On the role of isostasy in the evolution of normal fault systems

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ABSTRACT

The footwalls of west-dipping normal faults that separate the west-central Colorado Plateau from the Basin and Range province record at least 5-7 km, and perhaps as much as 15-20 km, of west-side-up Neogene uplift, with an axis just 10-20 km west of undeformed plateau strata. The uplift is expressed as folding and steep faulting in pre-Tertiary cratonic and disconformably overlying Neogene strata, forming a basement-cored anticline and coincident topographic high on the western margin of the plateau. We interpret the uplift as a nonelastic response of the crust to buoyancy forces accompanying the tectonic denudation of the plateau margin. Profound, isostatically driven deformation of the footwalls of major normal faults may be common in extensional terrains, calling into question several assumptions fundamental to existing models of the evolution of normal fault systems.

INTRODUCTION

Motion on normal faults imposes a negative load on their footwalls, causing broad footwall uplifts adjacent to large, steep normal faults (e.g., Vening Meinesz, 1950; Zandt and Owen, 1980). Similarly, the broad doming of regional extensional detachments in the Basin and Range province has been explained by differential tectonic unloading of the footwalls of large, low-angle normal faults (e.g., Howard et al., 1982; Spencer, 1982, 1984). The amplitude:wavelength ratios of these flexures (0.05 to 0.15) imply low flexural rigidity of the lithosphere, if it is assumed that the flexures are elastic (Spencer, 1984).

Implicit in many models of normal fault systems (e.g., Spencer, 1984; Bartley and Wernicke, 1984) is the supposition that the steep dip of the fault(s) near the breakaway zone is maintained after deformation, particularly in the upper 5 km of the preextension crust. To assume otherwise requires major penetrative strain of the footwall block near the fault, which seems at odds with (1) the gentle warping of detachments downdip from the breakaway fault, (2) the common observation on reflection seismograms of listric normal faults that flatten at depths of 5 to 15 km in the Basin and Range and elsewhere (e.g., Smith and Bruhn, 1984), and (3) the presumed flexural strength of the crust, which would tend to resist the formation of isostatically induced flexures with amplitude:wavelength ratios that are a large fraction of one. Observations discussed below argue strongly against this supposition, and we suggest that faulting and large amplitude:wavelength folding of footwalls near breakaway zones is the norm in extensional terrains. This concept has implications for kinematic and dynamic modeling of extensional terrains, for seismogenesis in extending regions, and for the physics of lithospheric deformation in general.

VIRGIN-BEAVER DAM BREAKAWAY ZONE

The Virgin-Beaver Dam breakaway zone (VBBZ) lies along the west-central margin of the Colorado Plateau, where middle to late Miocene, west-southwest-directed, down-to-the-west normal fault systems disrupt the plateau edge, carrying extensional allochthons of the Basin and Range province tens of kilometres to the west (e.g., Smith et al., 1987). Uplift at the Basin and Range-Colorado Plateau boundary is expressed by folding of the cratonic sedimentary cover of the plateau, by down-to-the-east faults, and by local topographic uplift immediately east of the easternmost exposures of major breakaway faults (Fig. 1; Wernicke, 1985; Smith et al., 1987). Although Moore (1972), Seager (1970), and Hintze (1986) have interpreted the uplift as the result of Mesozoic compression, all exposures of the basal Tertiary unconformity in the region are either disconformable or mildly angular (Fig. 1). We consider the structural style of the VBBZ in three cross sections (Fig. 2).

In the northernmost section (Fig. 2a), drawn parallel to the direction of extension across a dip-slip part of the VBBZ, Paleozoic (and to the north of the section, overlying Tertiary) strata bend abruptly upward, dipping 25°-45° to the east. The flexure is truncated on the west by a gently dipping detachment (10°-20°) that juxtaposes east-tilted Tertiary and underlying fault slices of Paleozoic strata above Precambrian crystalline rocks (Hintze, 1986). The reconstruction (Fig. 2b) indicates that (1) the breakaway fault began at a low to moderate angle (~32°) where currently exposed, but may possibly have steepened upward toward the surface, and (2) the fault penetrated to at least 7 km depth without flattening to a very low dip. The reconstruction indicates major reduction of structural relief on the footwall.

