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SHORT NOTES

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

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Abstract—The extent to which mid-crustal plutons have grown by diapirism cannot be deduced from the horizontal shortening of ductilely deformed host rocks and associated displacement of lateral intrusive contacts. By contrast, the vertical shortening above plutons and upward displacement of their roof contacts may provide a good measure of the diapiric component of pluton emplacement. This is related to the vertical bulk translation of buoyant material in immature diapirs and associated escape flow of overlying rocks.

The length change of a *vertical* material line situated above the crest of an immature upright diapir corresponds to the upward displacement of the local contact. The length change of *horizonal* material lines situated at lateral contacts of model diapirs, however, differs markedly from the contact displacement. This is related to the absence of horizontal symmetry planes in the finite-strain field about upright diapirs of any shape, and the importance of vertical shear at the lateral contacts.

The host-rock strain field of a hypothetical pluton grown *in situ* by spherical expansion ('ballooning') has an infinite number of symmetry planes. The strain field is characterized by large volume losses, but the length change of all radial lines corresponds to the local magnitude of contact displacement. This precludes the possibility of differentiating, in ductile host rocks above plutons, between vertical diapirism and spherical expansion—unless gauges of volume change are available.

INTRODUCTION

Magma ascent and pluton emplacement are 'hot topics' of current structural research (Lister & Kerr 1991, Paterson *et al*. 1991, Clemens & Mawer 1992, England 1992, Paterson & Tobisch 1992, Petford & Atherton 1992, Petford *et al*. 1993, Paterson 1994, Weinberg 1994). Many workers envisage that magma diapirism and/or spherical expansion ('ballooning') are processes contributing significantly to the emplacement of large granitoid plutons (Ramberg 1967, 1981, Holder 1979, Ramsay 1989, Weinberg 1994, Petford *et al*. 1994). Both diapirism and ballooning lead to shortening of ductile host rocks and associated transverse displacement of pluton contacts (Paterson & Fowler 1993, 1994).

Field-based estimation of shortening magnitudes in ductilely deformed rocks generally requires knowledge of the state of finite strain and associated solid-body rotation (Schwerdtner 1985, 1989). Except above the crest, local magnitudes of host-rock shortening and contact displacement *are not indicative* of the overall amount of host-rock volume removed by growing diapirs (Weinberg 1994). This is illustrated, in the present note, by means of a well-known diapir model. Also considered is a hypothetical geometric model of pluton growth by spherical expansion ('ballooning'), which necessitates large volume changes and remains to be substantiated on physical grounds.

DUCTILE SHORTENING OF HOST ROCKS

In the modern geological literature, amounts of shortening across tectonic structures are quoted in per cent and/or kilometres. This reflects the dual use of 'shortening' in specifying: (1) longitudinal strains; and (2) components of displacement difference (Fig. 1). Horizontal components are estimated, for example, from the strain-induced change in horizontal dimensions of partly eroded, large structures (Fig. 2, Shanks & Schwerdtner 1991). Such change may be expressed in per cent (Schwerdtner 1985), but amounts to a displacement difference if the original and final horizontal dimensions of a structure are measured along *different material lines*.

Longitudinal strains (Ramsay & Huber 1983, p. 3) are relative changes in length of *identical material lines* resulting from a ductile deformation. The strain is heterogeneous if a given material line loses or acquires curvature as a result of deformation.

Lines A′–B′ and D′–E′ (Figs. 3 and 4) are indicative of strongly heterogeneous, plane strain in the ductile mantle of a cylindrical model diapir. This model was made to simulate anticlinal gneiss diapirs emplaced in the solid state (Dixon 1975), but the flow pattern is found in a variety of model diapirs rising into ductile material (van Berkel 1988, Schmeling *et al*. 1988, Cruden 1990, Guglielmo 1993). Most finite elements transected by the traces of two hypothetical erosion surfaces

