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Re-examining pluton emplacement processes

SCOTT R. PATERSON and T. KENNETH FOWLER, JR

Department of Geological Sciences, University of Southern California, CA 90089-0740, U.S.A.

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Abstract—Previous pluton emplacement studies have attempted to explain how space is made during pluton emplacement. In fact, the only means of 'making space' during emplacement of mantle-derived magmas in the crust are (1) lowering the Moho or (2) outward displacement of the Earth's surface. Other 'pluton emplacement mechanisms' are material transfer processes (MTPs) that do not increase the volume of the crust. One frequently cited MTP for emplacement of concentrically zoned and ballooning plutons is ductile flow of wall-rocks around the plutons. The expected structures and total strains near such plutons are dependent on the three-dimensional pluton shape, the width of the deforming aureole, whether the pluton is a piercing or non-piercing diapir, and, in the latter case, the number of body radii the pluton travels. We have re-examined a few such plutons and calculated the amount of material transfer caused by ductile flow. In no case is more than 40%, and in most cases only 15–35%, of the required material transfer accommodated by wall-rock flow. The contact aureoles around these plutons are too narrow and/or strains too low, indicating that the plutons are predominantly discordant bodies with narrow (0.1–0.4 pluton radii) concordant aureoles. A comparison of strains in natural contact aureoles and those made in mechanical models of diapirs indicates that natural strains are at least an order of magnitude less than model strains. We suggest that the similarities between models of diapiric ascent of spherical bodies and concentrically zoned plutons are superficial because the models are too simplistic. Instead, we argue that the ascent and emplacement of magmas require multiple near-field and far-field MTPs. These MTPs will show gradients with depth, distance from the magma, and with time. Rates of near-field MTPs must be rapid, whereas far-field rates are probably nearer to long-term average rates of orogenic processes.

INTRODUCTION

WHEN James Hutton (1794) first suggested that magmas intruded into their wall rocks, geologists were faced with the challenging problem of how space is made for these bodies. Recent work has emphasized that making space at the level of pluton emplacement is a structural problem. Geochemical and petrological studies on plutons emplaced at mid to shallow crustal levels have concluded that (a) magmas have moved significantly from their source regions and (b) magmas do not incorporate large volumes of wall-rock material (Marsh 1982, Pitcher 1987, Ague & Brimhall 1988, Miller *et al.* 1988). Conclusion (b) is particularly true at the level of final emplacement where ambient wall-rock temperatures are lower and plutons are near their solidus. Barton *et al.* (1991) noted that in the western United States, the greatest exposed volume of plutons were emplaced at mid-crustal levels where wall-rock temperatures were significantly below magma emplacement temperatures. If the above observations are correct, this presents a staggering and often ignored structural problem: that is, what are the mechanical means by which huge volumes of magma are emplaced in the crust? Twenty percent to locally 90% of orogenic belts around the world consist of intrusive material added to presently exposed crustal levels. For example, in the central Sierra Nevada Batholity California, we estimate that more than 1,000,000 km^3 of material was added to the orogen during the Mesozoic.

By the turn of this century, most of the presently accepted emplacement mechanisms (caldera collapse, ring dikes, cone sheets, laccoliths, block elevation along faults, stoping, emplacement of dikes and sills along fractures, forcibly emplaced diapirs, emplacement in fold hinges and faults, and batch melting or assimilation) has been recognized (e.g. Daly 1903, Barrell 1907). Subsequent work has refined these models and made initial calculations of thermal and mechanical implications (see Buddington 1959, Shaw 1980, Spera 1980, Bergantz 1991 for reviews). Recent studies of emplacement mechanisms have tended to emphasize the syntectonic nature of igneous activity (Pitcher 1979, Hutton 1988a,b, Karlstrom 1989) and argued that plutons are sometimes emplaced in environments of local or regional extension (e.g. Billings 1972, Hutton 1988a,b).

We have recently completed a review of emplacement mechanisms (Paterson *et al.* 1991a) that convinced us that there are some misconceptions in the literature about emplacement processes and that single mechanism models are simply not supported by data from natural plutons. This paper is an attempt to address some of the misconceptions and to suggest a somewhat different perspective of pluton emplacement. For example, many studies simply divide pluton emplacement mechanisms into forceful and passive types. These terms were initially used to imply that space was made by body forces of the pluton pushing aside wall rocks (forceful emplacement) or by passive flow into fractures or openings formed by regional stresses. Hutton (1988a,b) elaborated on these terms and suggested that forceful emplacement occurs when the rate of buoyant uprise is greater than the rate of 'tectonic cavity opening', whereas passive emplacement occurs when the rate of 'tectonic cavity opening', is greater than the rate of buoyant uprise. We suggest that these terms should be discarded for the following reasons: (1) the ascent and emplacement of plutons *always* reflect a single and fluctuating stress field that is a combination of regional hydrostatic and deviatoric stresses plus thermal and buoyancy stresses (Spera 1980, Furlong *et al.* 1991); (2) it is now well documented that emplacement mechanisms around a single pluton vary with depth such that 'passive' and 'forceful' mechanisms as defined above may operate around the same pluton; (3) Hutton's use of the terms is only valid for particular types of emplacement, and may be misleading because at depth the rate of 'tectonic cavity opening' can never be greater than the rate of infilling. Below we argue that multiple mechanisms must operate during pluton emplacement and that the types of mechanisms operating will show vertical, horizontal and temporal gradients. Describing pluton emplacement as forceful or passive does not provide much information about these mechanisms and may give an overly simplistic impression of the processes involved.

THE NATURE OF MAGMA–WALL-ROCK SYSTEMS

Pluton–wall-rock systems are open, linked systems with mass, enthalpy and mechanical energy all transported across the pluton–wall-rock contact (Tai & Jaupart 1990, Bergantz 1991, Kerrick 1991). These systems are unique in crustal environments because of the extreme variability in conditions occurring over geologically short periods of time. Bulk compositions and fluids–gases in both the pluton and wall-rocks change with time due to crystal fractionation, magma mixing, fluid flow, etc. Temperatures vary over a range of 1000°C during emplacement and cooling. Deviatoric stresses due to buoyancy and thermal expansion can fluctuate by up to several kilobars (Spera 1980, Marsh 1982, Furlong & Meyers 1985, Barton *et al.* 1991). Viscosities, particularly of magmas, may change by 20 orders of magnitude during cooling and crystallization (Cruden 1990, Bergantz 1991). The durations of different processes operating during the emplacement of plutons vary by 10 orders of magnitude (e.g. Cashman 1990, Barton *et al.* 1991, Kerrick *et al.* 1991, Paterson & Tobisch 1992).

What makes these systems particularly unique is that all of the above changes occur during the cooling of the magma to ambient wall-rock temperatures, which most studies suggest take a few thousand to no more than a few million years (Jaeger 1968, Barton *et al.* 1988, Reagan *et al.* 1991, Paterson & Tobisch 1992). These large and rapid changes in conditions and material properties indicates that large and rapid changes in material behavior will occur during magma emplacement. This alone argues strongly against the standard approach of finding a single emplacement mechanism for a pluton. Multiple emplacement mechanisms operating at different times and at different rates must occur in such a dynamic environment.

MAKING SPACE DURING PLUTON EMPLACEMENT

We argue that during pluton emplacement in regions above the Moho there are only two ways to make space (i.e. increase the volume of the crust): (1) lower the Moho; or (2) displace the Earth's surface. All other 'pluton emplacement' or 'space making mechanisms' are better viewed as material transfer processes (MPTs) since they do not increase the volume of the crust. For example, processes like stoping and cauldron subsidence assume a *pre-existing magma chamber* and are simply transferring material from the top into or through the chamber. Ballooning models assume that material moves away from the center of the pluton or around the pluton, but rarely explain how space is made elsewhere for this displaced material (Fig. 1). Magmas generated *in* the crust only require material transfer (ignoring the slight volume increase that accompanies magma generation) as long as the space made by melt generation and ascent is not filled by magmas from the mantle (e.g. Bergantz 1989).

A third space making mechanism is volume loss. Volumetric changes during mineral reactions in contact aureoles, for example, can make some new space without removing materials from the system. However, such changes are small (maximum 10%?) and larger volume losses occur by transfer of material by fluid flow and thus are MTPs. Furthermore, we know of no documented example where large bulk chemical changes, which might support a large volume decrease, occur in contact aureoles.

