantle defines the distal boundary of zone B.

Within zone C, both crust and mantle lithosphere are extended. The locus of maximum crustal attenuation (and hence maximum net subsidence) is shown in Fig. 12 to lie within zone C, but it is geometrically possible for it to lie within zone B. A change from tectonic subsidence to uplift will occur in this zone, since the effect of thinning mantle increases in significance relative to the effect of crustal thinning as one moves from the proximal to the distal side of the zone. The distal limit of significant upper-crustal dilation (proximal margin of the discrepant zone) will occur in this zone, most likely (but not necessarily) in a distal position relative to the locus of maximum crustal thinning. The distal margin of zone C is defined as the point where the crust ceases to be involved in the thinning process and only mantle lithosphere is involved. This is also the distal margin of the discrepant zone.

In zone D, since only mantle lithosphere is thinned, the effect of uplift will be most pronounced because it contains the locus of maximum lithospheric thinning and will be manifest by broad topographic doming during rifting. Erosion of this dome may effectively thin the crust, thereby causing thermal subsidence to slightly exceed uplift.

Zone E, like zone A, is unstrained, but may be involved in uplift and, because of erosion, net subsidence from an edge effect if the shear zone in the lower lithosphere is sufficiently steep. Since zone E is especially close to the point of maximum asthenospheric upwelling in zone D, it may be susceptible to uplift from lateral conduction of heat from zone D.

Application of the hypothesis to the Basin and Range and Red Sea areas

The sheared lithosphere model successfully accounts for a number of observations in Arizona, Utah, and the Red Sea region, most notably the broad topographic arches that occur in the distal parts of all three rifts in areas that have experienced little surface strain. Indeed, the overall "sine wave" for tectonic subsidence is borne out extremely well by the topography in all three areas. The key tectonic features relevant to the model in Arizona and Utah are shown in Fig. 13.

In Arizona, a wide belt of extensional allochthons covering a width of over 150 km (not all of which are demonstrably northeast directed) is exposed from just northeast of Phoenix to the Gulf of California. The breakaway zone is thus difficult to define, and the model can only be applied beginning in zone B or C. Judging by the width of the extended zone, the mantle probably becomes involved in a relatively proximal position, and thus the B–C boundary occurs at the Moho hinge. Zone D

