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Local displacement of diapir contacts and its importance to pluton emplacement study: Discussion

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Schwerdtner (1995) points out that horizontal shortening of ductilely deformed contact aureole rocks cannot be used to infer the amount of host rock material displaced during diapirism. Instead, both longitudinal strain and solid-body rotation of the same material line must be used. We completely agree with Schwerdtner and applaud his clear exposition of this crucial point. However, we feel that several aspects of his note would benefit from further discussion, or are potentially misleading. We group these issues into three topics: (1) the question of ballooning vs diapirism, (2) validity of previous measurements of country rock displacement, and (3) additional tests of diapir models by comparison with natural systems.

Ballooning, the in-situ radial expansion of a magma chamber, continues to be a popular model for final chamber construction (e.g. Holder 1979, Ramsay 1989). Wide acceptance of the ballooning models is due, in part, to recent interest in magma ascent by diking which requires some means of chamber expansion to form large, elliptical plutonic bodies (e.g. Clemens & Mawer 1992, Petford *et al.* 1994). Schwerdtner downplays the importance of ballooning because the mechanics of this process are poorly understood; however, this is true for many ascent and emplacement mechanisms and seems to us to be an insufficient reason to discard the model. We also emphasize the difficulty of distinguishing diapirs and balloons, in the field (e.g. Bateman 1985). Thus, although we agree that there are many problems with the ballooning model (e.g. Paterson & Vernon 1995), we believe that the geological community should continue to evaluate both models.

In this context, our earliest attempts to calculate magnitudes of country rock flow during pluton emplacement were designed to assess ballooning. We did so by integrating aureole strains along traverses perpendicular to pluton margins, a technique Schwerdtner notes is valid for ballooning plutons. We recognized the problems inherent in using only outcrop-scale strain measurements and have incorporated deflections of pre-emplacement markers (e.g. Fowler 1994) along with the strain data in all subsequent studies (including those referenced by Schwerdtner). Marker deflections are insensitive to deformation mechanism and record solid-body rotation, translation and strain. Thus, marker deflections are useful for evaluating country rock displacements during ballooning or diapirism provided that either the pre-emplacement geometry of markers is known (as assumed in our studies), or that rigid rotations and stretches are known for many line segments along the deflected marker (Schwerdtner's note). For example, geometries of stratigraphic units and pre-emplacement faults are well known outside of aureoles around the Papoose Flat pluton, California, and Ardara pluton, Ireland (Paterson & Fowler 1993). Within the deformed aureoles, these same markers can be restored to their inferred pre-emplacement geometries and the necessary translations used to calculate magnitudes of material transfer. Our procedure is certainly quicker, and potentially more accurate, than trying to determine solid-body rotations and stretches from individual material lines across the deformed aureoles. If our calculations are incorrect it is because we have made incorrect assumptions about pre-emplacement host-rock geometries, not because we have ignored solid-body rotation and translation.

Schwerdtner (1995) nicely elucidates one of the most serious problems facing the use of deflected structural markers in emplacement studies. Planar markers (the most geologically common type) cannot record the component of the displacement vector that lies within the plane of the marker. For example, vertical displacement of host-rock material will not cause deflections of initially vertically-dipping bedding. However, we point out that at least four additional tests of diapir models can be used to verify (or invalidate) conclusions based on aureole strains and deflections of vertical markers.

First, if marker horizons behave as passive markers (as in the Dixon 1975 model used by Schwerdtner), then the magnitudes of marker deflections are directly related to the magnitudes and orientation of ductile strains. Thus, structural aureoles can be viewed as zones of general shear and the amount of vertical displacement of host-rock markers and pluton contacts should be related to strains in the aureole 'shear zone'. As Dixon's model shows, large vertical marker deflections require correspondingly strong ductile strains. Paterson and Fowler (1993) compared strain intensities around natural plutons to those predicted by the Dixon model and showed that aureole strains are an order of magnitude lower than predicted.

A second test is to compare the deflections of host-rock markers that had very different pre-emplacement orientations. In Dixon's model, horizontal markers display much larger deflections than vertical markers, because aureole displacements are predominantly vertical. Markers around the Ardara pluton (Paterson & Vernon 1995) provide an example of this test. Pre-emplacement markers (stratigraphic units, faults, dikes) have a wide range of dips outside the structural aureole. However, inside the aureole, none of these markers show particularly large deflections or strongly vertical deflections, arguing against a Dixon-type diapir model.

A third test, but one more difficult to apply, is to estimate vertical host-rock displacements in contact aureoles using paleobarometric gradients. This requires either paleobarometric information across aureoles, or knowledge of the composition and geometry of host-rock units below presently exposed levels (or above if aureole material is flowing downwards), neither of which is typically available for most plutons. Although no scale is given in Schwerdtner's figs. 3, 4 and 6, the model diapir has risen about 2 body radii. By analogy, a 10 km diameter diapiric pluton that had risen 2 body radii would need to have a paleobarometric gradient across the aureole of around 3 kbar or country rock units at the pluton contact that had been uplifted 10 km relative to outer aureole rocks. We are not aware of any documented examples where such a strong paleobarometric gradient exists.

A fourth test, discussed by Schwerdtner, is that the Dixon (1975) diapir model predicts extremely high strains in host rocks above the crest, or 'roof', of the pluton. However, our recent studies of many pluton roofs (Fowler *et al.* 1995, Paterson *et al.* 1995) support the conclusion of Buddington (1959) that most roofs show the exact opposite of this prediction. At every roof we have studied to date, we find little or no host-rock ductile strain, or at most, a large *decrease* in ductile strain from nearby walls to roofs. In all cases we find little or no deflection of pre-emplacement host-rock markers above the pluton roofs.

We conclude by noting that the failure of most natural plutons to fit the Dixon model by no means invalidates Schwerdtner's main conclusion that rigid-body rotations and translations of aureole material must be accounted for in emplacement studies. However, we also note that we have tried to do so in our previous work and stand by the conclusions stated in these papers.

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