This distinction between space making and material transfer processes emphasizes the need to view pluton

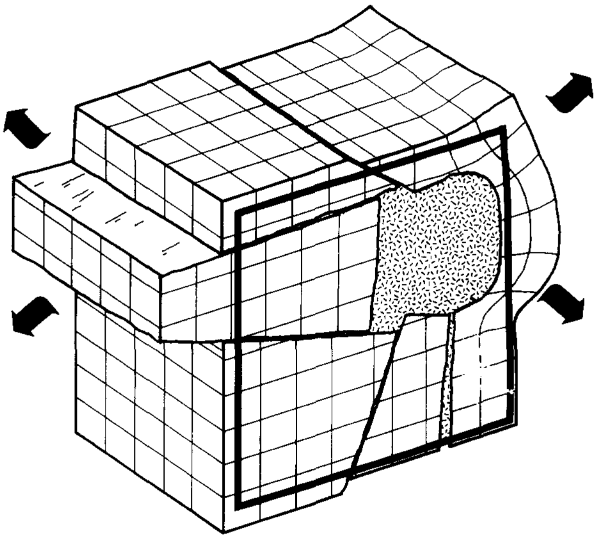

Fig. 1. Near- and far-field material transfer problems encountered during ballooning. Skematic diagram of a dike feeding a magma chamber that has expanded with time. The extent of wall-rock before pluton emplacement is outlined by the large bold box. Material outside this box was displaced by near-field MTPs (ductile flow and rigid translation along faults) and shows the need for far-field MTPs if sufficient ductile strain does not occur near the pluton. Black arrows emphasize the need for the far-field material to be transported towards the Earth's surface or towards the region of magma generation.

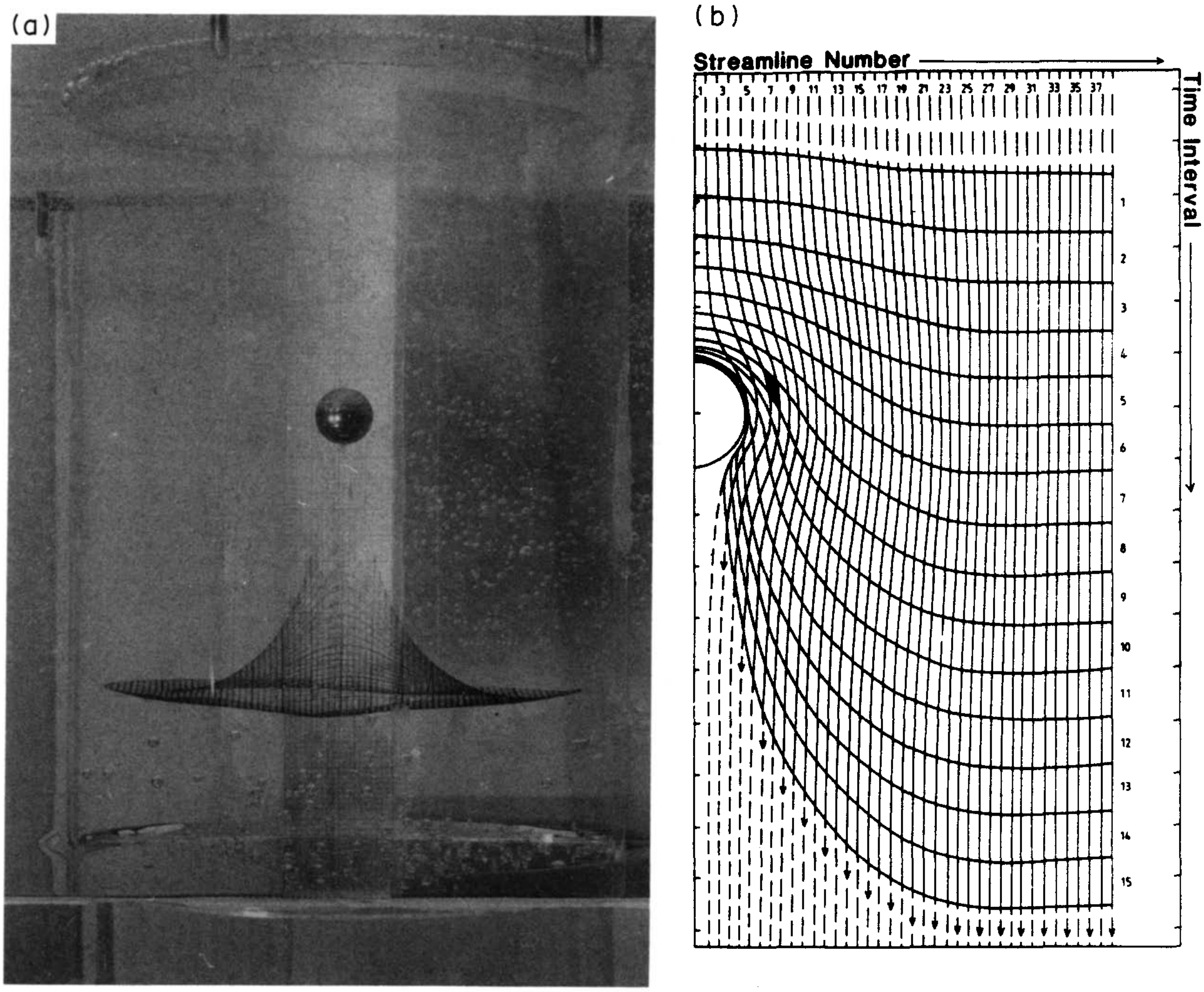

Fig. 2. (a) Photograph from Cruden (1988) of experiment where spherical balls were dropped through polymer containing a passive marker grid. Near-field and far-field MTP is flow of the polymer. Space for the spherical ball is made by raising the level of the polymer in the container by far-field MTPs. (b) Drawing of passive marker grid around the spherical ball that emphasizes the nature of the strain field produced during near-field material transfer. See Cruden (1988) for full discussion. Published with permission from A. R. Cruden.

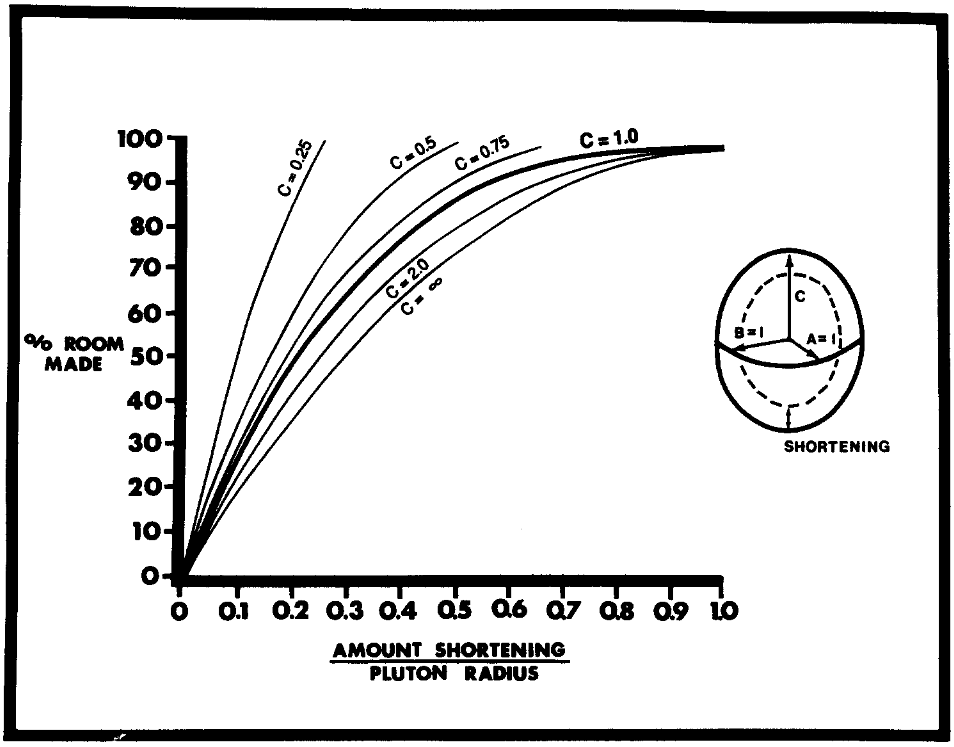

Fig. 3. Plot of percent room made vs bulk wall-rock shortening normalized to pluton radius assuming a three-dimensional spherical (thick line) or elliptical (thin lines) shape for the pluton. C = radius of third axis of pluton as shown in inset. $C = 0.25$ means pluton is tabular sheet, $C = 2.0$ means pluton is rod-shaped body.