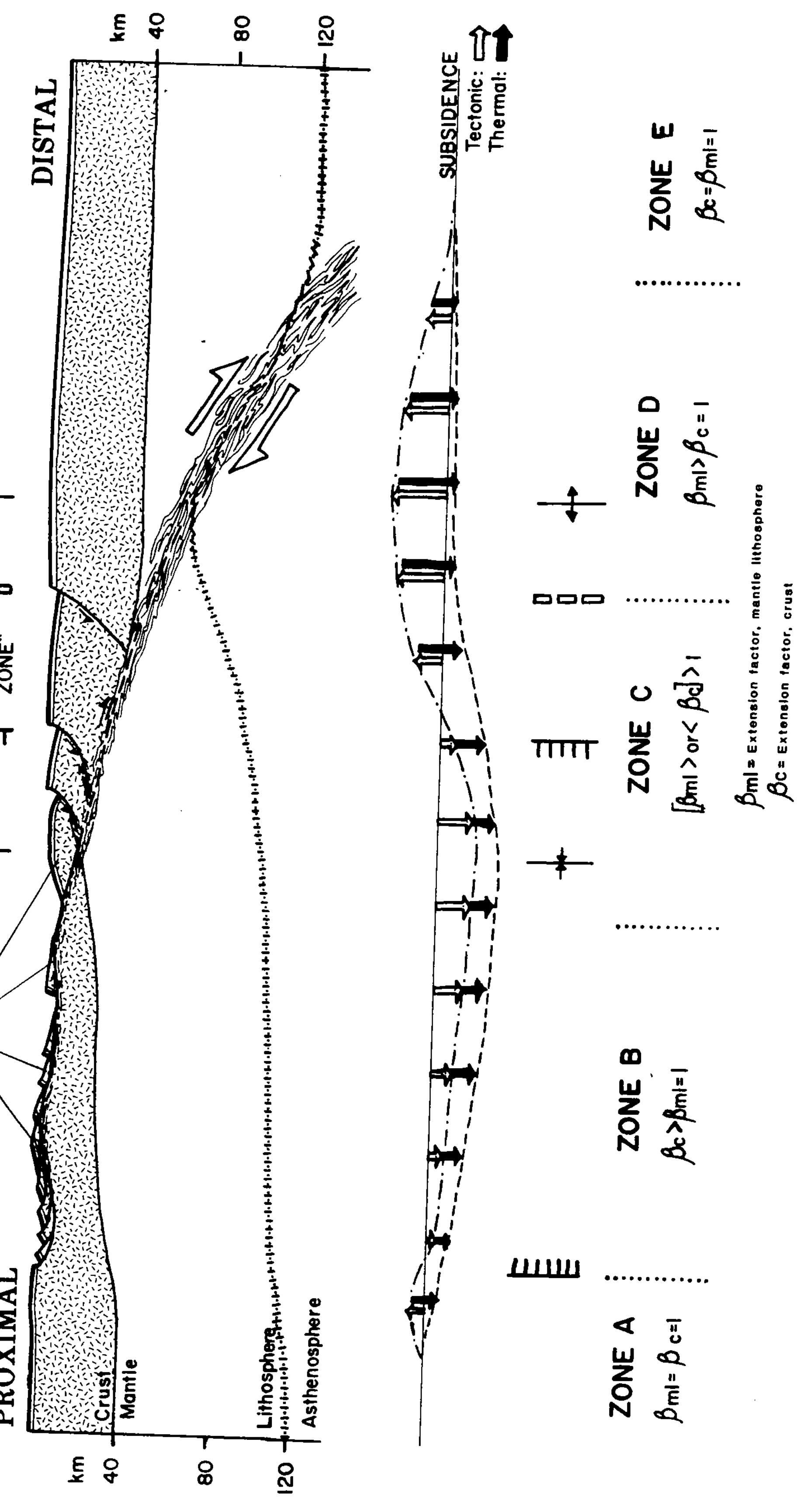

FIG. 12. Hypothetical normal simple shear of the entire lithosphere. See text for discussion.

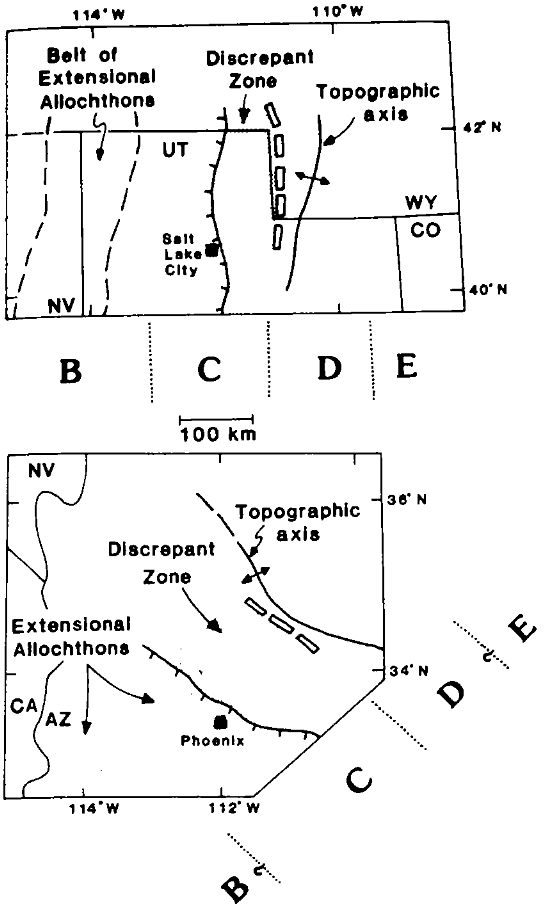

FIG. 13. Positions of extensional allochthon belts, discrepant zones, and topographic arches in Arizona and Utah that are interpretable as indicating a sheared lithosphere. Approximate positions of zone boundaries derived from the hypothetical normally sheared lithosphere in Fig. 12 are also shown. Topographic axes taken from Eaton (1979).

