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Steep schlieren and associated enclaves in the Vinalhaven granite, Maine: possible indicators for granite rheology

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Abstract Schlieren that form above the solidus are potentially diagnostic of the rheology of crystallizing granitic magmas and could provide insights into magma chamber structure. Here we focus on steep schlieren associated with comagmatic enclaves in the Vinalhaven granite. Steep schlieren extend 1–3 m upward from the sides of enclaves and appear to have steep cylindrical shapes in 3D. Analyses of schlieren widths and the sizes of associated enclaves suggest that granitic crystal mush in which they occur had a plastic rheology probably characterized by a yield strength. The enclaves, now enclosed in coarse-grained granite, must have existed at higher levels in a crystal-poor part of a magma chamber and settled downward until reaching material with a yield strength exceeding the buoyancy of the enclaves. In addition to constraining the local rheology of the granite, their relative positions may indicate vertical rheological variations and possibly the chamber floor.

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Introduction

Understanding how granitic plutons are constructed remains an intractable problem in igneous petrology, one that has implications not only for magma emplacement and the room problem, but also for how to view the genetic relationships between a pluton, its sources, and cogenetic eruptive rocks. Current models for the construction of granitic plutons range from emplacement as crystal-rich magma incapable of significant internal convection (e.g., Miller and Paterson 1999) to emplacement controlled by many small dike-fed injections of crystal-poor magma that results, at least temporarily, in the formation of crystal-poor magma chambers (e.g., Clemens and Mawer 1992; Petford et al. 2000). The recent recognition of the long time span represented by some plutonic bodies (e.g., Glazner et al. 2004) lends support to an incremental growth model. The occurrence of crystal-poor silicic magma in the crust is supported by recent studies of migmatites in probable source-regions (Sawyer 1994) and experiments indicating lower viscosities of silicic magma (Baker 1996). The existence of ephemeral magma chambers within growing plutons is also supported by the occurrence of mafic sheets in many intrusions (Wiebe 1994; Miller and Miller 2002; Collins et al. 2006). What is lacking, however, is clear evidence of the spatial and temporal variations in rheology within crystallizing granitic plutons. How do granite plutons grow and differentiate? What is the nature of internal physical processes such as natural convection and stirring? Do granitic plutons that lack mafic sheets preserve evidence of ephemeral crystal-poor magma chambers? These questions may be addressed by careful study of schlieren, finer-grained and more mafic bands that record the presence of deformable crystal-rich material during pluton construction. Schlieren that lack evidence for solid-state deformation are of special interest because they appear to record movement of melt and crystals at varying times during the solidification of the granite and have the potential to provide information about magma rheology.

A wide variety of subtle to strong, planar to curved schlieren occur in many granitic plutons. Some gently dipping layers closely resemble sedimentary features such as graded bedding and cross-bedding; these are thought to record magmatic flow, erosion and deposition at the effective floor of a silicic magma chamber (Gilbert 1906; Emeleus 1963; Wahrhaftig 1979; McCarthy and Groves 1979).

Schlieren that dip steeply (planar, arcuate, cylindrical or irregular and complex) also occur widely. Unless they have been rotated into their steep orientations, they cannot readily be interpreted as depositional in origin. Although there appears to be a great variety of such features in different bodies of granite (Wilshire 1969; Barrière 1981; Abbott 1989; Weinberg et al. 2001; Clarke 2003), most workers generally agree that these features record shear flow of crystal-rich magma. There is, however, no agreement on the causes of the shear flow or on the physical significance of the steep schlieren for pluton emplacement and crystallization. Some suggestions include multiple emplacements of crystal-rich magma (Wilshire 1969), flow of crystal-rich magma around sinking enclaves (Abbott 1989; Clarke 2003), hot, mafic injections that cause convection in granitic cumulates (Barrière 1981; Weinberg et al. 2001), and a rising vapor bubble (Clarke 2003). Unfortunately, none of these studies provide unequivocal evidence to distinguish among the possibilities. Neither has research to date established accepted criteria for distinguishing among these possibilities.

The Vinalhaven granite is an ideal setting for studying schlieren because it contains both a thick stratigraphic section of mafic sheets interlayered with granite and many well-exposed examples of steeply dipping, arcuate schlieren that closely resemble schlieren from many areas described in the literature. The interlayered unit of mafic sheets and granites preserve numerous indicators of paleo-vertical and provide a basis for interpreting the geometry of the intrusion through time (Hawkins and Wiebe 2004a; Wiebe et al. 2004). The schlieren include steep cylindrical, arcuate and apparently linear schlieren similar to those illustrated by Wilshire (1969), Barrière (1981) and Weinberg et al. (2001) and occur both within the layered section and at stratigraphically higher levels in the intrusion where mafic sheets are absent. Excellent 3D coastal exposures indicate that many (and possibly all) of these schlieren are associated with magmatic porphyry and granitic enclaves (from less than 1 to more than 4 m in diameter). Understanding the origin of these steep features has the potential to provide valuable information on the rheology of granitic magma during solidification and also has broad implications for the construction of granitic plutons and the existence and structure of granitic magma chambers at different times within the resulting plutons.

We first describe the geology of the Vinalhaven intrusion. We then characterize the schlieren in three ways: (1) field relations and geometry of the steep schlieren and the geometric relationships of steep schlieren to enclaves, (2) petrography, including modal analysis, and (3) analysis of the orientations of feldspar grains in granite adjacent to schlieren. We establish a simple relationship between schlieren thickness and enclave diameter and then consider the extent to which such geometric relations constrain the rheology of the schlieren-bearing granite. Lastly we consider the broader implications for vertical variations in rheology of the granitic magma and for a cumulate origin of the Vinalhaven granite.

The Vinalhaven intrusive complex

The 420 Ma Vinalhaven intrusive complex, roughly 12 km in diameter, consists of three main units (coarse-grained granite, gabbro-diorite and fine-grained granite) and several smaller bodies of felsic porphyry (Wiebe et al. 2004) (Fig. 1). It developed by multiple replenishments over a period of ~1.7 Ma, based on precise zircon geochronology (Hawkins and Wiebe 2004a). The complex intrudes deformed, low-grade schists of the early Paleozoic Calderwood Formation and, along its northwestern margin, weakly deformed, coeval volcanic rocks that include rhyolite flows and tuffs. The most extensive unit is coarse-grained granite that underlies most of the island and has a well exposed contact with country rock along its northern (upper) margin (Fig. 1). In the southeastern