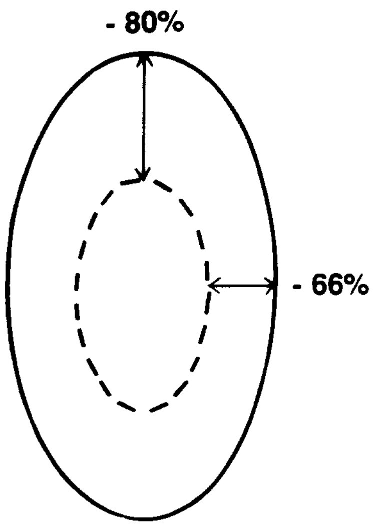

Fig. 4. Two-dimensional map view of pluton that was initially intruded with an axial ratio of 2:1 and expanded to a final ratio of 4:2. If the final aureole has a constant thickness of 0.5 (same units as pluton radii) and all local space was made by a near-field MTP of ductile wall-rock flow, then aureole strains would need to be higher at the ends (regions at the ends of the long axis) than along the sides of the pluton. Average percent (or bulk) shortening required for the aureole are as shown.

emplacement on two scales. We use nomenclature from studies of stress fields to propose the terms near-field and far-field MTPs. Near-field MTPs are those processes that operate within the structural aureole of each pluton and provide a means of moving material away from the immediate path of the magma. Many of the standard emplacement mechanisms discussed in the literature fall within this category. However, far-field MTPs are also needed to transfer material from the immediate aureole towards the surface of the Earth or back towards the region of magma generation.

A useful analogue model of near-field and far-field material transfer processes during diapiric ascent and emplacement is presented by Cruden (1990). Cruden dropped spherical balls through polymers and examined the flow of the polymer around the sphere (Figs. 2a & b). Near-field MTPs are spectacularly exemplified by flow of material around the sphere. However, this flow did not make space for the spherical ball. Space was made by raising the level of the upper surface of the polymer leading to an increase in the volume of material in the container. This raising of the polymer surface (analogous to lowering of the Moho or displacing the Earth's surface) was accomplished by far-field MTPs.

It is also useful to consider the nature of potential MTPs acting in a horizontal plane through which the upper half of the sphere in Cruden's model passes, since these are the processes that form structures around plutons. As the sphere begins to pass through a plane, one or more of three processes must happen: (1) the area of that plane must increase by an amount equivalent to the areal cross-section through the spherical ball requiring the sides of the container to expand due to horizontal MTPs; (2) the area of the plane will stay the same and an equivalent amount of material as that added to the plane must be removed from the plane (e.g. the vertical MTPs seen in Fig. 2b); or (3) the material in the plane must be sufficiently elastically compressed to allow passage of the spherical ball. Realistic emplacement models must include one or more of these processes. The behavior of materials used in experimental models obviously differs from rocks in several ways and we discuss some of these differences later.

The most common means of evaluating the relative importance of various near-field material transfer processes has always been field examinations of exposed plutons. However these studies may have introduced a bias into our understanding of emplacement mechanisms. Most studies have examined the sides of plutons simply because the sides are vertically more extensive than roofs or floors and thus more often preserved (our definition of the 'roofs' of plutons includes the frontal or lateral tips of dikes or sheet-like plutons, that is the wall-rock region directly in front of the magma path). Do structural–metamorphic characteristics along the sides of plutons adequately reflect which near-field MTPs operate during emplacement?

Several lines of reasoning suggest that the answer to this question may be a qualified no. First, several studies have noted that the nature of contacts and aureoles near tops of plutons differ remarkably from the sides (Buddington 1959, Hopson & Dellinger 1987). Wall-rocks near pluton tops tend to be more discordant and less ductilely deformed than wall-rocks near pluton sides (Buddington 1959, Bussell *et al.* 1976, Hopson & Dellinger 1987, Barton *et al.* 1988, Pitcher 1987). These changes are usually related to changing depth (Buddington 1959, Hopson & Dellinger 1987, Barton *et al.* 1991). However, an alternative possibility is that the structures near the tops better reflect the dominant near-field MTPs, whereas the sides reflect the effects of continued heating and local adjustments by ductile flow during the passage, plus or minus some expansion of the pluton. Careful studies of continuous tops and sides of plutons exposed at different crustal levels are needed to test this hypothesis.

Second, the internal margins and external contacts along pluton sides represent ductile or magmatic shear zones, some with a component of shortening across them (e.g. if the pluton radius expands during ascent or emplacement). Around any curved igneous body, these surfaces must be curved and material passing through these shear zones may undergo a complex sequence of deformation. For example, Coward & Kim (1981) and Coward & Potts (1983) documented complicated strain paths around bends in or at the tips of faults. Cruden (1988) and Schmeling *et al.* (1988) have emphasized the complex nature of strain paths within and along the margins of diapirs and how large flattening strains may occur along these margins *without any expansion* of the pluton. The initial parts of these complex paths will only be preserved in the wall-rocks near the roof of the pluton; it is the preservation of structures formed during these initial stages that may offer more information about near-field MTPs.

Third, many elliptical plutons intrude other plutons or metasedimentary rocks along sharp, undeformed contacts as if the intruding pluton simply took a 'cookie cutter bite' out of the surrounding wall rocks (e.g. Bateman 1988). The structures along the sides of these plutons provide little information about emplacement beyond indicating that emplacement likely involves brittle processes such as stoping, brittle faulting or roof uplift.

Thus, we argue that it is important to consider the characteristics of tops or frontal tips of igneous bodies: it is in these locations, both internally within the pluton and in the wall-rocks, that will provide important additional clues about near-field MTPs. To evaluate MTPs further, we now consider diapiric ascent and ballooning of roughly elliptical (in map-view) plutons.

EMPLACEMENT BY DIAPIRISM AND BALLOONING

It has been suggested that the MTP needed around many concordant elliptical plutons is ductile shortening and/or downward return flow of the surrounding wall-rocks during magma ascent and/or expansion during final emplacement (Holder 1979, Bateman 1985, Courrioux 1987, Ramsay 1989). Many geologists assume that concentric foliation patterns in the pluton and wall-rocks, strain fields dominated by flattening and margin-normal Z-axes (e.g. maximum shortening axes), or wall-rocks dominated by steep stretching lineations demonstrate the operation of these processes. The most common interpretation is that magma moves along fractures as dikes, or down stress gradients as tear-drop shaped diapirs, until the magma reaches a certain level in the crust (e.g. Spera 1980, Bateman 1984, 1985, Mahon *et al.* 1988). The magma then accumulates into a spherical chamber deforming its walls in the process (Figs. 1 and 2). The near-field MTP is assumed to be ductile flow away from the pluton, or around and down towards its tail. Far-field MTPs are rarely considered because of the assumption that sufficient material transfer occurs within the aureole.

To evaluate this emplacement model further, we first consider the geometrical relationship between pluton shape, strain within the aureole, and amount of near-field material transfer. We then briefly examine similar features around experimental diapirs. Finally, we evaluate available strain and structural data from several natural plutons.

Modeling diapiric emplacement

Estimates of the magnitude of material transfer by ductile wall-rock flow involve measurement of aureole strains along a two-dimensional slice (the Earth's surface) and extrapolating these results to three-dimensions. These estimates require knowledge about the bulk wall-rock shortening, obtained from either the changes in regional strain markers (stratigraphic sections, dike swarms) or by integrating strains over the width of the aureole.

The nearly circular plan-view of many plutons believed to have been emplaced as diapirs, has been used to justify modeling their three-dimensional shape as a sphere (Holder 1979, Ramsay 1989), or some modification of a sphere (Batemen 1985). Given this simplification, emplacement models have only two variables: (1) the amount of bulk wall-rock shortening normal to pluton contact; and (2) the radius of the pluton. The volume created for pluton emplacement by wall-rock shortening (and vertical transfer of material) is taken to be a spherical shell with outer radius equal to the pluton radius, and inner radius equal to the pluton radius minus the total amount of wall-rock shortening (bold line on Fig. 3). The percent volume made is expressed as the ratio of the volume of this spherical shell to the total pluton volume, times 100% (we normalize to final pluton volume to remove effect of actual size). Evaluation of the geometrical aspects of such spherical models (Fig. 3) yields two important results: (1) small errors in the estimation of the bulk shortening, particularly at low values, can lead to large errors in the estimate of space created for emplacement; and (2) the vertical dimension assumed for the model, which is almost always poorly constrained, can have a factor of 2 effect on this estimate (Fig. 3).

Pluton shapes may, of course, deviate significantly from spheres. Other shapes, such as sheet-like sills, horizontal layers, or vertical stocks, can be approximated in a manner analogous to the spherical model, that is, by a triaxial ellipsoid or rectangular sheet. This approximation yields four variables; length, width (horizontal) and height (vertical) of the pluton, and the amount of bulk wall-rock shortening. Horizontal dimensions and bulk wall-rock shortening are determined as discussed above. However, the vertical dimension of plutons is usually unknown. Although estimates of a pluton's buried shape can be made by geophysical techniques, the amount of material eroded off the top of the pluton remains difficult to determine.

