Magma flow within the Tavares pluton, northeastern Brazil: Compositional and thermal convection

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ABSTRACT

Crystallization coupled with gravity removal of depleted interstitial melt has long been recognized as a mechanism of magma differentiation. Similarly, heat released by synplutonic basaltic magma intrusions has long been recognized as capable of driving convection in granite chambers. Direct evidence of these processes has seldom been described in granites. In the Tavares pluton, we mapped a number of melt extraction structures from pores of a crystal-liquid mush (an effectively solid magma where crystals form an interconnected skeleton) and a variety of flow structures such as (1) meter-scale tear- or mushroom-shaped blobs representing within-chamber diapirs; (2) meter-scale ellipsoids representing frozen thermal plumes of granite, driven by heat released from disrupted diorite intrusions; and (3) ladder dikes and snail structures representing cross sections of several superposed cylindrical magma channels (possibly feeders of diapirs and plume heads). A fundamental feature of the structures in the Tavares pluton is that they are well delineated by mafic schlieren developed at active channel margins. We postulate a new model for the origin of marginal schlieren, which combines shear flow sorting and melt escape from the flowing magma into an effectively solid surrounding mush. Extraction structures (representing melt extraction from mush pores into melt pockets) and schlieren (representing regions where melt escaped into surrounding mush pores) are both favored by magmas that form an interconnected solid framework at low crystal fractions (~50%), because these mushes are ductile and permeable. Favorable magmas are those with a high wetting angle between melt and solid (~60°) and a propitious crystal size and shape distribution. We propose a model of compositional and thermal convection that accounts for all described structures.

Keywords: fluid dynamics, granite, magma chambers, magmatic, structures.

INTRODUCTION

The flow of magma within granite magma chambers is fundamental for understanding pluton emplacement, growth, and magma differentiation. For this reason, magma flow patterns and processes have been the center of considerable scientific interest. Chamber flow is controlled partly by magma inflow or outflow and contemporaneous tectonic deformation (e.g., Hutton, 1988; Ramsay, 1989; Weinberg, 1997; Archanjo et al., 1998), and partly by factors related to the pluton's internal dynamics, such as magma convection, crystallization, and differentiation (e.g., Martin et al., 1987; Weinberg, 1992; Jaupart and Tait, 1995). Structures defined by crystal alignment, xenoliths, schlieren, and synmagmatic enclaves (e.g., Cloos, 1936; Barrière, 1981; Abbott, 1989; Tobisch et al., 1997; Clarke and Clarke, 1998), as well as cryptic foliation defined by the anisotropy of magnetic susceptibility (e.g., Bouchez and Diot, 1990; Archanjo et al., 1998; Cruden et al., 1999), have all been used to define and understand magma flow and ultimately magma emplacement processes and dynamics.

Despite these efforts, mapping of magmatic flow has been hampered partly by the limitations of each of these flow markers, and partly by the masking of early-formed structures by late flow (e.g., Benn, 1994). As a result, evidence for several processes inferred to occur in granite plutons, such as chamber growth by addition of small magma pulses (Deniel et al., 1987), or thermal convection (e.g., Huppert and Sparks, 1988), commonly remain unseen. Similarly, extraction of light, depleted melt from the interstices of a solidifying magma has long been recognized as an important mechanism of magma differentiation (e.g., McCarthy and Groves, 1979), but structures indicative of this process have seldom been described in granites.

In the Tavares pluton in northeastern Brazil (Fig. 1), exceptionally well-exposed structures provide a wealth of information regarding magma flow, allowing us to infer the origin of structures seldom described but nevertheless fundamental to our understanding of magma chamber dynamics. In this paper we describe structures related to melt extraction from pores and magma flow structures developed during magma crystallization. We start by briefly describing the pluton and its regional setting. We then describe structures related to melt extraction from mush pores, followed by magma flow structures (mush is an effectively solid magma where crystals form an interconnected skeleton). We propose a model for the origin of the ubiquitous marginal schlieren and one for the development of all described

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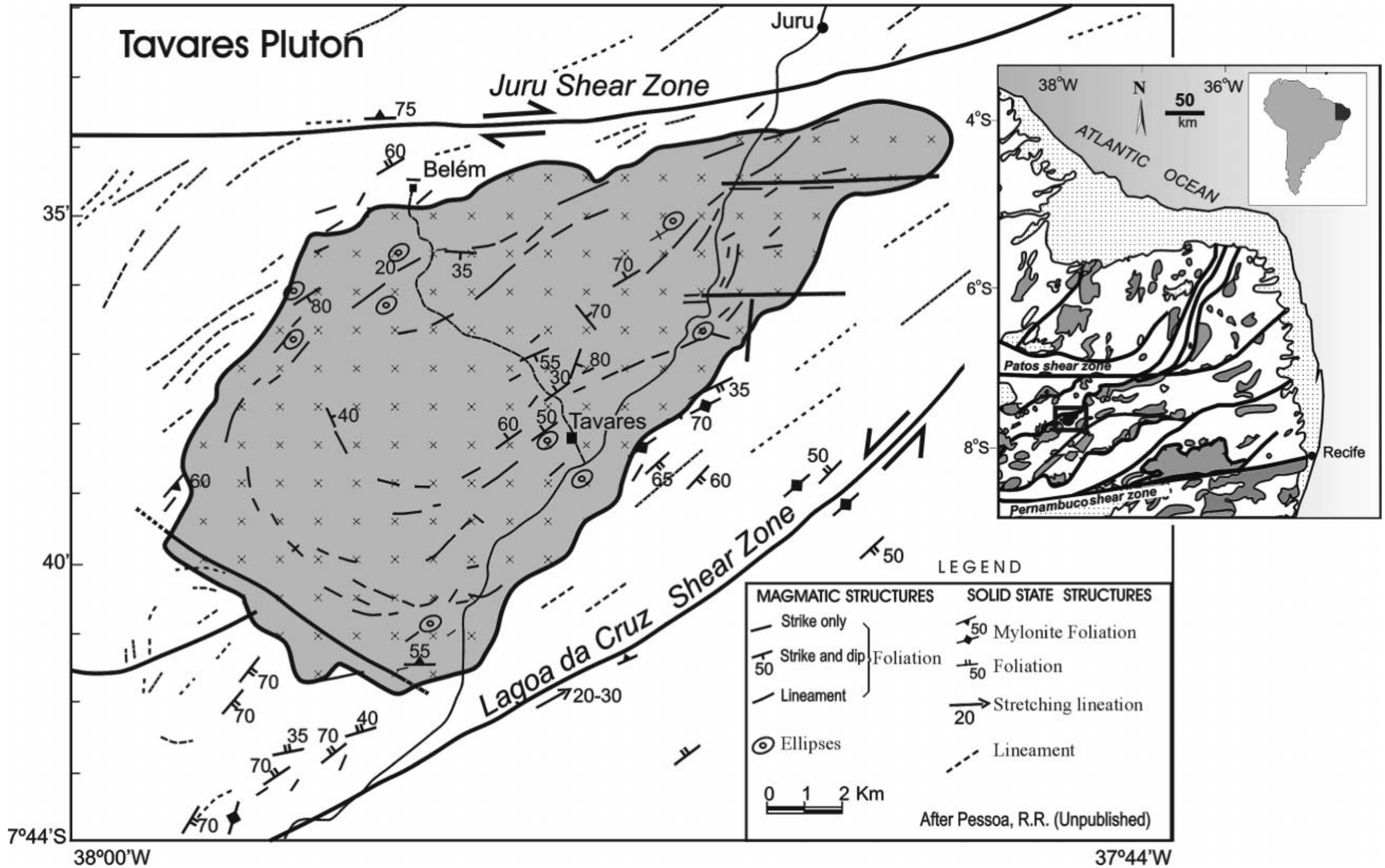

Figure 1. Geological map of the Tavares pluton. No major internal boundary was found. The ellipses mark outcrops where ellipsoids were found (from R.R. Pessoa's doctoral thesis, in preparation). Inset shows the position of the Tavares pluton (box) in the map of Brasiliano granitic bodies (in gray) and shear zones of the Borborema Province.

