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On the emplacement of tabular granites

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Abstract: Granites in both crystalline terranes and continental magmatic arcs tend to be circular to elliptical in map view and vary in width from about 3 to 100 km. Available gravity and structural data suggests that many of these plutons are tabular in shape with an average thickness of about 3 km. Ductile structures observed around mesozonal granites indicate that space is created by a combination of lateral and vertical displacements of wall rocks, whereas contact relationships of epizonal plutons imply that only vertical displacements are involved during emplacement. In both settings magma arrives at the emplacement site via one or more vertical feeder zones and flows laterally. With the exception of very high-level epizonal plutons, structural studies suggest that space for many tabular intrusions must be provided mainly by floor-depression (lopolith emplacement) rather than roof-lifting (laccolith emplacement). An emplacement model for this type of tabular granite is proposed which involves progressive depression of the floor of an initially horizontal chamber as it is filled by one or more vertical conduits. A crustal-scale balance in the rates of melt extraction, magma ascent and pluton-filling is required by the model, and transfer of material from the source to the pluton is accommodated by broadly distributed deformation of low strain magnitude. The process is evaluated with end-member cantilever and piston sinking mechanisms. The models predict that large (10–100 km wide), tabular plutons ($\lesssim$3 km thick) can be emplaced quickly (100 a to 1 Ma) with floor-depression and related wall-rock strain rates similar those expected during tectonic deformation (10^{-10} to 10^{-15} s^{-1}). Bulk strains in the intervening crustal column rarely exceed a strain ratio of 1.5, which is likely to remain undetected in the geological record unless the required deformation is accommodated on discrete structures such as normal faults or shear zones at the base of the pluton.

Keywords: granites, magmas, emplacement, laccoliths, lopoliths.

The emplacement of granites in the middle- to upper crust is the end point of a large scale exchange of mass and energy, starting with the generation and segregation of melt in the lower crust, ascent of magma and final construction of plutons and batholiths (Pitcher 1979; Marsh 1982; Brown 1994; Clemens this volume). The mechanisms by which plutons are emplaced have been under discussion since the intrusive nature of granite was established. One of the principal barriers in reaching a consensus is the incomplete nature of the geological record; although individual plutons crop out over <10 to >1000 km^2 with well-defined, generally vertical sides, opportunities to observe their roofs and floors and therefore establish their 3D geometry are limited. Structural studies of granites have established that the form and emplacement of many plutons is controlled by regional deformation (Hutton 1988). In these cases, space for granitic magma is created within local sites of dilation within wrench, transpressional and transtensional shear zones (e.g. Guiniberteau *et al.* 1987; McCaffrey 1992; Tikoff & Teyssier 1992), extensional structures (e.g. Hutton *et al.* 1990; Grocott *et al.* 1994; Sciallet *et al.* 1995), and thrust regimes (e.g. Ingram & Hutton 1994).

However, these models cannot readily explain the emplacement of many plutons. Such plutons are characterized by elliptical to circular map patterns, variable area and are particularly abundant in Precambrian terrains and the Mesozoic batholiths of the western American Cordillera, where they constitute between 60% and 100% of the exposed crust. The classical interpretation of these granites is that they formed by diapirism (Ramberg 1970; Marsh 1982). Evaluation of this mechanism on both structural and physical grounds suggests that it may not be viable for either the ascent or emplacement of most granitic magmas (Mahon *et al.* 1988; Clemens & Mawer 1992). Furthermore, an increasing body of direct observation and geophysical data shows that many large, elliptical plutons are tabular in shape with their horizontal dimensions much larger than their vertical dimensions (Hamilton & Myers 1967; Myers 1975; Vigneresse 1995; McCaffrey & Petford 1997). This paper evaluates the emplacement of tabular granites by firstly examining field and geophysical evidence for filling of plutons by lateral flow of magma from planar conduits, and secondly by developing a kinematic model for creation of their space within the crust.

Tabular granites in crystalline terrains

Granite plutons are frequent elements of all deeply eroded orogens, where they are typically 10 km^2 to 10 000 km^2 elliptical to irregular-shaped bodies in plan view. Contacts with their wall rocks vary from discordant to concordant, sometimes around the same pluton, implying lithologically dependent brittle and ductile deformation mechanisms during emplacement. Contacts and wall-rock structures are usually sub-vertical although both outward and inward dips are also observed. Studies of the former type, in conjunction with observations of (generally narrow) strain aureoles have been used in support of a diapiric origin for these types of plutons (Bateman 1984). However, in all cases where finite strains have been determined in the adjacent wall rocks, measured values fall short of model predictions for ductile diapirism implying

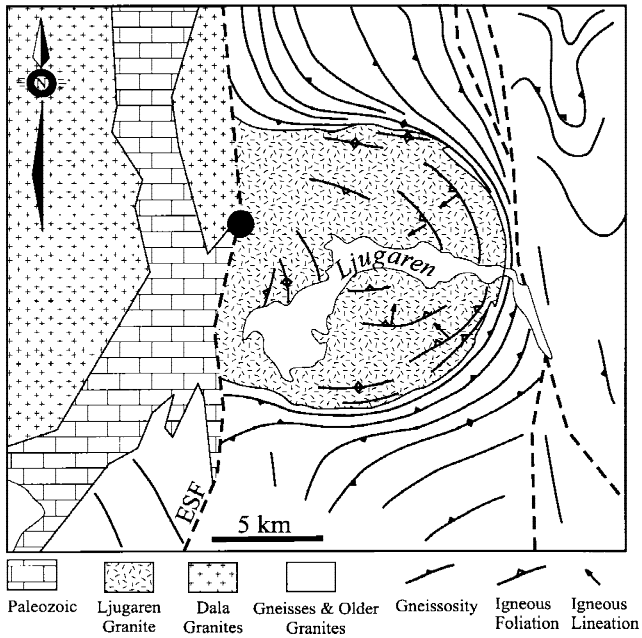

Fig. 1. Geology of the Ljugaren Granite (after Cruden & Aaro 1992). Heavy dashed lines are faults. The pluton is bound to the W by the East Siljan Fault (ESF) which juxtaposes Paleozoic sediments against mid-Proterozoic (Svecofennian) gneisses and granites. A late brittle fault also occurs on the E side of the pluton, causing a disruption of the structural pattern. The deepest part of the granite, as determined by gravity measurements is indicated with a filled circle.

the operation of other mechanisms during their emplacement (Paterson & Fowler 1993). Although field observations of plutons with inward-dipping contacts and wall-rock structure are relatively uncommon (e.g. Sylvester 1964; Bridgwater *et al.* 1974; Parsons 1987; Cruden & Launeau 1994; Weibe 1996), potential field and seismic reflection surveys indicate that many elliptical plutons, including those with outward dipping contacts at the surface, have floors with inclinations of *c.* 0° to 40° which steepen towards one or two root-zones or conduits (e.g. Sweeny 1976; Brisbin & Green 1980; Evans *et al.* 1994; Vigneresse 1995; Dehls *et al.* 1998). Although the root-zone is commonly associated with a pre- or syn-emplacement shear zone, which may have acted as a channel for magma ascent, there is often little indication that emplacement of the bulk of the magma itself is related to the structure. An example of this type of pluton is given below.