To evaluate the effect of varying the pluton height, we simplify the geometry by holding the horizontal dimensions of the pluton constant (e.g. the pluton has a circular map pattern) and examine the effects of varying pluton height and bulk wall-rock shortening. Figure 3 (thin lines) shows the effect of varying the pluton height, C, between a reasonable range of values, from 0.25 of the pluton radius (the pluton is a horizontal tablet) to $C = \infty$ (the pluton is a pencil-shaped, vertical stock), for typical values of wall-rock shortening. Within these limits, estimates of local space made for emplacement can vary by up to a factor of 2 for a given amount of bulk wall-rock shortening. Also note that in comparison to spherical plutons, emplacement of sheet-like plutons requires less bulk shortening at any one locality in the aureole.

The above values assume equal pluton and wall-rock expansion in all directions. It is useful to examine the implications of alternative models, for example, an elliptical diapir that was initially emplaced (by stoping?) with an axial ratio in plan view of 2:1 (Fig. 4). If this diapir then expands and maintains this same axial ratio, say to 4:2, then bulk wall-rock shortening must vary with position in the aureole. Bulk wall-rock shortening will be greater at the pluton ends where either the aureole width, strain gradient in the aureole, or the average value of shortening must increase (Fig. 4). Many plutons show the opposite, that is *less* bulk shortening at the pluton ends (e.g. Buddington 1959, Davis 1963), indicating that the above is not a common scenario in nature.

Models of experimental diapirs

Physical models that have been used to quantify total wall-rock strains during diapir emplacement share certain common features (Ramberg 1981, Cruden 1988). The wall-rock material is an incompressible Newtonian fluid with uniform viscosity and density, such as silicone putty (Dixon 1975) or polydimethylsiloxane polymer (Cruden 1988). Diapiric ascent of a material of contrasting density is induced in a centrifuge (Ramberg 1981, Dixon 1975) or simulated by slow flow past a spherical ball (Cruden 1988). Wall-rock strains are recorded by deformation of a grid of passive markers.

Wall-rock strain intensity can be quantified as a function of the change of length of the axes of an initially spherical object that is transformed into a triaxial ellipsoid during a deformation. We use the equation of Hossack (1968) to determine strain intensity:

$$E_s = 1/\sqrt{3}[(e_1 - e_2)^2 + (e_2 - e_3)^2 + (e_3 - e_1)^2]^{1/2}, \quad (1)$$

where e_1, e_2 and e_3 are the principal natural strains. The wall-rock strain intensities observed in physical models of diapirs are high adjacent to the pluton and significant strains extend large distances from the diapir contact (Fig. 2b). This is because the constant-volume deformation condition of these experiments requires that all of the MTPs for diapir ascent and emplacement within the container occur by ductile wall-rock flow. Cruden (1988) reported flattening strains with intensities $E_s \geqslant 4.0$ (equivalent principal axial ratios ($X = Y > Z$) for pure flattening would be >134:>134:1) in the wall-rock medium at the diapir contact. Dixon (1975) reported maximum wall-rock strains as high as $E_s = 3.34$ (ratios 60:60:1). The higher strains observed by Cruden are related to the greater ascent distance of the diapir in his model (Cruden 1988). Strong wall-rock strains in both models extend at least one diapir body radius into the wall-rock, and small to medium strains extend from two to 10 body radii (or greater) into the wall-rocks.

The behavior of materials used in experimental models obviously differs from rocks in several ways. First, the experiments have an artificial boundary condition: that is, the wall of the experiment. Numerical modeling of an infinite viscous wall-rock medium indicates that when this boundary condition is removed, deformation extends >20 pluton body radii into the wall-rocks (Cruden 1988, Schmeling *et al.* 1988). Second, real wall-rocks have a nearly exponential temperature-dependent viscosity (Marsh 1982, Mahon *et al.* 1988). Marsh (1982), Mahon *et al.* (1988) and Schmeling *et al.* (1988) have shown that temperature-dependent wall-rock viscosity concentrates deformation into the region near the pluton contact. Therefore, in nature, we would expect to find narrow ductile zones of deformation, with considerably higher strains than predicted by the isoviscous models discussed above.

Other ways that the strain fields in these experiments may or may not differ from strain fields around real plutons are whether or not slip occurs along the pluton–wall-rock contact, and whether or not the plutons are piercing or non-piercing diapirs (e.g. Van den Eeckhout *et al.* 1986). For non-piercing diapirs, the material adjacent to the pluton must continue to stretch and move along with the pluton (Fig. 2b). Thus strains in this material can eventually reach extreme values if the pluton moves a long distance: the exact values will depend on whether a no-slip or free-slip boundary condition exists at the diapir surface (Schmeling *et al.* 1988). Piercement diapirs only require strains that reflect the 'moving aside' of the wall-rocks to let the diapir pass, or require no wall-rock strains if other near-field MTPs (e.g. stoping, roof uplift) are used.

STRAIN FIELDS AROUND NATURAL PLUTONS

There are a number of elliptical plutons (in map view) considered to be 'classic' examples of plutons emplaced as diapirs and/or that have expanded (ballooned) during final emplacement. Paterson and coworkers have examined three of these plutons (Ardara, Ireland; Cannibal Creek, Australia; Papoose Flat, U.S.A.) because these plutons were thought to have some of the most highly strained aureoles around natural plutons and thus considered the most likely to be emplaced by a near-field MTP of ductile flow. We have also examined data from several others that are commonly mentioned in the literature (Chindamora, Zimbabwe; White Creek, Canada; Bald Rock and Bass Lake plutons, U.S.A.).

Ardara pluton, Ireland

The Ardara pluton, northwest Ireland, is one of the most often quoted examples of a ballooning pluton and one of the first where expansion was quantitatively examined (Holder 1979). This pluton is approximately 8 km in diameter (Fig. 5) with an eastern apophyses extending from the circular main mass of the pluton (Akaad 1956). The Ardara pluton intrudes Dalradian pelites and semi-pelites of the Appin Group (Pitcher & Berger 1972, Holder 1979) and is internally zoned, changing from quartz–diorite near its margins to granodiorite in its core. A foliation in the pluton increases in intensity near the pluton–wall-rock contact and is parallel to flattened, oblate enclaves (Akaad 1956, Holder 1979). Holder (1979) assumed that these enclaves were initially spherical and that they did not start to strain until the pluton solidified. He then used their deformed shapes to calculate thinning of the pluton margin and concluded that the pluton made 72% of its required local space by radial expansion.

Sanderson & Meneilly (1981) used the preferred

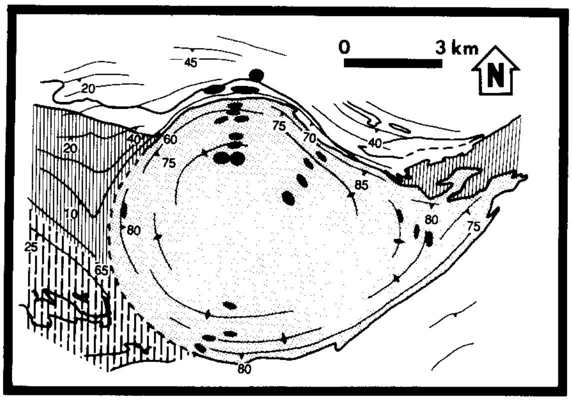

Fig. 5. Simplified map of Ardara pluton, Ireland, after Akaad (1956), Holder (1981) and Sanderson & Meneilly (1981). Trend lines and numbers show strikes and dips of largely magmatic foliation in pluton and cleavage in wall rock. Ellipses represent strains measured from enclaves in pluton (Holder 1979) or andalusite in aureole (Sanderson & Meneilly 1981). Thick lines show lithologic contacts. Vertical lined patterns mark regions where lithologic contacts or faults are definitely discordant (continous lines) or probably discordant (dashed lines) with respect to the pluton margin. Note cleavage only shows deflection near the pluton within a narrow contact aureole.

Table 1. Strains from Ardara contact aureole measured by Sanderson & Meneilly (1981)

X axis	*Y* axis	*Z* axis	Percent shortening	Lodes parameter	Distance from pluton (m)
1.65	1.5	1	−26	0.62	500
2.47	1.7	1	−38	0.17	500
5.81	3.5	1	−63	0.42	150
13.80	11.5	1	−82	0.86	150

alignment of andalusite porphyroblasts to estimate strains in the northern aureole. If we consider their results at face value (ignoring questions about mimetic growth, porphyroblast rotation, etc.), the strains range from quite low values beyond 500 m from the contact to moderately high values within 150 m of the pluton contact (Table 1). Holder (1979) noted a rapid increase in deflection–strain at the sillimanite isograd about 150 m from the contact.