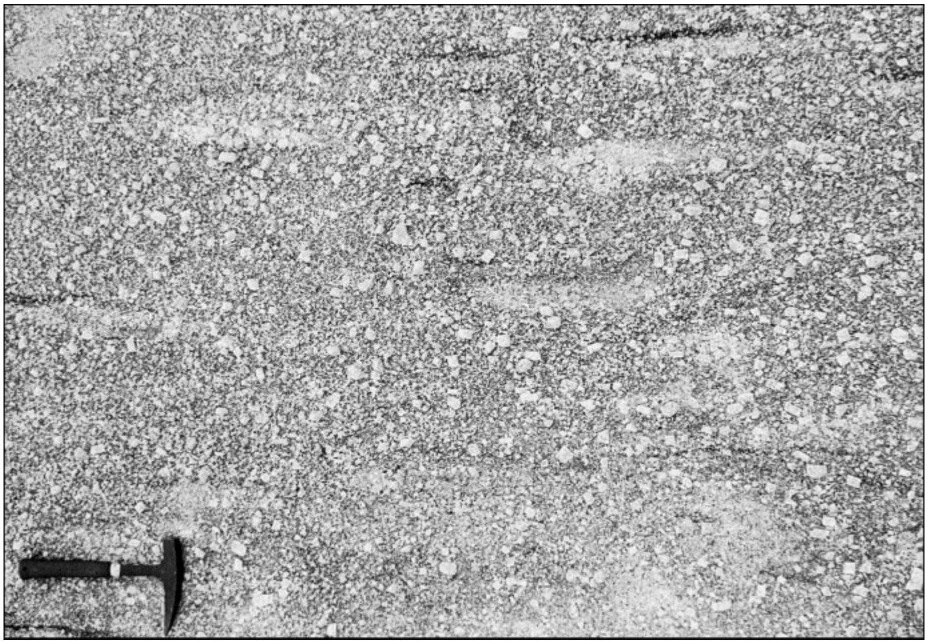

Figure 2. Typical streaky appearance of the Tavares granite, defined by mafic schlieren and concentrations of K-feldspar megacrysts.

structures in terms of compositional and thermal convection.

TAVARES PLUTON

The Tavares pluton was emplaced syntectonically during the Brasiliano orogen, which took place between 650 and 550 Ma (Sial et al., 1999). The pluton is part of a group of contemporaneous high-K calc-alkaline bodies that crop out in the Alto Pajeú terrane of the Borborema Province (Almeida et al., 1981), northeastern Brazil (e.g., Ferrreira et al., 1998; Sial et al., 1999). Many of the structures described here were also found in other plutons of this group, but are generally less well developed. The pluton is 200 km^2 in area and is elongated parallel to the N60E regional foliation. It is bounded on the east by the left-lateral N60E striking Lagoa da Cruz shear zone and in the north by the dextral, east-striking Jurú shear zone. The pluton intrudes mainly orthogneisses (including mylonites) and related migmatites, as well as schists, quartzites, marble, and cherts of the Alto Pajeú terrane (Fig. 1).

This pluton is composed of mainly high-K calc-alkaline granite-granodiorite with heterogeneously distributed K-feldspar megacrysts (in general 15%–25% modally) and accessory epidote, sphene, allanite, zircon, and only traces of opaque minerals. Due to heterogeneous megacryst distribution, rock classification varies between granodiorite and granite (referred to hereafter as granite, sensu lato). A typical outcrop is characterized by 0.5–1.0-m-long, mafic-rich and felsic-rich bands parallel to the regional foliation (Fig. 2), with a few curved, semicircular schlieren and occasional mafic enclaves. The pluton is intruded by synmagmatic diorite sheets and blobs, disrupted to varying extents giving rise to enclave swarms and widespread microdioritic mafic enclaves. Pillow-shaped enclaves with narrow darker rims and K-feldspar megacryst inclusions, as well as the preserved stages of disaggregation of the mafic intrusions, attest to contemporaneity between mafic and felsic magmas. Despite outcrop heterogeneity, rock composition varies little across the pluton.

Pluton elongation and granite foliation are preferentially parallel to the regional fabric. Except for an ~100-m-wide band near the pluton's margins, granites are free from penetrative postmagmatic deformation (no visible crystal deformation in thin sections), suggesting that the dominant foliation developed while the magma was still partially molten. This flow foliation is a result of external tectonic deformation contemporaneous with magma emplacement and cooling, and it lightly overprints the many magmatic structures, such as the ellipsoids, described in the following. Close to the margins, and generally parallel to them, foliation resulting from solid-state deformation becomes increasingly more important, with quartz developing subgrains and new grains, and microcline developing flame perthites.

MAGMATIC STRUCTURES

Leucogranite Pockets

Leucogranite pockets were found in a granite outcrop partly quarried for gravel (outcrop 51, near the town of Tavares, in Fig. 1). Here, dikes of a variety of granitic composition and textures crosscut one another, and irregular sheets and decimetric pockets of leucogranite aplite cut a typical megacrystic granodiorite. Granitic dikes show a variety of complex internal structures of uncertain origin. Here, we are mainly concerned with structures in leucogranites (Fig. 3). Leucogranite pockets have irregular shapes, and at grain scale they form irregular branches that grade into the felsic interstitial material in the granodiorite (Fig. 3A). Some pockets have horizontal layers of mafic minerals concentrated in their lower half (Fig. 3A). Others have narrow (0.5–2 cm) mafic layers (melanosomes) surrounding their lower half (Fig. 3B). Irregular sheets are randomly oriented, narrow, planar, or tortuous layers of mafic-rich granodiorite (melanosomes) of varying width (1–10 cm), containing narrow pockets of leucogranite (Fig. 3, C and D). Locally, sheets give rise to an interconnected network, with leucogranite blobs at intersections (Fig. 3D). Irregular aplitic dikes without melanosome margins, and melanosome layers without internal leucosome lenses are also common. In thin section, mafic-rich layers are rich in the mafic minerals typical of the surrounding granodiorite (hornblende + biotite + epidote + sphene).

Many of the granitic dikes in this outcrop are more evolved than the surrounding granodiorite, and have tortuous margins and complex crosscutting relationships (e.g., dike a cuts b, and b branches into a smaller tortuous dike that cuts a). Another leucogranite dike is linked to an irregular pocket of leucogranite that branches into numerous fingers that disappear into the granodiorite; others have sharp, wedge-like endings in outcrop view. Structures in this outcrop are interpreted as representing extraction of interstitial melt from a mush.

Schlieren and Magma Flow

Magmatic structures in the Tavares pluton are generally defined or delineated by mafic schlieren. These are commonly curved, either individually or in groups. Irregular structures, where schlieren bifurcate, crosscut one another, or are joined in a variety of composite shapes, are common (e.g., Wilshire, 1969; Barrière, 1981), but are not included in this paper because they most likely result from a complex history of magma flow. Here, we are concerned with regular, geometrical structures, which are likely to result from a single process. We first describe typical magma blobs and the schlieren that delineate them, and meter-scale ellipsoidal structures. We then describe schlieren defining snail structures and ladder dikes (the arcuate schlieren of Cloos, 1936) followed by a description of ubiquitous K-feldspar megacryst aggregates.

Common features of the Tavares pluton are schlieren-rimmed magma blobs, typically several in a single outcrop. These blobs are most commonly composed of granite of a slightly different color or fabric than that of the surrounding granite. Occasionally these blobs may be rich in mafic enclaves and mafic schlieren, and may have irregular margins or define mushroom or teardrop shapes with heads from 50 cm to several meters in diameter (Figs. 4 and 5A. Mafic schlieren marking the edges of magma batches are characterized by a sharp external boundary, where mafic minerals are concentrated, that grades inward to the typical granite (Fig. 5A). Marginal schlieren often occur in groups with crosscutting relationships spread over a zone to 50 cm wide (Fig. 5B). These relationships indicate that the effective margin of the flowing blob shifted with time.

Ellipsoids

Magmatic foliation and schlieren define meter-scale two-dimensional ellipses (Fig. 6) apparently randomly distributed throughout the pluton (Fig. 1). These ellipses are often accompanied by more irregular groups of curved schlieren similar to those previously described in the Ploumanac'h pluton by Barrière (1977, 1981). In subhorizontal exposures the ellipses are most commonly concentric (Fig. 6A), but they may be spiraling outward, or have two nuclei or cores, surrounded by a common external ring foliation. Crystals are generally parallel to the concentric elliptical foliation, but tend to transpose it and become parallel to the dominant regional foliation, where this is at a high angle to ellipsoid foliation. We found five ellipses exposed on nearly vertical surfaces close to horizontal exposures, showing that their vertical and horizontal dimensions are similar. Ellipsoid 17 (Fig. 7) is exposed on two vertical surfaces at right angles, and shows complex refolding patterns of schlieren. These observations are indicative of the three-dimensional nature of the structures (ellipsoids). Many ellipsoids have K-feldspar aggregates in their center (~20% of observed ellipsoids), and in some cases the aggregates occur as bands on the external parts of the ellipsoids.

We mapped the distribution of ellipsoids in part of a particularly well-exposed outcrop (Fig. 7). The ellipses range in size from <1 m to a maximum of 6 m in the longest direction, with typical aspect ratios of ~2 and longest axis within 20° of the dominant flow foliation (N65E). Because of their three-dimensional nature, their size distribution in two dimensions is unimportant. The granite between the ellipses in Figure 7 is characterized by a well-defined flow foliation, and where small ellipses (<1 m), curved individual schlieren, or groups of schlieren are common.

Snail Structure and Ladder Dikes

Isolated decimetric ring schlieren are common throughout the pluton. Several of them may occur together, defining a meter-scale structure that we call snail structure due to its two- dimensional shape (Fig. 8A). These are orderly arranged rings, with diameters increasing outward (ring schlieren; see Fig. 20 in Cloos, 1936), commonly cropping out in subhorizontal surfaces at a high angle to prevailing subvertical foliation. The more internal rings are younger and may be entirely inside, outside, or crosscutting earlier, larger rings (Fig. 8A).

