Role of tectonic denudation in warping and uplift of low-angle normal faults

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ABSTRACT

Large displacement on a low-angle normal fault results in isostatic uplift of the lower plate in response to tectonic denudation. Simple models of the denudation process predict warping of the lower plate into a broad antiform, or antiform-synform pair, with axes perpendicular to the direction of extension. The amount of warping is strongly influenced by initial fault geometry, surface topography, the amount of extension, and the distribution of extension within the upper plate. Late-stage processes that augment antiform growth include one-sided denudation of the antiform, reverse faulting due to concave-upward flexure, and wholesale detachment and reverse-drag folding of the antiform. Antiformal uplifts, now exhumed by erosion, form mountain ranges in the southwestern United States where conditions were favorable for warping during mid-Tertiary crustal extension. Four major structural domains are apparent in transects across these uplifts and adjacent areas: (1) unextended area, (2) synformal upper plate, (3) antiformal uplift, and (4) wedge-shaped upper plate. Each domain is separated from adjacent domains by the traces of a master low-angle normal fault.

INTRODUCTION

Antiformal or domal uplifts of metamorphic and plutonic rocks, overlain by outward-dipping low-angle faults of Tertiary age, are a common characteristic of Cordilleran metamorphic core complexes (Crittenden et al., 1980). These uplifts also occur in low-angle normal-fault terranes where mylonitic rocks characteristic of metamorphic core complexes are not present (e.g., Volborth, 1973). Since the inferred direction of upper-plate transport is typically unidirectional, upper-plate rocks appear to have moved up one side of the uplifts and down the other. Some uplifts are antiformal, with axes either parallel or perpendicular to the direction of upper-plate transport; others are domal and appear to represent constructive interference between antiforms of both orientations (Cameron and Frost, 1981). The subject of this paper is the origin of antiformal warps with axes perpendicular to the direction of upper-plate transport.

Low-angle faults associated with these uplifts are inferred to be normal faults. They typically juxtapose upper-crustal rocks, in many cases including mid-Tertiary clastic sediments, over rocks inferred to have acquired many of their characteristics at mid-crustal depths. Most upper plates are highly attenuated by numerous normal faults that merge with, or are cut by, a basal low-angle fault. The geometry and inferred kinematics of basal faults in many areas indicate that they are rooted, low-angle normal faults that accommodate major crustal extension (Wernicke, 1981).

MODELS OF TECTONIC DENUDATION

Assuming complete local and regional isostatic re-equilibration following tectonic denudation, the final form of a low-angle normal fault can be readily determined, given its initial form, the initial surface topography, and the amount and distribution of attenuation and lateral displacement of the upper plate. For example, uniform internal extension and down-dip displacement of a wedge-shaped upper plate above a planar, low-angle normal fault will result in a linear increase in the amount of tectonic denudation in the down-dip direction. In this case, an initially planar low-angle normal fault will be rotated to a more gentle dip but will maintain its planar form. Geologic evidence indicates, however, that the amount of attenuation ultimately decreases in the direction of upper-plate transport and that the thickest parts of the upper plate have undergone little or no internal extension (e.g., Lucchitta and Suneson, 1981). If attenuation decreases in the direction of upper-plate transport, a planar fault will be warped into an antiformal arch.

Some simple denudation models, using two different initial fault geometries and three distributions of extension, are shown in Figure 1. The models are based on the assumption of complete isostatic rebound (zero flexural rigidity) and flat initial surface topography. Beginning with a planar or listric basal fault, the

