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Depositional features and stratigraphic sections in granitic plutons: implications for the emplacement and crystallization of granitic magma

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Abstract—Many granitic plutons contain sheet-like masses of dioritic to gabbroic rocks or swarms of mafic to intermediate enclaves which represent the input of higher temperature, more mafic magma during crystallization of the granitic plutons. Small-scale structures associated with these bodies (e.g. load-cast and compaction features, silicic pipes extending from granitic layers into adjacent gabbroic sheets) indicate that the sheets and enclave swarms were deposited on a floor of the magma chamber (on granitic crystal mush and beneath crystal-poor magma) while the mafic magma was incompletely crystallized. These structures indicate 'way up', typically toward the interior of the intrusions, and appear to indicate that packages of mafic sheets and enclave concentrations in these plutons are a record of sequential deposition. Hence, these plutons preserve a stratigraphic history of events involved in the construction (filling, replenishment) and crystallization of the magma chamber. The distinctive features of these depositional portions of plutons allow them to be distinguished from sheeted intrusions, which usually preserve mutual intrusive contacts and 'dike–sill' relations of different magma types. The considerable thickness of material that can be interpreted as depositional, and the evidence for replenishment, suggest that magma chamber volumes at any one time were probably much less than the final size of the pluton. Thus, magma chambers may be constructed much more slowly than presently envisaged. The present steep attitudes of these structures in many plutons may have developed gradually as the floor of the chamber (along with the underlying solidified granite and country rock) sank during continuing episodes of magma chamber replenishment. These internal magmatic structures support recent suggestions that the room problem for granites could be largely accommodated by downward movement of country rock beneath the magma chamber. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

For many years most 'plutonic' geologists seem to have accepted that granitic plutons were emplaced as highly viscous, crystal-rich magmas, and that internal structures such as aligned minerals, enclaves and schlieren reflected flow of these crystal-rich magmas during emplacement (Balk, 1937; Pitcher and Berger, 1972; Pitcher, 1993). This view has been supported by studies proposing melt is retained at its site of origin until some rheological critical melt percentage is reached (Arzi, 1978), and a mixture of melt and residuum (restite) is able to rise diapirically (Wickham, 1987). The assumption that granitic magmas commonly carry substantial proportions of restite has led some workers (e.g. Chappell *et al.*, 1987) to suggest that restite unmixing is a major cause of compositional variation in granitic plutons.

Many recent field, structural and petrographic studies of volcanic rocks, migmatites and granitic plutons have found evidence which supports the view that granitic intrusions were initiated as crystal-poor silicic liquids rather than largely crystalline magmas. These observations include: (1) Studies of the volcanic record demonstrate the existence of large volumes of crystal-poor silicic magmas in shallow-level, crustal magma chambers (Smith, 1979). (2) Studies of migmatites (Sawyer, 1991, 1994; Collins and Sawyer, 1996) suggest that small volumes of granitic liquid may readily migrate during deformation from their site of origin and collect in conduits that, when appropriately interconnected, could feed dikes of crystal-poor magma that could be rapidly transported to higher crustal levels (Clemens and Mawer, 1992; Petford *et al.*, 1993). Such a view is supported by recent experimental work on the viscosities of granitic liquids (Baker *et al.*, 1997). (3) Recent structural and petrographic studies of granitic plutons have suggested that mineral foliations in many granitic plutons must have formed late in the crystallization history (Paterson *et al.*, 1989; Paterson and Vernon, 1995), even after the latest stoping of major blocks of country rocks from the chamber roof (Fowler and Paterson, 1997). (4) Textures in elongate microgranitoid enclaves typically reflect magmatic flow rather than subsolidus deformation (Vernon *et al.*, 1988; Paterson *et al.*, 1989). (5)

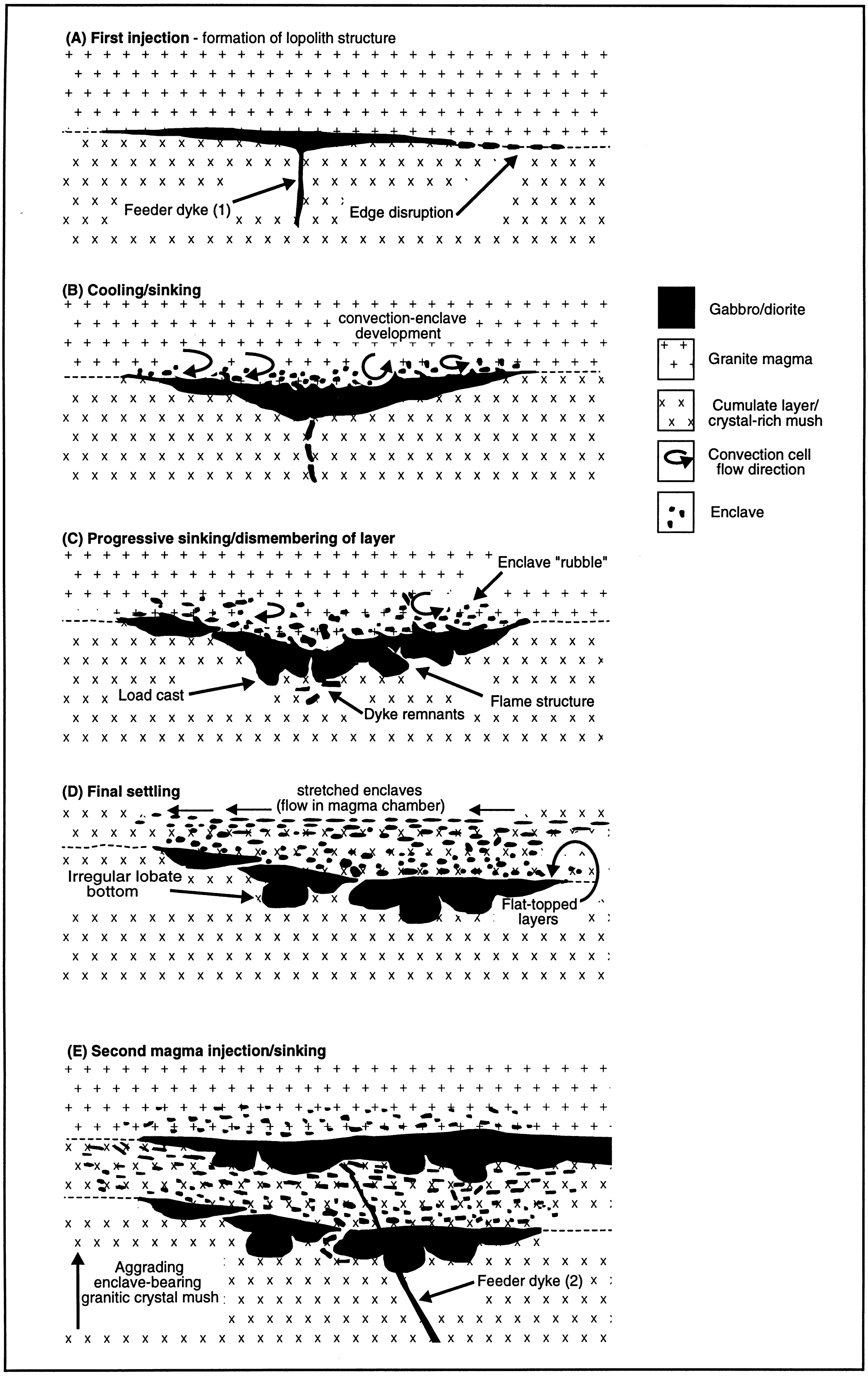

Fig. 1. Schematic drawings showing the development of sheet-like mafic bodies in granite due to sequential replenishments of mafic magma into a felsic magma chamber. The features shown here closely match relations in the Tuross Head Tonalite (see later) where mafic sheets extend hundreds of metres. Sheets in other intrusions may vary greatly in details. They are commonly more planar in form, ranging in thickness from tens of centimetres to tens of metres and extending laterally from metres to more than 1 km (Wiebe, 1993a, 1994). See text for details.

Basally chilled mafic sheets in some granitic intrusions appear to record ponding of mafic magma at the base of a crystal-poor granitic magma chamber (Wiebe, 1994; Patrick and Miller, 1997).

These five observations strongly suggest that magmatic structures and fabrics in granitic plutons need to be re-evaluated. Rather than reflect emplacement, we believe that these features generally reflect processes that operated in an active magma chamber during solidification—processes such as replenishment, convection, mixing, crystallization, deposition and compaction. Are mafic sheets and enclave swarms features that formed by deposition on a magma chamber floor? Were they deposited sequentially within the magma chamber during consolidation of the granite rather than formed all at one time during emplacement? If so, significant portions of many granitic plutons should retain cumulate stratigraphic records analogous to those in mafic layered intrusions (Wager, 1960; Morse, 1969).

The purpose of this paper is to draw attention to the widespread occurrence of mafic sheets and enclave swarms in granitic and composite mafic–silicic layered intrusions which we feel demonstrate that major portions of many plutons have formed by deposition on an aggrading floor of a magma chamber—that is, at the interface between a crystal-rich base of the chamber and the crystal-poor, liquid interior. The depositional nature of these plutons is most clearly shown by injections of denser mafic magma into a granitic magma chamber. These injections tend to spread laterally and form sheets at a level of rheological contrast, probably the interface betwen a crystal-rich mush and an overlying crystal-poor magma (Fig. 1a) (Wiebe, 1993a). Cooling and crystallization of a sheet may generate 'eddy' currents in the overlying felsic magma which are capable of ripping mafic magma globules off the upper surface (Fig. 1b). As the denser mafic sheet crystallizes and settles into the underlying crystal mush, load-casts and flame structures commonly develop along the base of the sheet due to filter-pressing of the underlying crystal mush (Fig. 1c). The mafic layer commonly develops a flat top that probably approximates the horizontal (Fig. 1d). Further cooling results in complete solidification of the mafic sheet and gradual deposition of an overlying, enclave-rich, granitic crystal mush. Highly stretched enclaves and a magmatic foliation in these deposits (Fig. 1d) probably formed due to convective flow in the overlying magma chamber prior to deposition. With repeated injections, the pluton leaves a sequence of deposits that provide a stratigraphic record of events in the intrusion (Fig. 1e).