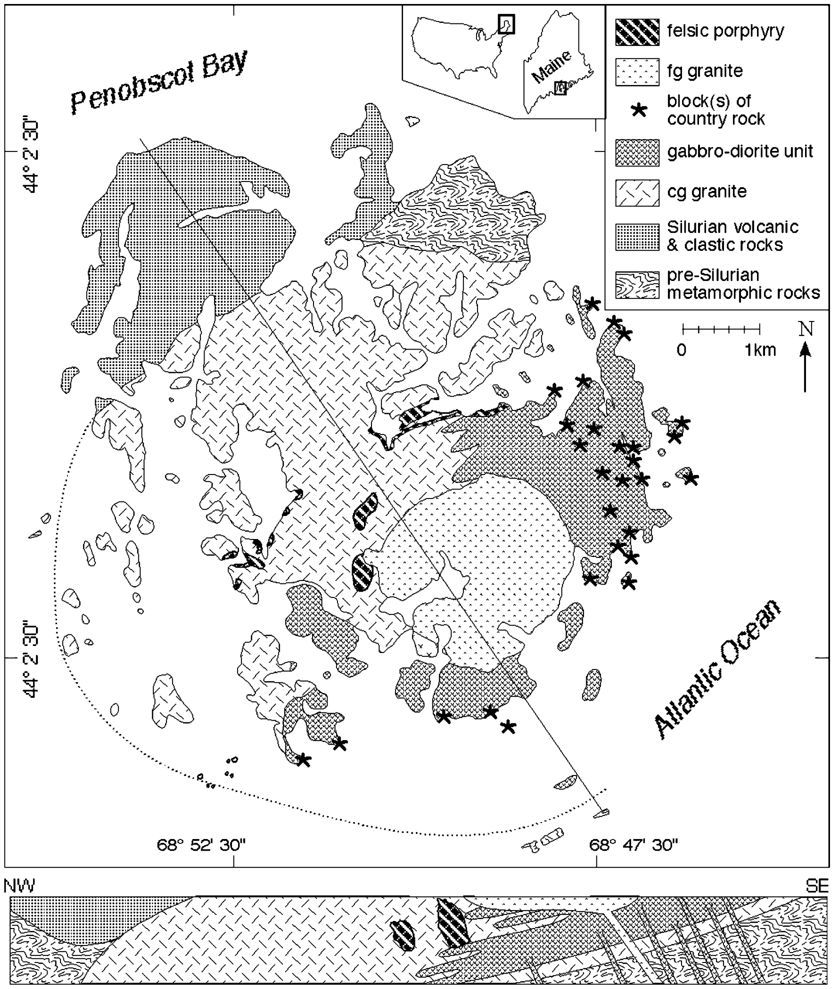


Fig. 1 Geological map of the Vinalhaven intrusive complex

half of the complex, coarse-grained granite is underlain by the gabbro-diorite unit, which consists of interlayered mafic, hybrid, and granitic rocks. This unit forms a curved, sheet-like body, 100s of meters to more than 1 km thick, which dips 10°–30° to the north and west beneath the granite. Extensive blocks of country rock, identical to country rock in the northern part of the island, occur within the gabbro-diorite unit. Metamorphism of pelitic blocks suggests pressures of between 1 and 2 kb (Porter et al. 1999). Fine-grained granite cuts through the gabbro-diorite unit and forms a small, inner core of the intrusion, about 2–3 km in diameter, mainly within the coarse-grained granite. Exposed contacts with coarse-grained granite are sharp (cutting crystals) in the south, whereas they are locally commingled and mixed with exchange of crystals in the north. The small bodies of porphyry represent remelted (rejuvenated) portions of once nearly solid granite due to injections of basaltic magma (Wiebe et al. 2004).

Much of the gabbro-diorite can be subdivided into macro-rhythmic units (layers), each of which is marked by a chilled gabbroic base. These macro-rhythmic units may vary in thickness from less than one to more than 50 m. Where gabbroic rocks form layers less than a few meters thick, they commonly have chilled upper margins against a more felsic, overlying layer that is compositionally similar to rocks beneath the sheet. Where gabbroic rocks form layers thicker than a few meters, they generally grade upward to hybrid dioritic and granitic rocks that display evidence for incomplete mixing between mafic and felsic magmas. Widespread load-cast and pipe structures at the chilled mafic bases of macrorhythmic units indicate the gabbro-diorite unit formed by a sequence of basaltic injections that ponded at the base of an aggrading silicic magma chamber and variably interacted with overlying granitic magma (Wiebe 1993; Wiebe and Collins 1998). They strongly suggest that granite, interlayered with and overlying the gabbro sheets, also formed by accumulation of crystals on a magma chamber floor. In the lower part of the intrusion, gabbroic layers extend for 15 km in a broad arc, suggesting the early chamber may have been laterally extensive. Prominent horizons of country rock blocks associated with these extensive gabbroic layers probably record major roof collapse during eruptions from the chamber triggered by mafic input (Hawkins and Wiebe 2004a).

Coarse-grained granite is largely massive and consistently leucocratic. It contains mainly two types of enclaves: (1) scarce fine-grained felsic magmatic enclaves, between 20 cm and 1 m in diameter, that closely resemble the intrusive porphyry bodies, and (2) rounded to angular bodies of texturally variable, more

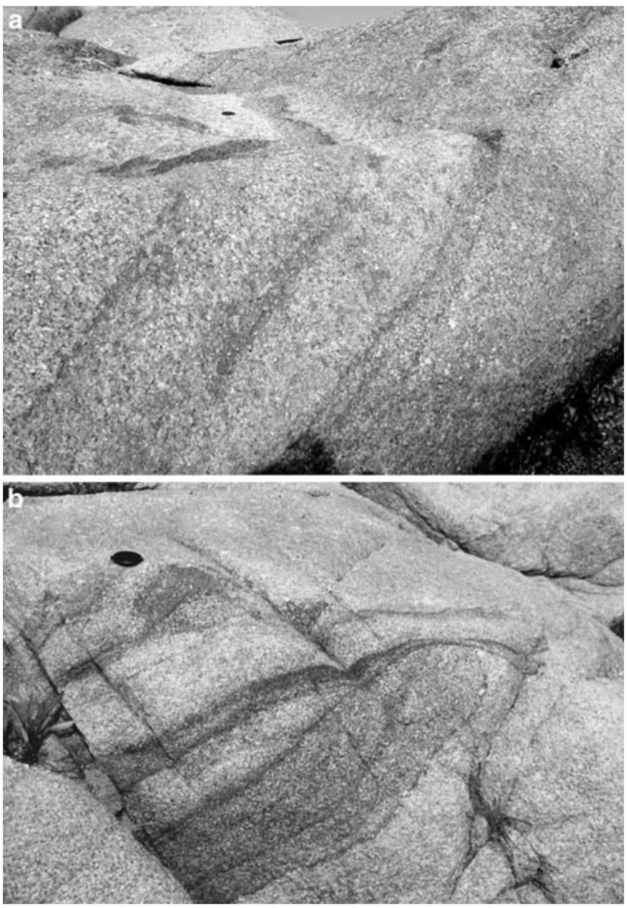


Fig. 2 Field photographs of gently dipping schlieren presumed to originate by magmatic flow, erosion and deposition within a rheological transition between a crystal poor magma and underlying solid granite. **a** Planar layering. Below the level of the photo, the lower finer-grained, more mafic layer wraps over a 10 cm enclave embedded in the underlying granite from a locality well in from the western margin of the granite (locality VH3-36 in Fig. 3). **b** Strong cross-bedded schlieren near the western margin of the granite (locality WI-3 in Fig. 3)

leucocratic granite that range from about 1 to at least 4 m in diameter.

Gently dipping groups of planar to arcuate schlieren occur widely but sparsely in the granite as thin (typically less than 1-cm thick) layers enriched in mafic minerals (Fig. 2). The schlieren variably consist of uniform, graded and cross-bedded layers. They closely resemble similar features that have been widely reported in other granites (Gilbert 1906; Emeleus 1963; Wahrhaftig 1979; McCarthy and Groves 1979). They are particularly well developed within 100 m of the southwestern margin of the granite. Mapping to date has established their distribution and orientation in the western half of the Vinalhaven granite (Fig. 3). Their attitudes are generally consistent with the orientation of the floor of the pluton inferred from the inward dipping (basin-form) mafic layers and the western margin of the pluton. We believe that these schlieren record flow of crystal-rich magmas and deposition on an aggrading floor of a magma chamber.

Steep cylindrical and arcuate schlieren, the focus of this study, are sparsely distributed in the Vinalhaven granite, and many are clearly associated with enclaves of felsic porphyry and granite.