The central section (Fig. 2c), drawn perpendicular to the slip vector of the hanging wall through a dominantly strike-slip part of the VBBZ, shows that flat-lying Paleozoic and Tertiary strata attain dips as great as 60°. In addition to folding, steep faults also accommodate uplift, some with subvertical offsets of at least 4 km (Moore, 1972). Reconstruction (Fig. 2d) suggests that a large mass of rock once existed above the footwall, although because of erosion, the geometry of the fault is not known at structurally high levels. Contiguity of the rotated rocks with plateau strata in these examples rules out structurally deeper faulting as a mechanism of rotation.

The southernmost cross section (Fig. 2e) contrasts with the more northerly ones in that the rotated rocks are separated from the plateau by a 6-km-wide basin, obscuring the relations between rotated and unrotated strata. However, over an east-west distance of less than 10 km, the flat-lying strata are rotated east to 60° dips. The rocks have also been shingled by top-to-the-west normal faults. The reconstruction (Fig. 2f) shows that, unlike the other sections, there has been up to 10 km of westward horizontal translation of the highest normal fault blocks with respect to the plateau. However, like the others, the reconstruction suggests that a substantial rock mass has been removed from above the block by some combination of erosion and tectonic denudation, depending on the precise geometry of structurally higher faults. The geometry of faults within the Precambrian basement is poorly known; if relatively unfaulted, the breakaway fault may have penetrated to depths in excess of 20 km at a moderate to steep angle. Alternatively, shingling faults like those observed in Phanerozoic strata may cut the basement rocks so that paleodepths of only ~5-10 km are exposed.

We conclude from these data that the footwalls of moderately to steeply dipping normal faults rebound isostatically so that most of the structural relief on the fault that would be present had the footwall remained rigid is eliminated. Uplift occurs along axes at both high and low angles to the regional extension direction, depending on the strike of the faults relative to the extension direction. The VBBZ is suggested as a type area for this style of crustal deformation because of its good exposure and contiguity with a large unstrained cratonic block.

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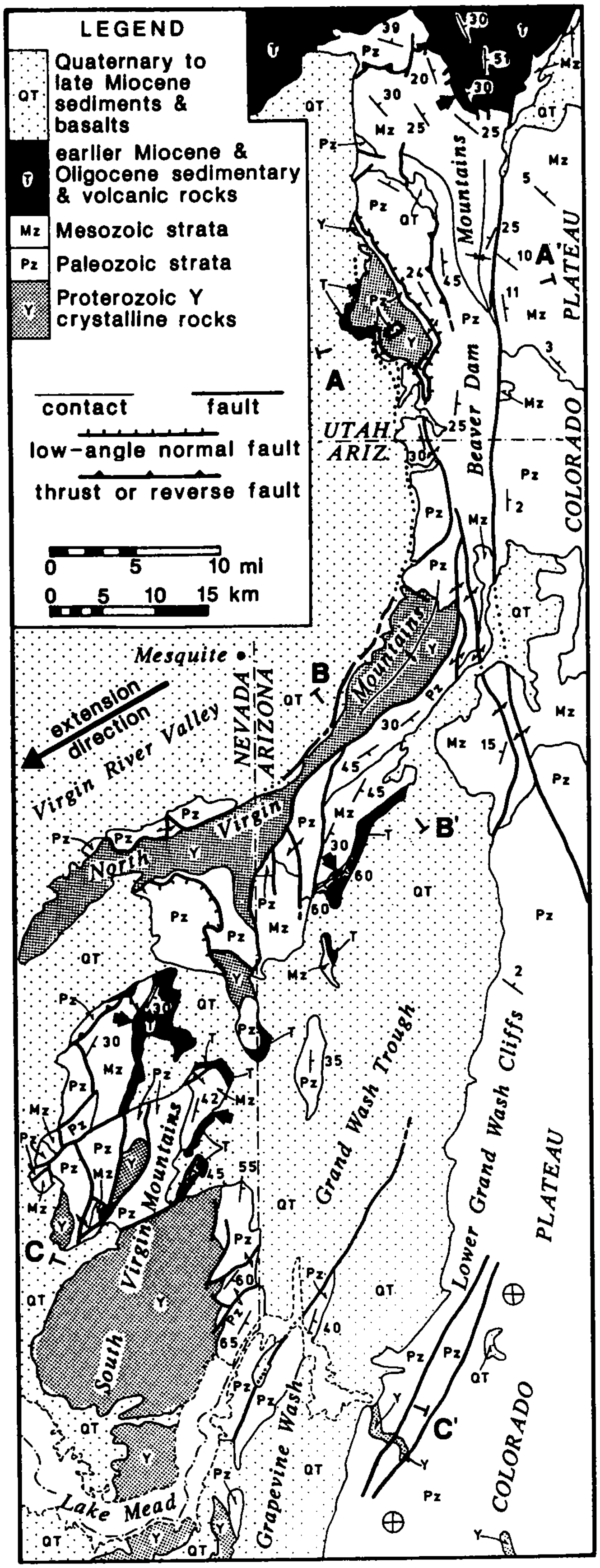