In many intrusions these planar structures typically dip inward moderately to nearly vertically. We suggest these steep dips developed by gradual downward sinking of the country rock beneath the pluton along with the cumulate material at the base of the chamber, thereby creating room for the pluton. After a review of these structures and evidence for their interpretation, we examine their occurrence in three major intrusive bodies and then consider the broader implications for the emplacement and crystallization of granitic magma and the construction of granitic magma chambers.

DEPOSITIONAL FEATURES IN GRANITOID PLUTONS

Sheet-like bodies

Sheet-like bodies of relatively mafic magmatic rock occur in many granitic plutons (Wiebe, 1974, 1993a, b, 1994; Barbarin, 1988; Michael, 1991; Blundy and Sparks, 1992; Chapman and Rhodes, 1992; Fernandez and Gasquet, 1994; Coleman *et al*., 1995). Individual sheets or lenses may be chilled on the base or on both margins and may laterally pass into a layer of globular enclaves. Sheets with a chilled base commonly display prominent convex-downward lobate structures that closely resemble sedimentary load-cast structures (Fig. 2a) (Wiebe, 1974, 1993a). The chilled base of a sheet is commonly molded around individual crystals in the underlying granite (Fig. 2b). Underlying granitic material typically shows petrographic evidence for compaction and has the chemical and petrographic character of a cumulate (Wiebe, 1974, 1993a).

The base of a mafic sheet is commonly perforated by flame structures and veins of leucogranite which provide way-up indicators (Wiebe, 1974). This felsic material appears to represent interstitial liquid which was filter-pressed from the underlying granitic crystal mush and rose upward into the overlying mafic body (Fig. 2a–c). In some mafic layers pipe structures (Fig. 2d) have formed as cylindical diapirs of crystal mush, which rose vertically from the underlying granitic crystal mush into the overlying unconsolidated mafic layer (Chapman and Rhodes, 1992). Where they have not been affected by slumping or magmatic flow in the host mafic layer, they appear to provide a record of the vertical during consolidation of the mafic layer and, hence, can be used to indicate the initial dip of the floor and the amount of tilting since deposition (Wiebe, 1993b). In the Cadillac Mountain granite, Maine, U.S.A. (Wiebe, 1994), pipes cutting sheets that now dip as much 70° indicate that the sheets were originally horizontal when they were deposited. Recently, Patrick and Miller (1997) have used pipes of this type to reconstruct the original geometry of a fractured and tilted pluton.

Upper margins may be sharp, typically when sheets are less than 2 m thick, or gradational to the overlying granite when they are thicker (Wiebe, 1974). Thick mafic layers generally have unchilled tops and commonly show evidence for mechanical mixing with the

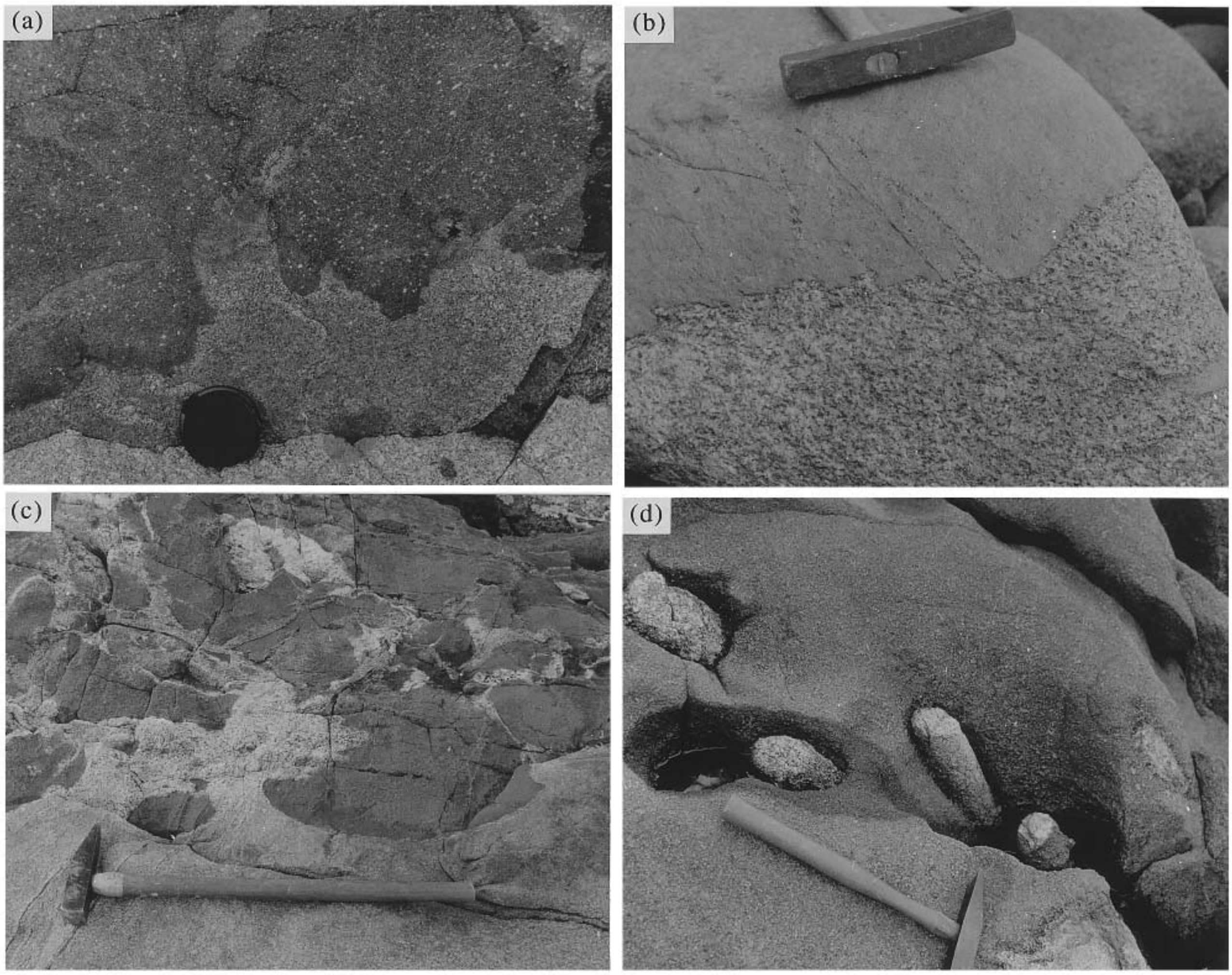

Fig. 2. Depositional features related to mafic sheets in granitic plutons. (a) Small load-casts at the base of a mafic layer (Jersey, Channel Islands, U.K.). Leuco-granitic material has concentrated at the top of the granite between convex-downward lobes, and veins have risen from these points into the mafic layer. (b) Base of a mafic layer is molded around individual plagioclase crystals in host tonalite (South Island, New Zealand). Beneath the hammer, thin veins of leucogranite represent silicic liquid filter-pressed from the underlying tonalite. (c) Prominent load-casts at the base of a gabbroic layer in the Pleasant Bay intrusion, Maine (Wiebe, 1993b). Coarse-grained, locally pegmatitic granite has collected at the base of this layer and intruded it. (d) Granitic pipes in a gabbro layer near the base of the Vinalhaven granite, Maine, U.S.A. They have attitudes that are approximately perpendicular to the base of the gabbroic layer.

overlying granite. For example, the size and proportion of feldspar or quartz xenocrysts commonly increases toward the top of the mafic layer (Wiebe, 1974). It is most likely that convective stirring in both layers led to mechanical mixing and break-up of the top of the mafic layer (Wiebe, 1974). In the overlying granite, the occurrence of enclaves that decrease in size and abundance upward from the top of the mafic layer provide further evidence for convection and mixing (Wiebe, 1974; Barbarin, 1988).

The contrasting character of the bases and tops of individual mafic sheets (indicated above) strongly suggests that thick sequences of parallel mafic sheets in granite formed by sequential deposition of each mafic layer at the interface between a crystal-rich base of a granitic chamber (an aggrading chamber floor) and a crystal-poor, liquid interior. Because these basally chilled mafic layers rest on rocks ranging from gabbro to granite (Wiebe, 1993a, 1994) their level of emplacement into the granitic bodies cannot be related to neutral buoyancy. Instead, the level of emplacement is probably controlled by the rapid change in rheology from a crystal-rich material beneath the active chamber to a crystal-poor liquid in the interior.

In occurrences we have studied we have seen no evidence to suggest that these sheets were emplaced as sills at random levels in the package of layers. We believe, therefore, that such a sequence of interlayered mafic and granitic rocks preserves a stratigraphic record of magma chamber processes that were active during the crystallization of the granite intrusion. This view apparently contrasts with that of several recent workers who have described apparently comparable thick sequences of sheet-like mafic bodies in granite as sills (Blundy and Sparks, 1992; Coleman *et al.*, 1995; Sisson *et al.*, 1996).

Smaller, more isolated lenses (or tabular mafic enclaves) up to several metres in length also occur in some plutons that consist mainly of granite. Where these lenses show chilled, or partially chilled, margins they are commonly molded around large feldspar crystals in the underlying granite and, less commonly, perforated by small veinlets of granitic melt pressed out of the underlying granitic crystal mush. These features are completely analogous to those in larger mafic sheets and, we believe, provide comparable information about the location and approximate attitude of the floor upon which the lens or enclave settled.

'Concordant' concentrations of magmatic microgranitoid enclaves

Concentrations or 'swarms' of microgranitoid enclaves occur widely in granitic plutons; they have a wide range of shapes on two-dimensional surfaces and locally appear transgressive or concordant with other structures in the granite (Elburg and Nicholls, 1995; Tobisch *et al.*, 1997). Where adequate three-dimensional exposures permit, it is possible to show that enclave swarms have a wide range of three-dimensional shapes with boundaries that may be relatively sharp or grade through a zone with decreasing proportions of enclaves (Wiebe, 1974). In this section we describe some common types of swarms that appear to be concordant with other structures in the host granite (e.g. schlieren, feldspar foliation).