Granite dikes and irregular sheets in the Tavares pluton commonly show complex internal structures with complex banding, schlieren, and K-feldspar megacryst aggregates. Ladder dikes are a particular form of these complex dikes formed by nested crescent-shaped dark and light layers (Reid et al., 1993). They are narrow, sinuous, magma channels with irregular walls. There is a range of varieties of ladder dikes in the Tavares pluton, from fully developed ones with gradation between mafic and felsic layers (Fig. 8, B and C) similar to those described in the Sierra Nevada (Reid et al., 1993), to simplified versions formed by stacked mafic schlieren (Fig. 9; see also Trent, 1995). Like their Sierran counterparts, fine-grained mafic layers grade into coarser light layers. The margins of ladder dikes are irregular and cusped, and the dike is sinuous, although its width remains roughly constant over tens of meters. The cusps have the same curvature as the arcuate schlieren inside the dike. The two sections across a ladder dike in Figure 9 depict its three-dimensional geometry. In the vertical face, lower schlieren are crosscut by those higher up, indicating upward younging. At the far end of the outcrop, the youngest layer merges with the surrounding granite. These features indicate that the ladder dike is a series of stacked channel bottoms (or side walls) with magma flowing parallel to the schlieren planes (Fig. 9B).

K-feldspar Megacryst Aggregates

Aggregates of zoned K-feldspar megacrysts, in granitic or aplitic matrix, are common throughout the pluton. They occur (1) as 10–20-cm-wide layers in the granite, (2) as irregular or rounded masses, from 10 cm to several meters in diameter, (3) inside or around mafic enclaves, or (4) within ladder dikes. Aggregates inside or around mafic enclaves are ubiquitous and form rims up to 20 cm wide. The cuspate margin of the enclaves against megacrysts indicates that the enclaves were less competent than the megacrysts. We also found a 2-m-wide round mass of megacrysts with mafic schlieren, associated with a sinuous enclave swarm (disrupted dike). Occasionally, we found meter-scale isolated masses within the granite, or several isolated patches defining a linear trend. In ladder dikes, K-feldspar aggregates form either curved layers, parallel to mafic schlieren, or bands up to 50 cm wide, close to the narrowest parts of the dikes (logjams in dike necks; see following).

ORIGIN OF STRUCTURES

In this section we discuss the origin of the structures we have described and propose a model for the origin of schlieren. We suggest that the structures described and observed separately could be linked and are a result of gravity instability.

K-feldspar Aggregates: Logjams and Filters

K-feldspar megacryst aggregates occur in a variety of structures, most of which we are unable to interpret. However, in two cases there is evidence to suggest that they result from flow necking and logjamming. In ladder dikes, aggregates occur on the younger, or upstream, side of dike necks, as inferred from crosscutting relationships in the dike. We interpret this as indicating that there was a flow component parallel to schlieren curvature, as inferred herein, and that flow necking led to a megacryst logjam, which grows by the filtering out of megacrysts upstream (Clarke and Clarke, 1998).

Megacrysts may also form logjams and act

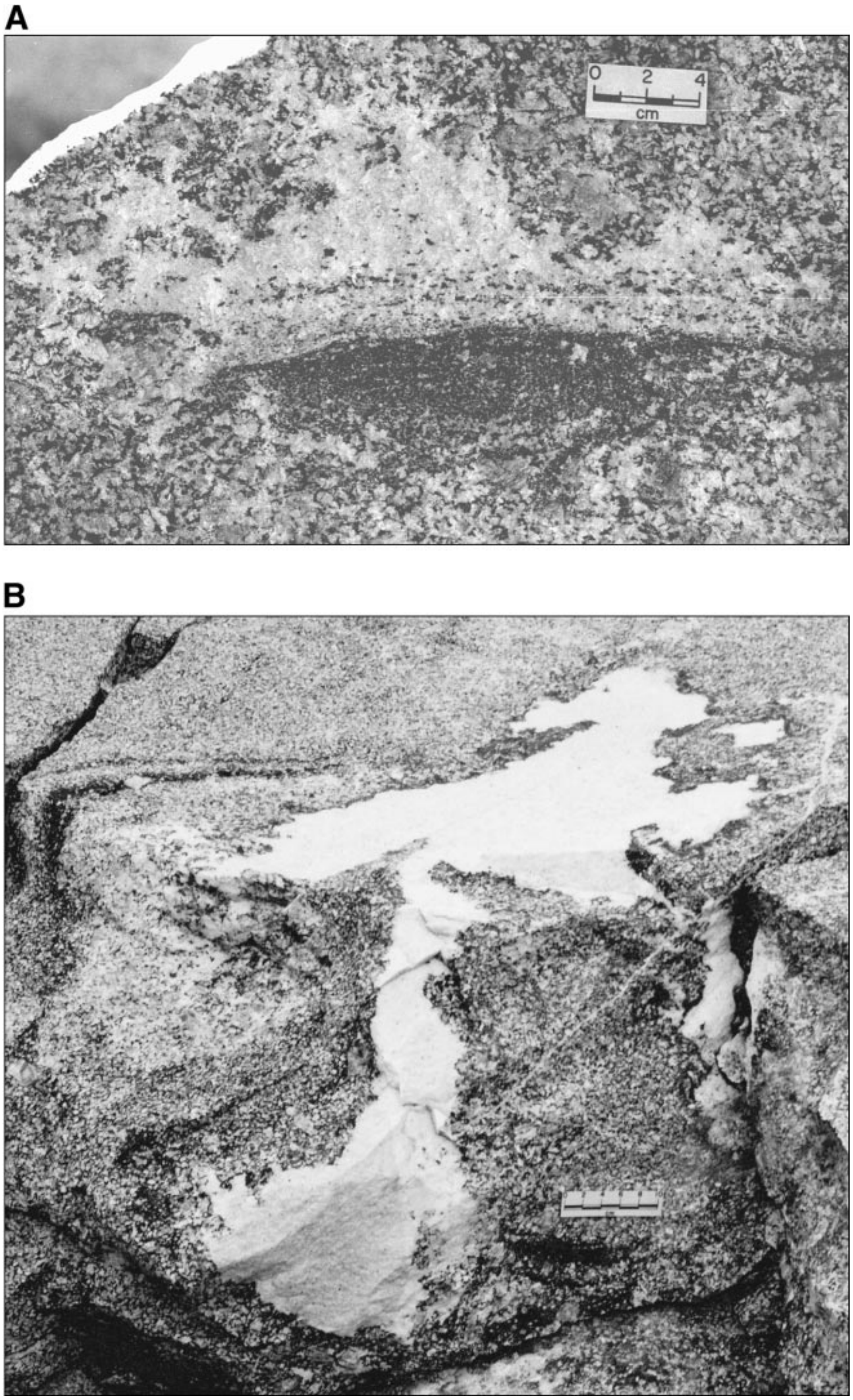

Figure 3. Leucogranite pockets. (A) Irregular pocket where melt has been extracted from the interstices of the granodiorite, leaving behind horizontal layers enriched in mafic minerals. (B) Irregular aplitic pocket exposed in two roughly perpendicular surfaces, with mafic mineral concentrations (melanosome) patches irregularly distributed in the immediately surrounding granodiorite; scale is 10 cm long.

as filters during the breakup of diorite intrusions. When a large diorite blob starts to break up, megacrysts form a logjam at the entrance to the growing granite magma channel, passing only megacryst-free melt to the growing channel. In other cases, K-feldspar aggregates may form around mafic dike walls and enclaves as a result of the combination of K-feldspar preferential attachment to or nucleation and growth at the contact with the mafic magma, and disturbance of granite magma flow by the presence of enclaves.

The mesh size of megacryst filters depends on the pressure gradient driving magma flow. A higher pressure gradient increases the mesh size, allowing larger particles through. Correlation between crystal size and mineralogy results in change of the modal composition of the magma crossing the filter and could give rise to magma layering.

New Model for the Origin of Mafic Schlieren

Several processes have been proposed for the origin of granite layering and mafic schlieren: partial assimilation of mafic enclaves, crystal settling, shearing out of inhomogeneities, steep physicochemical gradients at flow margins (e.g., Barrière, 1981) leading to preferential crystallization of ferromagnesian minerals and suppression of crystallization of felsic minerals (Naney and Swanson, 1980) and shear sorting against an effectively rigid wall (e.g., a more viscous magma, Barrière 1981). Shearing accounts for the size and/or mineral sorting of schlieren (Bagnold effect; e.g., Bhattacharji and Smith, 1964; Komar, 1972; Barrière, 1981), but because solid grains migrate away from the wall, it does not account for schlieren at flow rims. We postulate that schlieren with size worting, like the ones described here, may result from the combined effects of shear flow and loss of interstitial melt to the porous and/or permeable magmatic walls (Fig. 10) and crystal filtering. This requires a negative pressure gradient toward the walls, resulting from unbalanced pressures on a wider scale (beyond the local flow observed). However, we have not been able to show that melt has escaped outward into the walls, and we cannot dismiss the possibility that melt migrated from the flow margins into the blob by filter pressing of a crystal-rich margin.