Unpublished mapping by Vernon and Paterson indicates several additional constraints on the above observations. (1) Regional structures are generally deflected only up to 800 m from the pluton margin; this deflection is greatest near the northwestern and northern margins, weakest near the southwestern margin (Fig. 5), and complicated by post emplacement deformation near the eastern tail (Akaad 1956, Hutton 1982). (2) Regional structures and contacts (Fig. 5) locally show a weak to strong discordance with the pluton margin, sometimes right at the pluton–wall-rock contact. (3) Most of the structures in the aureole are regional structures, tilted, but not formed during magma emplacement. (4) The foliation in most of the pluton is largely magmatic. (5) Two types of inclusions exist within the pluton. Mafic microgranitoid enclaves show quite variable but generally increasing axial ratios towards the margin, whereas true xenoliths rarely show any increase in axial ratios. (5) Some syn- to post-emplacement deformation occurred, particularly along the southern margin.

The variable axial ratios of microgranitoid enclaves, lack of significant change in xenolith ratios, and widespread magmatic foliation support the interpretation that enclave ratios reflect magmatic processes and do not require significant pluton expansion (Cruden 1990), and thus, we view these numbers with some caution. More reliable estimates of emplacement-related strain are those measured in the aureole, although our data indicate that these aureole strains are heterogeneous and in part reflect pre- and post-emplacement deformation. However, if we use the strains calculated by Sanderson & Meneilly (1981), extrapolate these data from the pluton contact to 800 m, and assume that similar strains occurred everywhere around the pluton, then about 60% of the material transfer needed to emplace the Ardara pluton can be accounted for by ductile flow (assuming a spherical model). However, bulk shortening in the aureole is clearly lower along the southwest and northeast margins (Fig. 5): our recalculations indicate that bulk shortening in the aureole accounts for 40% of the needed local space for emplacement.

Papoose Flat pluton, California, U.S.A.

The Papoose Flat pluton is located in the White Mountains, California. At the present level of exposure, the Papoose Flat pluton has an elliptical main body 14 × 8 km and a narrow apophyses extending to the southeast (Fig. 6). The Papoose Flat pluton is largely a K-feldspar megacrystic, two-mica quartz monzonite with biotite as the main hydrous mineral. K/Ar and $^{40}Ar/^{39}Ar$ cooling ages range between 78 Ma (Evernden & Kistler 1970) and 85 Ma (Godin personal communication 1991). Stratigraphic reconstructions and mineral assemblages in the aureole suggest a depth of emplacement between 4 and 8 km (Sylvester *et al.* 1978).

Our mapping indicates that no well-developed magmatic foliation is visible in this pluton. Solid-state foliation is most intensely and penetratively developed within 20 m of the southwest, west and northwest margins and rapidly become non-penetrative in character or absent toward the center and eastern half of the pluton. In the eastern tail, foliations are weak or absent. Foliations are also developed in highly attenuated stratigraphic units in the wall-rock around the western third of the pluton (Sylvester *et al.* 1978). However, many of these same units are sharply truncated along the eastern margin of the pluton, and here show little to no foliations parallel to the pluton margin (Fig. 6). A well-developed NW–SE-trending stretching lineation is visible in the foliation in the western half of the pluton and nearby wall rocks. When viewed in planes parallel to this lineation, *S–C* and *C–C′* relations, rare asymmetrical porphyroclast tails, and the curvature of foliations into mylonite zones consistently indicate a northwest-over-southeast sense of movement (Paterson *et al.* 1991b).

Sylvester *et al.* (1978) suggested that sideways (westward) expansion or 'blistering' during the final stages of emplacement of this pluton strongly attenuated both its

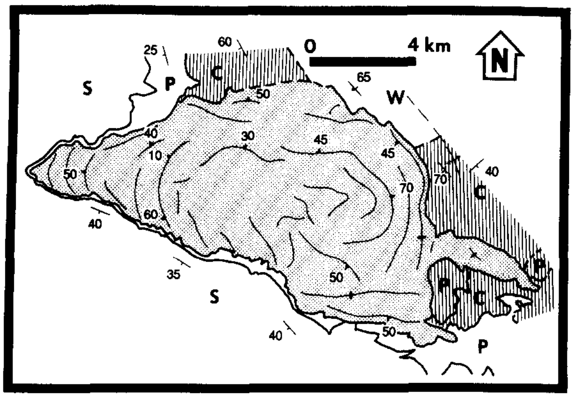

Fig. 6. Simplified map of Papoose Flat pluton, California, after Nelson *et al.* (1978) and unpublished data. Symbols the same as in Fig. 5. S = Mule Springs Formation and stratigraphically higher units, P = Poleta and Harkless Formations, C = Reed Dolomite and Campito Formation, W = Wyman Formation. Note that only the western and southern margins have a concordant aureole that is again narrow.

aureole and already solidified margin. It is difficult to explain many features of this pluton, using a simple ballooning or 'blistering' model, such as the lack of strong compositional zoning and a well developed magmatic foliation, lack of evidence for a transition from magmatic to high-temperature, solid-state structures, the strong stretching lineation, and the consistent top-to-southeast kinematic indicators. Paterson *et al.* (1991b) instead suggested that these features are associated with syn- to post-emplacement deformation of the pluton, but noted than an earlier, less intensely developed cleavage may be associated with pluton emplacement.

Thinning of stratigraphic units by up to 90% around the western side of this pluton led Sylvester *et al.* (1978) to suggest that space for the pluton was made by expansion of the pluton and thinning of the wall-rock. The maximum bulk shortening of the thinned aureole as reported by Sylvester *et al.* (1978) is 800 m. If a radius of 4.2 km is used for the pluton (Fig. 10), the stratigraphic thinning would provide 47% of the needed material transfer, if it occured *everywhere* around the pluton. But this thinning only occurs along the western and southern margins, thus providing 23% of the material transfer needed for emplacement of this pluton. Our observation that some of this stratigraphic thinning may reflect regional deformation, indicates that the above value of 23% is a maximum.

Cannibal Creek pluton, Australia

The Paleozoic Cannibal Creek granite (Fig. 7), located in Queensland, Australia, intrudes deformed Silurian(?) turbidites of the Hodgkinson Formation. Bateman (1985, 1989) noted that the pluton was emplaced after one regional deformation and before two others and argued that the pluton was emplaced by in situ expansion, or ballooning. This conclusion has been challenged by Paterson (1988, 1989) who argued that the features in and around the pluton were more consistent with a model of piercement diapirism.

Bateman (1985) estimated strains associated with the emplacement of this pluton as follows. He noted that near the pluton margins mafic enclaves had ratios of 5:5:1. By unstraining these enclaves until they were spheres, and by using a spherical expansion model, he calculated that 70% of the present volume of the pluton was made during ballooning. Bateman divided the aureole into three zones based on structures presumably formed during emplacement: an inner zone of mica schists, a central zone of crenulation cleavage, and an outer zone of kink folds. He argued that the schists represented about 40% shortening, that the crenulation cleavage represented about 15–25% shortening, and that the kinks represented about 10% shortening. Using these values of shortening and the width of each zone, he calculated that only 30% of the material transfer needed for pluton emplacement could be accounted for. Bateman (1985) called upon 1% shortening up to 45 km away from the pluton to account for the remainder, but failed to consider strain field incompatability problems posed by this hypothesis (see summary below). Again, as we contend that some of the aureole strain noted by Bateman is due to pre- and post-emplacement deformation and that evidence exists supporting piercement diapirism instead of ballooning (Paterson 1988), we argue that the 30% figure may be an overestimate. We also note that foliations in the pluton are largely magmatic and that the enclave ratios again likely reflect magmatic processes and not just ballooning.

Descriptions of other elliptical plutons

The Chindamora batholith intrudes greenstones of the Archaean craton of Zimbabwe, Africa (Snowden & Bickle 1976, Ramsay 1989). Like many large batholiths, the 2750–2550 Ma Chindamora batholith is composite, consisting of separate tonalite, granodiorite, adamellite and granite intrusions (Fig. 8). Strain estimates are currently only published for the pluton, and are based on the averaged ellipticities of deformed xenoliths and enclaves (Ramsay 1989). If the inclusions are assumed to have been deformed by stretching of the pluton margin, then the amount of growth during 'inflation' of the

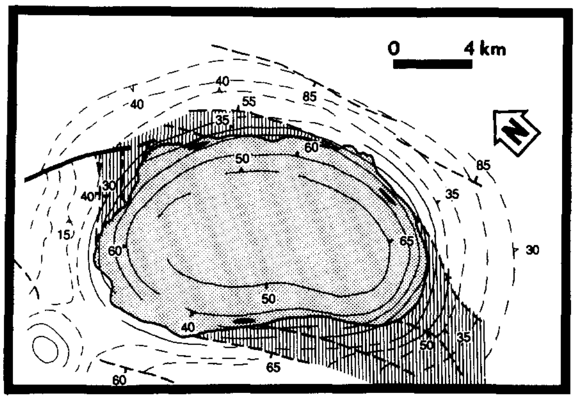

Fig. 7. Simplified map of Cannibal Creek pluton, Australia, after Bateman (1985). Symbols same as in Fig. 5. Vertically lined area is region where pre-emplacement structures are discordant with respect to pluton margin. Also note discordance between magmatic foliation dips in the pluton and cleavage dips in the wall-rocks.