Sheet-like deposits of enclaves are common in mafic–silicic layered intrusions and are commonly parallel to mafic sheets (Wiebe, 1974, 1994). Similar sheet-like deposits of enclaves occur more sparsely in many granitic plutons. They are typically parallel to foliations defined by tabular feldspars and to planar orientations of disseminated lensoid microgranular enclaves. Also common are lensoid concentrations of enclaves that are generally convex-downward (Fig. 3a). Where exposures are adequate, they appear to represent cross-sections through elongate channels of enclaves. Sheet-like and channel-like swarms commonly contain enclaves larger than a few centimeters that are tightly packed and relatively well sorted. Individual enclaves are commonly molded against each other (Fig. 3b & c) and locally around feldspar megacrysts in the underlying granite, indicating that they were still hot and soft (incompletely crystallized) when they came to rest. Tightly packed concentrations of feldspar megacrysts are commonly associated with, and concentrated below, the enclave swarms (Fig. 3c). Schlieren, consisting of concentrations of minerals found in the granite, commonly occur along the base or extend laterally from some of the channel-like swarms.

Several features of these enclave swarms suggest they were deposited on the floor of the magma chamber in a manner comparable to that indicated (above) for the mafic sheets. The well-sorted and rounded shapes of enclaves in sheet-like and channel-like swarms suggest movement in a current. The close packing and molding of the enclaves in the swarm, and the evidence for compaction in the underlying granite, are consistent with deposition from this flow. The more sharply defined margin of the swarm, where individual enclaves are commonly molded against underlying megacrysts in the granite, apparently represents the base of the deposit. Commonly, small amounts of leucogranite appear to have migrated upward into the matrix of the basal enclaves and locally collected beneath larger enclaves.

In the plutons that we have studied (see below) these sheet-like and channel-like swarms maintain a constant direction of dip and, where features that indicate way-up are present, a constant direction of way-up. Each individual swarm probably represents a single event involving the introduction of hotter magma into the chamber, comparable, although smaller in volume to the mafic sheets in granites. If true, it is probable that all of the intervening, relatively massive, granitic material was also deposited sequentially on the chamber floor.

Evidence for mode of emplacement of mafic magma into the chamber: transgressive mafic bodies and enclave swarms

Mafic–silicic layered intrusions are commonly cut by basaltic dikes, which have chemical compositions that closely match those of the chilled mafic sheets intercalated with silicic cumulates (Keay, 1992; Wiebe, 1993b, 1994). In the Pleasant Bay intrusion, it was possible to trace one dike directly into a sheet or layer of enclaves (Wiebe, 1993b). In the Cadillac Mountain intrusive complex, an outer granite is cut by many more basaltic dikes than a slightly younger core of the complex (Wiebe, 1994). Thus, little doubt exists that infusions of mafic magma into granitic magma chambers are commonly fed by basaltic dikes, which cut across the solid base or margin of a granite body and pass into the magma chamber. In mafic–silicic layered intrusions these infusions have ponded on and spread across the floor of the chamber (Wiebe, 1993b). Chilled globular enclaves that form layers parallel with the sheets have similar chemical compositions and were probably fed by comparable dikes.

The Undercliff Falls pluton in the New England batholith, eastern Australia (Phillips, 1969; Hughes, 1993) appears to provide some valuable insights into the generation of heterogeneous enclave swarms. Modal and textural variation and feldspar foliation in the host define a gently dipping basinal structure with the center of the complex (the highest structural level) consisting of a leuco-granite. A prominent concentric zone at mid-levels of the structure contains swarms of texturally and modally heterogeneous

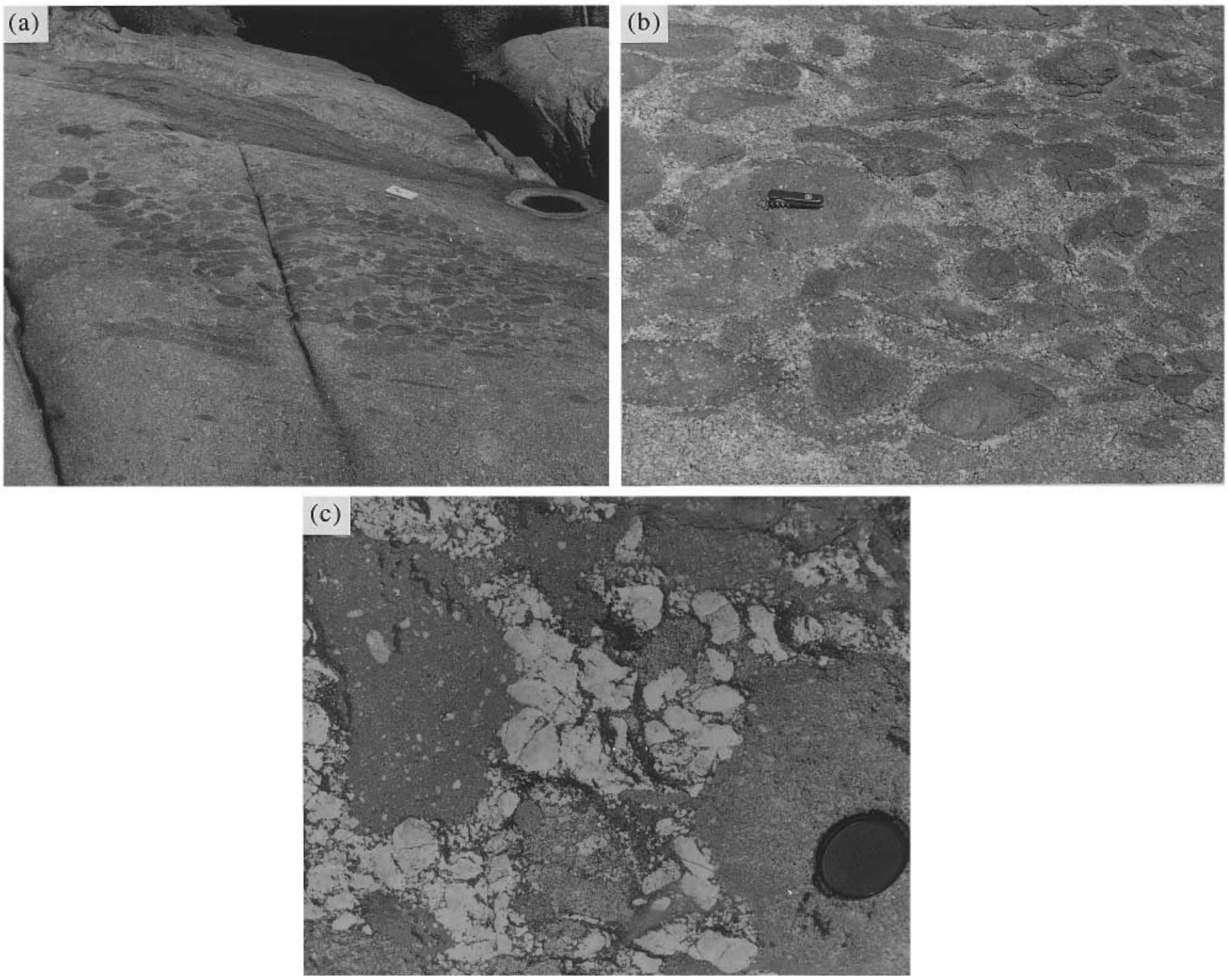

Fig. 3. Depositional features related to enclave swarms. (a) Section through a channel deposit of tightly packed rounded and sorted enclaves (Rame Head, Victoria, Australia). Way up is towards the top of the photograph. (b) Detail of (a). The enclaves have been packed so tightly, probably because of compaction, that they are molded against each other. (c) Detail of a channel deposit of mafic enclaves and K-feldspar megacrysts in the Undercliff Falls pluton (New England batholith, Australia). Megacrysts are impressed into the enclaves and locally bent against each other, suggesting significant compaction immediately after deposition. Way-up not apparent in this view.

enclaves that define sheets, channels and some more irregular bodies. Several roughly circular bodies of diorite up to 100 m in diameter occur at a stratigraphically and structurally lower level. Based on their occurrence in irregular topography, they appear to be sections through steep cylindrical bodies that are roughly perpendicular to the layering. The margins of these bodies are variably chilled and co-mingled with the host granite; where fine grained, the mafic rocks are generally molded around larger host crystals and have locally incorporated feldspars and quartz as xenocrysts. Multiple pulses of similar mafic magma reinjected these complex hybrid rocks before they were completely crystallized and generated rounded, unchilled enclaves, and double enclaves with variable mafic content and textures. Because the range of textures of these hybrid rocks and the sizes of many of the rounded bodies closely match those of enclaves in sheet-like swarms at higher levels in the intrusion, the equant diorite bodies were probably feeders for the enclave swarms.

Cylindrical bodies of tightly packed, rounded, mafic to intermediate enclaves have been described in several plutons (Wiebe, 1974; Elburg and Nicholls, 1995; Tobisch *et al.*, 1997). In the Wilson's Promontory batholith (Elburg and Nicholls, 1995) three-dimensional exposures strongly suggest that one pipe-like body, about 2 m in diameter and at least 6 m long, is approximately perpendicular to feldspar foliation in the host granite. Enclaves in this pipe are generally tightly packed and molded against each other, suggesting downward settling and compaction; their sizes and textures typically match those of enclaves that occur in sheet-like or channel-like swarms in the same intrusion (Elburg and Nicholls, 1995). Rarely, such pipes do merge into gently dipping sheet-like swarms within otherwise homogeneous granodiorite (Wiebe, 1974). These relations strongly suggest that the pipes fed enclaves into a granitic magma chamber and that the enclaves were deposited on a chamber floor, rather than being transported in a crystal-rich magma during emplacement (Wiebe, 1974).