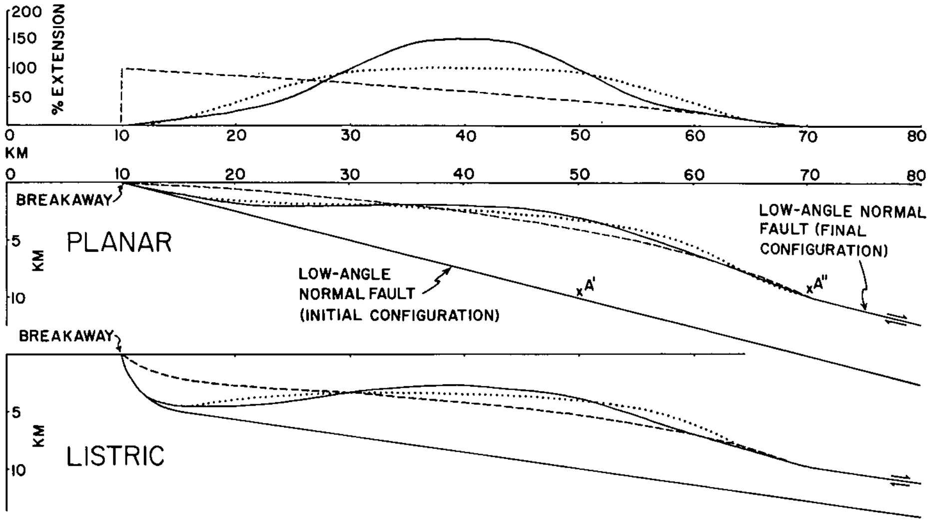

Figure 1. Isostatic rebound and warping of low-angle normal faults assuming complete isostatic rebound (zero flexural rigidity) and flat initial surface topography. Six different patterns of uplift and warping result from three different arbitrary distributions of extension within upper plates of two different forms (planar and listric). For example, dotted line at top, representing one distribution of extension, corresponds to dotted lines in two cross sections, representing final shape of fault after denudation and uplift. All cases are based on 20 km net extension; point A′, for example, is displaced 20 km to point A″. Part of upper plate initially to right of point A′ is uniformly displaced 20 km and undergoes no internal extension. Part of upper plate initially to left of point A′ is internally extended and displaced less than 20 km.

thickest parts of the upper plate (>10 km thick) are displaced 20 km laterally (to the right in Fig. 1), and undergo no internal extension. The tapered end (<10 km thick) of the upper plate, initially 40 km wide, is extended to 60 km and thinned by numerous normal faults (not shown). The amount of extension within the upper plate varies laterally. Three different lateral distributions of extension, after displacement, are shown at the top of Figure 1; they correspond to the three final, warped fault surfaces shown in each of the two cross sections. These models do not consider the density contrast between the upper crust and the level of isostatic compensation. Consideration of this density contrast would result in slightly reduced rebound and broadly depressed, instead of planar, final surface topography.

The most significant feature of these models is that they all produce an antiformal warp of the fault surface. Minimum antiformal warping results from an initially planar basal fault geometry and a broad distribution of extension, with maximum extension occurring near the breakaway (Fig. 1, planar model, dashed line). Maximum antiformal warping results from an initially listric basal fault geometry and a concentrated distribution of extension, with maximum extension occurring at a significant distance from the breakaway (Fig. 1, listric model, solid line; Fig. 2, A and B). Initial surface topography, not considered in Figure 1, will also influence the amount of antiformal warping and uplift. For example, if a mountain range, originally in isostatic equilibrium, is displaced laterally from a position above a developing antiformal warp, the warp will rise higher to compensate for the missing mass of the mountain range.

The assumption of complete local isostatic rebound is not strictly applicable because Earth's lithosphere has a finite flexural rigidity (resistance to bending). However, the presence of active low-angle faults results in a substantial reduction in the flexural rigidity of the crust. For this reason, flexural rigidity is greatest in the unfaulted region adjacent to the breakaway and decreases away from the breakaway in the direction of upper-plate transport (Spencer, 1982). Resistance to flexure in the breakaway region will accentuate development of a synformal warp between the breakaway and the antiformal uplift.