Figure 1. Geologic map of Virgin-Beaver Dam breakaway zone showing locations of cross sections in Figure 2 and critical sub-Tertiary unconformities (arrows). Compiled from Wilson et al. (1959), Volborth (1962), Beal (1965), Longwell et al. (1965), Morgan (1968), Seager (1970), Moore (1972), and Hintze (1986).

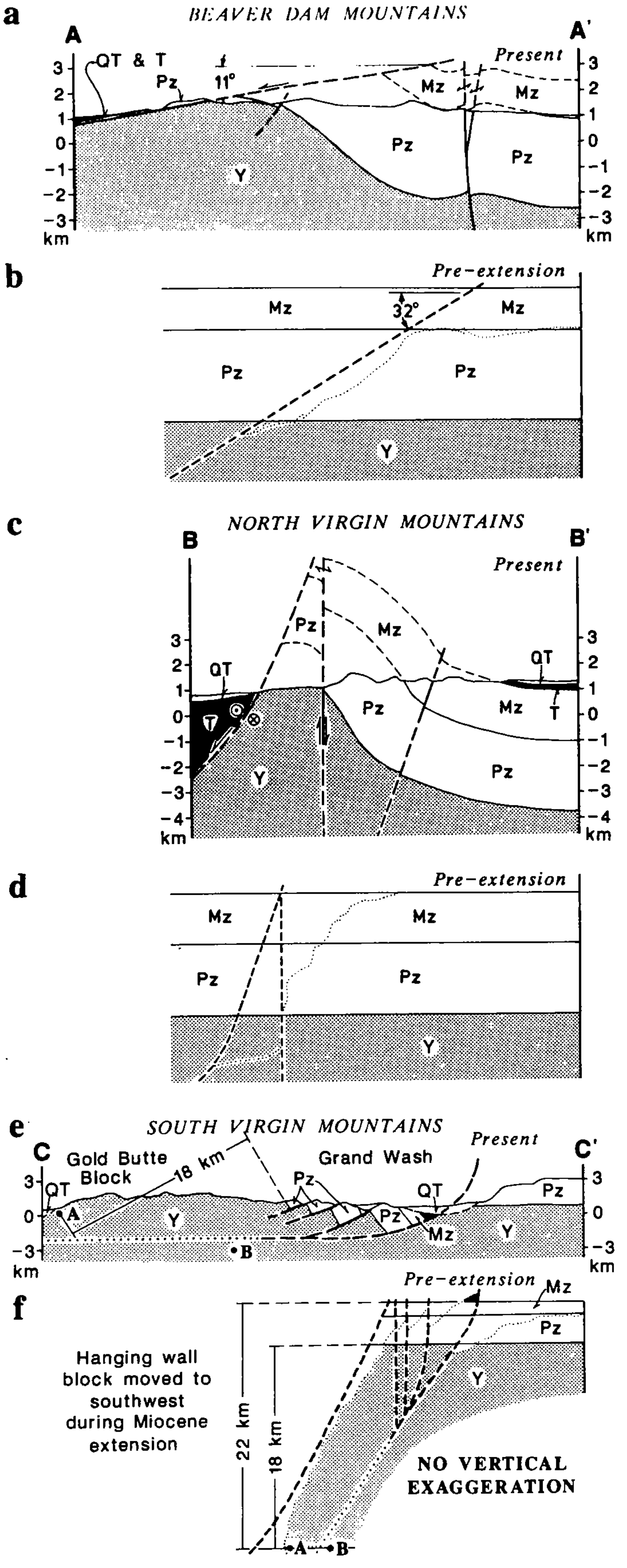

Figure 2. Balanced and reconstructed cross sections through Beaver Dam and Virgin mountains. See Figure 1 for locations and legend. B-B′ and C-C′ modified from Moore (1972) and Longwell (1945), respectively.