contains the topographic culmination evident in smoothed topography (Eaton 1979), which locally is nearly coincident with the Moho hinge, although the location of the hinge is imprecise. Total topographic relief from the extended area to the culmination is over 2 km, with the sharpest gradient occurring in the discrepant zone. The close proximity of the topographic culmination and Moho hinge may reflect a rather steep inclination (30–40°) of shear in the mantle lithosphere. The timing of uplift in zone D relative to the Basin and Range is virtually synchronous with extensional strain in the belt of extensional allochthons to the southwest. According to Peirce *et al.*'s (1979) and Mayer's (1979) analysis of the Mogollon Rim, drainage reversal and establishment of a "plateau edge" occurred during Oligocene time, as evidenced by sediments of that age deposited downslope from the modern rim.

In Utah (Fig. 13) it is also difficult to define a breakaway zone because a significant amount of extensional tectonism is present to the west in much of Nevada, and it is not yet clear what the geometric relationship is between this extension and the east-directed extensional allochthons present in the Raft River Mountains and Snake Range areas. A further complication arises because of the younger, west-directed extensional allochthons present in the Sevier Desert, within the Idaho–Wyoming thrust belt, and along the Wasatch Front.

Apart from these complications, the Raft River Mountains are interpreted here to lie in a zone B position, with the beginning of mantle involvement in the shear system (B–C boundary) and the area of thinnest crust (Smith 1979) occurring to the east. Part of the crustal thinning and the reason for the large gap between the proximal margin of the discrepant zone and the most distal east-directed extensional allochthons may be attributed to major west-directed extension ranging in age from Late Miocene to Recent times. As in Arizona, the Moho hinge lies within tens of kilometres of the topographic axis, suggesting relatively steep shear at depth. The D–E boundary is inferred to exist where the topography returns to a "background" level of about 1.5–2.0 km for much of the Plateau – southern Rocky Mountain region. Eastward transport of extensional allochthons began as early as Oligocene time in east-central Nevada (Gans 1981; Miller *et al.* 1983), but continued into at least the Late Miocene in the Raft River Mountains area (Compton 1983; Covington 1983). Although a regional topographic gradient of as much as 1500 m exists and as in Arizona has its sharpest gradient across the discrepant zone, it is not clear when the differentiation between the modern topographic axis and the lower terrain of zones B and C began. Just south of the area in Utah shown in Fig. 13, Bodell and Chapman (1982) have defined a boundary between high heat flow present along the western side of the Plateau and lower heat flow in the interior. The "hot corridor" along the western side is consistent with an area beneath the plateau in which lower lithosphere and asthenosphere are sheared up-and-to-west toward the Basin and Range.

The belts of extensional allochthons discussed below do not have easily defined breakaways against unstrained lithosphere, but both belts of east-directed extensional allochthons seem to die out toward the latitude of Las Vegas, Nevada, where all allochthons are west directed and primarily younger than the east-directed group (Wernicke 1982*b*). Here, the western side of the Colorado Plateau provides an excellent example of a breakaway zone. The sharp structural and topographic uplift of the northern Virgin and Beaver Dam mountains at about latitude 37°N at the Nevada–Utah–Arizona corner (Fig. 14) reflects the edge effect from unloading discussed below.

Another example of an extensional allochthon – topographic belt pair may be the region including the Spring Mountains, southern Nevada, and the Sierra Nevada Range, California (Fig. 15). A sharp breakaway zone of west-directed extensional allochthons has been defined by Burchfiel *et al.* (1983) along the western side of the Spring Mountains. To the west, a wide area of extensional allochthons is present in the Death Valley region; these lose intensity west of the Panamint Range into the mildly extended White–Inyo and Sierra Nevada ranges. Smoothed topography (Eaton 1979) shows an increase of 2 km from the highly extended Death Valley region to the Sierra–White–Inyo area. It is also interesting to note that the lowest and highest topographic points in the coterminous United States are present within the system, with a low of 86 m bsl in Death Valley to a high of 4419 m asl on Mount Whitney in the Sierra Nevada Range.

The general trend seems to be that most examples of highly extended terrains seem to have broad topographic domes developed in their distal portions.

