Does magmatism influence low-angle normal faulting?

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ABSTRACT

Synextensional magmatism has long been recognized as a ubiquitous characteristic of highly extended terranes in the western Cordillera of the United States. Intrusive magmatism can have severe effects on the local stress field of the rocks intruded. Because a lower angle fault undergoes increased normal stress from the weight of the upper plate, it becomes more difficult for such a fault to slide. However, if the principal stress orientations are rotated away from vertical and horizontal, then a low-angle fault plane becomes more favored. We suggest that igneous midcrustal inflation occurring at rates faster than regional extension causes increased horizontal stresses in the crust that alter and rotate the principal stresses. Isostatic forces and continued magmatism can work together to create the antiformal or domed detachment surface commonly observed in the metamorphic core complexes of the western Cordillera. Thermal softening caused by magmatism may allow a more mobile mid-crustal isostatic response to normal faulting.

INTRODUCTION

Anderson's (1951) theory provided a general framework to describe faulting in relation to the ambient stress field in the Earth's crust. The theory predicts that when the vertical lithostatic load is the greatest principal stress, normal faulting ensues at an angle ~45° to 70° from vertical, when the difference between the horizontal least principal stress and vertical greatest principal stress exceeds the shear strength of the rocks. As more faults are investigated worldwide, it is increasingly clear that Anderson theory alone cannot adequately describe many observed faults. For example, shallow-dipping to horizontal fault planes are commonly observed, often with extreme normal displacements. Because these faults are shear failures that respond to the local stress field, apparently either the greatest principal stress direction deviates from the vertical (e.g., Bartley and Glazner, 1985; Melosh, 1990), or a steeply dipping fault plane rotates to a more shallow dip after displacement (e.g., Davis, 1983). Reactivation along ancient low-angle fault planes is a less likely explanation, because in most cases the shear strength of a plane of weakness improperly oriented to the principal stress axes exceeds that for a new fault in fresh rock along a more favored plane (Sibson, 1985). There is clear evidence that rotation followed by initiation of new fault planes occurs, e.g., as at Yerington, Nevada (Proffett, 1977). However, evidence from structural reconstructions indicates that many detachment faults begin and propagate at low angles, including the Whipple Mountains (Yin and Dunn, 1992) and Chemehuevi Mountains of southern California (Miller and John, 1988), the Harcuvar Mountains of central Arizona (Reynolds and Spencer, 1985), and the Mormon Mountains of Nevada (Wernicke et al., 1985).

The expected pattern for brittle extension with a vertical greatest principal stress is finite motion along steeply dipping fault planes, a new plane forming when it is no longer efficient to continue motion along the first. When lower angled faults occur, they tend to expose sharp divisions between brittle deformation in the upper plate and ductile deformation in the lower plate; this has invited the suggestion that the low-angle faults represent the brittle-ductile transition (e.g., Gans et al., 1985). Models involving isostatic uplift suggest that unloading caused by movement on a normal fault causes upwarp of the footwall, which rotates the initially steep fault plane toward the horizontal (e.g., Heiskanen and Vening Meinesz, 1958; Spencer, 1984; Wernicke and Axen, 1988). Observation suggests that isostatic rebound of local features such as the footwall of a normal fault occurs in the mid-crust, rather than involving the entire crust. For example, analysis of gravity data suggests that the load differences between the relatively narrow (~20 km wide) basins and ranges in the western Cordillera of the United States are supported by the strength of the crust (e.g., Eaton et al., 1978; Kruse et al., 1991), which implies that isostatic compensation has occurred by midcrustal shear flow, rather than in the mantle. Seismic reflection profiles from the northern Basin and Range province tend to support that result, showing a flat Moho beneath both basins and ranges (e.g., Klemperer et al., 1986). Footwall rebound should occur equally on every steep normal fault of approximately the same offset, which indicates that the observed variation in dip angle is probably a consequence of heterogeneities in composition, rheology, or stress distribution. We suggest that magmatism causes a significant heterogeneity in the stress regime that can drive low-angle faulting.

ROLE OF MAGMATISM

Synextensional magmatism is a common characteristic observed across the Basin and Range province. Extension in the eastern Great Basin is typically preceded by a flux of magmatism into the crust (e.g., Gans et al., 1989). High-angle normal faults are observed independent of associated magmatism, whereas low-angle, core-complex–style faulting almost never occurs without accompanying magmatism. Tertiary plutons and dike swarms are present beneath virtually every metamorphic core complex of the Colorado River extensional corridor of southeastern California and southern Arizona. The Colorado River region is characterized by a linear gravity high, which is inferred to be the result of a series of Tertiary mafic intrusions (R. W. Simpson et al., unpublished). Tertiary dike swarms are present in the lower plate rocks of the Whipple Mountains (Davis et al., 1982), the Chemehuevi Mountains (John, 1982), Homer Mountain, the Sacramento Mountains (Spencer, 1985), the Castle Dome Mountains (Logan and Hirsch, 1982), and many others. The core complexes of central and southern Arizona are also sites of Tertiary plutonism (Reynolds and Rehrig, 1980; Keith et al., 1980). In many cases the bulk of magmatism