Shear sorting and melt loss are most effective when the walls enclosing the flow are a crystal-liquid mush. Mushes behave as a permeable viscoplastic material (i.e., flows viscously at stresses higher than its yield

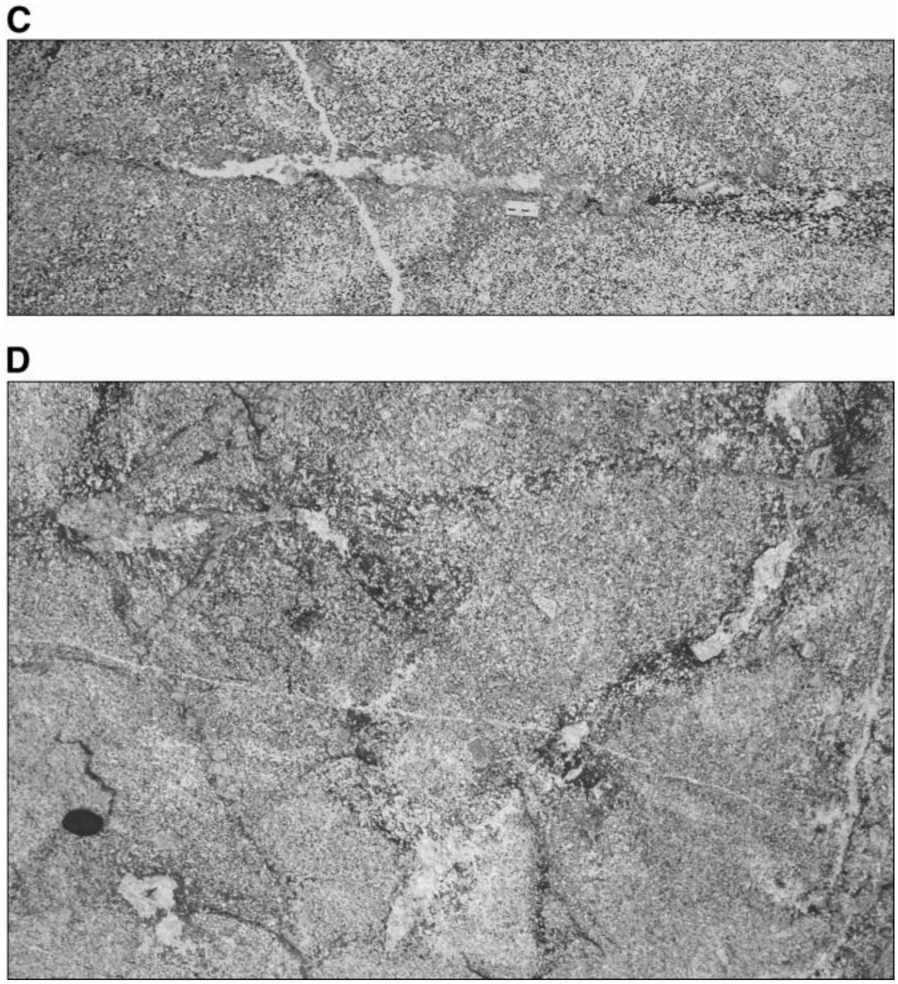

Figure 3. (*Continued*.) (C) Sheet of melanosome, associated with lenses of leucogranite, scale is 5 cm long. (D) Irregular sheets and patches of melanosome surrounding irregular patches of leucogranite; note 5-cm-wide lens cover for scale.

strength). Magmas prone to producing schlieren are those that develop a relatively weak solid framework at low crystal fraction (~50%), so as to keep a high permeability, k (a function of the cube of porosity), and ductility (to allow internal magma flow to develop). Permeable, weak mush not only favors the formation of marginal schlieren but also favors melt extraction from mush pores, as we show here.

Ladder Dikes and Snail Structures

Reid et al. (1993) interpreted ladder dikes as resulting from crystals settling out at the bottom of slushes flowing through narrow vertical channels in semisolid magma. Our observations suggest a different origin for the ladder dikes in Tavares. First, we note that an important flow component perpendicular to the curved schlieren in ladder dikes is not viable because it would destroy curved schlieren. Furthermore, grain-sorting characteristics of well-developed ladder dikes require shearing against a rigid wall. Thus, we conclude that curved schlieren in ladder dikes (or rings in snail structures) represent the walls of cylindrical magma paths (or the bottom of channels, as inferred from Fig. 9), and that the main flow direction is parallel to the walls, out of the plane of the arcuate schlieren (Figs. 11 and 9). We infer that a small flow component perpendicular to the arcuate schlieren must have occurred to produce curved cusps (in some dikes the schlieren are partly disrupted and reoriented toward parallelism with the margins) and wide homogeneous bands within dikes.

We interpret ladder dikes and snail structures as related features that result from the superposition of sequential cylindrical magma pathways. Movement between the position of the magma source and the section observed, associated with intermittent magma release, led to new channels being slightly offset from previous ones (Fig. 11). Snail structures result from random displacement, whereas ladder dikes result from a unidirectional relative displacement. An alternative for ladder dikes, which could account for their length, is that the magma instability is not fed from a point source but from a linear source. Our model explains cross-bedding structures associated with ladder dikes as observed in Sierra Nevada (Fig. 11; Reid et al., 1993). The flow in the channels is driven by local density inversions, while the unidirectional relative displacement between source and observation level results from large-scale flow within the pluton. We postulate that some of these magma pulses may have fed ellipsoids and blobs.

Ellipsoids are Thermal Plume Heads

Ellipsoids differ from simple diapiric blobs with marginal schlieren. Their concentric or spiralling form and similarity between the rock inside and outside them are features to be expected from thermal plumes of hot granite magma. A thermal plume is a gravitational instability originated from a low-density, hot thermal boundary layer that rises through liquid of similar composition (Campbell et al., 1989; Fig. 12). A bulbous head leads the plume, generally followed by a narrow feeder conduit that links the head to the hot source boundary layer. The plume heads grow during ascent by entraining their surroundings (Griffiths, 1986) through buoyancy (heat) diffusion away from the plume head. A thin layer of liquid adjacent to the head is heated and becomes unstable and stirred into the head. Griffiths (1986) showed that the entire hot boundary layer around the plume head is entrained, so that plume head buoyancy remains constant as it increases in volume and cools. The internal structure of laboratory plume heads (Fig. 12) is reminiscent of the ellipsoid structures and contrasts with compositional diapirs, which are unable to entrain surrounding magma because of much slower chemical diffusion as compared to thermal diffusion.

We tested whether the ellipsoids could have resulted simply from convection of a granite layer within the pluton, without any external heat source. On the basis of ellipsoid size, we found that a layer would have to be only a few meters thick and have a steep temperature gradient to convect. This is unlikely to exist within a large cooling pluton (Appendix 1).

We propose two possible alternatives for the origin of plumes: (1) they are hot granitic magma batches released directly from the source; or (2) they are granitic magma batches

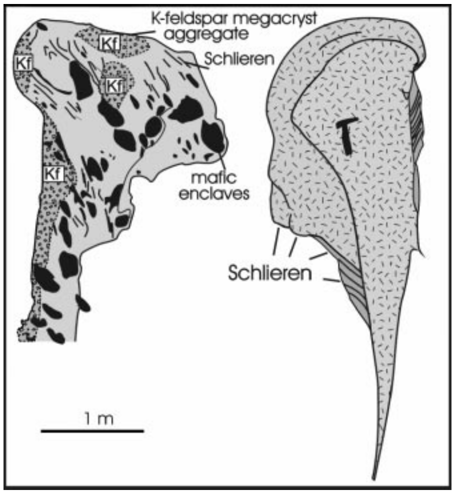

Figure 4. Two magma blobs from the same outcrop, defined by wide heads and narrow stalks. Both were exposed on round surfaces and were redrawn as a projection to a plane dipping ~30°–40° to the viewer. The blob on the left is formed by light colored granite with mafic schlieren, dioritic enclaves, and K-feldspar megacryst aggregates, concentrated on the left side of stem and head. Enclaves are oriented parallel to the regional foliation, at a high angle to blob length, and overlap the boundary between lighter and darker surrounding granite. The blob on the right is internally composite, and the external boundary is well delineated by graded mafic schlieren.