An excellent example of a distal topograhic dome is found in the Red Sea rift, which appears to have precisely the topographic profile predicted by the uniform-sense, low-angle normal shear hypothesis (Fig. 16). A narrow range of high topography adjacent to the rift interrupts the topographically

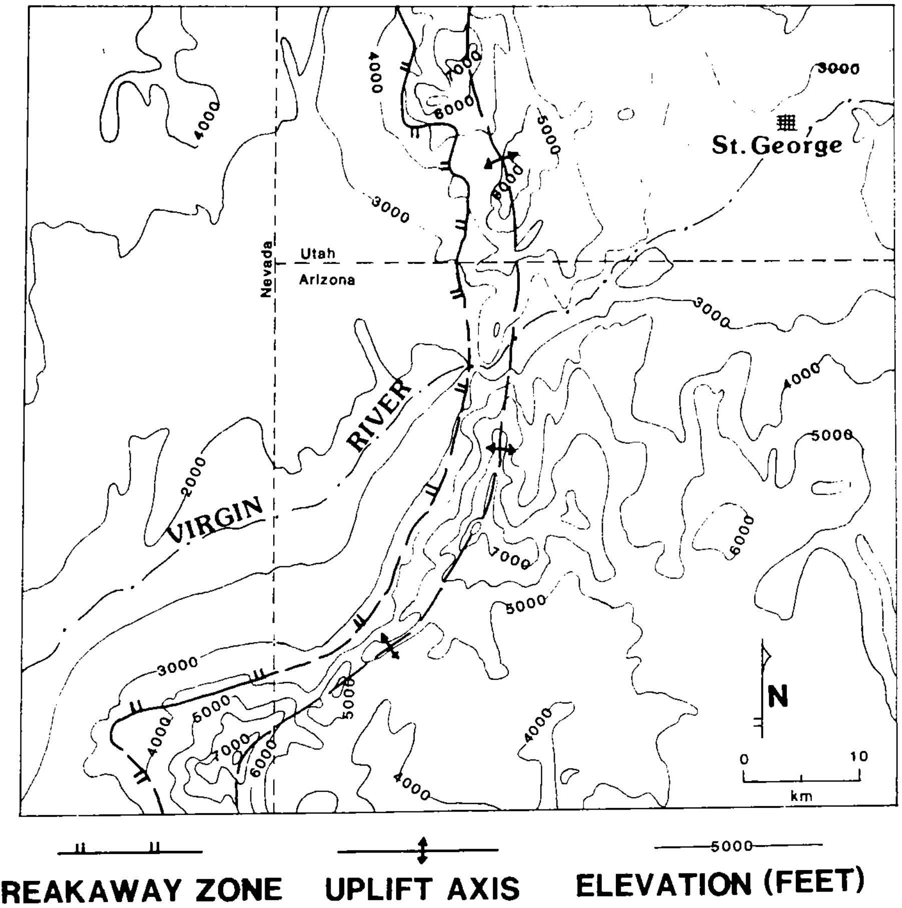

FIG. 14. Virgin–Beaverdam mountains breakaway zone, showing the easternmost trace of extensional allochthons and the closely parallel topographic axis. The system began deforming as early as mid-Miocene time (Bohannon 1979) and is probably still active. Geologically, undisturbed platformal cover of Paleozoic and Mesozoic age to the east turns abruptly upward just east of the uplift axis, which occurs largely within Precambrian crystalline basement. Faulted over the basement along the breakaway zone are extended masses of Phanerozoic strata.

low Egyptian Shield and is here interpreted as an edge effect of an exceptionally deep breakaway fault corresponding to the topographic escarpment on the west side of the range. That the breakaway may cut deeply over a relatively short distance is evidenced by the geology of Zabargad (St. John's) Island off the east coast of Egypt in the Red Sea itself (Fig. 6). Here, Bonatti *et al.* (1981, 1983) have mapped a fragment of upper crustal rocks that include metamorphic rocks of Egyptian Shield affinity nonconformably overlain by Cretaceous (?) through Miocene sedimentary rocks. In tectonic contact with this assemblage is a remarkably fresh complex of serpentinite-free peridotitic rocks, which locally contain gem-quality olivine. The stability of spinel in the complex suggested to Bonatti *et al.* (1981) that these rocks equilibrated at a depth of more than 30 km. They interpreted these field relations as indicating "... the peridotite bodies are protrusions of upper mantle material which cut through the crust and uplifted fragments of crustal units."