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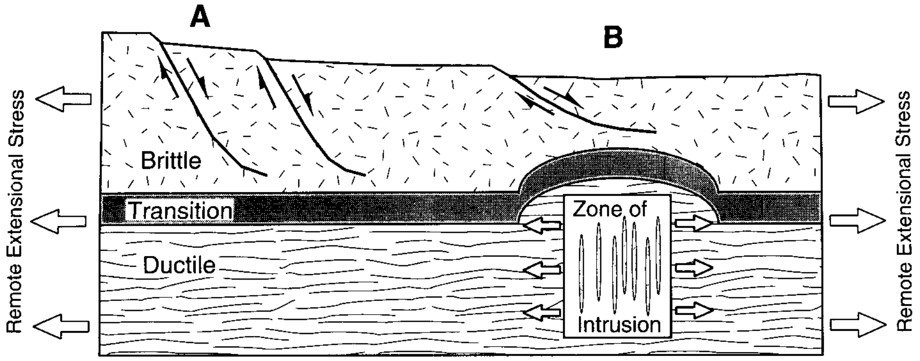

Figure 1. Vertical section of strain distribution caused by tectonic extensional stress. A: Extensional strain is accommodated on normal faults in brittle upper crust and by ductile flow in ductile lower crust. B: Large, rapidly intruded magmatic event in middle and lower crust occupies volume, thereby accommodating extensional strain, and heats host rock, causing thermal softening. Lower angled normal fault accommodates strain above intrusions, consequence of applied stresses from intrusions (see Fig. 3) and elevated transition from ductile to brittle rocks (e.g., Bradshaw and Zoback, 1988).

either closely preceded or occurred during the most intense episodes of extension (K. Howard, 1992, personal commun.). Dikes and low-angle faults crosscut one another, indicating simultaneous development in the Mopah Range, west of the Whipple detachment (Hazlett, 1990). The northward-migrating band of magmatism beneath the core complexes of the Colorado River extensional corridor may have been related to the passage of the Mendocino triple junction about 25–15 Ma (Glazner and Bartley, 1984). Eocene dike swarms, which compose 90% of the exposed core rock across zones up to 10 km wide, are associated with the development of the Kettle and Okanogan domes (core complexes) in northeast Washington (Holder et al., 1990). Dike intrusion and the emplacement of a mafic batholith accompanied unroofing of the footwall of the Black Mountains detachment fault in the Death Valley region of California (Holm et al., 1992). Several islands in the Aegean Sea have analogous structural relations to the core complexes of the Colorado River corridor (Lee and Lister, 1992) and have low-angle faults that have been related to a Miocene pulse of intrusive activity.

Intrusive magma bodies can be shown to have a significant effect on the stresses in extending regimes. When the crust extends by pure shear, it must thin if volume is to be conserved. The intrusion of magma introduces new volume to the system and absorbs extension, preventing the formation of normal faults in some cases (Parsons and Thompson, 1991). Mantle-derived basaltic melts can erupt from high volcanoes, which implies that the melt intrudes the crust at pressures exceeding the lithostatic stress. Consequently, high-pressured melts can impose stresses rivaling the principal stresses in the Earth (e.g., Rubin, 1990), and may change them. Dike-forming magmas are particularly effective in reducing extensional deviatoric stress, because dikes tend to intrude perpendicular to the least principal stress direction. As in hydrofracturing, the internal fluid pressure in an intruding dike forces open a conduit and pushes out against its walls. Unlike hydrofracturing, however, the magma freezes rapidly, propping open the fissure it creates and causing a lasting increase in the least principal stress. Individual dike widths are approximately the same magnitude as the horizontal-slip component on a normal fault during a large earthquake, which implies that the rapid intrusion of a large number of dikes can overwhelm the tectonic stresses. Magmatism affects the horizontal stresses in at least two ways: (1) the volume of new material added to the middle and upper crust relieves extensional tectonic stress, and overpressured magma can create locally compressional conditions; and (2) increased thermal activity can cause the crust to be rheologically weaker and thus less able to support large deviatoric stresses.