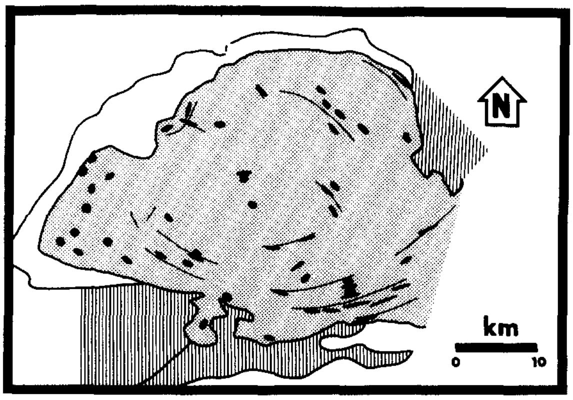

Fig. 8. Simplified map of Chindamora batholith, Zimbabwe, after Snowden & Bickle (1976) and Ramsay (1989). Symbols same as in Fig. 5. Note the variable pattern of strains obtained from enclave shapes within the pluton and that lithologic contacts are sometimes discordant to the pluton margin.

pluton is 81%. Snowden & Snowden (1981), however, argued for a narrow and locally discordant aureole, but noted that much more extensive folding occurred before, during and after emplacement. They also noted that enclaves did not always obtain their highest ratios at the margins of the batholith and argued that stoping and control by fractures played important roles during emplacement.

A particularly startling evaluation of one such pluton was that of the White Creek batholith described by Reesor (1958). Internal compositional zoning, a concentric magmatic foliation, flattened mafic inclusions near the margin, and local bending of wall-rock structures into concordance with the pluton margin (Fig. 9) were all used in support of emplacement by diapirism and ballooning (Reesor 1958, Buddington 1959). But most of the margin is in fact highly discordant (Fig. 9), and the concordant structures along the southern margin may pre-date intrusion since these structures are truncated by a fault that in turn is truncated by the pluton! We see no features that require expansion of this pluton: at best the amount of near-field material transfer by ductile flow appears to be minor.

We have recently completed analyses of structures and strains around the Bass Lake tonalite, Sierra Nevada, California, which consists of a series of elliptical magmatic lobes emplaced into foliated metasedimentary and metavolcanic sequences. Strains measured in the aureoles around these lobes indicate that only 21–37% of the needed material transfer required for pluton emplacement occurred by ductile flow. These figures again contrast sharply with calculations of 74% expansion based on enclave shapes (Fowler & Paterson 1991).

Many other concentrically zoned (and some unzoned) plutons show similar characteristics to those discussed above. Compton (1955) described the Bald Rock pluton, California, and to our knowledge was one of the first to argue that multiple mechanisms (stoping, ductile wall-rock flow and assimilation) were required during emplacement of a single pluton. Davis (1963) described the internal zoning, concentric foliations and margin-parallel structures in the contact aureole of the elliptical Cariboo Mountain pluton in the Klamath Mountains, California. This pluton provides an excellent example of a large elliptical pluton with a narrow aureole and little evidence of bulk shortening at the ends of the pluton. Buddington (1959) described examples of many zoned, elliptical, forcibly emplaced plutons from North America, all with narrow and sometimes discordant aureoles. Shimizu & Gastil (1990) have summarized characteristics of numerous such plutons in Baja, California, and in Japan. Although these plutons can, at present, only be qualitatively analyzed, we have not yet found examples where deflections of markers or descriptions of the intensities of foliation development or strains indicate adequate ductile flow in the wall-rocks to account for the material transfer needed for emplacement. Again, qualitative estimates suggest that the aureoles are too narrow, the strains in these aureoles too low, and that local cross-cutting relationships exist.

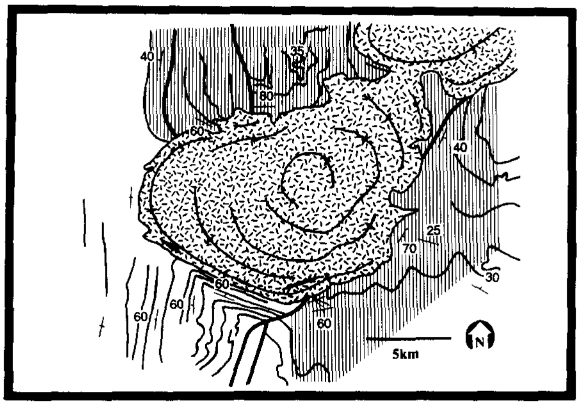

Fig. 9. Simplified map of the White Creek Batholith, Canada, after Reesor (1958). Symbols same as in Fig. 5. Thin lines in wall-rock are lithologic contacts. Thick lines are faults. Note that faults are consistently truncated by the pluton margin and that the faults in turn truncate lithologic contacts even where lithologic contacts show bends into concordance with pluton margin. We suspect these bends may not be related to pluton emplacement (see text).

DISCUSSION AND CONCLUSIONS

Summary of elliptical diapirs

Strain estimates based on the shapes of microgranitoid enclaves in plutons are systematically higher than wall-rock strains in every pluton considered: the amount of pluton expansion during emplacement based on these data average 75%, over twice the value obtained from wall-rock strains, even where these data are available from the same pluton (Table 2). We have noted, however, that these enclaves: (1) have axial ratios that are highly variable on the outcrop scale; (2) are associated with a magmatic foliation and preserve magmatic microstructures; (3) are sometimes spatially associated with xenoliths that are unstrained or weakly strained even near the pluton–wall-rock contact; and (4) sometimes show irregular patterns within plutons. We thus interpret the microgranitoid enclaves as mafic magma globules that were deformed largely during magmatic flow (e.g. Vernon *et al.* 1988). Unlike the clearly identifiable xenoliths, enclaves show little evidence of large viscosity contrasts with their matrix. We therefore caution against the use of single enclaves or xenoliths as strain markers (e.g. Hutton 1982, Vernon *et al.* 1988) and note that flow (and thus strain) within plutons and within their wall rocks are unlikely to be the same during pluton emplacement, an expected result given their different viscosities (e.g. Schmeling *et al.* 1988).

What then do structures and strain fields in the aureoles tell us about emplacement? Our estimates of the local space created for pluton emplacement by a near-field MTP of ductile flow are compiled in Table 2. The values range from 12 to 40%, and average around 30% for the plutons considered. However, we argue that even these values are overestimates of bulk wall-rock shortening during magma emplacement for the following reasons. (1) Because the principal axes of the

Table 2. Data from natural plutons

			Emplacement volume estimates		
Pluton	Radius (km)	Aureole (km)	Width aureole/ pluton radius	From wall-rocks	From enclaves
Ardara (Sanderson & Meneilly 1981) (Holder 1979)	4.5	0.75	0.17	40% (sphere)	75%
Bass Lake Tonalite (Fowler & Paterson 1989)	20	1–4	0.05–0.2	37% (multiple spheres) 21% (tablet)	74%
Cannibal Creek	6	3–4	0.5–0.66	30% (modified sphere)	70%
Chindamora (Ramsay 1989)	15–20	—	—	—	81%
Papoose Flat (Sylvester *et al.* 1978)	4.2	1	0.24	24% (sphere)	—
White Creek (Reesor 1958)	7	1–3	0.14–0.43	>>30%	90%

calculated ellipsoids are not exactly parallel to one another, the bulk strains for the aureole will be lower (e.g. Oertel 1981). (2) Since none of the calculated ellipsoids are perfect flattening-type ellipsoids (Lodes parameters of 1.00), the strains do not support a perfectly symmetrical ballooning model, and the bulk aureole strains are again lower. (3) There is some evidence that the Ardara, Cannibal Creek, Chindamora and Papoose Flat plutons underwent syn- to post-tectonic regional deformation (Snowden & Snowden 1981, Paterson *et al.* 1989, Paterson *et al.* 1991b), and thus aureole strains must, in part, reflect this regional deformation. (4) Finally, none of the aureoles are symmetrically developed: some regions invariably show small strains on different sides of the plutons (Figs. 5–9). These data indicate that a realistic figure for local space made by wall-rock flow is around 25% or less.