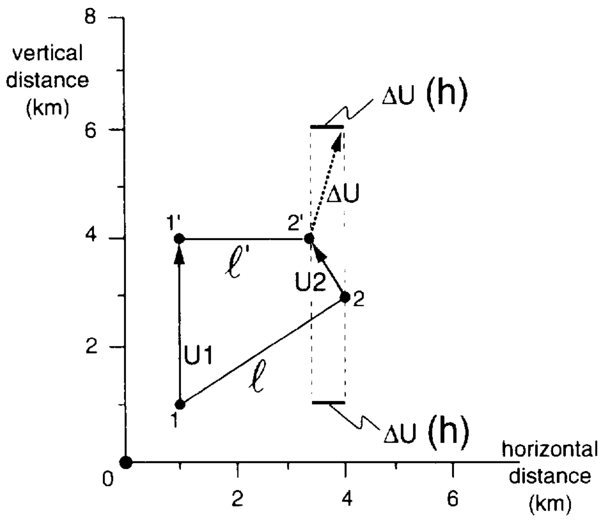

Fig. 1. Distinction between longitudinal strain, $(\ell' - \ell)/\ell$ of a marker line ℓ', and the displacement difference (ΔU) between point 1′ (located, for example, on a pluton contact) and point 2′ (within the host rocks). Primes signify the final geometric state; U1, U2 are displacement vectors, ΔU(h) = 0.6 km is the horizontal component of the displacement difference, an absolute measure of horizontal shortening in the host rocks.

(A′–B′, D′–E′) are tilted and horizontally shortened (Figs. 3 and 4). The traces are important material lines because all structural measurements are generally sited on a peneplain or curved erosion surface.

The trace of any erosion surface may be represented by a chain of line segments whose length and orientation in the undeformed state may be found by removing the geometric effects of strain and solid-body rotation (Schwerdtner 1985, 1989). This is best accomplished by the use of finite elements (Cobbold & Percevault 1983), but generally results in an angular chain of destrained line segments rather than the smooth curves A–B, D–E shown in Fig. 4.

A detailed evaluation of Figs. 3 and 4 provides valuable insight into the geometric complexity of immature diapirism. Lines A′B′ and D′E′ have shortening strains of about 40% and 10%, respectively. The horizontal components of the displacement-difference vectors **AA′**, **DD′** (Fig. 5) indicate an inward-directed relative motion of the local contact, which may be smaller than geometric errors introduced by the analysis of the putty model and the redrafting of Figs. 3 and 4. The absolute displacement vectors, which cannot be determined in most natural structures (Schwerdtner 1985, Shanks & Schwerdtner 1991), prove to be subvertical (Fig. 6).

CORRESPONDENCE BETWEEN LONGITUDINAL STRAIN AND DISPLACEMENT DIFFERENCE

The buoyant material in Dixon's (1975) immature diapir is a highly viscous putty chosen to simulate the behaviour of ductile granitoid rocks rather than felsic magma. Space for the cylindrical model diapir is created mainly by severe thinning of high-density material above the crest and associated escape-flow down the flanks. This is tantamount to having large components of solid-body translation in the middle and dip shear at the flanks of the immature diapir (Fig. 3). However, the flow pattern is not symmetric above the crest (Fig. 3).

Low-viscosity mantles of numerically generated model diapirs have >2 vertical symmetry planes across which there is no displacement of material points (Fletcher 1972). Here the longitudinal strain of vertical lines above the diapir crest is equal to the normal displacement of the contact. This correspondence explains the strategic value of vertical rock walls (deep canyons or fiords) exposing the host rocks above symmetric upright diapirs (cylindrical ridges and circular or oval domes).

Some authors envisage a nondiapiric process of *in situ* spherical expansion (ballooning of plutons) without prior rise of magma masses. Instead, magma moves in small batches along dilatant fractures and collects at structurally favourable sites while progressively displacing the enveloping rocks (Holder 1979, Ramsay 1989). A purely ductile deformation produces flattening strains at all localities around ballooning plutons, i.e. there is a large volume loss in, rather than escape flow of, the host rocks. Flattening strains also occur above the crest of circular diapirs (domes), but here the multi-lateral escape flow requires no volume change.