We consider that these enclave-rich pipes represent a higher-level intersection through a mafic feeder system than the more massive mafic and hybrid dioritic bodies in the Undercliff Falls pluton (Phillips, 1969), a level that is much closer to the interface between granitic cumulates at the base of the chamber and the overlying crystal-poor silicic magma. This interpretation would require that physical processes near the interface tended to break up the mafic magma during upward flow and, that, when upward flow waned, the disaggregated material collapsed back down into the pipe. The upward momentum of the rising mafic magma into the chamber may have been dependent upon release of vapor from the rapidly crystallizing mafic magma. With subsequent loss of vapor, much of the mafic material could collapse back down into the feeder. The rounded shapes of enclaves and double enclaves may reflect a kind of tumbling motion during ebb and flow in the feeder. This effect and the probably strong convection generated in the overlying silicic magma should break up the rising and rapidly crystallizing mafic material. The tendency of the mafic magma to break up into pillows could also reflect flow-front instability (Snyder *et al.*, 1997). If the floor of the chamber was sloping, much of this mafic material would tend to spread downward over the floor in sheets or channels, an environment which is also appropriate for the relatively good sorting typical of these heterogeneous enclave swarms (Fig. 4).

DISTINCTION BETWEEN LAYERED AND SHEETED GRANITIC INTRUSIONS

The presence of the depositional features described above provides a means of distinguishing between layers or a planar fabric that formed by deposition in granitic plutons from the intrusive sheeting that appears to characterize many other plutons. Sheet-like bodies in the former are marked generally by a relatively sharp, although irregular, base and a gradational or hybrid top, whereas sheets in the latter are marked by sharp intrusive boundaries on both sides and these sheets might be expected to cut across each other at least in some places. At the pluton scale, granites formed by deposition and replenishment may be relatively homogeneous, with only localized areas of lithological diversity where mafic layers, lenses or enclaves are abundant. In contrast, plutonic bodies that consist of intrusive sheets (whether initially steep or gently dipping) are commonly heterogeneous, with granitoids of differing composition and sheet thickness varying from centimetres to tens of metres (McCaffrey, 1992; Fowler, 1994; McNulty *et al.*, 1996). Compositional differences between sheets can be very subtle and individual sheets are generally homogeneous. If subcondordant mafic bodies occur, these should have sharp contacts with the granitic rocks. Commonly, subconcordant rafts of country rock, varying from metre to kilometre scale, separate some sheets. This is often described as 'ghost stratigraphy' (Pitcher and Berger, 1972). The occurrence of these rafts may not prove sheeted intrusions as comparable rafts could occur within depositional sections on the floor of a granitic intrusion if stoping of the roof occurred gradually during deposition.

Mutual intrusive contacts and 'dike–sill' relations also serve to distinguish sheeted intrusion from depositional plutons. Where outcrop is good, contacts between subtly different granitoid sheets can commonly be traced until one type terminates as an apophysis. If concordant apophyses of different granite types exist within the pluton, it is likely to be sheeted. In sheeted plutons, one granite phase can commonly be recognized as a dike intrusion within another type.

The depositional plutons described here and the contrasting sheeted plutons may represent two end-members of granitic intrusions characterized by replenishment. In the former, replenishment of felsic and mafic material would have occurred rapidly enough to maintain a single active chamber, which was capable of undergoing at least partial homogenization. In sheeted plutons, earlier injections would have crystallized almost completely prior to new replenishments, so that felsic and mafic injections can be recognized as individual intrusions.

DISTRIBUTION OF DEPOSITIONAL FEATURES IN THREE INTRUSIVE BODIES

In order to test our interpretation of the structures described above, we examined their occurrence and distribution in three intrusions. Two are plutons in the Paleozoic Bega batholith of the Lachlan fold belt (southeastern Australia): the Tuross Head Tonalite (Griffin *et al.*, 1978) and the Kameruka Granodiorite (Chappell *et al.*, 1990) (Fig. 5). The third intrusion is the Mesozoic Anglem Complex located on Stewart Island, New Zealand (Watters *et al.*, 1968; Watters, 1978). These three bodies differ considerably in their structure and composition. The Tuross Tonalite contains a large proportion of contemporaneous dioritic to gabbroic material, whereas the Kameruka granodiorite has much higher SiO_2 and K_2O content, and contains only small amounts of mafic material in the form of enclaves and enclave swarms, which is more characteristic of plutons in the Bega batholith (Chappell *et al.*, 1990). The Anglem Complex contains a wide range of rocks, ranging from gabbro–diorite to

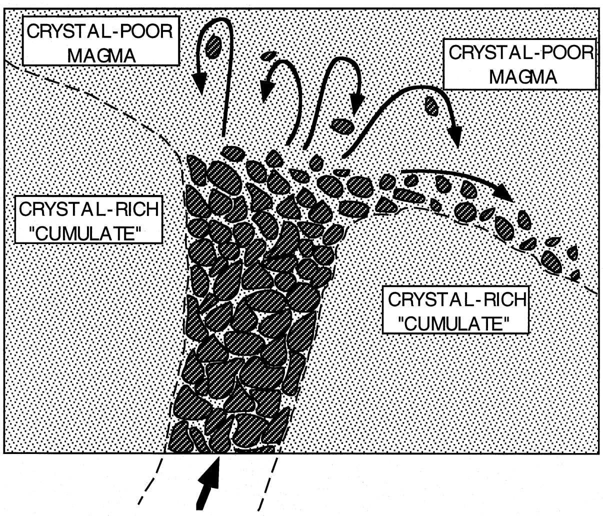

Fig. 4. Schematic drawing of the formation of a cylindrical enclave swarm feeding a layer of enclaves. Except for the hypothesized eruption of enclaves above the floor, this view closely matches that shown by three-dimensional exposures in a granodiorite pluton in Cape Breton Island, Canada (Wiebe, 1974).

granite and, on average, is tonalitic in composition (Watters, 1978).

Tuross Head Tonalite

The Devonian Tuross Head Tonalite (Fig. 6) was first described as a member of the Moruya batholith (Griffin *et al.*, 1978) which has recently been incorporated as a suite into the Bega batholith (Chappell *et al.*, 1991). It is well exposed as coastal outcrops where steep contacts against the Ordovician Adaminaby Group are exposed. Headlands typically contain major volumes of gabbro–diorite along with the tonalites. These mafic rocks, apparently more resistant to erosion, have commonly been referred to as the Bingi Bingi suite (Griffin *et al.*, 1978; Keay *et al.*, 1997), but, as they are interlayered and contemporaneous with tonalites, they are included here as an integral part of the Tuross Head Tonalite.

Griffin *et al.* (1978) characterized the petrography and chemical compositions of the main rock types in the intrusion. Felsic rocks range from granodiorite to quartz diorite. Plagioclase crystals are tabular with complex compositional zoning (An_{45-20}) and define a foliation. In most rocks hornblende is the dominant mafic phase, but biotite is locally prominent; magnetite, apatite, titanite and zircon are common accessory phases. The mafic rocks range from hornblende diorites to gabbros and vary widely in texture from very fine-grained rocks with basaltic textures to apparent cumulates; plagioclase is normally zoned (An_{60-30}).

The mafic rocks occur as well-defined layers, lenses and enclaves within the tonalite (Keay, 1992). Layers and lenses display all of the features characteristic of mafic layers in mafic–silicic layered intrusions (Wiebe, 1993a,b, 1994). In the Tuross Tonalite, these bodies dip steeply inward (Fig. 6) and are parallel to the feldspar foliation and the orientation of elongate enclaves in the tonalite. Load-cast structures, granitic veining and scarce felsic pipes along the outer contacts of these sheets are consistent with deposition on and compaction of the underlying cumulate material

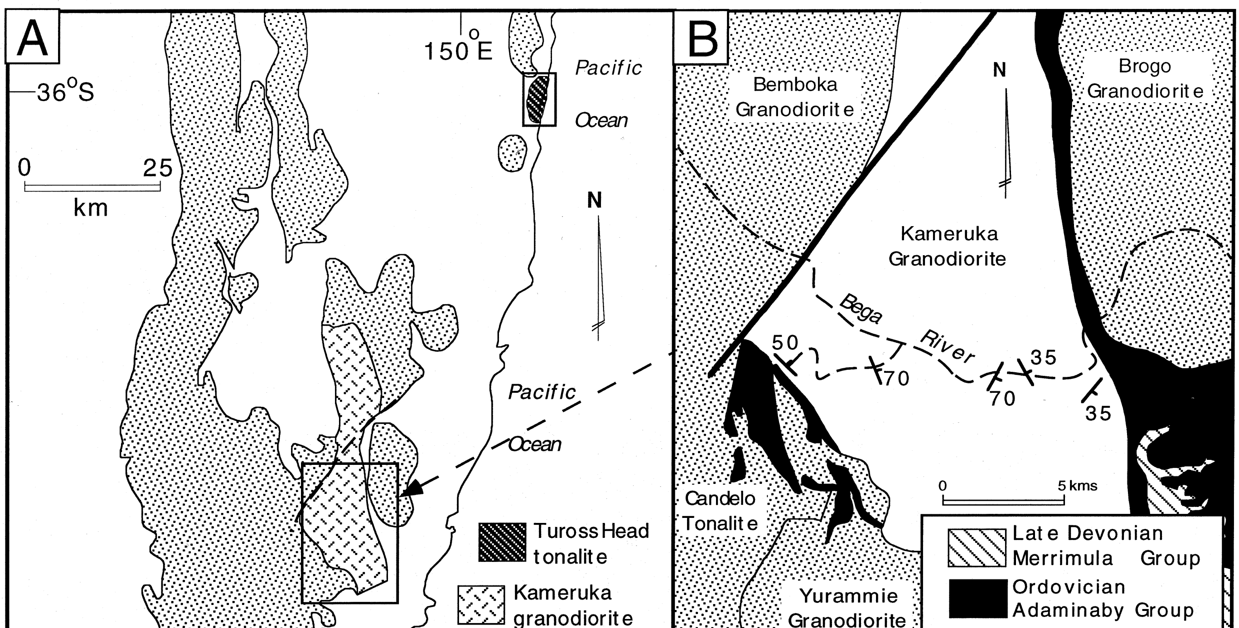

Fig. 5. (a) Locality map of the Tuross Head Tonalite and the Kameruka Granodiorite in the Bega batholith, southeastern Australia. (b) Geological map of a part of the Kameruka Granodiorite.