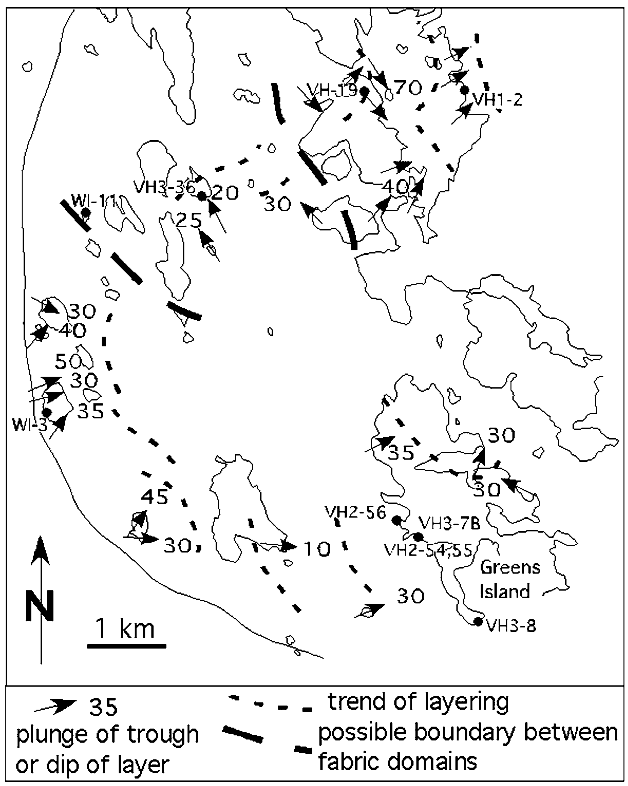


Fig. 3 Geologic map of the western half of the Vinalhaven granite, showing the occurrence of planar and trough schlieren and locations for all illustrated schlieren

Characterization of steep schlieren

Field relations and geometry of the steep schlieren

Steep arcuate and cylindrical schlieren, commonly associated with enclaves, occur most abundantly in granite exposed along the west coast of Greens Island (Fig. 3), where clean coastal outcrops, 10s of meters high, provide superb exposures on many different planes. The exposures on Greens Island allowed us for the first time to recognize the 3D form of schlieren and their striking association with pillow-like felsic and rounded to angular granitic enclaves. There, some cylindrical schlieren extend upward at least 2 m above an enclave; over that distance, the cylindrical schlieren maintain an average diameter roughly equal to that of the enclave. Axes of the cylindrical schlieren appear to plunge approximately 70°–80° SW. We believe this direction represents original vertical and that this part of the intrusion has been tilted 10°–20° NE for two reasons: (1) nearby tractional schlieren that appear to represent an aggrading chamber floor dip between 10° and 35° to the E and NE (Fig. 3), and (2) mafic layers at the southern end of Greens Island also dip gently to the NE and are cut by contemporaneous granitic pipes that plunge steeply to the SW (Wiebe et al. 2004).

Enclaves of felsic porphyry associated with the schlieren typically have rounded, pillow-like shapes. Some enclaves envelop larger crystals in the host granite. Even though the enclaves could not have been more than about 10% denser than the granitic crystal mush into which they settled, granite beneath the enclaves commonly shows a well-developed mineral foliation and flattening of smaller enclaves parallel to the base of the enclave. In Fig. 4a, the foliation extends to a depth of at least 15 cm below the enclave, whereas, away from the enclave, no foliation is readily apparent.

Within 3 m of this enclave, a vertical wall of granite exposes a similar, somewhat larger enclave (Fig. 4b). The accompanying sketch of the schlieren is a tracing of the photograph, informed by careful observation on the outcrop, where details are otherwise obscured by discoloration and surface irregularities. Pairs of schlieren can be seen to extend upward more than a meter from the outer margins of the enclave. They are defined by a concentration of mafic minerals in layers a few mm to 1-cm thick. Some lenses of adjacent parts of the granite are strongly depleted in mafic minerals. Larger tabular feldspars are weakly aligned sub-parallel to the schlieren in the outer granite, whereas granite between the inner steep schlieren appears to be massive. Several concave-upward schlieren occur beneath the enclave; to the left they terminate against the enclave, whereas they appear to connect with steep schlieren on the right side of the enclave (Fig. 4b).

Nearby another enclave with associated schlieren is exposed on a steep rock face (Fig. 4c). Here, steep schlieren are only apparent on one side of the enclave, and, instead of being sub-parallel, schlieren splay outward (to the left) from an innermost schliere that appears to be continuous upward from the enclave, well over 1 m. Otherwise, the character of the schlieren and the granite outside of the schlieren and above the enclave closely resemble those described for Fig. 4b.

Approximately 100 m to the north, more complex schlieren of similar character extend upward from the upper and lower ends of the left side of a similar enclave (Fig. 4d). The pattern of the left schlieren resembles that of Fig. 4c. The long schliere on the right terminates upward in folds. In this same area, a small enclave has associated schlieren that rise upward from its margins and bend inward, meeting in a single, double thick schlieren about 40 cm above the 50 cm wide enclave (Fig. 4e). To the north and much nearer the western contact of the granite, schlieren wrap around the base of a steep elongate enclave and extend upward and outward more than 1 m (Fig. 4f).

On the west coast of Greens Island a key outcrop provides a vertical section through an enclave and its associated steep schlieren and a horizontal section that displays ellipsoidal schlieren approximately 2 m above the enclave (Fig. 5). The vertical section (Fig. 5a) shows a relatively flat-bottomed porphyry enclave that dips about 15° to the right (east). Two apophyses of finer grained granite intrude the base of the enclave. A weak foliation with a similar attitude, defined by larger feldspar crystals, is apparent in the underlying and surrounding granite. Faint schlieren can be traced upward discontinuously from both ends of the enclave and appear to converge and possibly meet upward. Figure 5b is a view downward onto the roughly horizontal top of the outcrop. This horizontal surface shows intersecting ellipsoidal schlieren (one larger and one smaller) approximately directly above the enclave. In this same area several cylindrical schlieren of similar dimensions occur on subhorizontal surfaces (Fig. 6); these schlieren probably have the same origin as those in Fig. 5b.

Comparable schlieren are associated with granitic enclaves that range in size from about 1–10 or more meters in diameter. Several enclaves may be present in an area 10s–100s of meters in diameter. The enclaves are compositionally and texturally similar to the host granite, but generally somewhat finer-grained and more leucocratic. They have rounded to irregular margins that do not appear to cut crystals in the