High resistance to bending throughout the lower plate will inhibit antiformal warping and uplift, resulting in formation of deep sedimentary basins above low-angle normal faults. However, available geologic evidence indicates that antiformal uplifts were not deeply buried during and immediately after low-angle faulting. For example, clasts of mylonitic gneiss (Pashley, 1966) and chloritic breccia derived from the lower plate are present in the detached and tilted Rillito conglomerate at the foot of the Catalina-Rincon Mountains, indicating that lower-plate rocks reached surficial levels during faulting. Lithospheric flexural rigidity was apparently not sufficient to prevent uplift of the lower plate to surficial levels during or immediately after denudation. The short wavelength and large amplitude of some warps is additional evidence for low lithospheric flexural rigidity. For the purpose of modeling denudation and uplift, geologic evidence thus indicates that the assumption of negligible flexural rigidity is a reasonable approximation.

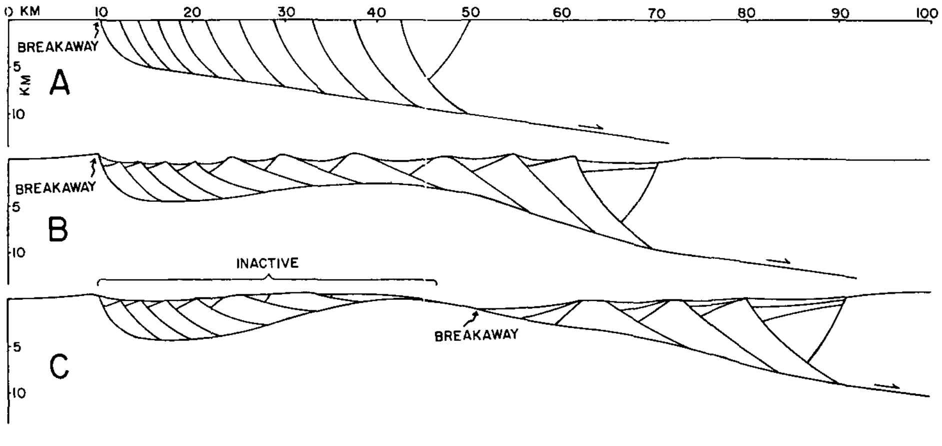

Figure 2. Schematic diagram of warping and uplift of detachment fault. A: Inception of master detachment fault and subsidiary normal faults within upper plate. B: After 20 km of extension an antiformal warp has developed. Shape of warp and amount of uplift are depicted in listric model of Figure 1 (solid line). Antiform is becoming barrier to movement of upper plate from left, upper plate in area of synformal warping is becoming inactive, and one-sided denudation of antiform is about to begin. C: 20 km of one-sided denudation has resulted in further uplift and initial exposure of lower plate to subaereal erosion. Shape of basal detachment fault and distribution of extension during one-sided denudation resemble planar detachment of Figure 1 and skewed distribution of extension (dashed line, Fig. 1), resulting in subdued arching of fault surface and amplified uplift in breakaway area.

The process of differential denudation and isostatic uplift, as modeled in Figure 1, can account for significant uplift and warping of lower-plate arches, but it cannot account for the surficial levels reached by some arches during faulting. The growth of a major arch along an axis perpendicular to the direction of upper-plate transport produces a barrier to lateral movement of the upper plate from the adjacent area of synformal warping, leading to the termination of faulting in the area of synformal warping. In this situation, continued extensional faulting causes denudation of only one side of the arch and formation of a breakaway fault above the crest of the arch. Continued isostatic uplift as a result of one-sided denudation may bring the crest of the arch to the ground surface (Fig. 2C). A secondary effect of one-sided denudation and continued uplift is concave-upward flexure on the inactive flank of the antiform, possibly leading to reverse faulting or folding that increases antiform height.

Late to postdenudation arching would occur if an entire antiform were detached on younger, listric normal faults with the same regional dip as older, shallower normal faults. Reverse-drag folding above deep listric normal faults (Hamblin, 1965) would amplify arching. For example, west-dipping normal faults that postdate and cut the San Pedro detachment fault in the eastern Rincon Mountains (Lingrey, 1982) may flatten with depth and accommodate reverse-drag warping and tilting of the Rincon arch. The large imbricate lenses recognized by Hamilton (1982) in seismic reflection profiles may represent detached antiforms originally warped during differential denudation and now bounded above and below by low-angle normal faults of similar vergence.