I suggest that Zabargad exposes Egyptian mantle lithosphere in low-angle normal fault contact with Egyptian upper-crustal rocks, and that several tens of kilometres of crustal and mantle material has been faulted away to east, a geometry analogous to the formation of a Cordilleran core-complex range depicted in Fig. 3, except that the lower-plate rocks are mantle lithosphere instead of middle crust. Indeed, the overall structural form of the contact between the supracrustal rocks and the peridotite is interpretable as a series of three doubly plunging, east-northeast elongate domes (see Bonatti *et al.* 1981, Fig. 1), the long axes of which are parallel to the direction of opening of the Red Sea (McKenzie *et al.* 1970). This geometry is very similar to low-angle normal fault structures (detachments) in the western United States.

In the context of the hypothesis of lithospheric shear, Zabargad represents an exposure of a sheared Moho within zone C (Fig. 12), suggesting the Egyptian breakaway faults penetrated to at least 30 km depth as little as 100 km east of the boundary between zones A and B. It should be noted that geochemical data on the Zabargad peridotites (Bonatti *et al.* 1983) suggest they have affinities with suboceanic rather than subcontinental lithosphere, inconsistent with the model suggested here. A possible test of the model may be in the gravity signature of the area. Such a pronounced removal of crustal material, elevating the Moho to the Earth's surface, should be reflected by a large positive gravity anomaly as one moves from the breakaway toward the Red Sea. Unfortunately, a complete gravity traverse from the Egyptian Shield to Zabargad Island is not yet available.

The broad topographic depression of the Red Sea is probably variously attenuated pieces of shield-type rocks and rift basin deposits sheared over mantle lithosphere within zone C. Although the C–D boundary is impossible to define at the latitude of Zabargad Island, farther south at latitude 18°N seismic refraction profiling by Mooney *et al.* (1984) suggests that normal Arabian Shield crustal thickness is attained approximately

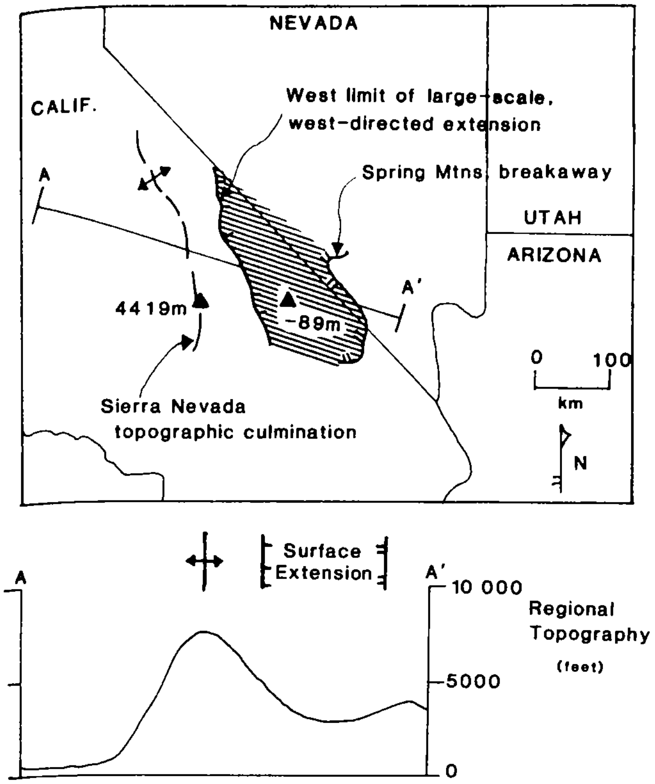

FIG. 15. Map and cross section showing breakaway, area of surface extension, position of topographic axis, and topographic profile across part of southern Nevada and central California. Triangles show locations of highest and lowest points in the coterminous United States. The zone of extensional allochthons depicted here is currently active.