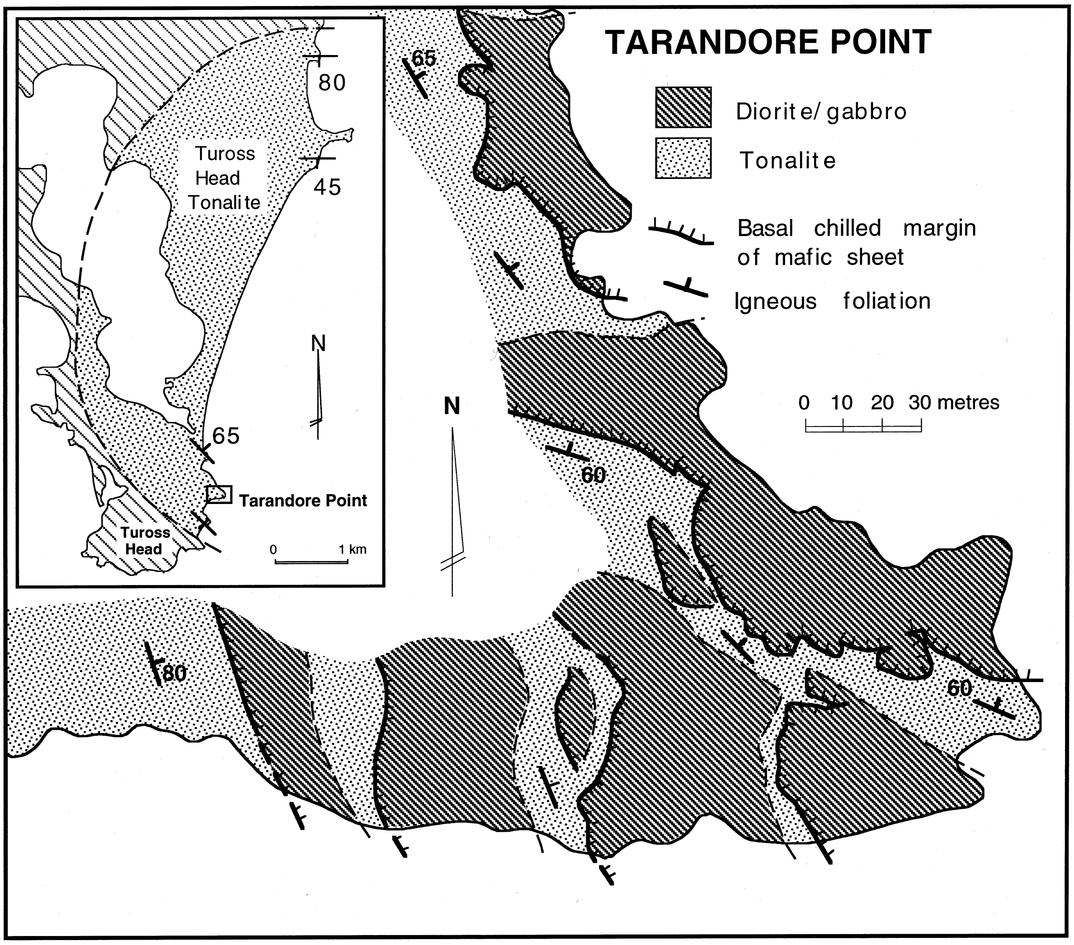

Fig. 6. Geological map of the Tuross Head Tonalite, southeastern New South Wales, Australia. For location, see Fig. 5.

(Fig. 7a & b). The inner contacts of layers typically show evidence of co-mingling and mixing with the overlying tonalite. These features indicate that the tops of all layers face towards the interior of the pluton, and they demonstrate that the steep structures in the Tuross Tonalite originally formed on a more gently dipping floor which subsequently sank inward. Structures in the pluton define a structural basin (Fig. 6).

Mafic to intermediate enclaves have textures, modes and mineralogy that are similar to those of the mafic sheets. They range from large globular and nearly equant bodies to highly elongate bodies (Fig. 7c). Where highly elongate, they contain very strongly aligned, tabular euhedral feldspar crystals, which led Vernon *et al.* (1988) to conclude that these enclaves must have deformed while they still retained melt. The most strongly elongate enclaves occur at several different levels within the tonalite and are not concentrated at the margin of the intrusion. Enclaves beneath the mafic sheets are typically large and subequant, indicating that the degree of elongation was not related to compaction caused by loading of the mafic layers. Rather, elongation must have been associated with flow, possibly during convection within the magma chamber.

Discussion. Mafic sheets represent replenishment of mafic magma into the Tuross magma chamber and mark various positions of the aggrading floor of that chamber. As the elongate enclaves and the feldspar foliation in the tonalite are parallel to and intercalated with the mafic sheets, they also define the position of the floor. The intercalation of mafic layers and tonalite strongly suggests that, even though layering is not apparent, the tonalite was also deposited gradually on the chamber floor between episodes of mafic input. This arrangement is similar to that in many mafic layered intrusions, where large portions of the cumulate section consist of massive, weakly laminated gabbro between subordinate, well-layered sections (Wager and Brown, 1967). The Tuross Tonalite probably has a stratigraphic record comparable to that seen in mafic layered intrusions, and the sequence of deposits should provide a time–stratigraphic record of processes in the magma chamber.

Systematic changes in the character of the enclaves above some thick mafic layers suggest a depositional record that reflects complex interactions between the mafic input and the overlying felsic magma (Clarke *et* *al*., 1987; Cruden *et al*., 1995; Snyder and Tait, 1996). Enclaves in the tonalite tend to become gradually smaller and more strongly elongate over several metres or tens of metres above some larger mafic layers. Fresh injections of hot dense mafic magma would probably promote convection in the overlying felsic magma. If convection were sufficiently vigourous, the top of the mafic layer could be disrupted into rapidly cooling magma 'globules' of varying size and carried upward within the overlying felsic magma. As convection waned and deposition occurred on top of the mafic layer, enclaves should decrease in size upward, and smaller enclaves which were immersed longer in the convecting magma might acquire more highly elongate shapes. The consistent alignment of the enclaves and feldspar foliation with the floor could simply reflect the fact that the last convective flow prior to deposition was parallel with the floor.

Stratigraphic changes in the tonalites also support these interactions. Tonalite beneath the lowermost mafic layer consists of relatively leucocratic biotite tonalite with euhedral plates of biotite, whereas tonalitic rocks stratigraphically above the mafic layers are more mafic with anhedral clots of biotite and hornblende. The more mafic character of the overlying tonalite was probably caused by mechanical mixing of small mafic clots (torn from the tops of underlying mafic layers) that remained suspended in the overlying felsic magma.

The Anglem Complex

The Anglem Complex is a Late Jurassic–Early Cretaceous intrusion with a calc-alkaline, subduction-related affinity which occurs within the Median Tectonic Zone in southernmost New Zealand (Kimbrough *et al*., 1994) (Fig. 8). The Paterson Group, which lies along its southern margin, contains silicic volcanic rocks of overlapping age and may be cogenetic (Kimbrough *et al.,* 1994). Deformation