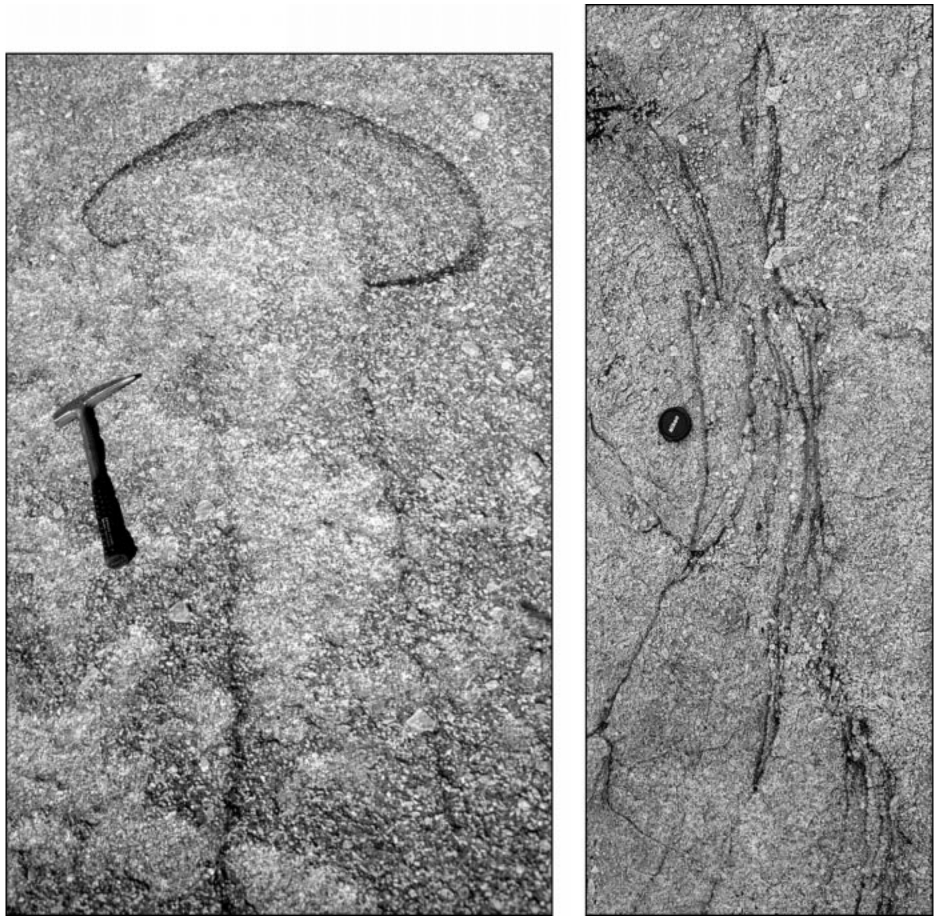

Figure 5. (A) Magma diapir with head delineated by schlieren and tail of light colored granite. (B) Mafic schlieren marking the boundary between an intrusive batch (on the right side) and resident magma. The boundary is characterized by a 50 cm zone of cross-cutting schlieren, indicating movement of the active boundary between the two magmas.

heated by intrusive diorite. We have no evidence that would favor one over the other; we have no knowledge of local sources of hot granite magma, nor have we found direct physical links between enclave swarms and ellipsoids. Here, we further explore alternative 2. Mafic enclave swarms are common throughout the pluton. In order to check whether they could be the local heat source for the plumes, we carried out a simple study of the effects of heat exchange between diorite and granite (Appendix 2). We assume for simplicity that the crystals in the granite magma melt immediately in response to heat diffused from the mafic intrusion. First we studied the increase in temperature and decrease in density of granite heated by diorite, then we studied the rise of a hot plume of granite through colder granite magma. We found that a small heat input could lead to a thermal head of granite of 60 cm radius, lightened mainly by the effect of crystal remelting. Such an ellipsoid could rise and grow to a radius of 3 m by entraining the surrounding, cooler magma.

Although there is little doubt, on the grounds of physics, that thermal convection should occur within granite magma chambers, there has been little field evidence of this process. Barrière (1981) interpreted the curved schlieren in Ploumanac'h as indicating turbulent convection. Authors before him also attributed curved biotite schlieren to convection currents (Mayo, 1941; Wilshire, 1969), but others attributed them to episodic shearing flow (Smith, 1975). Abbott (1989) mapped steep cylindrical structures at Chebucto Head in Nova Scotia. These are as much 500 m across and defined by platy K-feldspar megacryst foliation planes. He discarded the possibility that these represent frozen-in convection cells and suggested that they result from internal folding of the magma by forced flow. We interpret schlieren structures in the Tavares pluton, including structures like those mapped by Barrière (not discussed here), as a result of local laminar thermal or compositional convection. Although we were unable to find evidence for chamber-wide convection, mesoscale plumes indicate that small, localized heat input may cause substantial density difference, and drive gravitational instabilities.

Magma Extraction Structures: Energy Minimization, Gravity-Driven Compaction, and Contraction

Separation of melt from crystals has long been recognized as a diversification process of magmatic rocks. The extraction of viscous felsic melts from pores of partially molten rocks has often been used to explain cumulate texture in granites (sensu lato) and to explain their geochemical trends (e.g., McCarthy and Groves, 1979). However, extraction structures have seldom been described, and the process is fraught with difficulties, mostly related to slow extraction (Miller et al., 1988, p. 145; Petford, 1993; Weinberg, 1999). The struc-

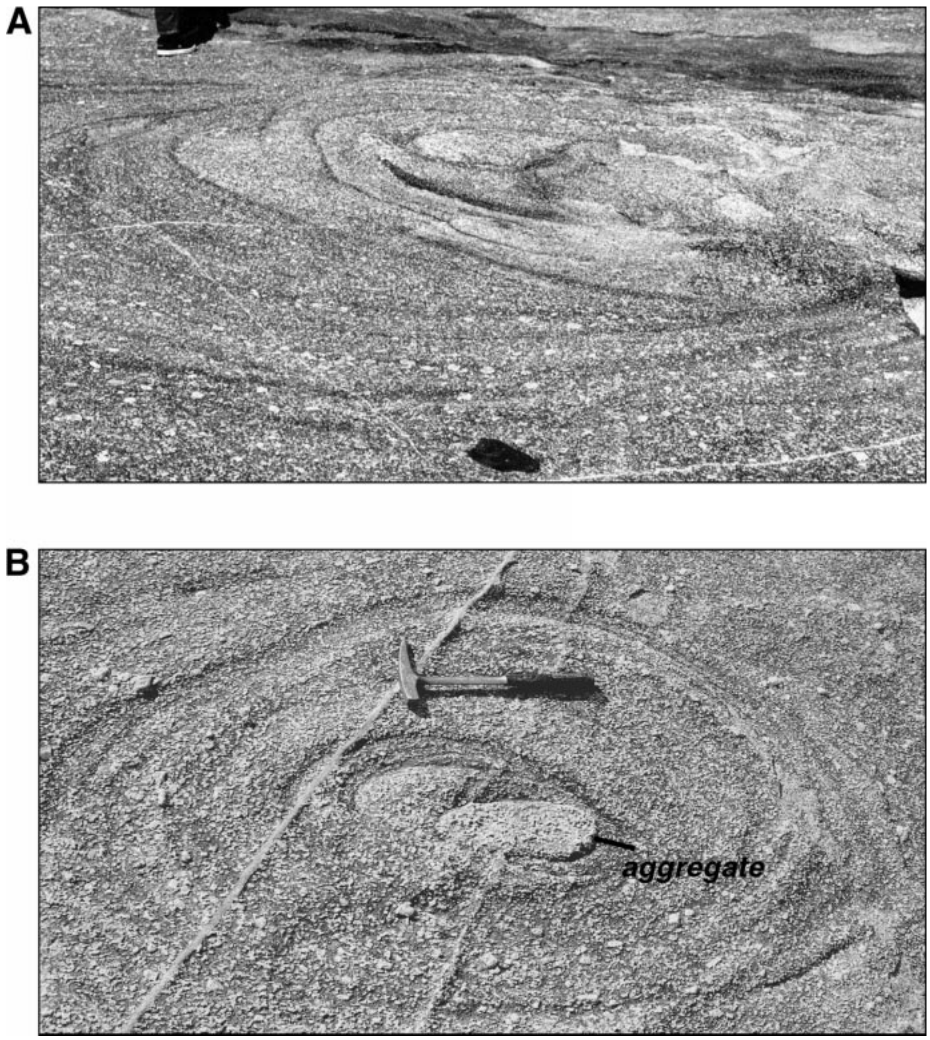

Figure 6. Concentric ellipsoids (horizontal exposure); note decimetric K-feldspar aggregate in the center of B.

tures in the quarry near Tavares village present a unique opportunity to understand how melt extraction from a solidifying magma takes place.

In the quarry, structures were interpreted to result from melt extraction from pores of a crystal-solid mush, similar to those developed in migmatites: leucogranite pockets are leucosomes extracted from mush pores, and the mafic-rich residue is the melanosome. In the pluton, melt extraction took place during rock solidification and volume decrease in a weakly foliated rock, in contrast to extraction structures in migmatites, which result from anatexis, generally accompanied by volume expansion, in strongly foliated rocks.

Details of some of the dikes exposed in the quarry and their composition suggest that they are locally derived, and represent earlier stages of extraction (possibly including crystals) from the original magma. The preserved leucogranite extraction structures in the quarry form a poorly developed network, which removed magma out of the pores of a mush, and gave rise to narrow dikes. Although we have no independent way-up structures, the concentration of mafic minerals consistently below or on the lower side of leucogranite pockets suggests vertical way-up in a system where gravity played an important role in segregating melt from solid mafic crystals. A significant difference to migmatites is the lack of a well-defined structural control in the extraction structures. This is due to the lack in the Tavares pluton of a strong foliation and permeability or strength anisotropy.