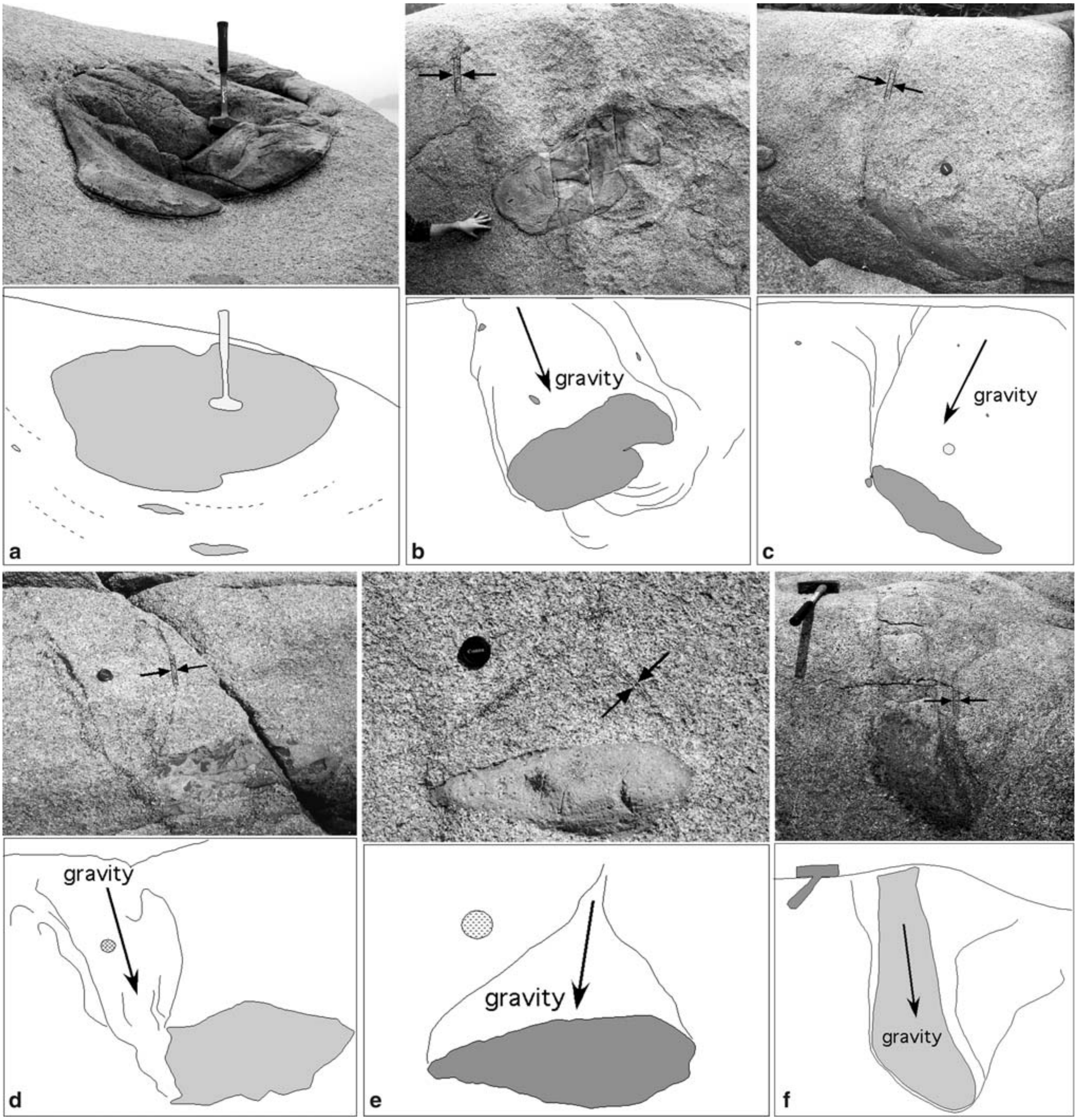


Fig. 4 Field photographs and traced sketches of felsic enclaves and associated steep schlieren as seen on steep outcrop surfaces. **a** Rounded enclave with underlying granite (and smaller enclaves) that show evidence of strong compaction (loc. VH2–54). Gravity is roughly parallel with hammer handle. **b** Large irregular enclave associated with multiple steep schlieren on both sides that rise from its margins at least 1 m upward into the granite. Multiple arcuate, concave-upward schlieren occur beneath and are truncated by the enclave. *Paired facing arrows* shown here and in later figures indicate the approximate location where schlieren thickness was measured. **c** Elongate enclave that is associated with multiple schlieren only on one side. (loc. VH2-54). **d** Arrowhead-shaped enclave with two sets of multiple schlieren attached to its left side. The arrangement of the schlieren suggests this enclave sank like those in (**b**) and (**c**), but underwent counterclockwise motion as it came to rest. (loc. VH2-56). **e** A small enclave with schlieren that rise upward from its margins and bend inward meeting in a single, double thick schlieren about 40 cm above the 50 cm wide enclave. (loc. VH2-56). **f** Steeply elongate enclave associated with steep schlieren that extend above the enclave. On both sides of the enclave the schlieren splay outward at higher levels: a single one on the *left* and multiple ones on the *right* (loc. WI-11)

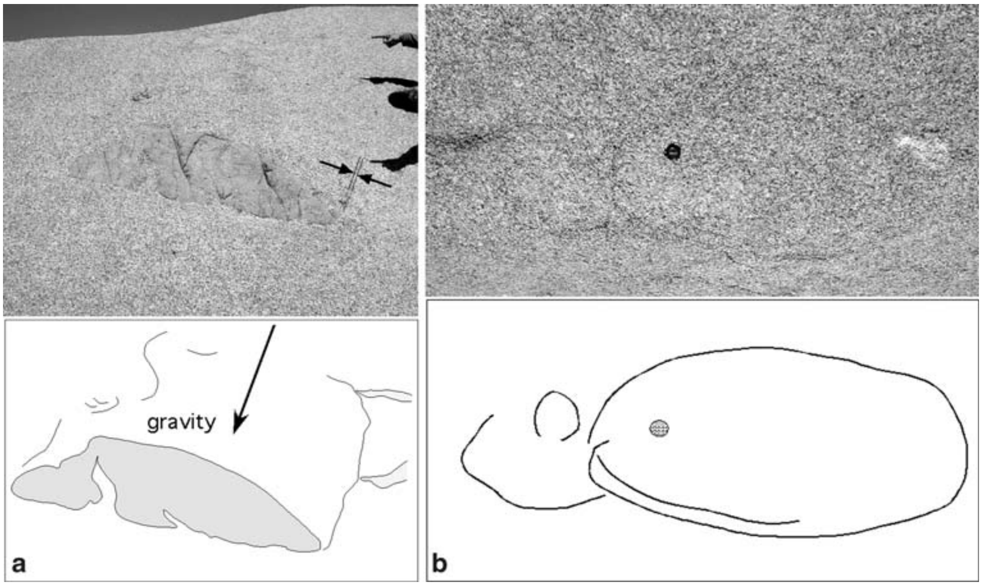


Fig. 5 Horizontal and steep surfaces intersect the same enclave–schlieren association (loc. VH2-55). **a** Photo and sketch of the steep surface that shows delicately curved schlieren extending upward from the enclave. **b** Photo and sketch of delicate ellipsoidal schlieren exposed on a sub-horizontal surface about 2 m above the enclave. Gravity is approximately perpendicular to the rock surface. These *ellipsoidal forms* approximately match the length of the enclave in (**a**)

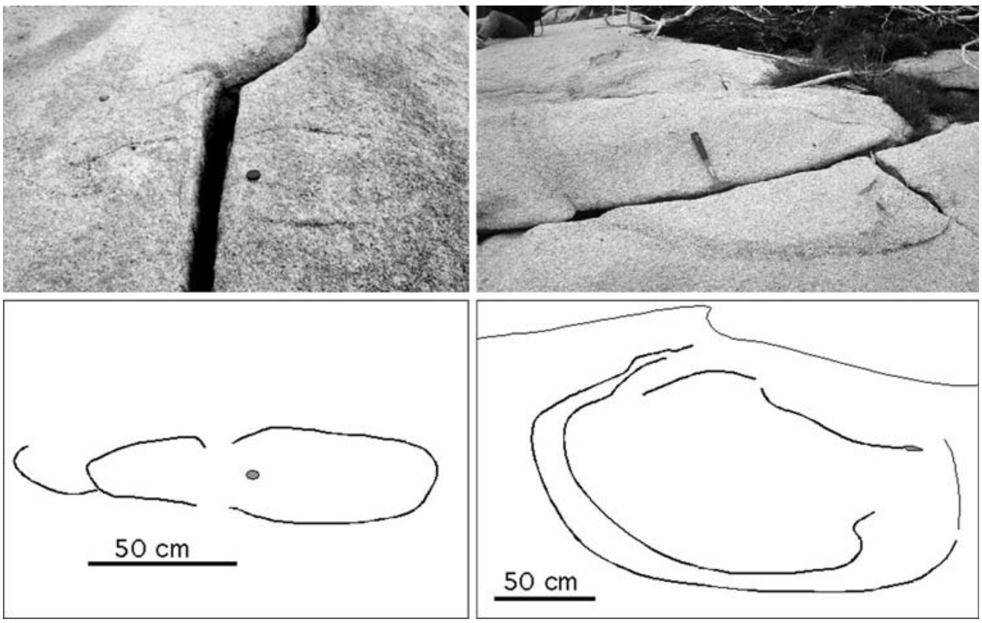
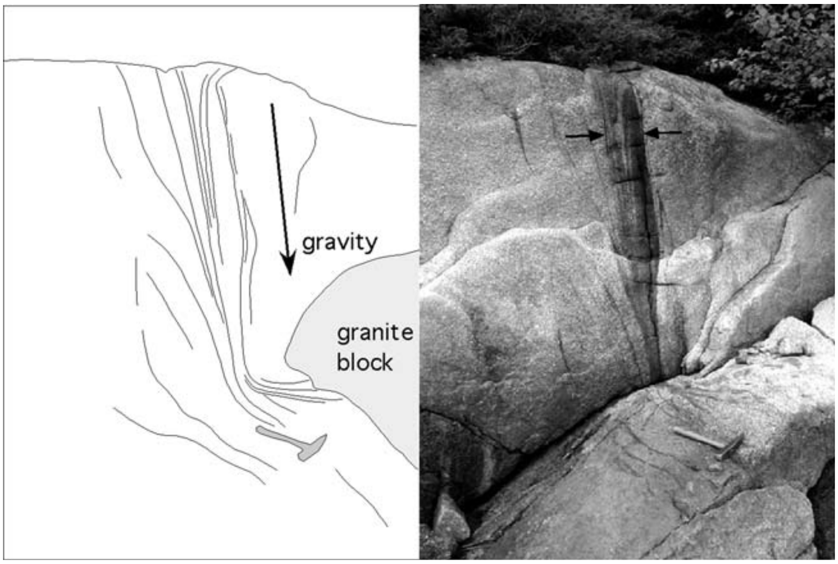