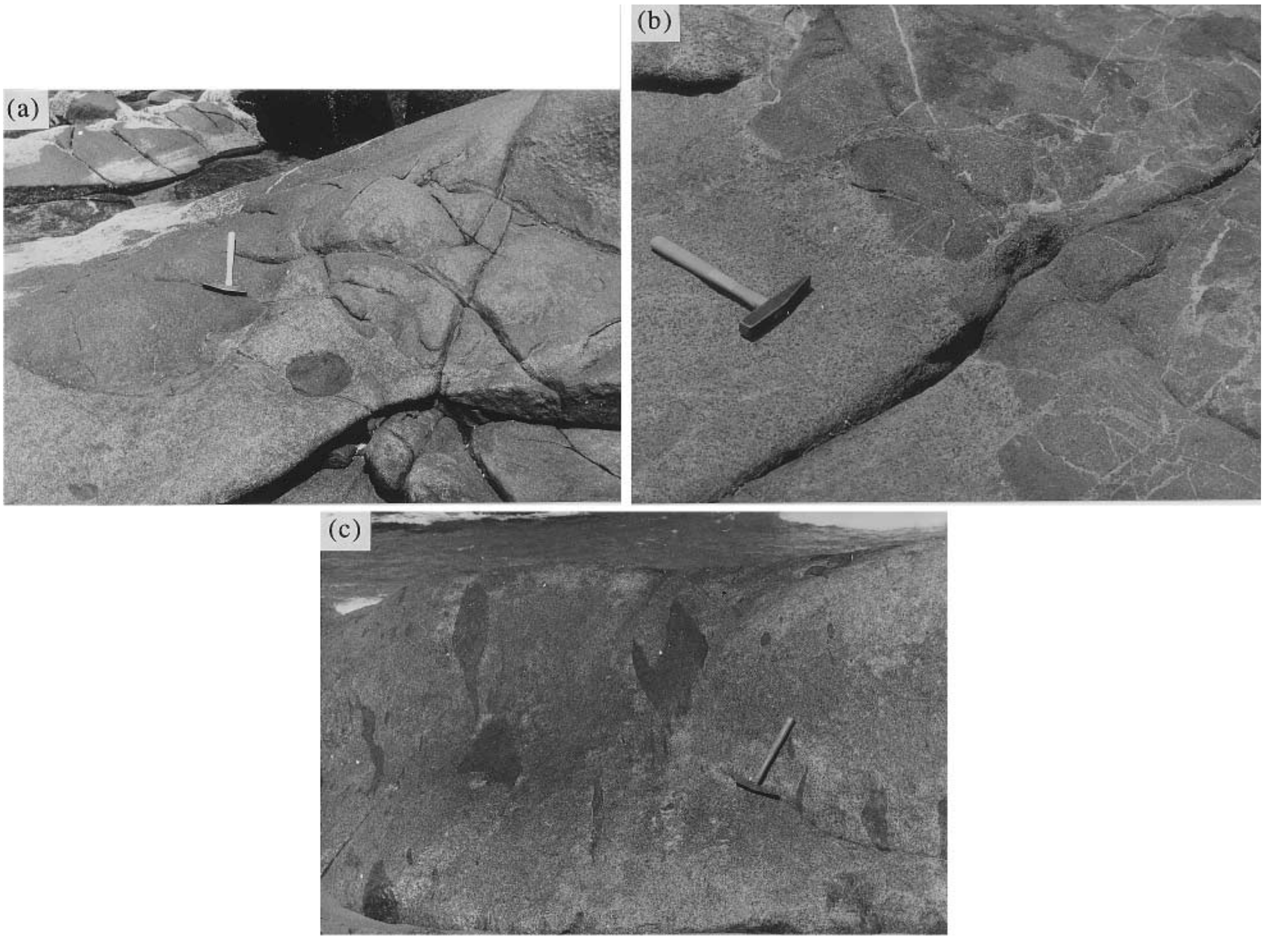

Fig. 7. Outcrop relations in the Tuross Head Tonalite. (a) The hammer rests on one of two large lobes at the base of chilled mafic layer in tonalite. (b) Dark rocks represent the chilled base of a gabbroic layer resting on diorite. Layer dips approximately 40° to the right. Light-coloured veins represent granitic material that was filter-pressed from the dioritic layer and injected upward into the overlying gabbroic layer. (c) Nearly vertically aligned mafic to intermediate enclaves in tonalite in outcrops south of Tarandore Point, closer to the contact (Fig. 6). Enclaves have strongly aligned, undeformed plagioclase (Vernon *et al*., 1988). Because this fabric is parallel to mafic layers which preserve evidence of deposition, these enclaves almost certainly were deposited on the floor of the chamber prior to being steepened. The 'fish-hook' enclave to the left of the hammer probably records compaction immediately after deposition (prior to steepening) (J. V. Smith, personal communication 1997).

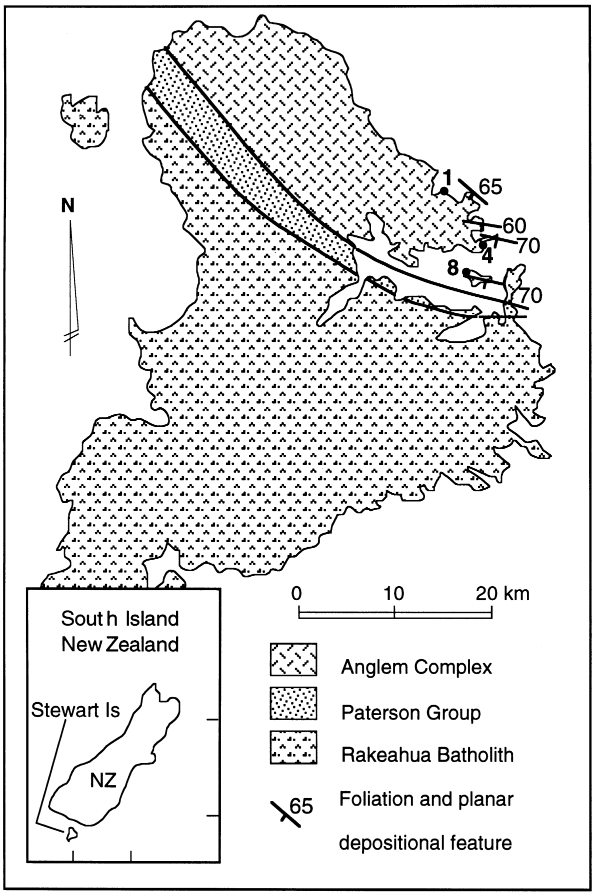

Fig. 8. Geological map of the Anglem Complex, Stewart Island, New Zealand.

increases toward the southern boundary of the Anglem complex into the Paterson Group, which is in fault contact with the Rakeahua batholith (Fig. 8). The felsic rocks in the Anglem Complex are dominated by tonalite with subordinate granodiorite and granite; mafic rocks, ranging from diorite to gabbro, are locally abundant as are extensive areas of co-mingled mafic and felsic rocks (Watters *et al.*, 1968; Watters, 1978; Cook, 1987, 1988). Petrographic descriptions and representative chemical compositions of hybrid rocks (Watters, 1978; Cook, 1988) indicate that these rocks are comparable to hybrid portions of the Tuross Tonalite.

Examination of a N–S section of the Anglem Complex (Fig. 8) shows a consistent S-dipping planar fabric (60–70°), variably defined by feldspar foliation, layers with subtle modal variation, scarce mafic sheets, elongate enclaves and lensoid swarms of enclaves. Most of this section consists of tonalitic rocks with enclave swarms and subordinate co-mingled mafic sheet-like bodies. Scarce alkali-feldspar megacrysts occur sporadically at many levels. In the southernmost 2 km the Anglem Complex displays a gradual southward transition from enclave-bearing tonalite through porphyritic granodiorite with alkali-feldspar megacrysts and fewer enclaves, to granite with more densely packed alkali-feldspar megacrysts and scarce small enclaves.

Several mafic sheets were observed between localities 1 and 8 (Fig. 8). In each of these sheets small-scale structures (strong chilling, convex downward lobes resembling load-casts, pipes and veins of granitic material) indicate that the northern margin is the depositional base of the layer (Fig. 9a & b). Abundant feldspar xenocrysts commonly occur in the southern (upper) portions of these mafic sheets. Their presence is consistent with mixing between the top of a layer of mafic magma and overlying liquid-rich tonalitic magma. All of the mafic layers appear to represent replenishments of mafic magma that were deposited at the interface between a crystal-rich floor and a crystal-poor liquid, and all indicate tops to the south.

Elongate enclaves and swarms of enclaves (Fig. 9c) have attitudes that are parallel to these sheets (Cook, 1988) and, hence, are parallel with the chamber floor. Enclaves that are highly elongate characteristically have well-aligned, thin, tabular crystals of undeformed, euhedral plagioclase, suggesting deformation in the magmatic state (Vernon *et al.*, 1988). Lensoid swarms of enclaves are common, and, where exposures are adequate, it appears that they have the shapes of channels that are elongate approximately down-dip.

Discussion. Because we were unable to find intrusive contacts between different varieties of the felsic plutonic rocks, it is possible that the entire 8 km section of the Anglem Complex was deposited on an aggrading magma chamber floor and represents a single southward-younging depositional system. This interpretation is strongly supported by the southward gradational transition from tonalite to granite and the occurrence, immediately above the granite, of a contemporaneous suite of rhyolitic volcanics. As in the Tuross Tonalite, deposition of the more mafic layers and elongate enclaves must have occurred on a more gently dipping floor.

The Kameruka Granodiorite

The Devonian Kameruka Granodiorite (Fig. 5) is a relatively large (570 km^2) I-type pluton in the Bega batholith (Chappell *et al.*, 1990; Chappell, 1996) with an estimated age of ~420 Ma (Williams, 1992). It consists mainly of coarse-grained biotite granodiorite with variable amounts of alkali-feldspar megacrysts, up to 5 cm in length. The intrusion was emplaced into the Ordovician Adaminaby Group and is cut by a large number of mafic dikes, which generally trend NNW-SSE and dip steeply (Lewis *et al.*, 1994; Lewis and Glen, 1995), as well as some felsic and composite dikes.

We are currently studying an E–W section centred on excellent exposures within the Bega River (Fig. 5b). The western contact of the Kameruka Granodiorite

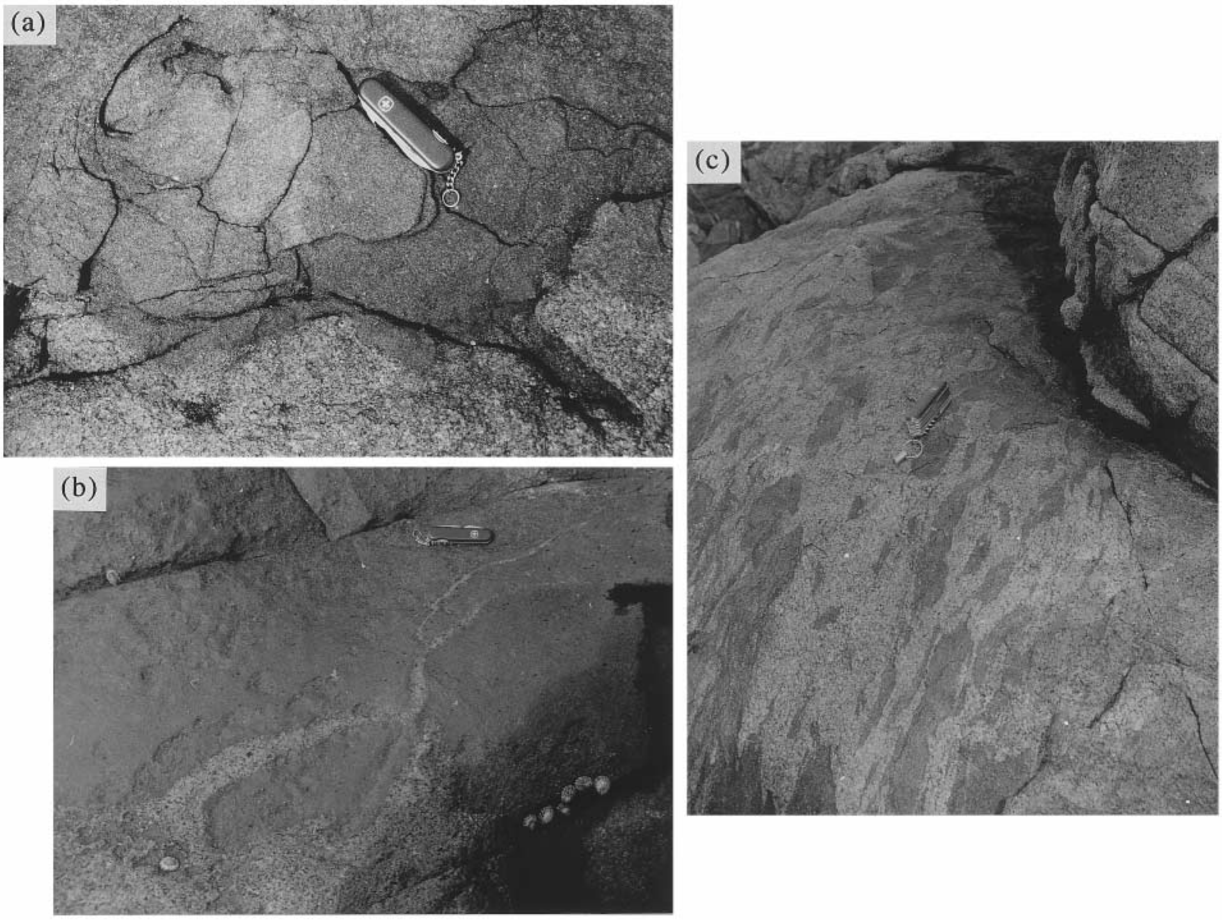

Fig. 9. Outcrop relations in the Anglem Complex. (a) Small load-cast structures along the chilled base of a gabbroic layer resting on tonalite. Layer dips about 70° towards the top of the photograph. (b) Lobate enclaves related to the chilled base of a gabbroic layer in tonalite. Small veins represent liquid that was filter-pressed from the tonalite and injected upward into the gabbroic layer. Layer dips about 70° towards the top of the photograph. (c) Highly elongate mafic to intermediate enclaves in tonalite. This foliation is parallel to mafic layers which preserve evidence of deposition.