Because of the perfect symmetry of the deformation

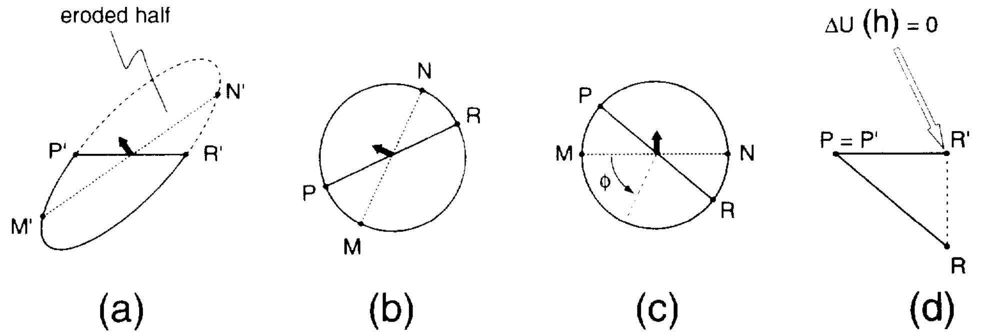

Fig. 2. Removal of the geometric effect of homogeneous deformation (strain and solid-body rotation) on a pair of material lines across a partly eroded, elliptical rock mass: P′–R′ = peneplain trace and M′–N′ = strained trace of bedding with younging direction (short arrow). The removal of strain changes the length and orientation of both material lines (now P–R, M–N), but the bedding trace fails to return to horizontal (b). The magnitude of solid-body rotation (φ) is equal to the angular departure of bedding from horizontal (c). The longitudinal strain of P′–R′ is −0.3 (shortening by 30%), but ΔU(h) is zero and implies no change in horizontal dimension.

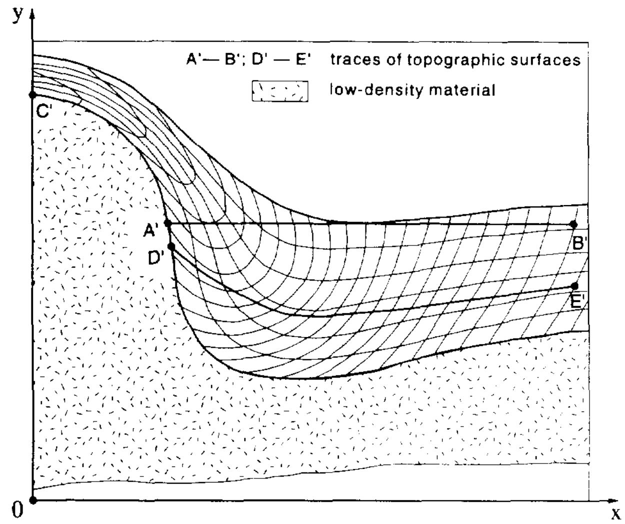

Fig. 3. Cross-section through a putty model of an immature diapiric ridge (redrawn from Dixon 1975, fig. 6). A', B', C', D', E' are displaced marker points.

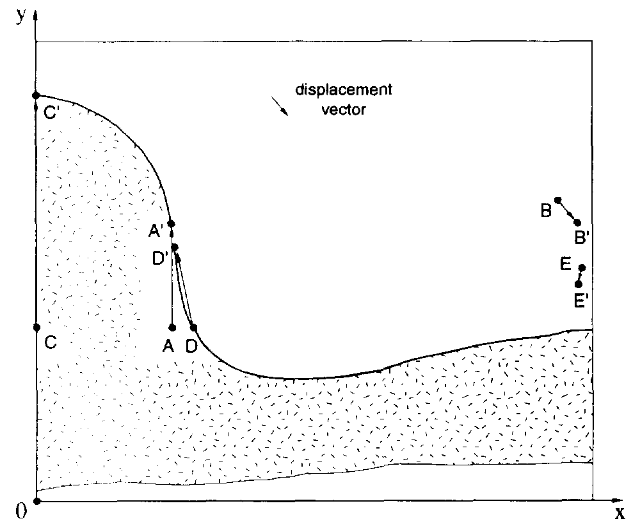

Fig. 6. Displacement vectors of five material points in a spatial reference frame (x, y). Based on distorted grids in Dixon's (1975) figures.