Fig. 6 Two examples of elliptical to circular schlieren on subhorizontal surfaces. Irregularities on both surfaces suggest that schlieren are steep. Original gravity was roughly perpendicular to the outcrop surfaces

enclaves. Because the granitic enclaves are larger than the felsic enclaves, it is more difficult to find exposures adequate to establish the full 3D character of their relationship to schlieren; in most occurrences one sees only a small part of any single feature. At several locations, parts of individual enclaves are exposed for distances ranging from about 1–10 m, and schlieren are generally apparent along their lower margins in the host granite.

The largest granite enclave that we have observed on a steep rock face is associated with the thickest and most mafic-rich schlieren found to date (Fig. 7). The enclave extends below the low tide line and is at least 3 m high and 3 m wide perpendicular to the rock face; its upper margin extends sub-horizontally to the right (parallel to the shore) about 6 m along the steep rock face, outside of the field of view. Steep schlieren extend at least 2 m upward from the edge of the granite enclave. The most intense group of discrete schlieren splays out upward to the left; downward, these thin and converge, curving toward the horizontal where they are truncated locally by the granite inclusion. Two other enclaves of texturally variable leucocratic granite occur within 30 m to the east along the shore on sub-horizontal rock surfaces. Each extends for roughly 8–10 m along the shore, and thin schlieren are visible along

Fig. 7 Photograph and traced sketch of intense schlieren in Vinalhaven granite and an adjacent inclusion of slightly more leucocratic granite (loc. VH1-2). The inclusion extends downward past the low tide line and must be at least 4 m tall; its upper margin extends sub-horizontally to the right about 6 m along the steep rock face, outside of the field of view. The most intense group of discrete schlieren splays out upward to the left; these thin and converge, curving toward the horizontal where they are truncated locally by the granite inclusion



parts of their margins. Large steep cylindrical schlieren that are not connected to granitic enclaves also occur in an area of Greens Island. They have diameters comparable to diameters of granitic enclaves in nearby outcrops.

Schlieren widths and enclave sizes

There is a linear relation between schlieren thickness and enclave size (Table 1; Fig. 8). Where possible, we measured schlieren width, w, (at positions shown in Figs. 4b–f, 5a, and 7) and enclave length, l. The scale l is taken to be the maximum measured side length for elongate blocks and the average of the maximum and minimum lengths for equant enclaves, and is discussed in more detail below. In Fig. 8, the inset is the same plot expanded to include an additional measurement obtained from the largest enclave. Both plots constrain the average slope to be approximately 15.5 over a more than 1.5 orders of magnitude variation in enclave length.

Table 1 Steep schlieren thickness and sizes of associated enclaves in the Vinalhaven granite

Illustration	Schlieren thickness (mm)	Size of enclave
Fig. 4b	50–70	75 cm (50 × 100)
Fig. 4c	20–30	45 cm (20 × 70)
Fig. 4d	10–20	22 cm (15 × 30)
Fig. 4e	10	35 cm (20 × 50)
Fig. 4f	15–20	50 cm (20 × 80)
Fig. 5a	10–15	65 cm (30 × 100)
Fig. 7	200–300	>400 cm >(300 × 300 × 600)

Schlieren thickness is defined as the distance from sharp edge (toward enclave) back into ‘‘normal’’ granite. Most enclaves are seen only in two dimensions; the average size stated is the average of length and width. The (minimum) size of large granite enclave (Fig. 7) is the average of exposed distances in three dimensions

Petrography

The coarse-grained granite is leucocratic with a color index (CI) between 2 and 7; representative modes are listed in Table 2. The granite commonly shows very weak foliation and lineation defined by the shape-preferred orientation of the most abundant phase, tabular alkali feldspar (5–10 mm). Orientation and

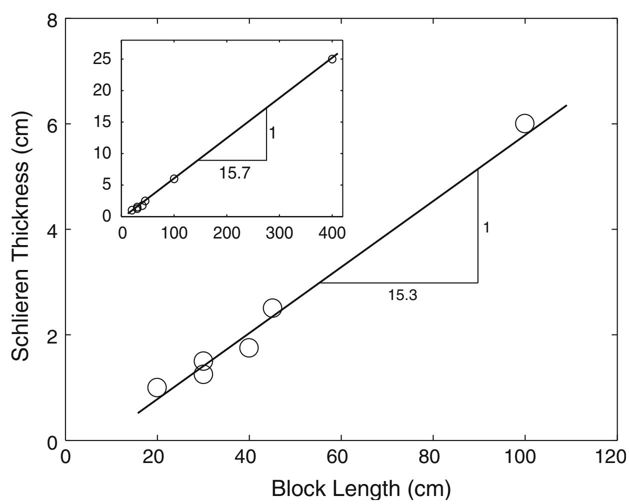


Fig. 8 A plot of enclave length versus schlieren thickness. Schlieren width is measured at positions shown in Figs. 4, 5 and 7. *Inset* is expanded to include an additional measurement obtained from a very large granitic enclave. See text

Table 2 Modes of Vinalhaven granite

Sample no. (%)	VH-019	VH-002	VH-003x	WI-14A	WI-15	WI-23	WI-27	WI-33A
Plagioclase	27.4	19.2	18.5	26.6	33.3	18.6	26.4	25.3
K-feldspar	36.8	43.3	46.9	42.8	36.9	41.6	33.0	43.4
Quartz	33.7	34.4	30.5	26.9	25.8	34.6	35.8	27.0
Biotite	2.0	2.6	3.5	3.4	3.6	4.4	4.3	3.0
Hornblende	0.0	0.0	0.1	0.2	0.1	0.4	0.3	1.1
Opaques	0.0	0.4	0.5	0.1	0.3	0.4	0.2	0.2
Allanite	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Apatite	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Zircon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Titanite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.1	100.0	100.0	100.0	100.0	100.0
Color index	2.1	3.1	4.2	3.7	4.0	5.2	4.8	4.3
Grid	1 × 1 mm	2 × 2 mm	2 × 2 mm	1 × 1 mm	1 × 1 mm	1 × 1 mm	1 × 1 mm	1 × 1 mm
No. of points	811	1,000	1,000	1,319	1,320	1,328	1,358	1,326