In order to understand the origin of extraction structures, we now consider the development of a solid framework magma and the process of melt extraction from pores. Crystals in a cooling melt will tend to form a contiguous network in order to achieve minimum energy configuration (Jurewicz and Watson, 1985). The development of a solid skeleton is controlled by the volume fraction of solid, X, the average melt-solid wetting angle, θ (generally $\theta = 20°–60°$, Holness, 1997), and on crystal size and shape distribution (Miller et al., 1988). The main control on the crystal fraction X necessary to develop a solid skeleton, X_{crit}, is θ. X_{crit} decreases as θ increases. However, for a given θ, X_{crit} will be largely controlled by crystal size and shape distribution, specific to each magma. Miller et al. (1988) estimated that the crystal fraction required to form a skeleton ranges widely, but could be as low as 50%.

Once a solid skeleton is developed, melt will tend to migrate into larger melt pockets in order to attain a minimum energy configuration. Jurewicz and Watson (1985) determined the equilibrium melt fraction that would minimize the interfacial energy state in two-dimensional partially molten crystalline aggregates. The equilibrium melt fraction decreases with increasing θ, tending to zero as θ tends to 60°. In oversaturated systems, i.e., those with melt fraction above equilibrium, excess melt coalesces to form large pools that could be tapped by fractures or could build up interconnected conduits (Jurewicz and Watson, 1985). These observations imply that crystal-melt systems with θ approaching 60° are ideal systems for the development and preservation of extraction structures. This is because they develop a permeable solid skeleton at low crystal fraction, and are further from equilibrium than systems with lower θ. These features are the same as those ideal for producing marginal schlieren as previously concluded here.

We envisage two possible gravity-driven compaction models to account for the horizontal mafic layers in the lower half of melt pockets or melanosome surrounding their lower half (Figs. 3A and B): (1) settling of mafic minerals in locally liquefied magma pockets due to melt migration; and (2) textural ripening of a crystal mush, accompanied by the detachment and sinking of grains and upward segregation of melt (Miller et al., 1988). Volume shrinkage and accompanying tensional stresses may have eased segregation by creating low-pressure melt sinks and favoring crack and/or dike propagation.

Some granite dikes/sheets in this outcrop seem to start out of the surrounding granodiorite. Their tortuous shape suggests they cut across magma (mush?). We suggest that the dikes are also a result of a local process of magma extraction from the surrounding granodiorite magma. Because of their textural similarity to the granodiorite (as opposed to the sharp contrast between leucogranite melt and granodiorite), there is less evidence for the process of extraction. This conclusion raises some questions about the state of the surrounding magma when granitic magma was extracted: was it still liquid magma capable of cracking elastically; was it a mush capable of liberating granitic melt from its pores; or was the flowing melt able to extract solid crystals as well? In future work we aim to establish, on the basis of trace element and rare earth element patterns, as well as mineral chemistry, the amount of melt that has been extracted from granodiorite pores, and to determine whether melt extraction was more widespread and involved the granitic dikes.

In summary, extraction structures developed through melt expulsion from pores into melt pockets, and schlieren developed through melt expulsion from blob margins into pores of surrounding magma. Both are favored by magmas that develop a permeable and ductile solid framework at low crystal fraction, possibly as a result of high wetting angle and favorable crystal size and shape distribution. Whether melt migrates out of or into pores depends only on the sign of the pressure gradient, which is controlled by both large- and small-scale pressure balance within the chamber.

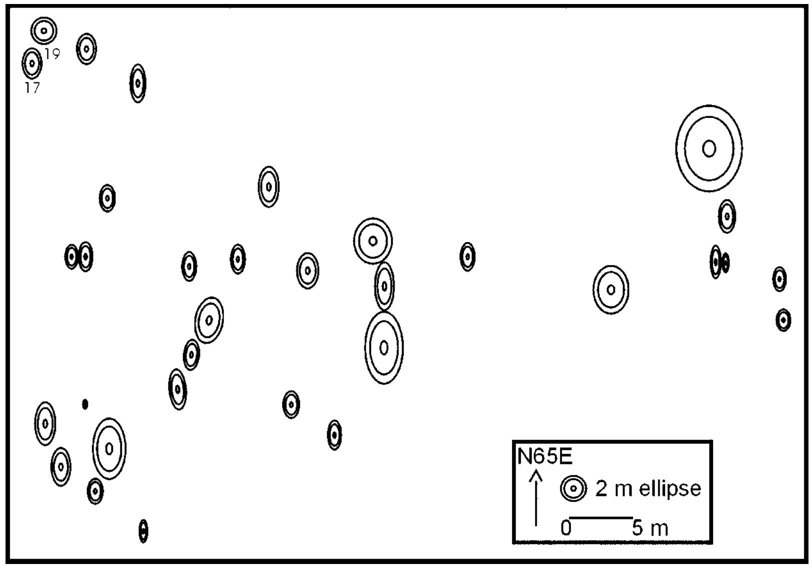

Figure 7. Size and distribution map of ellipsoids exposed in outcrop. Size measurements have a large error, because elliptic foliation weakens outward (width error ±1 m, length error ±50 cm, dashed ellipses are poorly defined structures). Ellipsoids 17 and 19 are exposed on a vertical wall. Ellipsoids smaller than 1 m long are not shown.

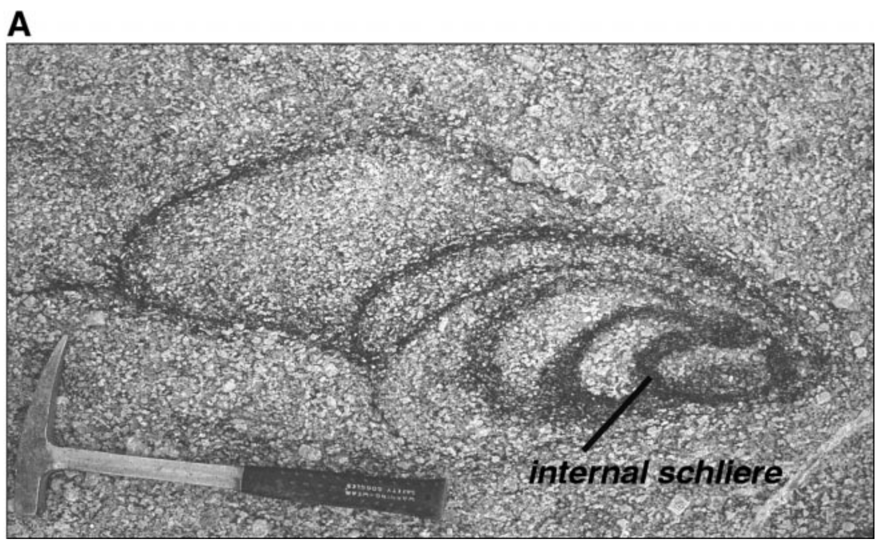

Figure 8. (A) Snail structure. The centers of internal ring schlieren are displaced in relation to the center of external ones, forming an elongated structure. Note that the more external schlieren on the right tend toward a ladder dike shape.

Diapirs and Compositional Convection in Granite Mush

Magma blobs are interpreted as compositional diapirs, driven downward or upward by contrasting density to surrounding magma resulting from, for example, magma fractionation or disruption of dense diorite magmas. We have not attempted to determine density differences between rocks inside and outside the blobs partly because heat and melt content must have played a key role in controlling density inversion, and partly because melt may have been expelled out of the crystallizing diapir (as proposed herein for the origin of schlieren).

Compositional convection in magma mush has been proposed based on laboratory models and supported by observations in mafic-ultramafic magma chambers (e.g., Tait and Jaupart, 1992; Jaupart and Tait, 1995). We use our separate observations and interpretations on leucogranite melt extraction, diapiric blobs, and our model for the origin of schlieren to propose a model of compositional magma convection in a granitic mush (Fig. 13). We stress that extraction structures described herein are not directly related to granite in the blobs, but are simply used here as an example of extraction structures. The starting point of the process is melt segregation from pores into pockets and sheets. The example of the aplite dike linked to a melt pocket suggests that diking is a possible mechanism of tapping melt pockets. Field relations, however, suggest that melt may have been removed from the mush pores by amplification of porosity fluctuation and the formation of chimneys due to dissolution and precipitation related to melt flow. In regions of faster melt flow, chemical and heat advection leads to increased porosity and possibly grain detachment from the solid skeleton, either through remelting or through Ostwald ripening (Miller et al., 1988), in a