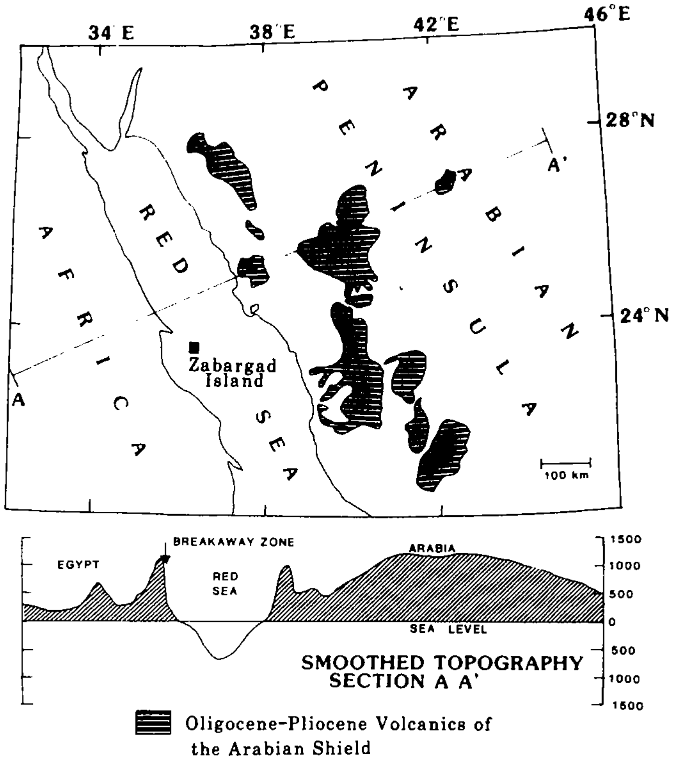

FIG. 16. Map of the Red Sea region showing the location of Zabargad Island, the rift volcanics of the relatively unextended Arabian Shield, and the asymmetric topographic profile of the rift. See text for discussion.

along the steep topographic escarpment on the west side of the Arabian Shield, similar to the situation near the Mogollon Rim in Arizona. According to Coleman (1974), the topographic escarpment on the eastern side of the Red Sea is not fault controlled but is associated with monoclinal downwarping of the Arabian Shield toward the southwest, another point in common between this area and the Mogollon Rim. The extremely wide zone of high topography (1000 m) throughout the Arabian Shield may be attributed to up-to-the-west normal shear of the lithosphere and its replacement with asthenosphere in the absence of any crustal thinning (zone D tectonics). The D–E boundary is presumably east of the zone of high topography, although it may occur within that zone because of the edge effect discussed above or because of a small amount of lateral conductive heating of unstrained zone E lithosphere from the uplifted "keel" of asthenosphere to the west.

In addition to topographic uplift, zone D high topography of the Arabian Shield is mantled by a suite of Oligocene to Recent ultramafic xenolith-bearing volcanic rocks composed largely of alkali olivine basalts, with lesser volumes of andesite and rhyolite (Coleman 1974) (Fig. 16). This distal, zone D volcanic province may be interpreted as resulting from partial melting of mantle lithosphere and asthenosphere caused by rapid unloading. The shear-zone geometry of Fig. 2, for example, shows a rise of over 60 km of lower lithosphere because of extension. Pyrolitic continental lithosphere in the Red Sea region had probably been strain free since the Cambrian consolidation of the Arabian Shield (Brown 1970). Upward shear and sudden unloading of many kilobars of the lower lithosphere beneath the shield are conceivable means of generating these magmas.

Role of magmatism

Footwall rocks across the entire width of a simply sheared lithosphere are subject to many kilobars of rapid unloading. The overall environment of rising material in any type of extensional setting will promote melting because dry melting curves typically have shallower slopes than adiabatic paths on pressure versus temperature plots (e.g., Carmichael *et al.* 1974). The geometry of Fig. 12 predicts that extension in proximal areas of the rift may induce melting of dry middle- and lower-crustal rocks as well as the entire lithospheric column. In distal volcanic belts, however, only deep lithosphere and asthenosphere should be subject to melting by the unloading mechanism. Hypersthene-normative rocks dredged from the Red Sea versus the alkaline character of the Arabian Shield volcanics (Coleman *et al.* 1977) is a possible reflection of contrasting depths of anatexis across the rift, although alkalinity need not be an indicator of depth.