Ljugaren granite

The *c.* 1700 Ma semi-circular Ljugaren granite intrudes amphibolite-facies gneisses of the Svecofennian orogen, Baltic Shield (Fig. 1). It is bound to the west by the East Siljan fault which drops higher level Palaeozoic sediments associated with the Siljan ring impact structure down against the granite (Cruden & Aaro 1992). Although a late feature, regional geophysical data suggests that this fault reactivates a fundamental Svecofennian-aged structure. Foliations and lithological contacts in gneisses and granites surrounding the pluton are bent into conformity with its steeply inward dipping contacts. Foliation trajectories are markedly asymmetric and suggest that the gneisses were displaced laterally to the east

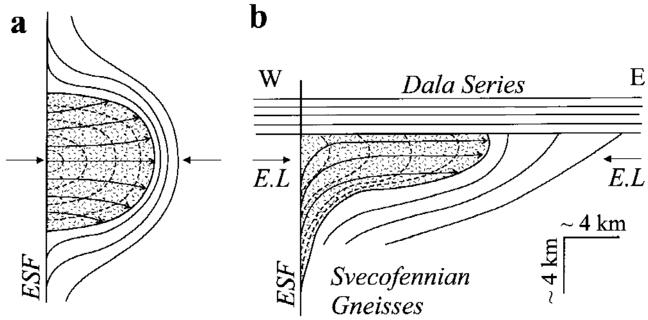

Fig. 2. Emplacement model and cross-sectional structure of the Ljugaren Granite. (**a**) Asymmetric deflection of gneissosity in the wall rocks (solid lines), together with the internal structural pattern (dotted lines) suggest that magma (shaded) spread laterally (indicated by lines with arrows) from a vertical planar conduit corresponding to the East Siljan Fault (ESF). Short arrows indicate location of cross section. (**b**) E–W cross-section of the granite with thickness constrained by gravity modelling. The pluton is inferred to have spread beneath a cover of coeval volcanics (Dala Series). Note the tabular geometry of the pluton and the downward deflection of wall rocks beneath it. (E.L., erosion level).

during emplacement. Pluton-parallel foliations are confined to a <1 km wide aureole, which is characterized by an increase in foliation intensity but does not contain mylonitic fabrics indicative of high strain (Cruden & Aaro 1992). The granite itself is homogeneous, displays igneous microstructure and contains a weakly defined foliation concentric to its east half and a down-dip lineation where observed (Fig. 1).

A detailed gravity survey of the Ljugaren granite reveals a residual anomaly (> -6 mgal), centred on the west central part of the pluton within the East Siljan fault, which decreases outwards towards the margins (Cruden & Aaro 1992). Model gravity profiles show that the bulk of the pluton is tabular and <3 km thick with a deeper (*c.* 6 km) root on its east side (Fig. 2). Examination of the structural pattern in combination with the gravity data suggests that the ductile wall rocks must have been displaced downwards as well as outwards during emplacement of the granite and that movement of magma was from west to east, emanating from a conduit coincident with the East Siljan fault (Fig. 2). Because the roof of the pluton has been removed by erosion, the amount of space made by roof uplift cannot be evaluated. However, higher levels of exposure of equivalent intrusive rocks west of the East Siljan fault suggest that the Ljugaren granite probably spread beneath a syngenetic cover sequence of Dala volcanics (Fig. 2, Cruden & Aaro 1992).

Similar asymmetric lateral ductile displacement patterns of wall rocks have been observed around tabular bodies in the Canadian Shield and California (Law *et al.* 1992; Cruden & Launeau 1994). More commonly, wall-rock fabrics are disposed symmetrically around plutons to form the well-known triple point pattern (Brun & Pons 1981). Although normally interpreted in terms of expansion of an ellipsoidal pluton during region deformation, such structural patterns could also form by symmetrical spreading, combined with downward depression of the ductile floor of a tabular body fed by a conduit parallel to the regional foliation. Gravity studies of well-defined intrusions in crystalline terrains generally support this geometry, finding that many plutons have model thicknesses <4 km beneath much of their outcrop, thickening only in the vicinity of one or more root-zones (Vigneresse 1995).

Direct evidence for the downward displacement of wall rocks during the emplacement of intrusions with steep to inwardly inclined margins includes observations of 'downfolding' of wall-rock structures towards the contacts of granitic plutons (e.g. Bridgwater *et al.* 1974), alkaline complexes and layered mafic intrusions (see papers in Parsons 1987).

Some granites in crystalline terrains are emplaced as 0.5 m to 500 m thick sheets which are exposed in tilted or folded sections. Examples include the stratoid granites of Madagascar, emplaced at mid-crustal levels parallel to gneissosity in their host rocks (Nédélec *et al.* 1994) and the 500 m thick, 17–55 km wide Mount Scott Granite emplaced at a high crustal level at the interface between rhyolitic cover rocks and a gabbroic basement (Hogan & Gilbert 1995). An extreme variation on this style of emplacement are Precambrian orthogneiss belts, many of which appear to be constructed by multiple injection of originally sub-horizontal granitoid sheets which are later rotated to steep attitudes by regional deformation (Myers 1978; Lucas & St-Onge 1995).

Horizontal granite sheets in Cordilleran batholiths

Granitic plutons which make up the Mesozoic batholiths of the N and S American Cordillera generally define large elongate bodies (10 to 100 km long, 5 to 50 km wide) striking parallel to the inferred axis of the magmatic arc (Pitcher 1979; Bateman 1992). Emplacement depths vary from about 2 km to 15 km (Myers 1975; Bateman 1992; Sisson *et al.* 1996). Individual plutons have steep contacts with adjacent granites that are usually sharp, and less frequently marked by vertical septa of deformed meta-supracrustal rocks. Where preserved, pluton roofs are generally sub-horizontal and capped by either pre-batholithic supracrustal sequences or coeval volcanic ejecta (Hamilton & Myers 1967; Myers 1975; Bussell *et al.* 1976). In both cases, the pluton–roof contact is usually discordant and cuts across pre-intrusive structures regardless of the depth of emplacement, and turns down sharply at the roof–wall transition (Myers 1975; Bussell *et al.* 1976; Pitcher 1979; Paterson *et al.* 1996).