Are the strains measured in the aureoles truly representative of the amount of wall-rock shortening, or do the markers used fail to record a certain amount of 'hidden' strain? All of the aureoles preserve a variety of markers at different scales, such as the following: recognizable stratigraphic units or dikes, deflected regional structures, and/or locally preserved primary sedimentary or volcanic features (e.g. bedding, cross-bedding, pebbles, sand grains and volcanic lapilli). Furthermore, the aureoles do not show widespread mylonitization or zones of high strain that would indicate much more intense deformation. Comparison of Figs. 5–9 shows that all of these plutons have local (Chindamora) to extensive (White Creek) discordant margins. These features show or argue for strains or deflections quite compatible with the low values of bulk shortening presented in this paper. In addition, wall-rock strains observed around these plutons are at least an order of magnitude smaller than values predicted by models of diapiric ascent and emplacement (Fig. 10), and extend for relatively small distances away from the pluton, 0.1–0.5 body radii compared to 5–20 body radii in the models (e.g. Figs. 3 and 10). The similarities between plutons and the models, such as concentric foliation patterns associated with radial flattening strains, are largely qualitative and often have other equally permissive explanations (e.g. Cruden 1988, Paterson & Tobisch 1988).

Some authors have suggested that small strains occurring over large areas can account for all of the needed material transfer, or that small strains outside a narrow, high-strain aureole account for the missing strain. Small ductile strains over large distances are not likely because of the temperature dependant nature of wall-rock viscosities. There are also large strain field incompatibilities implicit in these suggestions (Fig. 11). During constant volume strain, enough radial shortening, but not enough margin-parallel extension occurs, particularly near the pluton margin, resulting in the need for radial dilatant cracks with increasing margin-parallel displacement towards the pluton (Fig. 11a). Figure 11(b) is a schematic drawing of a pluton with a moderate strain gradient near the margin separated from small far-field strains by a discontinuity (fault). This scenario still requires radial dilatant cracks or other near-field MTPs. We know of no documented examples of such faults,

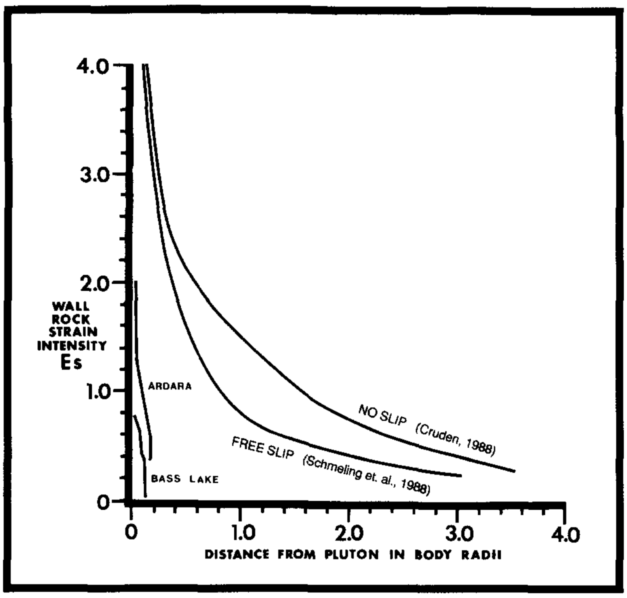

Fig. 10. Plot of strain intensity in wall-rock vs distance from pluton contact normalized to radius of pluton for modeled and natural plutons. Only two natural plutons shown for clarity although all plutons discussed in text would show similar curves. Note that aureoles around models of diapiric ascent have much greater strains and have strains that extend a much greater distance from the pluton contact than strains around natural plutons.

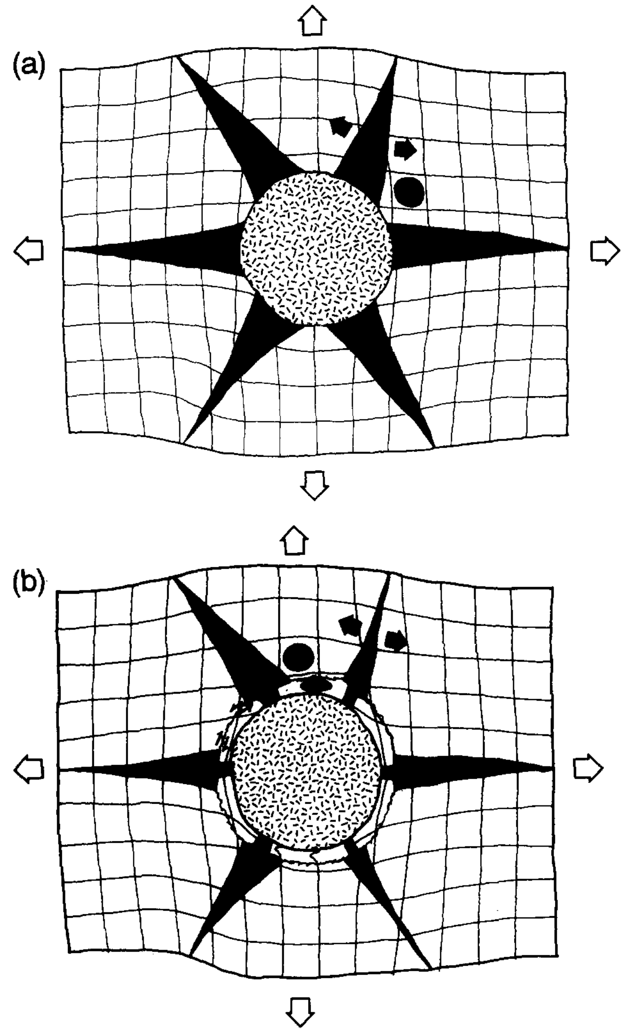

Fig. 11. (a) Schematic diagram of pluton and wall-rock showing implications of attempting to make local space for plutons by very small wall-rock strains spread over a large region. Pluton initially emplaced with half of present radius yielding bulk extension parallel to pluton margin = 100%. Only 8% of this extension can occur by the constant volume wall-rock strain in each grid square: thus the remaining 92% of margin parallel extension must occur by other near-field MTPs. Large dilational cracks (black regions) are depicted: the displacement across the cracks increases towards the pluton margin and accounts for the remaining 92% of the required extension. Large open arrows indicate that the small strains must continue in regions well off the diagram. (b) As (a), except that in the inner aureole, 50% of margin parallel extension is accounted for by ductile wall-rock flow and 50% by displacement across tear faults. Note the large change in strain shown by the two ellipses from the inner to outer aureoles. This abrupt change in strain requires a margin parallel strain discontinuity (fault) between the inner and outer aureoles.

although the faults recognized by Woodcock & Underhill (1987) around the Northern Arran granite, Scotland, may be a more complicated example.

The plutons re-examined above all have ductilely deformed, partly concordant contact aureoles. Many other circular or elliptical, compositionally zoned, concentrically foliated plutons sharply truncate wall-rock units or other plutons without deflecting structures, or in any obvious way deforming these units (Buddington 1959, Pitcher & Berger 1972, Bateman 1988, Shimizu & Gastil 1990). These truncations can occur on a scale of meters to centimeters, clearly indicating that these types of plutons must be emplaced by some mechanism that does not involve ductile flow of the immediately surrounding wall-rock.

Because ductile flow of wall-rock is an inadequate near-field MTP, we must consider other MTPs (i.e. assimilation, stoping, roof lifting, rigid-body translation of wall rocks, elastic strain, volume loss) must account for the remaining two-thirds of the material transfer needed around plutons with concordant aureoles, and all of the material transfer for plutons with discordant aureoles. Furthermore, even if wall-rock strains were high enough and aureoles were wide enough, or if other near-field MTPs were recognized, the 'space problem' has not been solved, but simply removed one step further away from the pluton. If wall-rock deformation during pluton emplacement is a constant-volume process, the wall-rock material flattened during expansion must move somewhere. The only two choices are the following: (a) the material moves downward and fills the space made by the removal of the magma or lowers the Moho, or (b) the material ultimately moves upwards towards the surface of the Earth.

Rates of near- and far-field MTPs

Although rates of magmatic and tectonic processes are variable and sometimes hard to quantify, many studies suggest that the ascent and emplacement of magmas occur over shorter time periods than average rates of tectonic deformation can make space for plutons (see review by Paterson & Tobisch 1992). This dichotomy of different rates of magmatic and tectonic processes is further exacerbated by results from recent advances in the use of actinide-series disequilibria in igneous rocks. These data present new rates for mafic magma flow velocities (Rubin & MacDougall 1991, Turekian *et al.* 1991), residence times and fractionation rates in magma chambers (Schaefer *et al.* 1991, Volpe & Hammond 1991) and lifetimes of mafic magmas (Fukuoka 1991, Reagan *et al.* 1991). For example, Reagan *et al.* (1991) examined basalts and andesites from Nicaragua and argued that "the entire process of slab dewatering, melting, magma transport, differentiation, and eruption takes about 50,000 years" or less (Reagan oral communication 1991). Although there are uncertainties in actinide series disequilibria (e.g. La Tourrette & Burnett 1991), and some conflict between these conclusions and those noted by previous studies (e.g. evidence that the construction of magma chambers may be as long as several million years), certainly these new rates need consideration.