Sample no. (%)	WI-34A	WI-37	WI-39A	97VH-7A	97VH-6	VH3-7B1	VH-001	Average
Plagioclase	14.5	19.2	27.5	28.5	28.4	32.9	34.6	25.4
K-feldspar	54.6	43.3	38.9	35.0	29.0	34.4	26.2	39.1
Quartz	27.0	32.5	28.8	33.2	37.9	30.1	32.0	31.3
Biotite	3.5	4.1	3.9	2.5	3.2	2.5	6.8	3.6
Hornblende	0.3	0.4	0.5	0.4	1.2	0.0	0.1	0.3
Opaques	0.1	0.5	0.4	0.2	0.1	0.0	0.3	0.2
Allanite	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0
Apatite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zircon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Titanite	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Color index	3.9	5.0	4.8	3.3	4.7	2.6	7.2	4.2
Grid	1 × 1 mm	1 × 1 mm	1 × 1 mm	1 × 1 mm	1 × 1 mm	1 × 1 mm	0.5 × 1 mm	
No. of points	1,357	1,405	1,281	1,345	1,276	1,100	1,167	

relative strength of foliation and lineation appear to be variable even at the outcrop scale. Equant quartz is the next most abundant phase (3–8 mm) followed by weakly tabular plagioclase of comparable size. Biotite (1–3 mm) is the dominant mafic phase along with sporadic minor hornblende and accessory Fe–Ti oxides, apatite, allanite, titanite and zircon. Mafic microgranular inclusions are sparsely distributed in many areas of the granite; they are rarely larger than 1 cm in diameter and consist mainly of fine-grained plagioclase and hornblende.

The mineralogy of the schlieren is identical to that of the granite; the schlieren differ mainly in being more fine-grained with higher concentrations of mafic minerals (Table 3). One side of the schlieren has an abrupt grain-size and modal contrast with the granite and the other side grades in grain-size and mode back to cg granite (Fig. 9). Typically a zone about 1 cm thick has the finest grain-size. In this zone mafic minerals are greatly concentrated: on average, the color index of this zone is about ten times that of the granite. Quartz and plagioclase are, on average, only slightly depleted in abundance compared to granite, although in the thickest fine-grained mafic zone plagioclase is strongly depleted, while quartz is only slightly depleted. K-feldspar, on average, has only about 25% of its abundance in compared to granite (~10% in schlieren and ~40% in granite).

In the finest grained zone of the schlieren, all minerals have comparable size ranges (e.g., 0.5–2.5 mm) (Table 4). Biotite and hornblende have similar sizes in both granite and schlieren, but the range extends to larger sizes in granite. The sizes of both quartz and plagioclase are smaller than in typical granite (0.5–2.5 mm compared to 0.5–8.0 mm); the size range of K-feldspar is about 0.5–3.0 mm compared to 0.5–10.0 mm in the granite. The smaller crystals that occur in this zone, including biotite, are nearly equant. As a result there is no obvious preferred orientation in that zone. Schlieren that extend upward from the margins of enclaves consistently have a sharp boundary against granite that lies above the enclave and grade (in grain-size and mode) outward into the surrounding granite. Larger, tabular crystals in the outward gradation to

Table 3 Modes of schlieren

Sample no. (%)	01-RW-1	VH3-29C	VH-019vt	VH3-8-1-B	VH3-7B-2	Average
Plagioclase	8.1	25.4	22.3	32.8	24.1	22.5
K-feldspar	1.3	10.8	17.7	13.0	7.9	10.1
Quartz	26.6	28.9	33.6	21.0	21.1	26.2
Biotite	48.5	30.4	23.4	20.9	37.1	32.1
Hornblende	10.8	3.0	1.5	8.5	7.1	6.2
Opaques	3.8	1.0	1.0	1.4	2.1	1.9
Allanite	0.2	0.0	0.4	0.0	0.4	0.2
Apatite	0.5	0.2	0.1	0.4	0.2	0.3
Zircon	0.2	0.1	0.0	0.0	0.0	0.1
Titanite	0.0	0.2	0.0	0.0	0.0	0.0
Other	0.0	0.0	0.0	2.0	0.0	0.4
Total	100.0	100.0	100.0	100.0	100.0	100.0
Color index	64.0	34.9	26.4	33.2	46.9	41.1
Grid	0.5 × 1.0 mm	0.5 × 1.0 mm	0.5 × 1.0 mm	0.5 × 1.0 mm	0.5 × 0.5 mm	
No. of points	1,223	1,269	1,100	494	1,000	

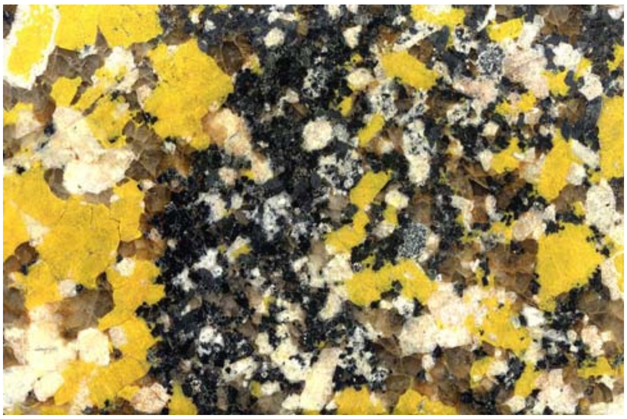


Fig. 9 Stained slab (4 × 8 cm) of a schliere showing strong modal and grain-size asymmetry (Spec. VH3-7B). The asymmetry is clearly shown by stained alkali feldspar. The finest-grained zone is about 1 cm thick and essentially lacks alkali feldspar. This zone is in sharp contact with cg granite on the *left*. The first occurrences of alkali feldspar to the right are much finer grained and coarsen to the *right*

Table 4 Comparison of crystal sizes in schlieren and granite

	Approximate ranges in crystal sizes (mm)	
	Schlieren	Granite
Plagioclase	0.5–2.0	0.5–8.0
K-feldspar	0.5–3.0	0.5–10.0
Quartz	0.5–2.5	0.5–8.0
Biotite	0.2–2.0	0.2–3.0
Hornblende	0.2–3.0	0.2–5.0
Opaques	0.1–0.5	0.1–0.5
Allanite	0.2–1.0	0.2–1.0

granite typically have a preferred orientation that appears approximately parallel to the schlieren. Granite that occurs above the enclave and within the schlieren typically appears to be massive.

The most common enclave type is felsic porphyry with between 5 and 40% variably corroded phenocrysts of quartz, K-feldspar, plagioclase, biotite and trace allanite. Texturally, they closely resemble the several bodies of porphyry that intrude and commingle with the granite. Phenocrysts in the porphyry bodies and in the enclaves have compositions and sizes comparable to minerals in the granite (Wiebe et al. 2004). The matrix of many enclaves is characterized by very fine-grained granophyric to spherulitic textures.

Feldspar orientations in granite adjacent to schlieren

Although it has proved difficult to gather samples of steep schlieren and adjacent granite that are large enough for analysis, we have worked on two samples (sample VH-19 and sample VH3-8) that appear to be representative and comparable to schlieren associated with enclaves. Because we are testing models for how schlieren form, we quantify foliation in granites adjacent to schlieren in order to evaluate deformation of the crystal mushes around enclaves. For both samples, stained vertical slabs are cut perpendicular to schlieren (i.e., vertical cross-sections through individual schliere). On these slabs, we outline individual feldspar grains and approximate the shape of each grain as an ellipse. Below and in figure captions we present two measures of the foliation defined by orientations of these feldspar grains in cross section: (1) an ellipse that represents the average of all feldspar grain shapes, and (2) rose diagrams of a subset of the feldspar grains, elongate ones whose axial ratio is greater than or equal to 1.5. Because so many of the feldspar grains are essentially equant, the axial ratios of the average ellipses are small (1.03–1.15), and the subset of elongate grains defines the foliation for both measures. Both measures of foliation generally agree with each other, but the rose diagrams suggest that some grain populations show two preferred orientations.