It is interesting to note that in Arizona the volcanic belt composed of predominantly calc-alkaline basaltic andesites occurring in the transition zone and on the Colorado Plateau (mentioned above) are in general coeval with, or slightly younger than, the emplacement of extensional allochthons to the southwest. These rocks may have an origin akin to that proposed here for the Arabian Shield volcanics.

The major observation that the simple-shear theory does not specifically predict is the presence of anomalously warm mantle in proximal parts of the rift. The Basin and Range Province is characterized by low P_n velocities and high regional topography. Apparently, the mantle lithosphere is absent under parts of the Basin and Range (P_n velocities 7.4–7.8 km/s in many areas), and the regional elevation of the western United States suggests thinner than normal lithosphere is present over the entire region (Thompson and Zoback 1979). Neither the pure-shear stretching model of McKenzie (1978) nor the simple-shear concept discussed here is capable of producing tectonic uplift within a region of *crustal* thinning unless crust and lithosphere are abnormally thin prior to rifting. However, if the Basin and Range is composed of a small number of extensional belts overlapping in space and time, the simple-shear theory provides a means by which large areas of mantle lithosphere may be completely removed mechanically in different areas across the province (as well as outside of it). A pure-shear stretching model does not permit this to occur. The mechanism of lithospheric attenuation advocated here is one of mechanical extension by shear, aided by permeating magmas, without any major extensional strain of the lower lithosphere within zones A, B, and C, and a combination of both mechanisms in zones D and E. In this scenario, magmatism and its potential role in adding heat to the lithosphere are viewed as "passive" responses to extensional strain of the lithosphere and may occur in the absence of major convective overturn in the asthenosphere. Although the role of magmatism is admittedly important and ever more so complex, the simple-shear theory provides a reasonable explanation of magmatic belts in rifts far removed from areas of crustal extension. It is not obvious how a pure-shear geometry would generate such a belt.

Discussion and conclusions

Most readers need not be reminded that the hypothesis of a normally sheared lithosphere is precisely that and that many of the interpretations made here are based on data that are, within their uncertainty, ambiguous as to whether or not they support simple or pure shear. In particular, seismic refraction profiles in the Basin and Range are often unreversed (e.g., Braile *et al.* 1974) or use simple delay-time techniques that require an assumed P_n velocity and crustal thickness at one end of the profile (e.g., Warren 1969). Combined with the usual uncertainties in picking arrivals and drawing lines through them on travel-time plots, the Moho profiles indicated by the refraction data, and hence the entire notion of discrepant zones, are clearly open to question. No rigorous attempt has been made here to analyze the uncertainties in these data, and the existence of the discrepant zones cannot be proven until either this has been done or a more complete data set amassed. The purpose here is not so much to prove a point as it is to outline a new hypothesis and, by its defense, suggest methods by which it may be tested. As suggested by Armstrong (1982), pure-shear and simple-shear strains likely occur within the same extensional zone, so the two concepts are not mutually exclusive.

Of foremost concern is the integration of surface geologic mapping with Moho geometry in order to confirm or rule out the existence of discrepant zones. This type of analysis can be carried out any place where extensional allochthons appear to have a "root zone," including the western margin of the Death Valley extensional terrain, the area northeast of the Nevada–Utah and Arizona "core-complex" terrains, the area east of the Priest River crystalline complex in northern Idaho and northwestern Montana, and the southwestern margin of the Arabian Shield. Inversion of other forms of geophysical data such as gravity, magnetics, and electrical resistivity will provide important tests. Geochemical variations in rift volcanism and xenoliths may also be analyzed in light of the theory and are capable of placing restrictions on the overall strain geometry within extended areas.

Analysis of heat-flow patterns in rifts, in conjunction with thermal modeling of various strain geometries at depth, may require important restrictions or modifications of the hypothesis. Subsidence profiles of passive continental margins yield information as to the nature of the extensional process, and as shown by Royden and Keen (1980) the geometry of the profile is sensitive to the proportion of crustal versus mantle–lithospheric thinning. Royden and Keen showed that these profiles in the Labrador Sea area in eastern Canada are more consistent with a model of differential thinning of crust and mantle than with the pure stretching model.