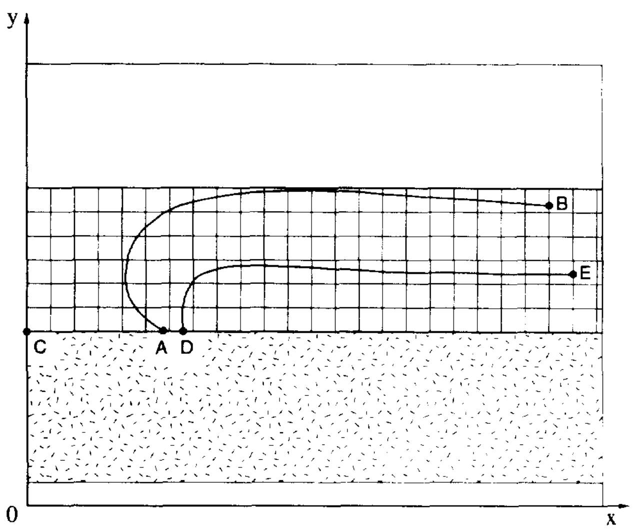

Fig. 4. Configuration of lines AB, C0, DE before deformation (cf. Fig. 3). Further explanation in the text.

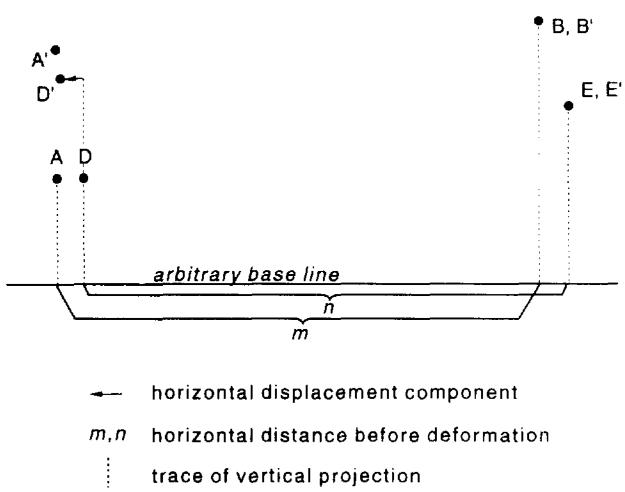

Fig. 5. Approximate horizontal displacement of the subvertical contact at points A' and D' (Fig. 3), using changes in horizontal distance between pairs of points (Fig. 4). The small horizontal arrow between A and A' is omitted.

field about ballooning plutons, amounts of radial shortening (displacement differences) are equal to those of longitudinal strain at all localities. This contrasts with the late-stage deformation field around laterally expanding, mature diapirs, which lacks inclined planes of symmetry. The tabular geometry of large granitoid plutons is compatible with lateral spreading rather than spherical ballooning, which remains to be modelled on a realistic physical basis. A mechanical justification is required, in particular, as to why ballooning plutons remain stationary rather than ascend buoyantly into overlying ductile rocks.

DISCUSSION AND CONCLUSIONS

Small amounts of host-rock shortening and associated normal displacement of local intrusive contacts have recently been used as evidence for the importance of nondiapiric processes in creating space for large granite plutons (Paterson & Fowler 1993). As illustrated in the present note this use is problematical, except above the pluton crest.

In general, the normal displacement of diapir contacts cannot be determined by simple unstretching of transverse line segments, but requires the use of local tilt values (Fig. 2) together with longitudinal strains (Schwerdtner 1985, 1989). Moreover, the contact displacement decreases markedly from the roof to the flanks of most upright diapirs, and can be inward directed at low structural levels.

Dixon's (1975) two-dimensional model of high-viscosity gneiss diapirs and their low-viscosity mantles may be inappropriate for most granitoid plutons (Ramberg 1981, pp. 252–259), but can be used to illustrate a general technique of estimating the local magnitude of contact displacement. Only where transverse line segments, drawn on geological maps or vertical sections, are parallel to an intersection trace between symmetry planes of the pluton deformation field (e.g. line C'–O in

Figs. 3 and 6) is the unstretching procedure applicable. (Material points on such intersection traces are compelled to remain there, no matter how heterogeneous the strain.) This is true for localities above symmetric upright diapirs and the mantles of plutons grown by spherical 'ballooning', a hypothetical process which remains to be fully substantiated by physical modelling.

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