dips moderately to steeply to the east subconcordant with highly deformed, migmatitic Ordovician metasediments and interlayered granitoid sheets of the Bemboka granodiorite. The eastern contact is steep and locally marked by sharp cross-cutting contacts of granodiorite with contact metamorphosed country rock, which is not migmatitic. Scarce angular blocks of country rock occur in the granodiorite near the contact. The internal structure of the intrusion consists mainly of locally developed feldspar foliation, lensoid swarms of mafic enclaves and scarce, large tabular bodies of diorite. These features occur sporadically throughout the studied section and consistently dip moderately to the east (Fig. 5b).

Enclave swarms and individual enclaves display a range of small-scale features suggesting that they were deposited on a loosely packed mixture of crystals and interstitial melt (i.e. the floor of a magma chamber). Larger, chilled mafic enclaves typically have slab-like or pillow-like shapes and are strongly molded around underlying feldspar megacrysts, which are commonly very tightly packed beneath these enclaves (Fig. 10a & b). In many swarms, individual enclaves are commonly molded around each other, leaving only a very small residual matrix of megacryst-rich granodiorite (Fig. 10c). All of these features suggest that compaction occurred immediately after deposition of the enclaves, while most of them were still soft (partly liquid). Where criteria for tops are present, swarms consistently indicate tops to the east.

Enclaves display abundant evidence of variable mixing. Double enclaves are common, and most enclaves contain some megacrysts identical in size and shape to crystals in the Kameruka Granodiorite (Fig. 10). Alkali-feldspar megacrysts in the enclaves are commonly rounded in shape and typically have very broad rims consisting of intergrown small, normally zoned, subhedral to euhedral plagioclase crystals with interstitial quartz. Adjacent enclaves have widely different proportions and sizes of megacrysts, suggesting that mixing occurred remotely, prior to deposition. These relations are consistent with observations of heterogeneous enclave swarms in other intrusions (see above).

The proportions and character of the feldspar megacrysts varied widely on the scale of the entire intrusion and, more locally, within large well-exposed stream outcrops. Near the western margin of the intrusion, alkali-feldspar megacrysts are generally homogeneous, evenly distributed and lack rims of sodic plagioclase. Further to the east, stratigraphically above some major swarms of mafic enclaves, alkali-feldspar megacrysts are generally more scarce and unevenly distributed; most show plagioclase rims of varying thickness identical to rapakivi megacrysts found within the enclaves. These relations strongly suggest that the common reaction rims on alkali-feldspar at higher structural levels in the Kameruka were caused by the input of higher temperature, mafic magma as preserved in enclave swarms. These relations suggest that mafic input only affected local volumes of the magma chamber and indicate that batches of magma with different crystallization histories did not mix completely.

Discussion. Because depositional features in the Kameruka Granodiorite occur throughout the studied section and provide a consistent sense of tops to the east, the western margin should be the base of the intrusion and the eastern margin the roof. This interpretation is consistent with the contrast in metamorphic grade of the contacts and with the eastward change in the character of the megacrysts. Therefore, this section of the Kameruka Granodiorite appears to have been deposited on the floor of a chamber and provides a stratigraphic record of events (e.g. crystallization, replenishment of mafic and felsic magmas, and mixing) in a granodioritic magma chamber.

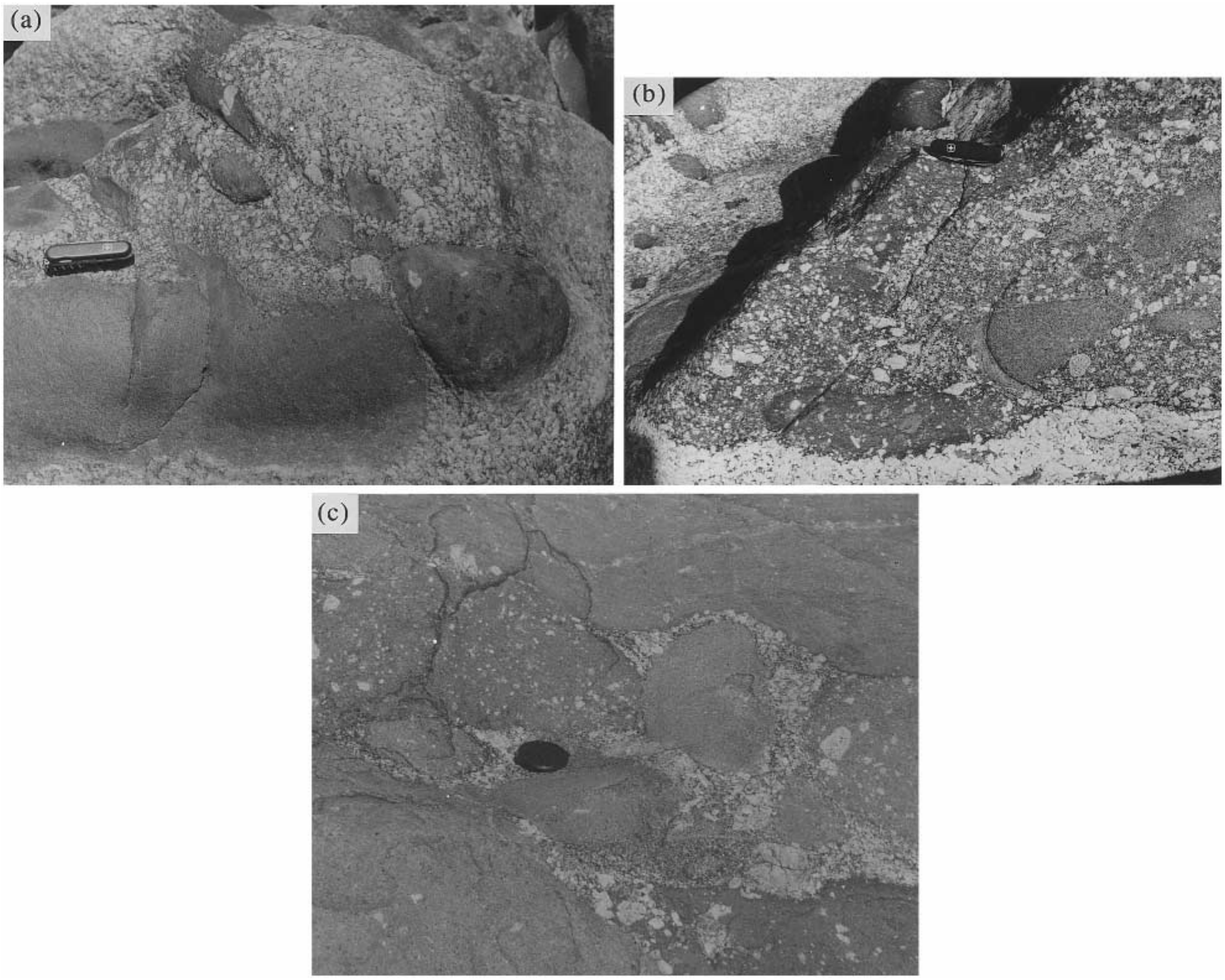

Fig. 10. Outcrop relations in the Kameruka Granodiorite. (a) Base of a sheet of mafic enclaves closely associated with concentrations of feldspar megacrysts. The large sheet-like enclave at the base appears to have caused intense compaction of the underlying granitic crystal mush. It also appears to have been deformed and offset along ductile fractures as compaction occurred. (b) Base of a hybrid sheet consisting of heterogeneous enclaves and double enclaves showing variable degrees of mixing with the granite. The base of this sheet is sharp and molded around individual feldspar crystals in the underlying granite. Hybridization occurred remote from the site of deposition and probably formed in a single event as mafic magma entered the chamber. (c) Tightly packed heterogeneous enclaves within a large sheet-like enclave swarm. Origin is comparable to (b), but the degree of hybridization is less and individual enclaves more clearly defined.

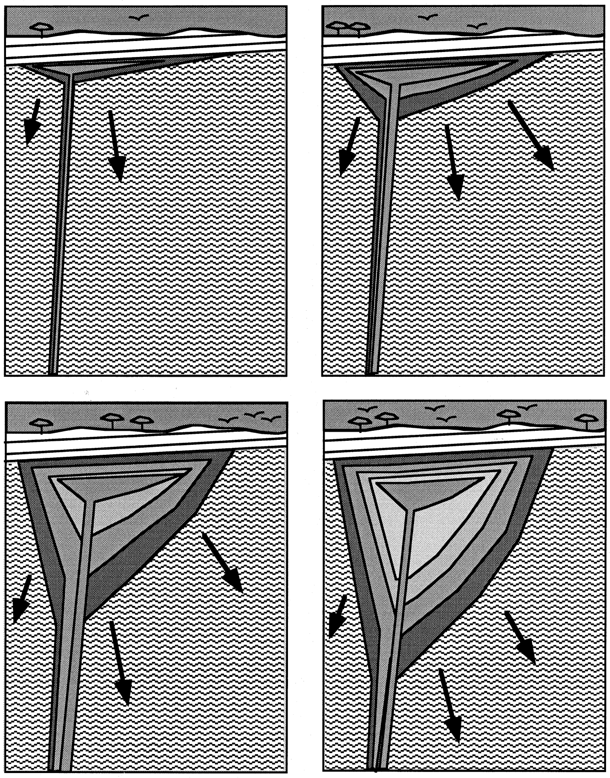

Fig. 11. Schematic diagrams showing development of a granitic pluton by gradual replenishment, crystallization, and sinking of the floor and basal cumulates.