High-level 'bell jar'-type annular intrusions are often associated with ring dykes and are interpreted as ring-complexes associated with cauldron subsidence (Bussell *et al.* 1976). However, lack of distortion of the roof and wall rocks of large elongate plutons in the Coastal Batholith of Peru also suggests that most space for substantial volumes of magma must also have been created by downward displacement of material (Myers 1975). Here, granites are inferred to have been fed by ring dykes located at the margins of the plutons, implying that magma flow at the emplacement level was mainly horizontal. Structural investigations of Cordilleran plutons by Paterson *et al.* (1996) also conclude that downward displacement of wall rocks is an important space-making process. The mechanism for this downward transfer of material remains uncertain, the two main candidates being repeated cauldron subsidence of a large block into an underlying, and unexposed, magma chamber at depth (Myers 1975; Bussell *et al.* 1976) and stoping (Paterson *et al.* 1996). The former requires that individual plutons are tabular in form and the latter that they pass downward into mid- to lower-crustal depths and a graveyard of xenoliths. Downfolding is a third possible mechanism as implied in cross-sections of the Boulder Batholith (Hamilton & Myers 1967). Clearly, constraints on the nature of what underlies individual plutons and batholiths are required to resolve this issue.

Determination of the thickness of Cordilleran plutons is hampered because modelling of their associated Bouguer gravity anomalies is intractable due to the low density contrast between plutons and their igneous wall rocks, and lack of sufficient relief within any one pluton to expose both its roof and floor. However, several observations support the notion that many of these plutons, and the batholiths themselves, are tabular in nature (Hamilton & Myers 1967). Fortuitous exposure conditions in N Peru establish that the 12×7 km Patorumi pluton is horizontal in form and *c.* 2 km thick (Myers 1975). A tilted section in the Old Woman–Piute Range batholith exposes a suite of tabular granites with inferred thicknesses <5 km (Miller *et al.* 1990).

Deep erosional dissection of the east crest of the central Sierra Nevada reveals that the 92 ± 1 Ma, possibly connected, granite of Goodale Mountain and Lamark granodiorite form a *c.* 1 km thick sheet which is overlain by the Split Mountain pendant and underlain by the sheeted, mafic Aberdeen and Onion Valley complexes (Coleman *et al.* 1995; Sisson *et al.* 1996). The structural and composition patterns determined by measurements of anisotropy of magnetic susceptibility in the 102 ± 1 Ma Dinkey Creek pluton, central Sierra Nevada (Bateman 1992; Tobisch *et al.* 1993), suggest that it was fed by a NNW-trending conduit located in the centre of the intrusion and that magma spread laterally to the SW and E to occupy the bulk of the body (Cruden *et al.* 1996). Constraints provided by the preservation of roof pendants at high elevations together with fluid mechanical modelling of the foliation pattern indicate that much of the pluton is underlain by a sub-horizontal floor and that its pre-erosion thickness was between 800 m and 3500 m (Cruden *et al.* 1996). The conduit used by the Dinkey Creek pluton appears to have been re-used *c.* 6 Ma later by the smaller, probably tabular 96 ± 3 Ma Bald Mountain leucogranite (Tobisch & Cruden 1995). Granite emplacement before 90 Ma in the Sierra Nevada occurred under weakly extensional to contractional conditions with a minor dextral shear component (Tobisch *et al.* 1995) which may have resulted in the formation of magma conduits (Tobisch & Cruden 1995) but were unlikely of importance for pluton space creation.

Emplacement of tabular granites

Despite their traditional separation into the mesozone and epizone, the granite plutons reviewed above share three fundamental characteristics: their shape, size and tabular geometry. The degree of ductile wall-rock deformation associated with intrusion appears to be a function of emplacement depth and the mechanical properties of the host during emplacement. Plutons emplaced in a ductile environment show evidence for components of lateral and vertical displacement of wall rocks, whereas those emplaced in brittle environments can only have involved vertical translation of material. Deeper level, isolated granites with well-defined Bouguer gravity anomalies often have model shapes with flat to gently inward dipping floors and one or more roots, but no exposed roof. Higher level Cordilleran intrusions preserve discordant flat roofs, steep sides and rare, but significant evidence for gently inclined floors. Reasonable generalizations for many, but not all, granites are therefore that they are emplaced as tabular sheets with thicknesses ranging from 1 m to 7 km, they are fed by one or more vertical conduits, the bulk of magma flow at the emplacement level is horizontal, and that the role of lateral

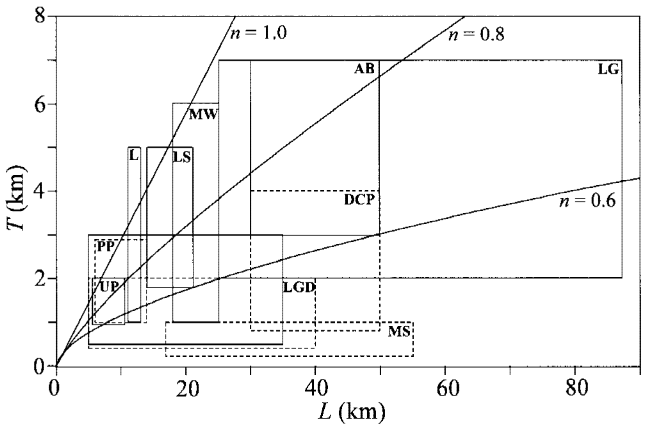

Fig. 3. Compilation of gravity and field estimates of pluton thicknesses (T) and horizontal dimensions (L). Curves are from McCaffrey & Petford's (1997) empirical power law with $n = 0.8 \pm 0.2$. Solid boxes are gravity studies: AB (Aulneau Batholith; Brisbin & Green 1980), E (Exeter Granite; Bothner 1974), L (Ljugaren Granite; Cruden & Aaro 1992), LS (Lisjö Granite; Öhlander & Zuber 1988), UP (Ulu Pluton; Dehls *et al.* 1997). Plutons with thicknesses determined by field observation or structural analysis are indicated boxes with dashed borders: DCP (Dinkey Creek Pluton; Cruden *et al.* 1996), LGD (Lamark Granodiorite; Coleman *et al.* 1995), MS (Mount Scott Granite; Hogan & Gilbert 1995), PP (Poturumi Pluton; Myers 1975). See also Vigneresse (1995) for a similar number of gravity studies of granites.

displacement in creating space diminishes with decreasing ductility of the wall rocks.