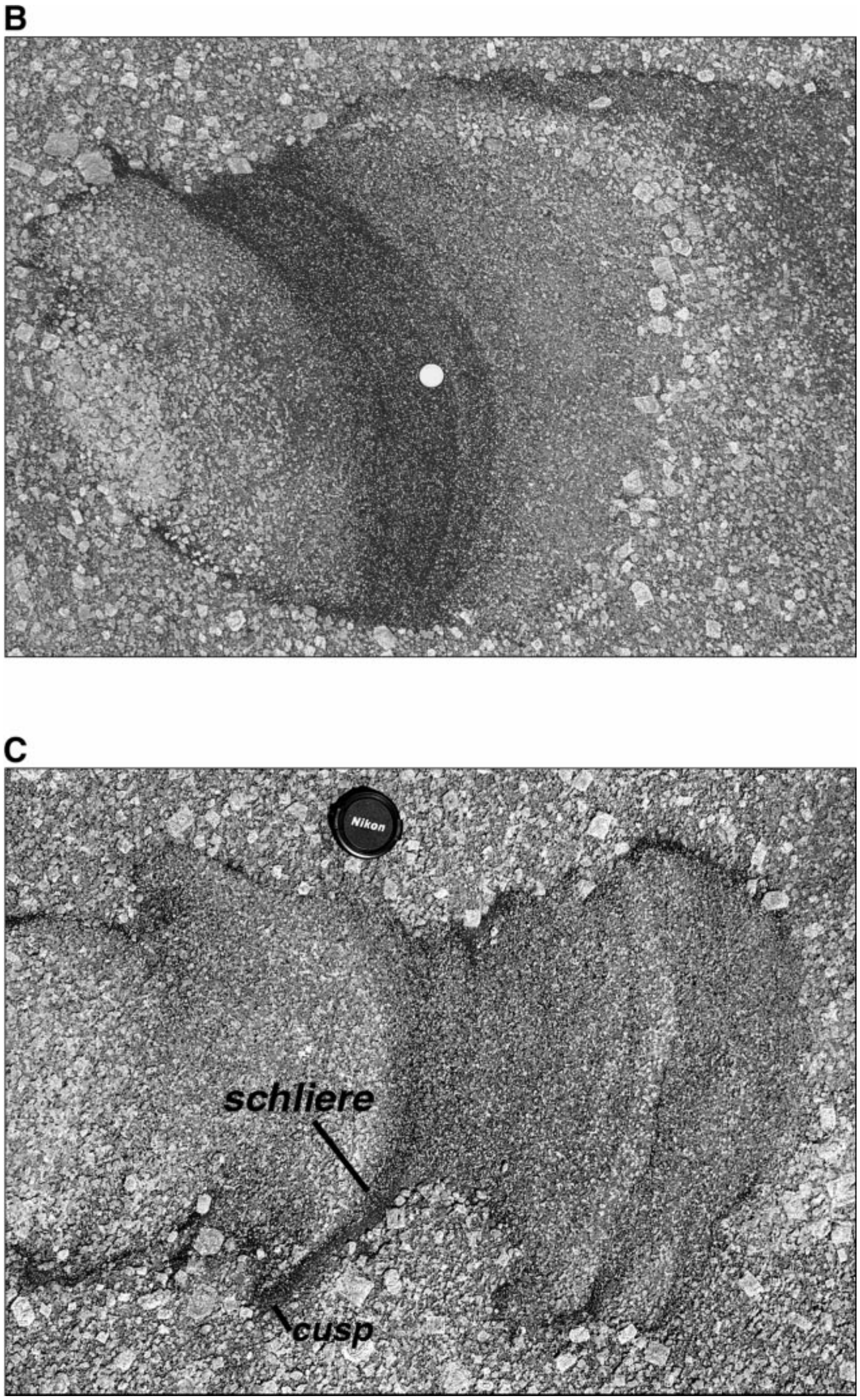

Figure 8. (*Continued*). (B) Starting point of a fully developed ladder dike in the Tavares pluton. (C) Small section of a long ladder dike with cusped outlines. Cusps are continuous with curved internal schlieren.

mechanism akin to that described by Jaupart and Tait (1995, p. 17624–17626). The position of the channels may migrate with time in search of a wider scale equilibrium and may be the underlying cause of ladder dikes. Once flow is channeled, melt will rise through the mush until it reaches its neutral buoyancy level or is trapped in strong surroundings. High magma pressure at the diapir's head drives melt out of the blob into the surrounding mush, giving rise to marginal schlieren. The importance of compositional convection in the chemical evolution of the Tavares pluton remains undetermined, and unfortunately mapping indicates a relatively homogeneous exposure level.

Why the Tavares Pluton?

We have proposed that uncommon structures cropping out in the Tavares pluton are a result of processes likely to be common to many granites. Why are these structures not widespread and yet are well developed in the Tavares pluton? First, they may not be so uncommon, but perhaps they have just been overlooked because they are seldom sufficiently well developed and/or preserved to allow us to understand their origins. We note, for example, that ellipsoids and ladder dikes are widespread in high-K calc-alkaline plutons of the Borborema province, but not as well developed as in Tavares. The presence of similar structures in high-K granites of the Sierra Nevada (e.g., Cloos, 1936) suggests that they may be best developed or preserved in granites of this composition. Second, although convective overturns may occur at any time before the magma reaches advanced stages of solidification, structures will only be preserved when developed under particularly favorable conditions. If they develop early, marginal schlieren will not develop and overturn structures will tend to be destroyed by later flow and crystallization. We have argued that marginal schlieren, extraction structures, and consequently ladder dikes, snail structures, diapirs, and thermal plume heads are ideally developed and preserved when a solidifying magma produces a weak, high-permeability crystal mush. The development of this type of mush depends on the characteristics of the solid framework structure developed during crystallization, particular to each magma. Structures developed in the mush stage are also more likely to withstand later deformation and be preserved until the end of crystallization.

SUMMARY AND CONCLUSIONS

Melt extraction and flow structures are particularly well developed in the Tavares pluton, and rendered visible by widespread mafic schlieren. These structures indicate a dynamic, viscous environment during pluton crystallization, where gravity instabilities played an important role. We describe meter-scale tear- or mushroom-shaped blobs and ellipsoids that were interpreted as the leading heads of compositional and thermal instabilities, respectively, trailed by stems and/or feeders represented

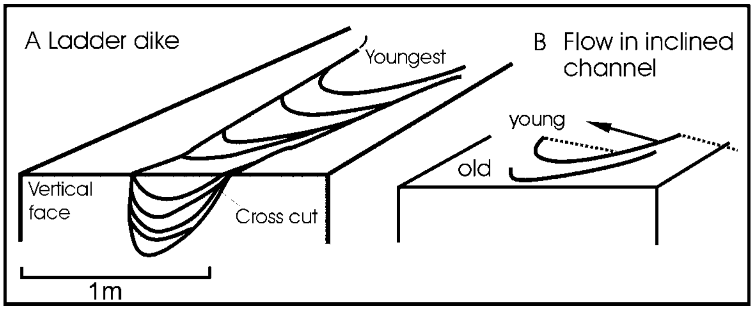

Figure 9. (A) Two perpendicular sections of a ladder dike as seen in outcrop. Note the crosscutting relationships of schlieren in the frontal, vertical face. (B) Interpretation of A. The dike is composed of a series of stacked, inclined, U-bottomed channels, younging inward (in the concave direction), as evidenced by crosscutting relationships (as shown by details in A). Mafic schlieren develop at the wall (bottom) of each channel, where shearing is maximum. Magma flow channeling initiates at the far end of the drawing.

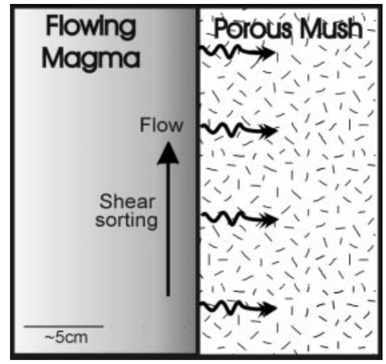

Figure 10. An intrusive magma flows along a wall of magma sufficiently crystallized as to have a well-connected, permeable, crystal network. Crystals in the intrusive magma are sorted by size as they migrate inward from the contact (Bagnold effect), at the same time as the crystal-poor melt layer developed near the flow margins leaks into the porous resident magma.

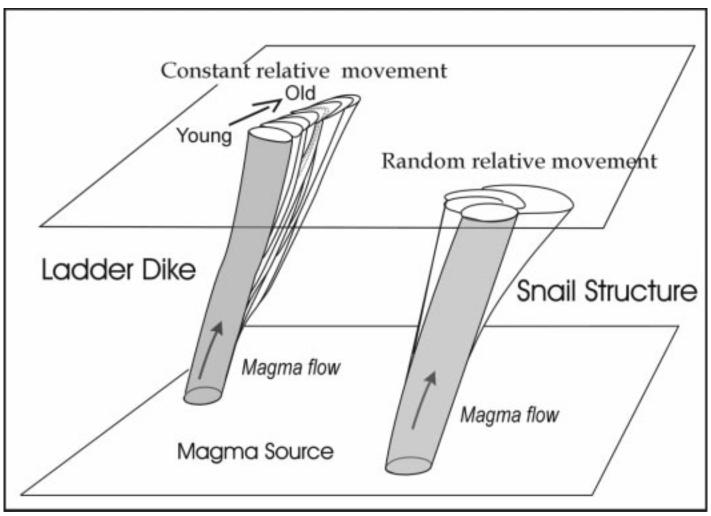

Figure 11. Ladder dikes and snail structures result from the relative motion between a point magma source and the observation level of the magma pathway so that each new pulse is displaced in relation to earlier pulses. Random relative motion between source and observed section leads to snail structure, whereas constant relative motion leads to ladder dikes.