We believe that several other areas in the Basin and Range are analogous. Figure 3 shows a compilation of interpretive cross sections through possible examples, contrasting the uplift geometries between areas with gently tapered, wedge-shaped hanging walls, as in the Sevier Desert basin, and those with faults that penetrated to mid-crustal levels over short distances, as in the Butte Mountains breakaway zone. Where the faults initially penetrate deeply into the crust over short distances, footwall uplift is abrupt, and where the faults dip gently through the upper crust, footwall uplift is relatively gentle. In all cases, uplift of 5–15 km occurs across a distance of 10–50 km. Other examples may include the western sides of the Spring Mountains and the Sheep Range, Nevada; the Ladron Mountains in the Rio Grande rift; the eastern side of the Catalina-Rincon core complex in southeastern Arizona; and the west side of the northern Red Sea rift.

DISCUSSION

Figure 4 depicts an end-member kinematic model stressing the potential role of footwall uplifts in the evolution of normal fault systems. Aspects of this model challenge three commonly held assumptions about the kinematics and dynamics of rifting: (1) that rotation of normal faults and fault blocks results primarily from either reverse drag flexure or domino-style imbricate normal faulting; (2) that reverse drag flexure, or hanging-wall strain of any kind, is the dominant mechanism of accommodating the space problem created by motion on curved normal faults; and (3) that the flexural rigidity of extending lithosphere is negligible compared with that in compressive tectonic regimes.

The mechanism of rotation of the breakaway fault and the little-displaced block on its hanging wall results primarily from differential isostatic rebound (Fig. 4). This is, in a sense, a form of fault-bend folding in which the hanging wall remains rigid and the footwall deforms to accommodate both the bend in the fault plane and the condition that the earth's surface remain flat. We envision a general model of listric normal faulting in which the space problem is solved by simultaneous collapse of the hanging wall relatively downward and flexure of the footwall relatively upward into the void.

Dynamically, this model suggests that the extending lithosphere can support differential loading caused by motion on a normal fault up to a point, before which the hanging wall collapses into the void (Fig. 4b). At this stage, the negative load created by lower topography in the basin and the density difference between basin fill and bedrock is uncompensated locally, supported by the elastic strength of the lithosphere. If the lithosphere had zero strength, basin formation and hanging-wall collapse could not occur; the space problem would be accommodated entirely by footwall strain. Substantial elastic strength of the Basin and Range lithosphere is indicated by the fact that most of the ranges in the province are not locally compensated (Eaton et al., 1978). Thus, the load may be accommodated by topographic uplift distributed over an area several hundred kilometres wide with an amplitude of a few tens to perhaps a few hundred metres.

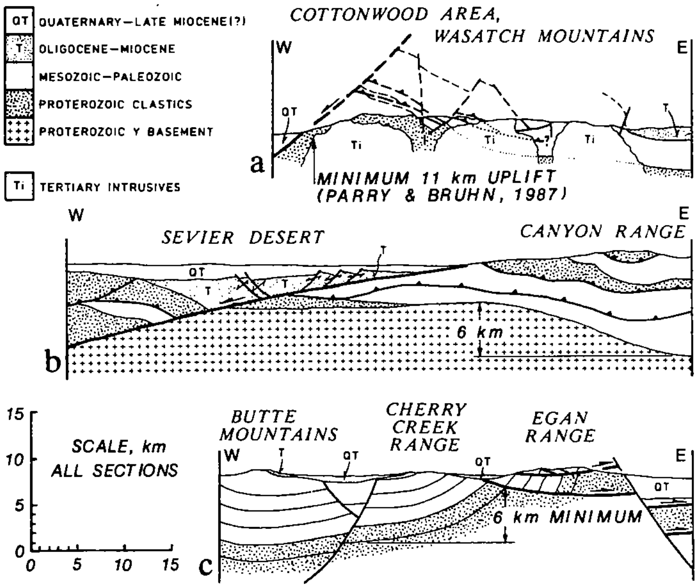

Figure 3. Cross sections through (a) central Wasatch Range, (b) Canyon Range, and (c) Butte Mountains breakaway zones, modified from Parry and Bruhn (1987), Allmendinger et al. (1983), Gans and Miller (1983), and Bartley and Wernicke (1984).