Limited data for plutons suggest that their thickness (T) is related to width (L) according to an empirical power law, $T = 0.29L^n$ where $n = 0.8 \pm 0.2$ (McCaffrey & Petford 1997). This relationship is evaluated using the plutons cited here where constraints on thickness are provided from field, gravity or structural data (Fig. 3). The width of the individual plutons is taken as the longest and shortest dimension visible on published maps and the thickness range is taken to be the minimum and maximum values, excluding root-zones where present. Despite a large scatter of values, particularly at larger pluton sizes, the data suggest that McCaffrey & Petford's (1997) power law value (n) may be overestimated. In fact, an equally valid characterization of the data is $T = 3.0 \pm 2.0$ km, i.e. the thickness of tabular plutons may be independent of their width. This result is similar to that of Vigneresse (1995) who found that the bulk of the area underlain, and the volume occupied by 16 plutons is 3 km thick, with deeper root zones occurring within restricted areas.

Laccoliths v. lopoliths

Tabular sheets of granite can form by impingement and spreading of a diapir which has been arrested by some kind of mechanical barrier (e.g. Brun & Pons 1981; Cruden 1990) or by injection and subsequent thickening of a sill fed by a dyke (Pollard & Johnson 1973; Brisbin 1986; Corry 1988; McCaffrey & Petford 1997). Evidence for lateral ductile displacement of wall rocks has been discussed above and is permissible evidence for spreading diapirs. However, it was also noted that the narrowness of the deformation aureole and the strain magnitude within it are unexpectedly low for a diapiric mechanism (Paterson & Fowler 1993). A complete

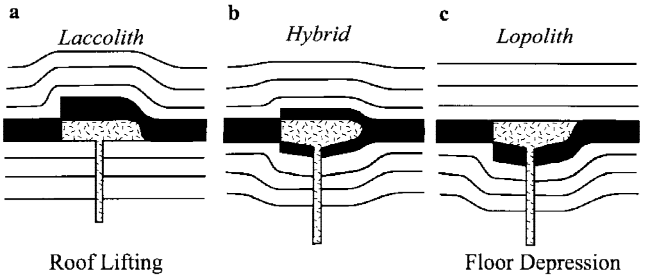

Fig. 4. Modes of tabular granite emplacement. On the left-hand side of each diagram space for the granite (stippled) is created within the intruded unit (black) by offsets on faults, whereas space is created by ductile deformation on the right-hand side of each diagram.

absence of wall-rock strain around higher level discordant plutons precludes spreading of diapirs as a viable mechanism for their emplacement. A major objection to the dyke transport of granite was that magma would freeze in the dyke before a volume sufficient for filling a pluton could travel through it (Marsh 1982).

However, re-evaluation of this problem has shown that dyke transport of felsic magma may be sufficiently rapid to prevent freezing, and furthermore, pluton-sized upper crustal chambers can be filled over geologically rapid times (Clemens & Mawer 1992; Petford *et al.* 1993; Petford 1996). The driving force for dyke transport is normally assumed to be buoyancy, however both internal magmatic and tectonic over-pressuring (Robin & Cruden 1994; Hogan & Gilbert 1995) are also attractive mechanisms for forcing magma up vertical conduits. Vertically propagating magma dykes must be arrested and thereafter be able to propagate horizontally in order to form a sill. Arresting mechanisms or 'crustal magma traps' have been reviewed by Brisbin (1986), Corry (1988), Clemens & Mawer (1992), and Hogan & Gilbert (1995) and include intersection with a freely slipping horizontal fracture, stopping of the propagating dyke by a ductile horizon or a unit with high fracture toughness, and arrival at a level of neutral buoyancy. Once an initial sill has formed, it can inflate provided a sufficient magma pressure is available (Johnson & Pollard 1973; Pollard & Johnson 1973; Corry 1988). The question now is whether it inflates to plutonic dimensions by lifting its roof (i.e. laccolith emplacement) or depressing its floor (i.e. lopolith emplacement) (Fig. 4).

The dynamics of laccolith emplacement by roof lifting are well established (Pollard & Johnson 1973; Jackson & Pollard 1988; Corry 1988). Most models assume a two-stage process involving the formation of an initial sill following by vertical growth. Both stages are driven by the overpressure of magma at the emplacement site. The magma driving pressure, P_d is given by:

$$P_d = P_h + P_m - P_v \pm \sigma_h \qquad (1)$$

where P_h, P_m and P_v are the hydrostatic pressure, overpressure in the magma due to volatile release, and the viscous pressure drop, and σ_h is the magnitude of the tectonic stress normal to the dyke wall (Hogan & Gilbert 1995). Field and theoretical considerations show that vertical growth of laccoliths occurs by elastic, elastic–plastic or ductile bending of the roof rocks (e.g. Johnson & Pollard 1973; Pollard & Johnson 1973; Dixon & Simpson 1987; Roman-Berdiel *et al.* 1995), lifting of a piston by displacement on faults (e.g. Corry 1988), or a combination of these mechanisms (Fig. 4) (Jackson & Pollard 1988). Note that 'space creation' here is ultimately accommodated by surface uplift and subsequent erosion. The amount of vertical growth is a function of the horizontal cross sectional area of the laccolith, the strength and effective thickness of the roof rocks, and the available driving pressure (Pollard & Johnson 1973; Dixon & Simpson 1987). It would appear that laccolith growth is self-limiting and rarely exceeds 2 km (Corry 1988). Further growth requires either rapid removal of the roof at the surface by erosion or gravity collapse, or simultaneous depression of its floor (Fig. 4).

Most studies consider laccoliths to be shallow level intrusive phenomena, with all documented examples occurring at palaeodepths <3 km (Corry 1988). Experimental work suggests that the aspect ratios of laccoliths increase with depth. This is because horizontal sill propagation or growth is favoured over roof lifting with increasing overburden thickness (Roman-Berdiel *et al.* 1995). Corry (1988) proposes that at greater depths lopoliths form and that there is a continuous transition between intrusive styles from the epizone to the mesozone (Fig. 4). Although the depth of this transition is not well constrained it is noteworthy that the majority of the tabular granitic plutons cited above were emplaced at palaeodepths >3 km. Lack of evidence for roof-lifting (e.g. Myers 1975; Paterson *et al.* 1996) coupled with structural observations of downfolding of wall rocks (e.g. Hamilton & Myers 1967; Bridgewater *et al.* 1974; Parsons 1987) and gravimetric models of granites with inwardly inclined floors (e.g. Vigneresse 1995) suggest that many plutons are geometrically similar to lopoliths (Fig. 4). However, the form and wall-rock structure of lopoliths are inferred to have formed by downward sagging of wall rocks after intrusion of the magma (Corry 1988). The inference here is that space for tabular granites is made by depression of the floor during intrusion, as evaluated below.