However, the presence of plutons in the crust requires that rates of wall-rock deformation were fast enough to get them there, implying that there is something wrong with the assumptions made or results obtained in our evaluation of rates. We propose two alternatives, both of which seem likely to us. First, as suggested above, multiple near-field displacement processes must operate during emplacement of igneous bodies. Most studies of rates only consider the rate of a single mechanism and thus would only estimate the rate of near-field material transfer for that mechanism. Second, near-field mechanisms must operate at a faster rate than far-field mechanisms because the wall-rock volume over which far-field mechanisms operate is much greater (increases by R^3, where R is the distance from the pluton center). Rates of tectonic processes are often determined well away from plutons and more likely reflect rates of far-field deformation. This would suggest that rapid processes such as brittle faulting, elastic straining and magma fracturing would be favored near-field MTPs, although ductile flow is still a viable mechanism if natural strain rates are faster than the generally assumed rates of 10^{-12}–10^{-14} s^{-1}.

Hollister & Crawford (1986) have suggested that emplacement of magma into orogenic belts might trigger 'tectonic surges' by increasing heat, fluids and melt-lubrication of faults. Alternatively, we argue that near-field rates *must* show large increases and far-field rates moderate increases during pluton emplacement in the middle and upper crust: one means of doing so is that suggested by Hollister & Crawford (1986). Field observations around some plutons support this contention. For example, we have found open to tight folds of meter thick sills near the Mount Stuart batholith, Washington, that have magmatic foliations in the sills parallel to the axial planes of the folds. This implies that the folds formed faster than the sills crystallized (10^2–10^4 years?), requiring much faster rates of shortening than commonly associated with folding (e.g. Price 1975, Vita-Finzi 1979, Rockwell *et al.* 1988, Paterson & Tobisch 1992).

Summary of pluton ascent and emplacement

Following the studies of Pollard *et al.* (1975), Sibson *et al.* (1975), Shaw (1980), Spera (1980), Turcotte (1982), Spence & Turcotte (1985) and others, we suggest that magma ascent and emplacement is driven by magma moving down deviatoric stress gradients caused by gravity, plate motions and the development of structures in an anisotropic material (e.g. Ellis & King 1991). The rapidly changing conditions in pluton–wall-rock systems and the lack of evidence that any single near-field MTP can make sufficient local space for pluton emplacement, argues for the simultaneous operation of multiple near- and far-field MTPs (Fig. 12). In Fig. 12, we have tried to emphasize that the relative importance of various MTPs will vary with depth, distance from pluton and time, and will of course depend on temperature, bulk composition of the magma and wall-rocks, fluids present, viscosities of the magma and wall-rock, anisotropy of the wall rocks, and other factors (e.g. Bergantz 1991). Near-field MTPs will be dominated by the quickest process, although multiple processes operating at different rates probably always occur.

Far-field MTPs are required to move materials away from the aureoles of plutons towards the source of magma generation or towards the surface of the Earth and are also required by the lack of near-field MTPs of sufficient magnitude. Regional deformation, which may or may not be distinct from far-field MTPs, plays two important roles during the emplacement of igneous bodies: (1) forming local deviatoric stress fields favorable for the emplacement of magma; and (2) increasing the amount or rate of far-field material transfer. Volume loss that occurs during regional deformation and metamorphism may also be an important far-field MTP. It is for these reasons that plutons must be syn-tectonic with respect to at least some deformation in the wall-rocks.

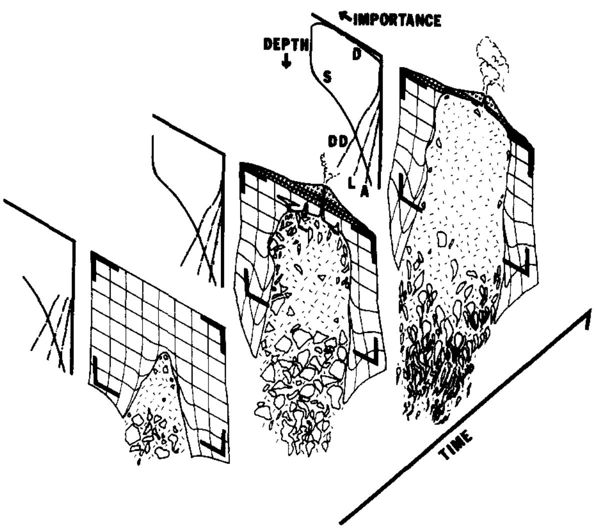

Fig. 12. Diagram showing one possible scenario of changing near- and far-field MTPs with time during pluton emplacement. Each section is areally balanced in a region outlined by the thick black corners. Material displaced during emplacement of the pluton is shown outside these corners. Diagrams to left show relative importance of different MTPs. D = doming of roof rocks, S = stoping, DD = ductile shortening, L = rigid translation of wall-rock, A = assimilation. Note that the relative importance of MTPs change with depth, time and distance from pluton.

Near-field MTPs associated with concentric, zoned plutons, and their aureoles indicates that a maximum of 30% near-field material transfer occurs by ductile flow of the wall-rocks. These plutons are in fact piercement diapirs with narrow concordant margins requiring the operation of other near-field MTPs. What other MTPs are likely candidates? Most zoned plutons in mid- to shallow crustal levels show little if any migmatitic material in their aureoles indicating that the plutons did not melt their way through the crust. The discordant nature of these plutons and features preserved near roofs, suggest that two possible alternatives are stoping and roof uplift. Many of these plutons have only a small percentage of wall-rock xenoliths preserved in the plutons. As pointed out by previous workers (Buddington 1959, Marsh 1982), pluton floors with large piles of stoped blocks are not common and certainly not yet recognized on the scale needed to emplace large batholiths. Roof uplift may be a viable emplacement mechanism at shallow levels (e.g. Buddington 1959, Leitch 1976, Corry 1988). However at deeper levels buoyancy forces due to density contrasts between magma and common wall-rocks are insufficient to significantly raise the roof of the pluton. Regional deviatoric stresses would enhance the magma's ability to push up the overlying rocks (e.g. Castro 1987). If so, we would expect evidence of simultaneous regional deformation since the wall-rocks should also deform in response to these deviatoric stresses. Finally, we also suspect that much unrecognized brittle faulting and fracturing occurs at the tops of plutons and at the outer margins of contact aureoles during emplacement (e.g. Roberts 1970, Bussell *et al.* 1976, Leitch 1976, Woodcock & Underhill 1987).

Parts of the above analysis are speculative, although field data, experimental results and theoretical studies are in agreement with these hypotheses. However, we feel that the real strength of our proposal that pluton emplacement requires multiple near- and far-field MTPs is that it clarifies what observations are needed from natural plutons and what processes need further evaluation from a theoretical and experimental standpoint. For example, what are the far-field mechanisms that accommodate near-field material transfer? What are the linking mechanisms between near-field and far-field processes? Are the rates of the processes appropriate? What do tops and bottoms of plutons look like, or the frontal tips of sheet-like plutons? Do large volume losses occur near plutons? And are there brittle and/or non-pervasive structures developed in the outer aureoles of most plutons?

In an attempt to address these questions, we propose the following approach for future studies of pluton emplacement.

(1) We strongly feel that workers need to look for multiple emplacement mechanisms rather than a single mechanism, and that the concepts of passive and forcible pluton emplacement particularly should be avoided. Contact aureoles around plutons are gradients in many ways (thermal, strain, viscosity, etc.), and we should expect and look for spatial and temporal gradients of emplacement mechanisms.

(2) We need to identify and clearly state what mechanisms are near-field and far-field material transfer processes during pluton emplacement and attempt to identify the linking mechanisms. The magnitude of material transferred by each mechanism should be quantified when possible.

(3) We also need to evaluate rates of near-field and far-field mechanisms and compare the required durations of tectonic processes to those of igneous processes. Thermal models of magma chambers built up by successive increments would be useful in this regard. A clear implication of this paper is that rates of wall-rock deformation are faster during pluton emplacement relative to previously determined rates.

(4) It is very important to examine roofs and roots of plutons at different structural levels and to better integrate these observations into emplacement models.

(5) Ultimately, a very difficult but extremely important goal is to understand near- and far-field stress fields and to determine the thermo-mechanical response of magma–wall-rock system to these stress fields. To this end, field studies and increasingly sophisticated thermal–mechanical models should be further integrated.

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