One of the most persistently debated points about low-angle, uniform-sense normal shear of the continental lithosphere is its mechanical unlikelihood. It requires that (1) large areas of ductile lower crust and mantle lithosphere within the divergent zone remain undeformed during rifting, and (2) that shear of the lithosphere, presumably, occurs at low angles to the least principal stress axis.

In considering the first point, clarification of the terms *brittle*, *ductile*, *localized*, and *penetrative* is warranted. In a rock mechanics laboratory, samples that accommodate strain by the volume-increasing process of fracturing mineral grains are said to be brittle, and those that accommodate strain by the non-volume-increasing process of dislocation climb and glide (as well as other recrystallization mechanisms) within mineral grains are referred to as ductile. At laboratory scales, strain via brittle fracture tends to be localized, and strain via dislocation mechanisms is relatively penetrative. On geologic scales, rocks under either brittle or ductile $T-P$ conditions can deform either penetratively or on localized shear planes. Some degree of confusion exists between specialists in rock mechanics and other earth scientists because many have *defined* localized deformation as brittle and penetrative deformation as ductile. However, the complex problem of the overall strain field of a deforming lithosphere is a problem quite separate from experimentally determined deformation modes of mineral grains. Thus one cannot conclude that the mantle lithosphere and lower crust penetratively flatten directly beneath discontinuous upper-crustal normal fault systems, given that rocks under these conditions exhibit ductile behavior in the laboratory. There is currently no means of theoretically predicting what the strain field of a compositionally heterogeneous, extending lithosphere will be, and it is therefore worthwhile to entertain any hypothesis that is consistent with observations that bear directly on strain geometry. In compression zones, on a crustal scale, thrust belts such as the Canadian Rockies or the Appalachian Valley and Ridge Province are clear examples of a case where the upper crust deforms in a penetrative manner under brittle conditions, whereas the middle crust and lower crust (and probably mantle lithosphere) remain intact or are only mildly deformed relative to supracrustal rocks.

To the second point, Ramsay's (1980) observation that conjugate ductile shear zones are typically observed to form an acute angle about the maximum elongation direction is particularly relevant. The overall dip of the shear zone depicted in Fig. 12 is consistent with Ramsay's findings. The shallowing of the surface in the upper crust is largely a function of the upper-plate rocks being thinned so drastically that the fault surface eventually ends up near the geoid by isostatic rebound. Typical initiation angles for these major shear zones seem to be in the 10–30° range (e.g., Bartley and Wernicke 1985), whereas mature detachment terrains commonly have a regionally exposed, subhorizontal brittle detachment. Another reason for keeping an open mind about shallowly inclined normal shear zones is the fact that it is not clear that the least principal stress axis is horizontal in the deeper parts of rifts. Direct observational data bearing on the orientation of the principal stress axes at great depth within intracontinental rifts are lacking.

The downward-steepening shear-zone geometry of Fig. 12 represents a tidy means by which tens or hundreds of kilometres of asthenospheric upwelling may be accommodated by a lithospheric shear zone without creating too much topography. Any steeply inclined normal or reverse shear zone on the scale of the lithosphere develops large isostatic resistance after a relatively small amount of displacement. The shallower the inclination of the shear zone, the less is the energy invested in creating topography per unit of lithospheric divergence.

The tendency of the lithosphere to localize strain within narrow zones of uniform strain geometry is in essence the theory of plate tectonics itself. Within the continental lithosphere, transform structures such as the San Andreas Fault represent uniform-sense shear of the lithosphere on a large scale. Similarly, intracontinental convergence is typically expressed in regionally uniform-sense thrust faulting, as is the case in the western Alpine chain in Europe. If the tendency toward relatively localized, uniform-sense simple shear applies to intracontinental divergence as well, consideration of the above mechanical arguments demonstrates that only low-angle normal shear can accommodate the amount of strain necessary to shear the continental lithosphere completely apart. It is perhaps only until the asthenosphere is sheared to the surface that sea-floor spreading may begin.

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