Magma emplacement by floor depression

The effectiveness of floor depression as an emplacement mechanism is evaluated here in terms of the required rates, displacements and bulk strains. The space created for magma by floor depression must be redistributed at the crustal scale (Figs 4 and 5). Material can either be forced away from the column underlying the pluton, which is a form of crustal-scale boudinage, or it can be accommodated by volume loss at depth (Fig. 5). Given that the magma is steadily, or episodically, withdrawn from a source region in the lower crust, the latter mechanism is more attractive. The crustal column between the growing emplacement site and the source can therefore be viewed as foundering into a deflating layer of partial melt. Although the pluton and source region are likely to have different geometries, the volume of magma lost from the lower crustal reservoir must be balanced by the volume emplaced in the pluton. Hence, the volumetric withdrawal rate in the source, Q_W, and the volumetric flux in the feeder dyke (or dykes), Q_A, and the volumetric filling rate of the pluton, Q_E, must all be equal (Fig. 5).

The deformation mechanisms that allow this downward transfer of material are not well constrained. However, given that this deformation occurs in the lower to mid-crust (Fig. 5) of regions with high heat flow and a large advected mantle heat component, it is reasonable to assume that the principal mechanism will be by ductile flow. Homogeneous deformation as well as discontinuous mechanisms such as displacements on shear zones, or flexural slip on initially horizontal anisotropic planes, are likely. Vertical compaction of the partially molten source region combined with lateral flow towards the withdrawal point is also predicted. This may result in the formation of asymmetric melt-filled structures, analogous to those observed in migmatite terranes (e.g. Brown 1994).

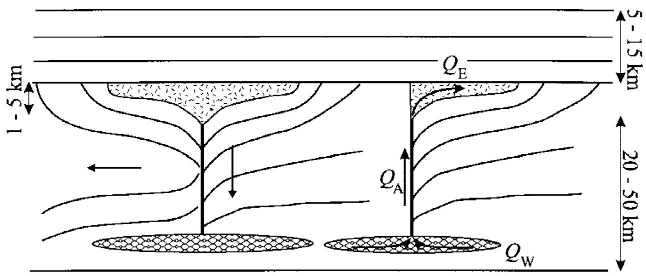

Fig. 5. Pluton emplacement by floor depression. The pluton (stippled) on the left side is symmetrical and fed by a central conduit (thick vertical line). Thin horizontal lines are initially horizontal markers. Subsidence of its floor is accommodated by either horizontal and outward flow of the underlying ductile crust away from the conduit (arrow on left side), or by downward displacement of the crust into a deflating magma source region (anastamosing pattern) in the lower crust (arrow on right side). The pluton on the right is asymmetric and fed by a conduit located on one side. Arrows indicate the flow of melt within the system, in terms of volumetric flow rates of extraction (Q_W), ascent (Q_A) and emplacement (Q_E).

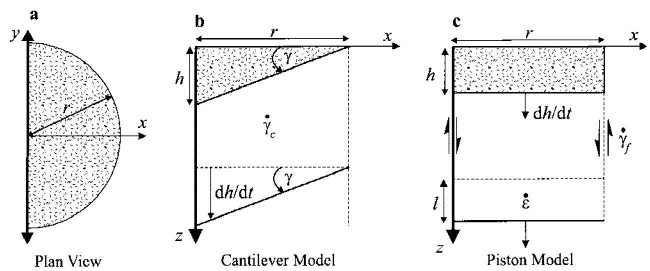

Fig. 6. Model geometries and parameters for floor depression models. (**a**) Plan view of top of pluton (stippled) for both models. (**b**) Cantilever model. (**c**) Piston model. Note that in both cases the pluton is fed by a planar conduit (thick line) located on its left side. For plutons with symmetrical geometry fed by a central conduit, the other half of the pluton is a mirror image about the *z* axis.

Cantilever and piston models

Intuitively, rapid rates predicted for magma transport in dykes and filling of large tabular plutons (e.g. Petford 1996) appear to be at variance with ductile flow of wall rocks, and therefore low strain rates of the mid- to lower crust. This is evaluated using two simple end-member models for floor depression (Fig. 6). Both models are hemispherical in plan view (Fig. 6a) with radius *r* but differ in their cross-sectional geometry. It is also assumed in both cases that pluton inflation starts after the formation of an initial sill, although this may not be strictly valid in plutons with ductile wall rocks, as discussed below. The plutons in both models are fed by a planar conduit on their left side. The models are also valid for a symmetrical, circular pluton fed by a central conduit, in which case the models presented here simply represent one half of the system.

In the 'cantilever' model, pluton growth occurs by tilting of the floor about a pivot point located at the perimeter of the pluton, farthest away from the feeder dyke or pipe (Fig. 6b). The underlying crust deforms by bulk progressive simple shear as it sinks into a regional of partial melt in the lower crust. It is assumed that resistance to slip on the melt-filled conduit is negligible.

In the 'piston' model, growth occurs by depression of a horizontal floor, which is accommodated by a vertical, cylindrical shear zone (or ring dyke) at the perimeter of the pluton and displacement along the feeder channel itself (Fig. 6c). The piston falls into a partially molten source region at depth.

Although greatly simplified, aspects of these two models show a reasonable geometric similarity to many of the tabular granites discussed above. Note that the models can equally well be formulated for circular or elliptical shapes, fed by a central feeder zone, in which case the rates given below should be halved. In both cases, the pluton is filled at a rate Q_E, which is assumed to be constant. For the cantilever model:

$$Q_E=\frac{dV}{dt}=\frac{\pi r^2}{4}\frac{dh}{dt} \tag{2}$$

where V is the pluton volume, and h is the depth of the floor adjacent to the feeder zone (Fig. 6b). The bulk shear strain in the underlying crust is:

$$\gamma=\frac{h}{r} \tag{3}$$

and the shear strain rate is given by:

$$\dot{\gamma}_c=\frac{1}{r}\frac{dh}{dt}=\frac{4Q_E}{\pi r^3}. \tag{4}$$

This is also the shear strain rate in the source region if it is assumed that the magma is withdrawn from an area of similar volume and shape in the lower crust. However, since melt percentages in the source are likely to be low, melt extraction and related deformation will be distributed over a much larger volume. Hence this shear strain rate is a maximum value for the source region.