LOW-ANGLE FAULTING

Magmatism may provide the stress heterogeneity required to initiate low-angle faulting. If the stress conditions in the crust are nonuniform, then the distribution of extensional strain is also likely to be nonuniform. Igneous mid-crustal inflation that occurs at a rate faster than tectonic extension would focus intense extensional stress above the zone of intrusion (Fig. 1). A low-angle normal fault plane indicates a greatest principal stress direction inclined from the usual vertical orientation. If a magmatic intrusion is approximated as internal pressure opening a vertical crack (analogous to a vertical dike pushing out horizontally, normal to its walls) then the applied stresses are (1) horizontal compression and (2) shear applied on horizontal planes perpendicular to the plane of the dike (Pollard and Segall, 1987). The applied stress field at points near the dike is characterized by three principal compressional stresses that are rotated to balance the shear stresses caused by the dike (Fig. 2). The new principal stress axes describing the field near a dike tend to form a radial pattern around the dike (Fig. 3), the predicted inclinations of the greatest principal stress direction being as much as 45° in the zone above the dike where large deviatoric stresses might be preserved. Horizontally expanding intrusions of more complex shape will produce a stress field that is less regular, but similar to that shown in Figure 3.

A greatest principal stress orientation rotated off vertical by magmatism could produce lower angled faults if sufficient deviatoric stress persists above the intruded zone. When a low-angle fault plane is favored, it can have a large and rapid offset, because all the extensional strain may be concentrated on a single fault (Forsyth, 1992), whereas strain below the fault may be accomplished through magmatism. Perturbations in the orientations of the principal stresses may be magnified at or near rheological contrasts (e.g., Bradshaw and Zoback, 1988), and such effects may help maintain a rotated stress field through continued magmatism maintaining an elevated brittle-ductile transition. For example, the crust beneath many of the most highly extended terranes in the Basin and Range province is as thick as that of neighboring, less-extended provinces, and a combination of magmatism and ductile flow is apparently required to maintain crustal thickness (e.g., Gans, 1987; Thompson and McCarthy, 1990).

DOMING OF THE FOOTWALL

Regions of extreme extension often demonstrate doming and uplift of the footwall, sometimes to the extent that the fault plane is rotated past horizontal (e.g., Coney, 1980). The uplift and warping of a low-angle fault plane can be explained through two different mechanisms. (1) Increased midcrustal mobility due to thermal softening from magmatism allows isostatic compensation of shorter wavelength features, such as the footwall of a normal fault. (2) Intrusion of dikes and other types of magmatic bodies tends to cause a net local uplift above the intrusion. For example, when a dike intrudes into the host rock it applies a stress in the widening direction, and the resulting strain increases the other principal stresses. Because the upper bound is a free surface, the stress applied in the vertical direction causes topographic relief (e.g., Rubin and Pollard, 1988). Much of the crystalline rock in highly extended