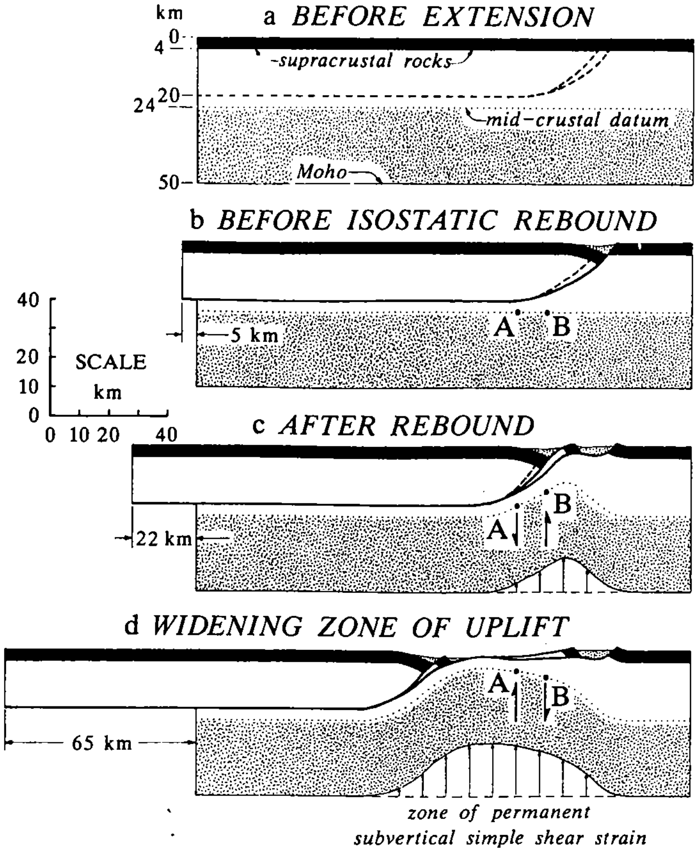

Figure 4. Conceptual model of evolving breakaway zone. Note migration of footwall strain and reversal of shear sense between points A and B.

As the hanging wall moves away from the footwall, the negative load may reach a steady state in which hanging-wall rollover and sedimentary infilling become subdued and footwall uplift dominates. Thus, to the extent that sediment is available, hanging-wall collapse may dominate the kinematic evolution. To the extent that it is not, only footwall uplift is available to mitigate the load. We believe that there is a broad spectrum of systems with variable components of hanging-wall collapse and footwall uplift. We suggest, following Zandt and Owen (1980), that uplift is a nonelastic response to the load. Thus, elastic strain may accumulate (Fig. 4b) to a point where the load exceeds the elastic limit of the lithosphere. In a steady-state situation, viscous relaxation may occur on a time scale that is short relative to tectonism. If stress is relaxed to a point just below the elastic limit, then at all times the system may have a component of long-wavelength elastic flexure superimposed on it. In this case, the geometry of the uplift is not indicative of the elastic properties of the extending lithosphere, because they do not represent flexures that store elastic energy.

If displacement on the detachment is large enough (Fig. 4d), a wave of middle or lower crustal uplift may migrate laterally, sequentially stranding crustal slabs broken off the hanging wall, "meatslicer-style," atop the uplifted footwall (e.g., Bartley and Wernicke, 1984; Wernicke et al., 1988; Hamilton, 1988). Two important aspects of these kinematics are that (1) the footwall goes through two episodes of subvertical simple shear (Fig. 4): one, breakaway-side-up as it passes beneath the edge of the hanging wall, followed immediately by another with the opposite sense as it passes completely out from under the hanging wall; and (2) the detachment itself may have a path through the upper crust at a relatively high angle to both its initial and final dip. Hamilton (1988) has reached conclusions, based primarily on geologic relations in the eastern Death Valley region, quite similar to ours.

The latter of these points may in part resolve the paradox between geological studies that indicate the widespread occurrence of subhorizontal detachments that have clearly been active in the brittle crust (e.g., Reynolds and Spencer, 1985) and studies of seismicity in actively extending regions, which reveal few if any earthquakes that occur on fault planes that dip less than about 30° (Jackson, 1987). One frequently suggested resolution to this problem (e.g., Jackson, 1987) is that shallowly dipping normal faults begin at a steep angle and are rotated to shallow dips by younger high-angle normal faults (e.g., Proffett, 1977). The sequential isostatic rebound of the detachment depicted in Figure 4 indicates a solution that may resolve the two sets of data: the detachment begins at a shallow angle in the ductile, aseismic, middle and lower crust; steepens on its ascent through much of the brittle, seismic crust; then shallows to its final orientation. Seismicity in this setting might only record transient deformation on the detachment as it passed from beneath its hanging wall. This solution does not, however, reconcile the seismic data with those faults active at low dip in the brittle crust, such as the Sevier Desert detachment (e.g., Allmendinger et al., 1983), the Mormon Peak detachment (Wernicke et al., 1985), the Whipple Mountains detachment (Davis, 1988), and the northern Panamint Valley fault system (Burchfiel et al., 1987).

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