In the piston model:

$$Q_E=\frac{\pi r^2}{3}\frac{dh}{dt} \tag{5}$$

and the strain rate in the compacting source region is:

$$\dot{\varepsilon}=\frac{1}{l}\frac{dh}{dt}=\frac{2Q_E}{\pi l r^2} \tag{6}$$

where l is the compaction length in the source (Fig. 6c). In the current geometry $l=h$, which implies that melt is extracted from an equivalent volume to that of the final pluton in the source. As in the cantilever model, this strain rate is also an upper bound on the deformation rate in the source region. An alternative measure of strain rate for the piston model is the shear strain rate on the bounding fault:

$$\dot{\gamma}_f=\frac{1}{w}\frac{dh}{dt} \tag{7}$$

where w is the width of the fault.

Volumetric flow rates

The variable of greatest uncertainty in the above equations is the rate of pluton filling, Q_E. A reasonable estimation can be proposed by equating Q_E with the volumetric flow rate in a feeder dyke (or dykes) such that:

$$Q_A=Q_E=\frac{\Delta\rho}{12\mu}ga^3b \tag{8}$$

where, $\Delta\rho$ is the density difference between crust and the magma, is magma viscosity, g is gravitational acceleration, a is the dyke width and b its length (Petford 1996). Taking the following ranges in these parameters, $\Delta\rho=10$ to 400 kg m^{-3}, $\mu=10^4$ to 10^8 Pas, $a=1$ to 10 m, and $b=1$ to 10 km, gives possible flow rates ranging from $<10^{-2}$ to $>10^3$ m^3 s^{-1}.

Strain rates and pluton filling times

Using the above Q_E values as lower and upper bounds, strain rates required to fill a pluton of final thickness, $h=3$ km, have been determined in terms of the time required, t, and the pluton radius, r for both model geometries (Fig. 7). Strain rates fall within the range 10^{-9} to 10^{-16} s^{-1} to fill 1–1000 km wide plutons in 10 to 10^8 a. For a constant filling time, in the piston model the strain rate varies only as a function of Q_E (Fig. 7a), whereas in the cantilever model the strain rate is also dependent on pluton width (Fig. 7b). This is due to the rotational nature of deformation associated with the cantilever model, and produces an interesting result. For the same filling time, larger plutons require lower strain rates to depress their floors, provided the magma supply rate is sufficient. Another consequence of the model geometries is that filling times for cantilever plutons are half those of pistons, although this does not profoundly influence the resulting strain rates.

Clearly, it would be useful to place limits on these results. Using the plutons discussed above pluton radii fall in the range $r\approx 5$–100 km. A lower bound on the filling time can be determined from estimates of solidification times of plutons, which are likely to vary from *c.* 1 a to *c.* 1 Ma, depending on a number of factors including size, depth and composition of the pluton, volatile content and whether heat loss is conductive or convective etc. (e.g. Paterson & Tobisch 1992). Upper bounds on the emplacement time are indicated by the strain rates. Average rates of tectonic deformation vary between 10^{-13} and 10^{-15} s^{-1} (Pfiffner & Ramsay 1982) which roughly correspond to the lower bound constrained by solidification times. Faster strain rates on the order of 10^{-10} s^{-1} have been inferred from mylonite zones (Schmid 1989) in agreement with average rates of faulting and observed rates of fold displacement (e.g. Paterson & Tobisch 1992).

Evaluation of feasible strain rates can also be made on rheological grounds. Taking a maximum value of $P_d\approx 100$ MPa (Corry 1988; Hogan & Gilbert 1995) and a strain rate of 10^{-10} s^{-1} gives and effective crustal viscosity $\mu_{eff}\approx 10^{18}$ Pa s. A strain rate of 10^{-13} s^{-1} yields $\mu_{eff}\approx 10^{21}$ Pa s. Both values fall within effective viscosities predicted from empirical creep laws for crustal rocks deforming under high

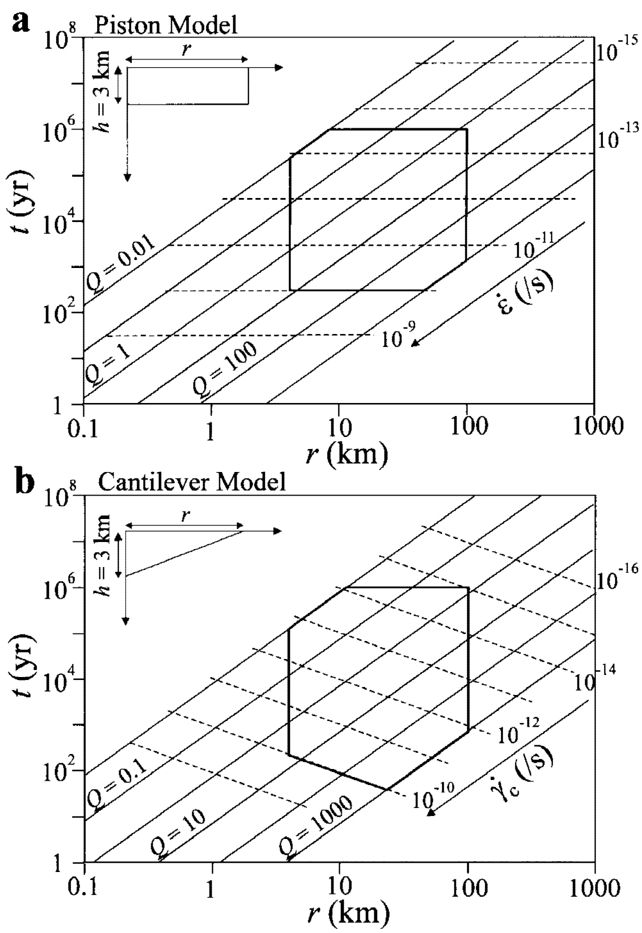

Fig. 7. Nomograms showing the time (t years) required to fill 3 km thick plutons of a variety of widths (r) for a range of possible volumetric emplacement rates (Q m^3 s^{-1}; solid lines). The corresponding strain rates ($\dot{\gamma}_c$ and $\dot{\varepsilon}$ s^{-1}) are indicated with dotted lines. (**a**) Piston model. (**b**) Cantilever model. Areas within heavy lines indicate likely filling times and widths for tabular granite plutons, as discussed in the text.