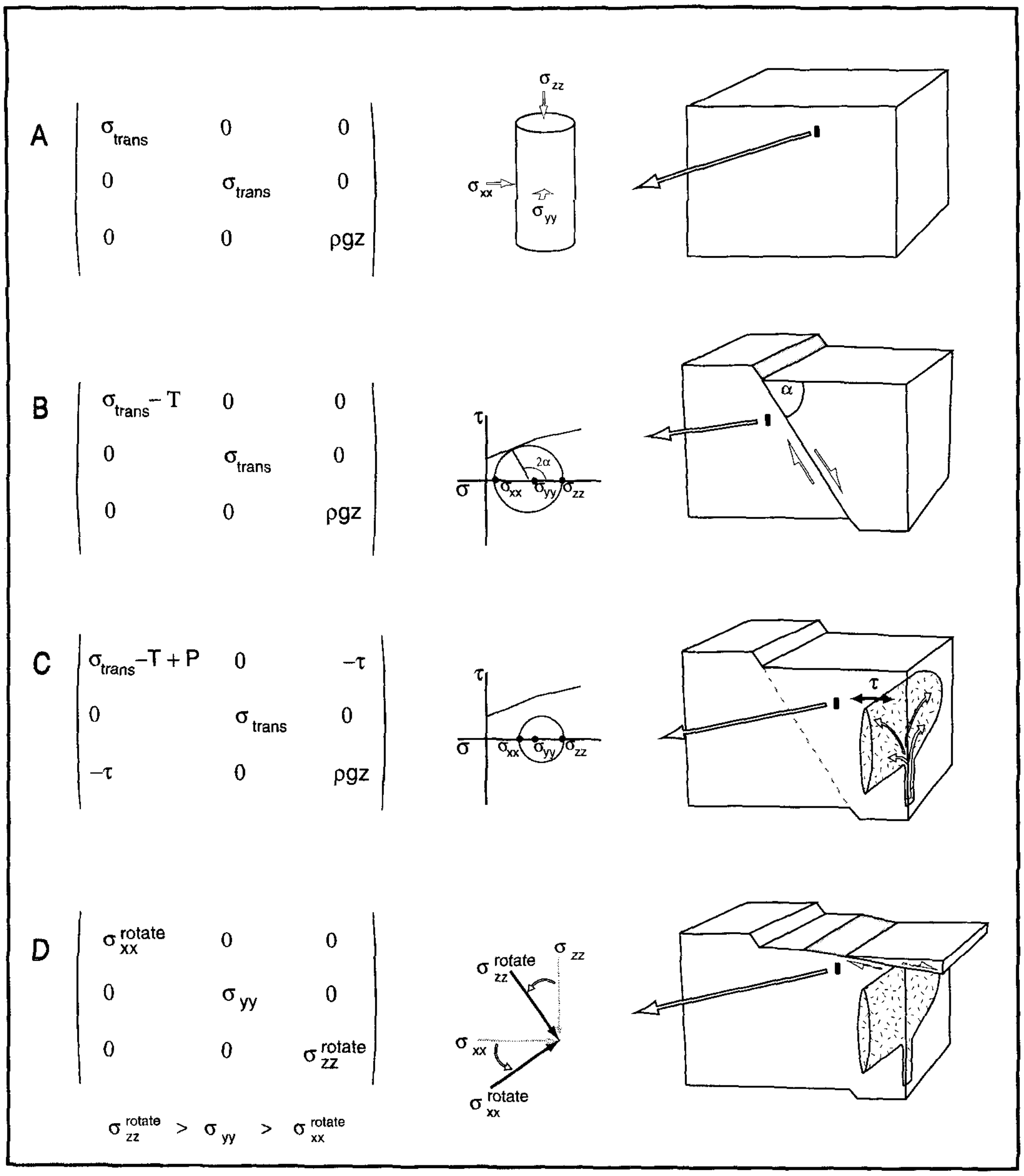

Figure 2. Applied stress field and faulting before and after intrusion. A: State of stress due to lithostatic load. Applied stress field is described by three principal compressive stresses; σ_{zz}, lithostatic load, and two initially equal transverse stresses, σ_{xx} and σ_{yy}. B: Horizontal stress in X direction is reduced by factor T, caused by remote tectonic extension. Reduction in horizontal stress creates deviatoric stress sufficient to break normal fault. C: Vertical dike intrudes parallel to Y direction, applying horizontal compressive stress P in X direction, and shear stress τ on XZ and ZX planes. Dike is symbolic of large-scale intrusive event. D: Because intrusive event applied new shear and compressional stresses, principal stress axes must be rotated to balance stresses caused by intrusion. Provided that fault angle is related to principal stress orientations and that sufficient deviatoric stress exists above intruded zone, then low-angle normal fault may begin to form.

regions is laced by intense dike swarms of compositions ranging from basalt to rhyolite, which implies some degree of crustal melting as well as intrusions from the mantle. Direct uplift caused by magmatic events, which in turn cause a thermally weakened middle crust that allows enhanced isostatic rebound of the footwall, have probably combined to generate the doming effect.

CONCLUSIONS

Our primary conclusion is that intruding magma, because of its high pressure relative to the crustal stresses, can take an active role in driving low-angle faults. Specifically, we are suggesting that a low-angle fault will result when rapid, primarily midcrustal magmatism occurs within a terrane subjected to strong extensional tectonic stress. We view the effects of magmatism primarily as an initiation mechanism for low-angle faults, be-

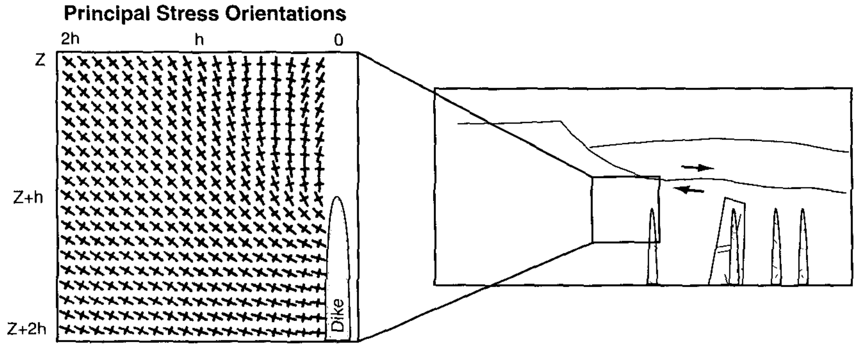

Figure 3. Principal stress trajectories above intruded vertical dike calculated with method of Pollard and Segall (1987). Initial stresses are held fixed with vertical lithostatic load σ_{zz} exceeding melt pressure, which exceeds initially horizontal least principal stress, σ_{xx}. New greatest and least principal stress directions are indicated with long and short ticks, respectively.

cause if strain is to be balanced through the crust, then the width of intrusion below a low-angle fault must be equal to the total offset on the fault, which is unlikely for extreme offsets. However, continued magmatism can contribute to a low-angle fault evolving into a core complex both through its direct influence on the stress field, and through thermal softening of the crust, which can sharpen rheologic boundaries that lead to stress refractions as well as facilitate isostatic response to unloading of the footwall.

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