Antiformal arches with axes *parallel* to the direction of upper-plate transport may have breached the ground surface while flanking, parallel synforms remained beneath the upper plate. Thus, elongate, doubly plunging, antiformal ridges bounded by outward-dipping tear faults may have been the source of lower-plate clasts in syntectonic, upper-plate sedimentary rocks (Teel and Frost, 1982).

GEOLOGIC EXAMPLES

Four subparallel structural domains are apparent in transects, parallel to extension direction, across low-angle normal-fault terranes where antiformal uplifts of the type modeled here have been exhumed by erosion. These are (1) an area of upper-crustal rock not significantly affected by extensional faulting, (2) a detached, synformal upper plate of distended upper-crustal rock, (3) an antiformal or domal upwarp of middle-crustal rock flanked by outward-dipping low-angle faults, and (4) a

TABLE 1. STRUCTURAL DOMAINS OCCURRING IN TRANSECTS THROUGH LOW-ANGLE NORMAL FAULT TERRANES WITH ANTIFORMAL UPWARPS

Transect	Unextended Area	Synformal Allochthon	Antiformal Uplift	Wedge-Shaped Allochthon
A. Newberry	Homer Mtn. (1), Piute Rng. (1, 2), Castle Mtns. (2)	East flank of Homer Mtn. (1), West flank of Newberry and Dead Mtns. (3)	Newberry and Dead Mtns. (3)	East flank of Newberry Mtns. (3, 4), Black Mtns. (5, 6)
B. Whipple	Old Woman Mtns. (7), Turtle Mtns. (8)	Turtle Mtns. (7), Mopah Rng. (7, 8)	Whipple Mtns. (8)	Mojave and Bill Williams Mtns. (9)
C. Harcuvar	Granite Wash and Little Harquahala Mtns. (10)	Not preserved or never present	Harcuvar and Harquahala Mtns. (10)	Ferra (Aguila) Ridge (10), Date Creek Mtns. (11), Merrit Pass Mtns.
D. Santa Teresa	Galiuro Mtns. (6)	Eagle Pass detachment (12, 13)	Santa Teresa Mtns. (13)	Northern Santa Teresa Mtns. (head of Black Rock Wash) (13), Gila Mtns. (6)
E. Rincon	Galiuro Mtns. (6)	Teran Basin (west flank of Galiuro Mtns.) (14), east flank of Rincon Mtns. (15, 16)	Rincon Mountains (16, 17, 18, 19, 20), Catalina Mtns. (18, 19, 20)	Southwest toe of Rincon and Catalina Mtns. (17, 18, 19, 20), Tucson Mtns. (6)

Note: Location of transects shown in Figure 3. Sources of data: (1) Spencer and Turner (1982); (2) Hewett (1956); (3) Volborth (1973); (4) Mathis (1982); (5) Longwell (1963); (6) Wilson et. al. (1969); (7) Howard et. al. (1982b); (8) Davis et. al. (1980); (9) Howard et. al. (1982a); (10) Rehrig and Reynolds (1980); (11) Otton (1982); (12) Davis and Hardy (1981); (13) Blacet and Miller (1978); (14) Grover (1982); (15) Lingrey (1982); (16) Drewes (1974); (17) Drewes (1977); (18) Davis (1980); (19) Keith et. al. (1980); (20) Banks (1980).

detached wedge of upper-crustal rock overlying a rooted, low-angle normal fault. The boundaries between domains are represented by the traces of a warped, master, low-angle normal fault.