(*c.* 700°C) to moderate (*c.* 400°C) lower- to mid-crustal temperature conditions (e.g. Kirby 1983), and are significantly above effective viscosities expected for partial melts (e.g. Cruden 1990). Therefore, taking into account the possibility of high temperatures, 10^{-10} s^{-1} is a reasonable upper bound for bulk strain rates in the crust and source region associated with the cantilever model (Fig. 7b). In the piston model, downward displacement of the crust is accommodated by vertical faults. The corresponding strain rates, $\dot{\gamma}_f$ on these faults are systematically higher than the bulk strain rate in the source region for all faults less than *c.* 1 km wide (Fig. 8). For example, a 1 m wide fault requires $\dot{\gamma}_f \approx 3 \times 10^{-6}$ s^{-1} for $\dot{\varepsilon} = 10^{-10}$ s^{-1}, whereas the same fault will deform with $\dot{\gamma}_f \approx 10^{-10}$ s^{-1} when $\dot{\varepsilon} = 10^{-13}$ s^{-1}. Such fast rates are reasonable if the fault is lubricated by magma, as in the case of ring dykes. However, if they are not this places a limit on the efficiency of piston sinking for space creation, and suggests that the cantilever mechanism is energetically more favourable.

Finite strains

Deformation associated with piston sinking is localized in the source region and on bounding shear zones. Large finite strains

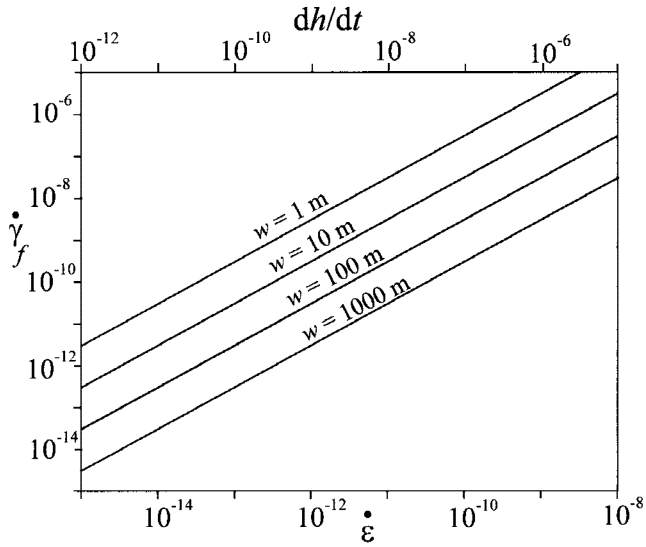

Fig. 8. Shear strain rates ($\dot{\gamma}_f$) required on the bounding faults of a subsiding piston for a range of bulk strain rates ($\dot{\varepsilon}$) in the compacting source region and a variety of fault widths (w).

leading to the formation of detectable fabrics are therefore expected and their magnitudes will be dictated by the dimension of the source and the shear zone width. In the cantilever model, the underlying crust must also deform as well as the source region and a melt-filled conduit. In this case it is informative to determine whether bulk crustal deformation will also result in detectable fabrics. The 2D finite strain in a cross section of the crustal column underlying the pluton is given by:

$$\mathbf{D} = \begin{bmatrix} 1 & 0 \\ \gamma & 1 \end{bmatrix} \tag{9}$$

and the strain ratio $S_r = a/b$, where a, b are the eigenvalues of **D**. For a pluton with maximum final thickness $h = 3$ km, $S_r < 1.4$ for all pluton sizes $r > 10$ km (Fig. 9a). S_r can also be expressed in terms of the dip of the pluton floor, φ, in which case it is evident that for $S_r > 2$ floors must be tilted by more that about 30° (Fig. 9b). For realistic geometries of plutons, bulk finite strains are therefore predicted to be low and may not result in distinctive fabrics.

Implications, predictions and limitations of the models

Although greatly simplified and subject to further theoretical analysis and testing by field observation, the floor depression models provide several robust results. Large tabular granites can be emplaced over geologically rapid times (<100 a to 1 Ma) without requiring unreasonably fast deformation rates in the underlying crust. This is particularly the case for the cantilever mechanism for which there is an inverse relationship between bulk crustal shear strain rate and r^3. Plutons emplaced by the piston sinking mechanism require displacements to be accommodated by relatively faster shear strain rates on bounding faults. This mechanism may therefore be favoured when the bounding faults are also magma conduits (i.e. ring dykes) in which case very rapid emplacement rates are possible. Although not investigated here, the rate-limiting process for the emplacement of tabular granites by both mechanisms is

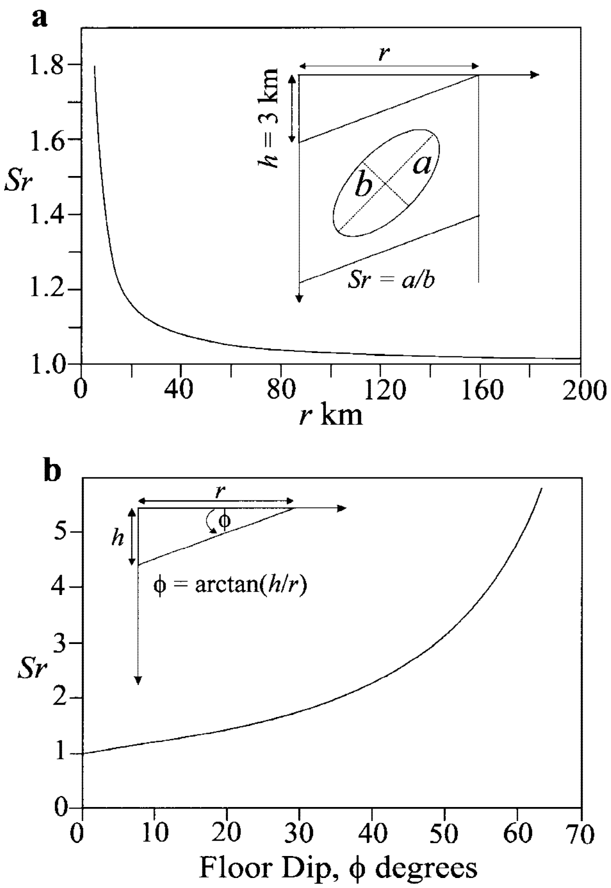

Fig. 9. Finite strains due to pluton emplacement by the cantilever mechanism. (**a**) Strain ratios (*Sr*, insert) in the underlying block for a final pluton thickness of 3 km and a range of pluton widths (*r*). (**b**) Strain ratios as a function of the dip of the pluton floor (φ, insert). Note that only very narrow, thick plutons (i.e. those with steeply inclined floors) result in significant finite strains.

likely to be the magma supply rate, Q_A. This is in turn governed by the rate, Q_W, at which melt can be extracted from the source region.