MAGMA CHAMBER FLOORS IN GRANITIC PLUTONS

We have found widespread evidence for magma chamber floors, and thick deposits of magmatic rock (cumulates) on those floors in two plutons of the Bega batholith and in the Anglem Complex; our reconnaissance fieldwork suggests such relations are common in other Bega plutons. The features which we believe demonstrate the existence of magma chamber floors appear to resemble closely features common in many granitic plutons. Previous workers have generally assumed that these features formed during the *emplacement* of crystal-rich (and sometimes, inclusion-rich) magma (e.g. Vernon *et al.*, 1988; Castro *et al.*, 1995; McNulty *et al.*, 1996; Tobisch *et al.*, 1997). As an alternative, we suggest that many of these occurrences may have formed instead by deposition on a chamber floor and subsequent rotation downward. The long-standing perception by most geologists that floors are rarely preserved in granites may be related to the tendency of these floors to sink downward along with the underlying country rock, acquiring attitudes that are much steeper than that of the original deposition.

We think it is also possible that other evidence for magma chamber floors in granites has been misinterpreted. Although many exposures of granitic plutons are essentially massive and apparently lack structures that could define the floor, it is possible that 'suspended' stoped blocks of country rocks may mark the position of an aggrading floor. Blocks of country rock that appear to preserve 'ghost stratigraphy' (Pitcher, 1970, 1993) may actually have been stoped from the roof and settled on to the floor of a thin tabular magma chamber as stoping migrated upward through an overlying section of country rocks. Alternatively, the 'ghost stratigraphy' might reflect sheeted intrusion. Careful observation of the internal features of the pluton are necessary to distinguish between these two possibilities.

Fowler and Paterson (1997) described large stoped blocks which apparently fell about 360 m from the roof of the chamber and now are suspended in homogenous granite well above the inferred base of the intrusion. Because these blocks appear to have had little effect on the fabric in the enclosing granite, Fowler and Paterson (1997) suggest that, when stoping occurred, the magma was largely liquid and that the blocks were trapped by gradually crystallizing magma as they settled through the chamber. It seems highly unlikely that the magma could have crystallized sufficiently in the time it took for these large blocks to fall 360 m. The same relations could, however, be easily explained if the stoped blocks sank through the liquid-rich interior of the chamber and came to rest on the crystal-rich floor.

Steep primary magmatic structures in granitic and hybrid rocks (e.g. mafic sheets, elongate enclaves) have typically been interpreted as a record of subvertical flow of partly crystallized granitic and mafic magmas in conduits or in magma chambers. In an earlier study of the Tuross Head Tonalite, Vernon *et al.* (1988) emphasized the role of mixing in a conduit to explain the steep alignment of elongate enclaves. However, during our recent field work together, Vernon agreed that the small-scale structures associated with the mafic bodies in the tonalite yielded a consistent sense of tops, and that the mafic layers and parallel zones of elongate enclaves were most probably deposited on a gently dipping floor and subsequently steepened. It seems possible that other bodies with comparable steep structures may record steepened depositional sections. For example, Castro *et al.* (1995) described a sheet-like, steeply layered hybrid complex in terms of conduit flow. Their detailed illustrations of outcrop relations show mafic layers which are chilled only on one side and which have many features (pipes, granitic veins, load-cast structures) characteristic of mafic layers deposited on cumulate floors. Sabine (1992) described subhorizontal felsic pipes in steeply layered mafic–felsic rocks of the Crystal Range suite (Sierra Nevada batholith, California). In some basin-form mafic–silicic layered intrusions, felsic pipes are roughly perpendicular to layers even where layers dip as steeply as 70° (Wiebe, 1993b, 1994). The presence of these small-scale features suggests that these steep layered sequences were originally deposited on a gently dipping magma chamber floor.

We think that all three of the plutonic complexes described here were initiated by crystal-poor magma on gently dipping floors which steepened during deposition on the floor. We suggest that foliations in these plutons (defined by highly elongate enclaves and feldspar crystals) initially developed during convection within the chamber and were preserved by increasing crystallization and deposition with the last waning movement parallel to the chamber floor. This model is consistent with recent studies which have suggested that crystal-poor granitic magma was transported from its source in dikes and emplaced in the middle and upper crust, along roughly horizontal discontinuities, producing tabular magma chambers (Clemens and Mawer, 1992; Petford *et al*., 1993). Voluminous mid-crustal sheeted intrusions identified in the Arunta Inlier, central Australia (Collins and Sawyer, 1996) provide excellent examples of such bodies. However, many plutons are at least several kilometres thick and may tend to increase in thickness proportionally to the length (McCaffery and Petford, 1997). To provide space for relatively thick plutons, there is a growing appreciation that country rock must be transported downwards in the region now occupied by the pluton (Paterson *et al*., 1996; Cruden, 1997, 1998).

If magma chambers are fed gradually with new magma, downward movement of country rock can also occur gradually, and realistic crustal strain rates for the growth of the pluton can be achieved (Cruden, 1998) (Fig. 11). Any cumulate material existing at the base of the magma chamber probably behaves as part of the country rock, sinking downward beneath a gradually replenished magma chamber. While this tendency to sink would be enhanced by the presence of hybrid and mafic cumulates (e.g. Glazner, 1994), even without this mafic component the basal cumulates would normally be more dense than the overlying magma.

Our interpretation of these plutons implies that most of the granitic material we observed is cumulate in origin. We have begun studies to test this hypothesis in the Tuross Tonalite and the Kameruka Granodiorite (Wiebe and Collins, in preparation). Using the compositions of closely associated fine-grained granitic dikes as liquids and mineral composition data from the granites, our initial mixing calculations for both plutons suggest that the most mafic (lowest SiO_2) representative granitic rocks (excluding material that represents mafic replenishments) consist of mixtures of about 30% early forming crystals and 70% liquid. The relatively linear trends of these suites on Harker diagrams may reflect crystal accumulation rather than restite separation as proposed by Chappell (1996). Cumulates with such a high percentage of trapped liquid may not show clearly the expected touching framework of cumulus minerals characteristic of cumulates in mafic layered intrusions (see Irvine, 1982).

The suggestion that the floors of granitic plutons commonly sink downward as deposition occurs is compatible with upward movement of the pluton roof. This apparent contradiction can be resolved if magma chambers are filled and crystallize gradually. Whether the roof of the chamber remains at the same level or rises upward would depend upon the rates of magma replenishment, crystallization and downward movement of the country rock (Cruden, 1998). A recent study of the Bergell pluton (Switzerland) draws attention to very different contemporaneous behaviour of the lower and upper portions of a granitic pluton (Rosenberg *et al*., 1995). Their structural analysis suggests that the floor of the Bergell intrusion was folded during syn-magmatic shortening while the upper part of the pluton was undergoing 'ballooning'. Although they relate the deformation to a regional tectonic event, it seems possible that the syn-magmatic shortening of the floor may have resulted simply from downward movement of the pluton floor while further replenishments inflated the roof.

We do not suggest that all granitic plutons crystallize only, or even mostly, by accumulation on the floor. We expect that most plutons also crystallize inwards from the walls and roof of a magma chamber in varying amounts. For example, the bulk of the Cadillac Mountain granite appears to have crystallized from the roof and walls; very little granite could accumulate on the floor because of numerous mafic replenishments (Wiebe, 1994). Well-developed domal foliations defined by feldspar alignment have been described for many plutons (e.g. Davis, 1963; Courrioux, 1987) and appear to have formed in the upper part of the plutons. Accumulation on the chamber roof and the development of these foliations in the upper part of the intrusion could develop contemporaneously with floor cumulates like those described in this paper. Where replenishments of granitic magma occur faster than the floor of the chamber can sink, the roof and roof 'cumulates' could be bowed upward (Cruden, 1998). What one observes, then, in a given pluton would depend upon the level of erosion through the chamber and the relative balances between magma replenishment, crystallization and deformation.

CONCLUSIONS

The granitic plutons we studied contain small-scale features demonstrating that large portions were deposited on an aggrading floor of a magma chamber. We suggest that these floors and the basal cumulate material on them sank downward, during growth of the pluton, in response to continued replenishments of the magma chamber and downward movement of underlying country rock. The resulting steep orientation of these structures may be a major reason why most geologists have not recognized them as magma chamber floors. We believe that some comparable steep foliations, zones of elongate enclaves and mafic sheets found in many granitic plutons may need to be re-evaluated with this model in mind.

Stratigraphic relations, preserved in depositional sequences, suggest that the plutons we studied formed from many separate pulses of crystal-poor granitic magmas with lesser input of more mafic magmas. As long as an active liquid-rich chamber existed, felsic replenishments probably mixed with resident magma, while denser, more mafic and generally hotter replenishments tended either to pond on the floor as sheet-like masses or break up on entry and leave swarms of enclaves. If replenishments were all felsic and occurred sufficiently rapidly so that they continued to mix into a long-lasting chamber, the resulting pluton may appear to be quite homogeneous and massive. If earlier pulses were largely solidified before later ones, plutons could be built up gradually by separate sheet-like masses (Brown *et al.*, 1981; Fowler, 1994; Scaillet *et al.*, 1995). The size of the active magma chamber at any one time may much smaller than the final size of the pluton, and the inflation rate of the magma chamber may be largely controlled by the rate of melt segregation from the source.

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