These four structural domains are apparent in transects across several areas in the southwestern United States (Table 1; Fig. 3) and had been previously recognized in some of these areas. Correlation of a breakaway fault with a basal fault dipping outward from the flanks of an antiformal arch, as suggested for transects through the Whipple Mountains of southeastern California (Davis et al., 1980; Howard et al., 1982a, 1982b) and the Rincon Mountains of southeastern Arizona (Lingrey, 1982), constitutes recognition of most of the geometric features of these domains. Recognition of the rooted nature of the low-angle normal fault on one side of the arch was essential to understanding the complete geometry and significance of these terranes (Lucchitta and Suneson, 1981; Shackelford, 1981; Wernicke, 1981).

Hypotheses concerning the causes of arching and uplift are dependent on inferences of the relative dates of faulting and arching. Synchroneity of arching, uplift, and faulting is required for an isostatic uplift model (e.g., Rehrig and Reynolds, 1980; Hyndman, 1980; Howard et al., 1982a, 1982b). Other workers have suggested that uplift and arching occurred after faulting (Davis et al., 1980; Lingrey, 1981, 1982). It is suggested here that, in many cases, uplift and arching occurred both during upper-plate attenuation and displacement (two-sided denudation), and during later one-sided denudation after substantial arch growth. Younger high-angle faulting is also responsible for much of the present-day topographic relief of some antiforms such as the Rincon Mountains (Drewes, 1974; Lingrey, 1982). However, there is no compelling evidence for either one-sided denudation or younger high-angle faulting in some areas such as the Whipple Mountains, and another, undiscovered mechanism may be involved.

CONCLUSION

The factors that influence the magnitude and location of initial warping and uplift during denudational faulting include (1) the initial form of the basal fault, (2) the distribution and magnitude of upper-plate attenuation and displacement, and (3) initial surface morphology. Secondary effects or late-stage processes that promote arch growth include (4) one-sided denudation, (5) reverse faulting, or folding related to incipient reverse faulting, and (6) wholesale detachment and reverse-drag warping of the arch. Another possibility, not modeled or discussed here, is that the original form of the basal fault was broadly arch-like, and the arch was amplified by the processes outlined above. Finally, apparent uplift may be increased by later high-angle normal faulting.

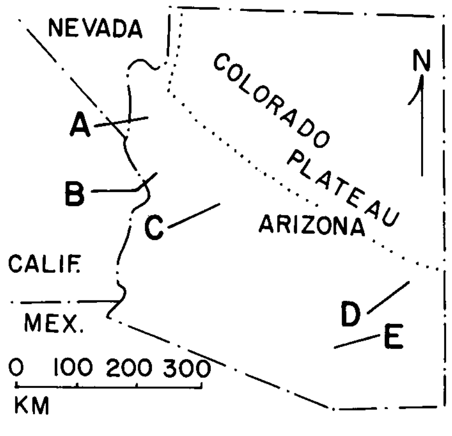

Figure 3. Location of transects listed in Table 1. Letter designating transect is at end of transect corresponding to unextended area.

Four distinct structural domains are recognized in transects across low-angle normal-fault terranes where conditions have been favorable for arch growth and levels of erosion are appropriate. These are (1) an area not significantly affected by extensional faulting, (2) a synformal upper plate, (3) an antiformal upwarp, and (4) a detached, tapered wedge. All domains are separated from adjacent domains by the surface traces of a master low-angle normal fault.

Evidence that antiforms reached surficial levels during or immediately after denudational faulting and the large amplitude and short wavelength of many warps suggest that the flexural rigidity of the lithosphere was low during mid-Tertiary denudational faulting. Low flexural rigidity may have been due to (1) slip on subhorizontal faults during flexure (Spencer, 1982), (2) high heat flow, and (3) absence of any significant mantle contribution to flexural rigidity due to thick crust and high heat flow (e.g., Chen and Molnar, 1983) or to complete decoupling of crust and mantle (e.g., Bird, 1979; Mayer, 1983).

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Reviewer's comment

Addresses an important, historical problem in interpretation of metamorphic complexes—i.e., the origin of uplift and arching of these terranes. Detailed analysis of the style and timing of denudation faulting, as presented here, should begin to lay to rest the interpretation of many core complexes as diapiric "gneiss domes" à la Eskola.

Robert Varga

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