Recent evaluations of the rates of pluton emplacement have focused on comparing the required rates of pluton *widening* to displacement rates on possibly related faults (e.g. Paterson & Tobisch 1992; Tikoff & Teyssier 1992). Such 2D approaches find that tectonic opening rates are insufficient to accommodate plutons in the required times. If the same plutons are viewed as tabular and that the bulk of their volume is produced by floor-depression, as opposed to lateral opening, then this problem becomes less acute. Note that the models presented here do not exclude the operation of tectonic or other mechanisms (e.g. stoping) during the emplacement of granites (Fig. 10). In such cases, floor depression should be regarded as a component of the space making process. In fact, emplacement in actively deforming crust is probably easier because downward transfer of material can be accommodated by displacements on a large number of active, and in some cases melt-lubricated faults and shear zones. This scenario may correspond to tectonically induced pervasive magma migration as described by Collins & Sawyer (1996), in which case the resulting pluton may be filled by a number or structurally controlled channels rather than a single dyke.

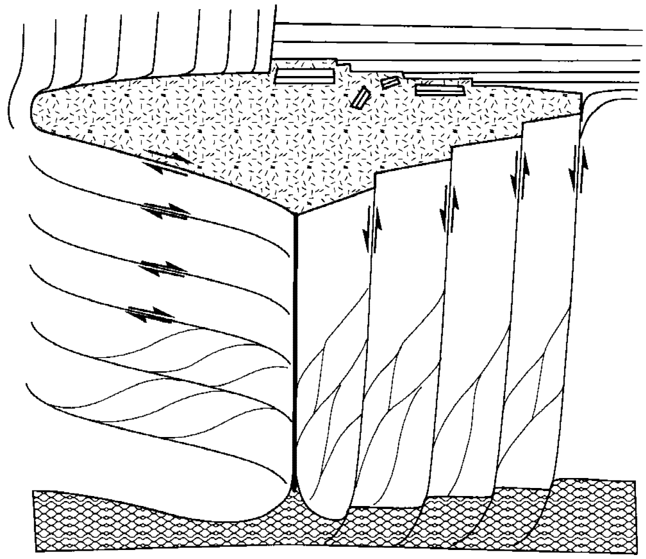

Fig. 10. Schematic cross-section of a pluton (stippled) emplaced by a combination of the cantilever and piston mechanisms. Shear strain of the crust underlying the pluton required by the cantilever mechanism is accommodated by displacements on high angle normal faults (right side) or low angle shear zones (left side). With increasing depth, deformation associated with these structures is likely to become more distributed, and may also contribute to the upward channelling of magma. Note heterogeneous thinning of magma source region (anastamosing pattern) due to decrease in volume withdrawn away from conduit. Some modification of the pluton roof (with initially horizontal and vertical markers) either by stoping (right half) or ductile deformation during initial lateral spreading (left half) is also likely.

Plutons emplaced by floor-depression mechanisms should show a number of diagnostic features. The cantilever mechanism results in a pluton with a floor that is inclined toward a vertical root and low bulk strains in the underlying crust. However, progressive rotation of the floor of the pluton and deformation of the underlying rocks may be accommodated by displacements on discrete structures, rather than a homogeneous shear strain. For example, steepening of an originally horizontal floor may occur by displacements on a series of high-angle normal faults resulting in a stepped basal contact (Fig. 10). Alternatively, deformation may be focused on low angle shear zones, sub-parallel to the tilting pluton floor (Fig. 10). Evidence for synmagmatic normal faulting and associated steps have been described from the bases of layered mafic intrusions (Irvine 1987; Carr *et al.* 1994) and may be associated with emplacement-related sagging of their floors (J. Cowan pers. comm.). Deformation fabrics in the lower parts of some mafic intrusions indicate a radial stretching component (Cowan 1996) which may also be associated with progressive steepening of the basal contact. Weibe & Collins 1998 have documented a number of structures in the lower parts of felsic intrusions consistent with steepening of the floors of these plutons before the magmas were fully crystallized.

Plutons emplaced by the piston mechanism will have flat floors, vertical sides that correspond either to faults, ductile shear zones or feeder dykes, and negligible bulk strains in the underlying crust. A hybrid mechanism can also be proposed in which a component of piston sinking results in vertical sides and a cantilever component produces an inclined floor (Fig. 10). Some of the upper crustal plutons discussed above display these characteristics, and it is also noteworthy that the steep, angular margins of these granites often correspond to regional fracture sets which may have provided readily available sites for downward displacement of the floor (e.g. Bussell 1976; Dehls *et al.* 1998). More distributed deformation of wall rocks in the mid-crust can account for the downfolding observed around some plutons (e.g. Bridgewater *et al.* 1974). A component of lateral displacement of wall rocks observed around some mid-crustal plutons is not predicted by the models. This is due to the assumption of sill emplacement followed by vertical thickening. If the pluton spreads and thickens at the same time, and wall-rock displacements are accommodated by ductile flow, then a tabular granite with attributes similar to the Ljugaren granite is expected. A similar problem exists with laccoliths, and the question of whether emplacement and growth are two- or one-step processes can be resolved by careful analysis of both internal magmatic and external wall-rock structures (e.g. Hunt *et al.* 1953; Jackson & Pollard 1988).

Many of the gravity surveys discussed above find root zones that are substantially wider than the narrow conduit assumed in the models. The floor also appears to steepen approaching the root, such that the base of the pluton resembles a palm tree in cross section (e.g. Vigneresse 1995; Dehls *et al.* 1998). One possible explanation for this geometry is the nature of melt withdrawal from the source region. The flow rate in the source is likely to be greatest in the vicinity of the conduit draining the melt. For this reason the amount of melt extracted from the source region may be heterogeneous and greatest near to sites of collection and vertical removal. This will result in differential subsidence of the overlying crust and the observed thickening of plutons toward the feeder zone (Figs 5 and 10).

The models have also assumed that magma emplacement is continuous and that the pluton grows to a final thickness of 3 km. They are also equally amenable to the growth of plutons by emplacement of discrete pulses. In these cases emplacement times for individual pulses are substantially shorter than the times reported here, although strain rates will remain similar for each pulse. If each pulse uses the same conduit then a simple inward younging of intrusive phases will be observed in plan view, and the pluton will consist of inwardly inclined layers in cross-section. However, if more than one conduit is used and if early phases are not fully solidified, then both complex internal compositional and structural patterns can be expected, particularly if the pluton floor is steepening with the introduction of each new pulse (e.g. Weibe & Collins 1998).

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