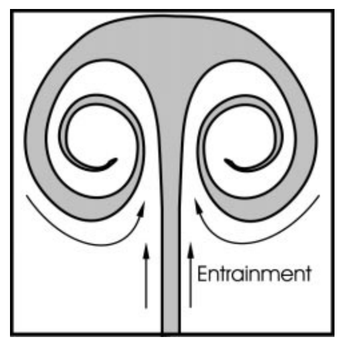

Figure 12. Structure in a vertical section across a thermal plume head. A horizontal section would have the form of concentric circles. Surrounding magma is entrained into the plume head by buoyancy gain due to heat diffusion from the plume head.

by ladder dikes and snail structures. The latter two result from the partial superposition of the cylindrical paths of consecutive magma batches. K-feldspar megacrysts tend to form aggregates in a range of situations. In some of these they may behave as filters, separating megacrysts and passing melt. These filters have variable mesh size, depending on the magma pressure gradient.

We propose a new model for the origin of marginal schlieren that requires shear flow sorting against a rigid wall and melt escape into the pores of this same wall. We also describe structures developed by melt flow in the opposite direction, from the pores of a mushy magma into melt pockets, sheets, and channels. We conclude that magmas that develop an interconnected network of solid crystals at relatively low crystal fractions (~50%), those of wetting angles approaching 60°, and favorable crystal size and shape distribution, are ideal systems from which to extract or intrude interstitial melt. Depending on the sign of the pressure gradient, melt will flow into or out of a melt pocket.

We propose a general model for small-scale compositional and thermal convection inside mushy (effectively solid) magma bodies. Compositional convection results from melt fractionation, gravity-driven segregation and extraction, aided by magma contraction, giving rise to diapirs. Thermal convection is driven by heat released by mafic intrusions, giving rise to thermal plumes of melt-rich granite blobs. Although direct evidence for chamber-wide convection is lacking, small-scale instabilities indicate the importance of gravity instabilities during pluton evolution.

APPENDIX 1

ELLIPSOIDS AND A CONVECTING LAYER

If the ellipsoids represent thermal plumes resulting from thermal convection within a granite layer, we can infer the depth of the convecting layer based on the distance, l, between ellipsoids. The depth of the layer, h, can be determined from: $\lambda = l/h = 2.828$ or 2.016, depending on whether the top and bottom boundaries are free slip or no slip. For a typical distance between ellipsoid centers of $l = 10$ m, then $h = 4-5$ m. For convection to occur, the dimensionless Rayleigh number, Ra, must reach a critical value $Ra_c \sim 10^3$ (e.g., Turner, 1973) ($Ra = \alpha\rho g \Delta T h^3/\eta\kappa$, where α is the coefficient of expansion, ρ is magma density, g is gravitational acceleration, ΔT is the temperature difference between top and bottom of the convecting layer, h is the height of the layer, η is magma viscosity, and κ is thermal diffusivity.) For $\alpha = 10^{-5}$ K^{-1}, $\rho = 2500$ kg/m^3, $g = 10$ m/s^2, $h = 4$ m, $\kappa = 10^{-6}$ m^2/s, and $\eta = 10^4$–10^6 Pas, Ra_c will be reached for a ΔT between 0.5 and 50 °C. For large, stable magma chambers, such temperature differences are unlikely to develop over such short distances without the aid of a local source of heat, such as mafic intrusions.

APPENDIX 2

PLUME ORIGIN AND HEAT EXCHANGE BETWEEN DIORITE AND GRANITE

Modeling the evolution of a boundary layer around an intrusive diorite is beyond the scope of this paper. Here we simply want to know whether heating the granite magma by a small diorite enclave swarm is sufficient to produce a granite plume of the sizes observed. For this purpose we assume a linear relation between magma temperature, crystal fraction X, and magma density ρ, and study the case where the initial magma temperature T_i is between that of the magma solidus and liquidus (T_s and T_l, respectively). More complex relations between T, X, and ρ could have been used, but we chose the simple approach just to exemplify the processes involved.

Heat released by the diorite (H) to a surrounding granite at initial temperature, T_i, and crystal fraction X_i will raise the temperature and remelt part of the crystals. A unit mass of granite magma to which H has been added will increase in temperature, ΔT ($T_f - T_i$; subscript f represents final) by

$$\Delta T = H/[c_p + (L/\Delta T_{ls})] \quad (1)$$

for $T_f < T_l$, where c_p is the heat capacity (kJ/kg/°C), L is the latent heat (kJ/kg), and ΔT_{ls} the temperature difference between magma liquidus and solidus.

For $T_f > T_l$:

$$\Delta T = [H - (T_l - Ti)\cdot(L/\Delta T_{ls})]/c_p. \quad (2)$$

Given our initial assumptions, the decrease in crystal fraction will be directly proportional to the increase in temperature $X_f = X_i - \Delta T/\Delta T_{ls}$ for equation 1, or $X_f = 0$ (no solids left) for equation 2.

In order to determine the density difference between heated granite magma and surrounding granite magma, we assume a linear variation of density with temperature whereby

$$\Delta\rho = \Delta\rho_{ls}\, \Delta T/\Delta T_{ls}, \quad (3)$$

where $\Delta\rho_{ls}$ is the total density difference between solidus and liquidus (of the order of $0.1\rho_{rock}$).

We assume, as an example, that the diorite released heat equivalent to 100 °C of sensible heat ($H = c_p \times 100$ °C) per unit mass of granite containing initially ~60% crystals. Using equation 1 and typical values for magmas of $L = 3 \times 10^5$ kJ/kg, $\Delta T_{ls} = 100$ °C, and $c_p = 1.3 \times 10^3$ kJ/kg/ °C, we obtain $\Delta T = 30$ °C, a loss of 30% of crystals and a decrease in density of $0.3\Delta\rho_{ls}$ (or $\Delta\rho 0.03\rho_{rock}$). The density decrease, due to crystal melting, compares with the much smaller effect of thermal expansivity alone of $\Delta\rho = 1.5 \times 10^{-3}\rho_{rock}$ (for a 30 °C temperature increase and $\alpha = 5.10^{-5}$ K^{-1}). Magma viscosity will also drop, but with only minor effect on the rise of the thermal plume.

On the basis of the size of exposed plume heads, the initial size of the head that left the boundary layer may be back-calculated using the rough assumptions that plume growth is entirely due to entrainment. To produce a typical ellipsoid of radius, $r = 3$ m, which stopped rising when its excess temperature reached a subjective 1 °C, the initial plume radius would be roughly 0.6 m, and this plume would rise with an initial velocity, $V = 140/\eta$ or $V = 1.4 \times 10^{-4}$ m/s for $\eta = 10^6$ Pas. The heat input per unit mass of granite we have assumed is modest. A diorite volume similar to that of the initial felsic plume head ($r = 0.6$ m), and intruded at its liquidus temperature, would be able to heat that volume of granite magma by releasing approximately one-third of its suprasolidus heat content.

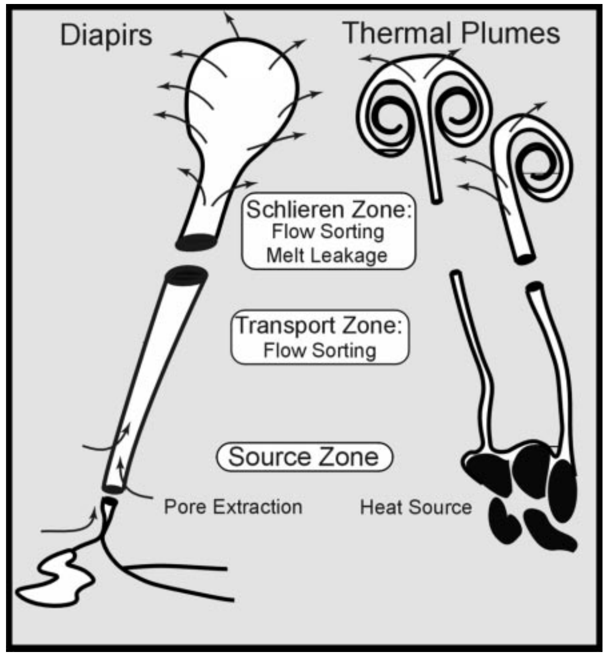

Figure 13. Compositional and thermal convection model for the development of structures observed in the Tavares pluton. Compositional convection develops in a magma mush (magma with a solid framework), where light unstable magma is released from pores into pockets and sheets, driven by gravity and forces resulting from the minimization of energy and pressure gradients related to magma contraction. Light melt is channeled upward, giving rise to ladder dikes and snail structures (not shown) and topped by a bulbous diapiric head, from where melt is driven out and into the pores of the mushy surrounding, to produce schlieren. Thermal convection is driven by heat released by diorite intrusions that expand and melt back surrounding magma (which becomes unstable), rise, and entrain surrounding magma. In this case the surrounding magma need not be a mush, but thermal plumes developed in mushes are more likely to be preserved.

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