Sample VH-19 (Fig. 10a) shows steep schlieren that occur well north of Greens Island (Fig. 3). The magmatic foliation in the granite here is sub-vertical and strikes NE. This sample contains two schlieren that are about 10 cm apart; they are sub-planar, parallel, and vertical. The schliere in the east is about 5-cm thick and grades towards the west. The schliere in the west is about 1 cm thick and also grades towards the west. Granite in between the two schlieren (Fig. 10b) is unusually poor in plagioclase feldspar and rich in quartz. The average of feldspar grain shapes has a long axis that dips steeply towards the thicker schliere. Individual elongate grains define two populations: one sub-vertical and another dipping steeply towards the thicker schliere. Granite adjacent to the thinner schliere (Fig. 10c) contains more plagioclase feldspar but is still unusually rich in quartz. Both the average of feldspar grain shapes and the preferred orientation of elongate grains show a vertical foliation. Granite further west (Fig. 10d) is more typical of the local granite (alkali feldspar 41%; quartz 40%; plagioclase feldspar 16%; mafic minerals 2%). Again, the average of feldspar grain shapes and the preferred orientation of elongate grains agree and show a foliation that dips moderately away from both schlieren.

Sample VH3-8 (Fig. 11) comes from Greens Island (Fig. 3). In the sample location, horizontal exposure is much more extensive than vertical exposure, and we did not identify any enclave associated with this sample. The schlieren in sample VH3-8 are nested and annular (Fig. 11a), the axis of the cylinders plunges steeply, and the schlieren grade outward, as do most of the schlieren discussed above. Major mineral modes and orientations differ inside and outside the schlieren (Getsinger 2004). Inside the schlieren (Fig. 11b), in a zone about 10-cm wide, tabular alkali feldspar is the most abundant mineral. Feldspar grains define an ambiguous sub-horizontal foliation. The average of feldspar grain shapes has a horizontal long axis. Individual grains whose axial ratios are long enough to define a clear shape-preferred orientation show two populations of grains: some dipping steeply away from the schlieren and others sub-horizontal. Outside the schlieren (Fig. 11c), in a zone of similar width, quartz is the most abundant mineral. Both the average of feldspar grain shapes and the preferred orientation of elongate grains show an unambiguous foliation that dips steeply towards the schlieren.

Discussion

Origin of felsic porphyry and granite enclaves

The granite and felsic porphyry enclaves have chemical compositions and petrographic characteristics that closely match those of the host granite and contemporaneous bodies of felsic porphyry (Wiebe et al. 2004). Furthermore, they both have margins that suggest they were not completely solid when they came to rest in the host granite: the granitic inclusions have irregular margins that do not appear to cut crystals, suggesting that interstitial melt remained, and the porphyry enclaves have rounded margins that commonly mold around larger crystals in the host granite. These data and observations suggest that the felsic enclaves are comagmatic with the host granite.

Because the upper contact of the granite cuts into volcanic rocks that are coeval with granites near the base of the exposed intrusion (Hawkins and Wiebe 2004b), any early accumulations of crystals at the roof of the magma chamber must have been removed. Because the granitic inclusions are typically more leucocratic than the average granite and are comparable to the present roof granites, they probably represent material stoped from an earlier roof of a Vinalhaven magma chamber. The fact that they are common only in restricted areas suggests that each of these areas records a specific localized stoping event.

The porphyry enclaves closely match the compositions and textures of intrusive bodies of porphyry mapped in Fig. 1, some of which demonstrably formed by remobilization (rejuvenation) of granitic crystal mush by mafic injections (Wiebe et al. 2004). Individual bodies of porphyry have contacts with the enclosing granite that range from sharply crosscutting to gradational and commingling. While some of this rejuvenated magma appears to have established new magma chambers (Wiebe et al. 2004), it is equally likely that at times some of this rejuvenated magma encountered an existing chamber where movement and thermal contrast between resident magma and heated porphyry could have quenched and disrupted the rejuvenated magma, generating the felsic enclaves.

Enclaves sinking in granitic crystal mush produce steep schlieren

Steep schlieren are observed to extend upward from the sides of enclaves. This relationship strongly suggests that the schlieren formed in response to bodies sinking through weak granitic crystal mush. Three specific observations lend strong support to this interpretation:

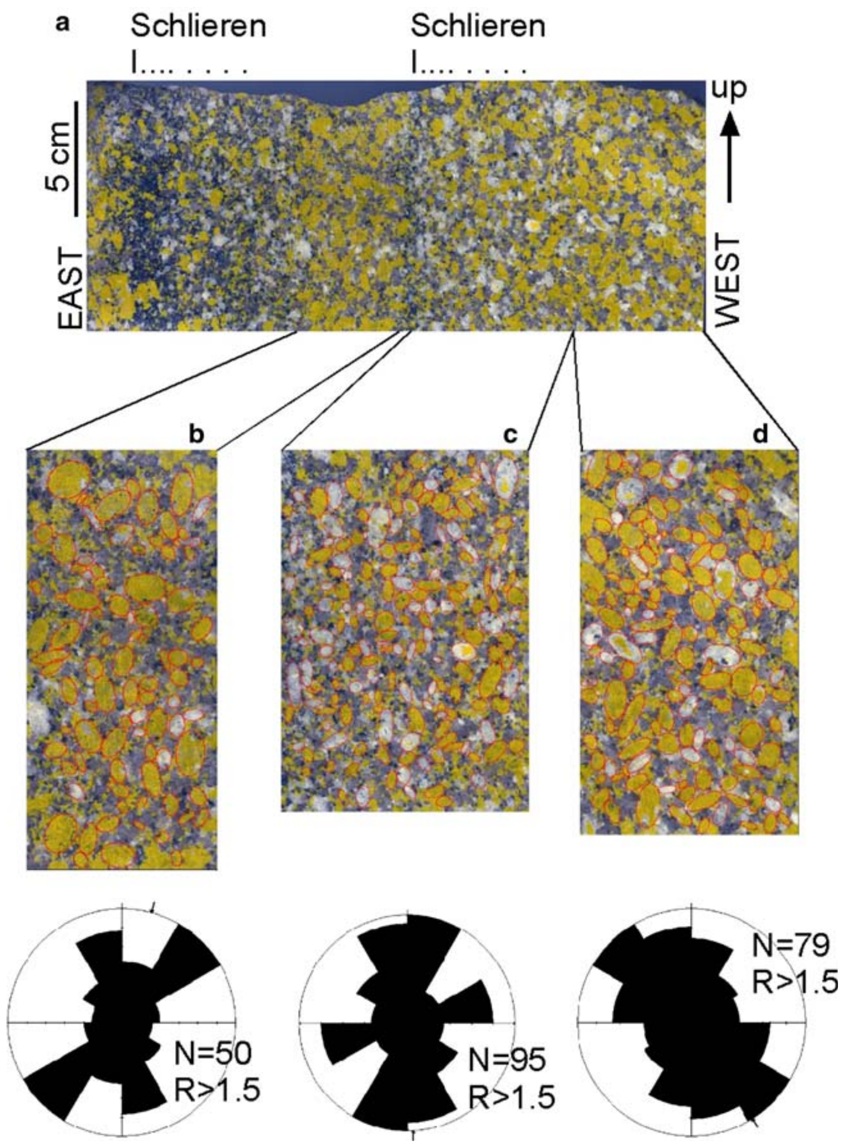


Fig. 10 **a** A stained vertical slab of sample VH-19. Alkali feldspars are *yellow*, plagioclase feldspars are *white*, quartz is *gray*, and mafic minerals are *black*. ''Up'' approximates original gravity. In *insets*, the feldspar grains used in rose diagrams and to calculate average ellipses are shown as *red ellipses*. **b** *Inset* of granite in between the two schlieren. The average of all feldspar grain shapes (N = 88) is an ellipse whose long axis dips 70° to the east, and the axial ratio of this ellipse is 1.04. The *rose diagram* below shows the orientations of elongate (axial ratio $R > 1.5$) feldspar grains (N = 50). These individual elongate grains define two populations: one sub-vertical and another steeply dipping to the east, toward the thicker schlieren. **c** *Inset* of granite adjacent to the thinner schliere. The average of all feldspar grain shapes (N = 164) is an ellipse whose long axis is vertical, and the axial ratio of this ellipse is 1.05. The *rose diagram* below shows the orientations of elongate ($R > 1.5$) feldspar grains (N = 95), and these grains show a vertical preferred orientation. **d** *Inset* of granite further west. The average of all feldspar grain shapes (N = 131) is an ellipse whose long axis dips 55° to the west, and the axial ratio of this ellipse is 1.15. The *rose diagram* below shows the orientations of elongate ($R > 1.5$) feldspar grains (N = 79), and these grains define a moderately west-dipping preferred orientation

(1) Ellipsoidal schlieren occur on a horizontal rock face about 2 m above an enclave, the size and shape of which are consistent with the apparent shape of the enclave (Fig. 5). The two views of schlieren shown in Fig. 5 strongly suggest that schlieren in the 3D shape of ellipsoidal cylinders formed as the enclave sank through crystal mush. The apparent convergence of schlieren on the steep wall suggests that this surface is an oblique slice through the cylinder. The photo and sketch in Fig. 12 illustrate this interpretation. (2) The orientation of magmatic foliation (defined by the orientation of feldspar grains) associated with schlieren is consistent with deformation of crystal mush associated with a sinking enclave. Feldspars in Figs. 10b–c and

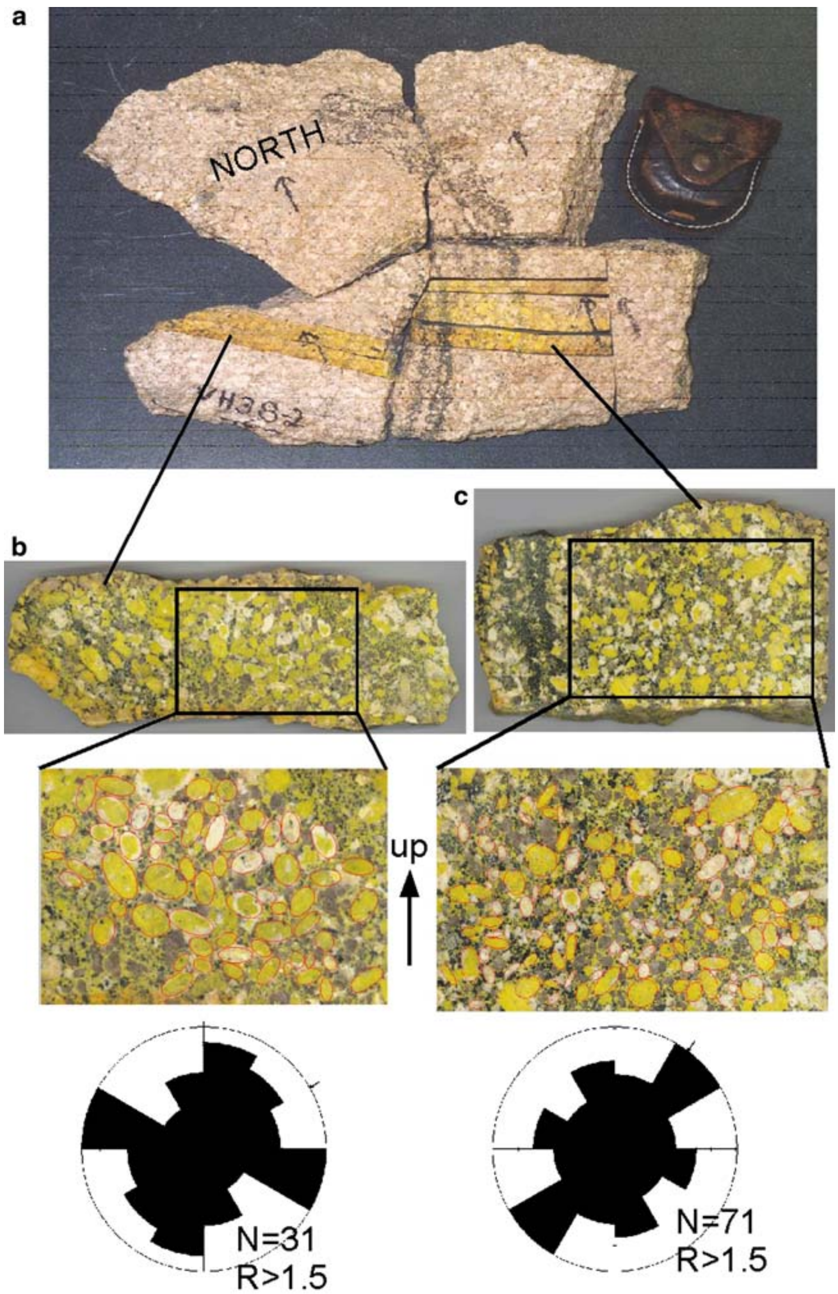


Fig. 11 **a** A map view of sample VH3-8, with Brunton compass for scale. Note the nested steep arcuate schlieren. In *insets*, both slabs are stained as in Fig. 10, and "up" approximates original gravity. The feldspar grains used to calculate average ellipses are shown as *red ellipses*. *Rose diagrams* are for a subset of these feldspar grains, those whose axial ratios (R) are greater than 1.5. **b** Slab of granite inside the schlieren. The average of all feldspar grain shapes (N = 60) is an *ellipse* whose long axis is horizontal, and the axial ratio of this ellipse is 1.03. The *rose diagram* below shows the orientations of elongate (R > 1.5) feldspar grains (N = 31). These individual elongate grains define two populations: one sub-horizontal and another steeply dipping to the west, away from the schlieren. **c** Slab of granite outside the schlieren. The average of all feldspar grain shapes (N = 112) is an ellipse whose long axis dips 45° to the west, towards the schlieren, and the axial ratio of this ellipse is 1.05. The rose diagram below shows the orientations of elongate (R > 1.5) feldspar grains (N = 71), and these grains also define a moderately west dipping preferred orientation

11b–c define foliation either parallel to or at moderate angles to vertical schlieren. If the relative orientation of schlieren and foliation is a kinematic indicator of strains acquired as a result of the gravitational settling of the associated enclaves through the magma, then vertical schlieren formed at the sides of the enclaves may record the accumulation of simple shear strains, and horizontal schlieren formed at the bases of the enclaves indicate pure shear strains (e.g., Abbott 1989). In the case of sample VH3-8 (Fig. 11), the moderate angle between schlieren and adjacent feldspar foliation gives a sense-of-shear that is consistent with a sinking enclave inside the schlieren. (3) There is a linear relationship between enclave size and schlieren width (Fig. 8). In particular, by far the largest enclave (granite) exposed on a vertical wall is associated with the most strongly developed and longest schlieren (Fig. 7).

Implications of schlieren for magma rheology

The linear relationship between enclave length and schlieren width in Fig. 8 suggests that schlieren and textural gradients identified in Figs. 4, 5 and 7 are kinematic indicators of shear strains acquired as a

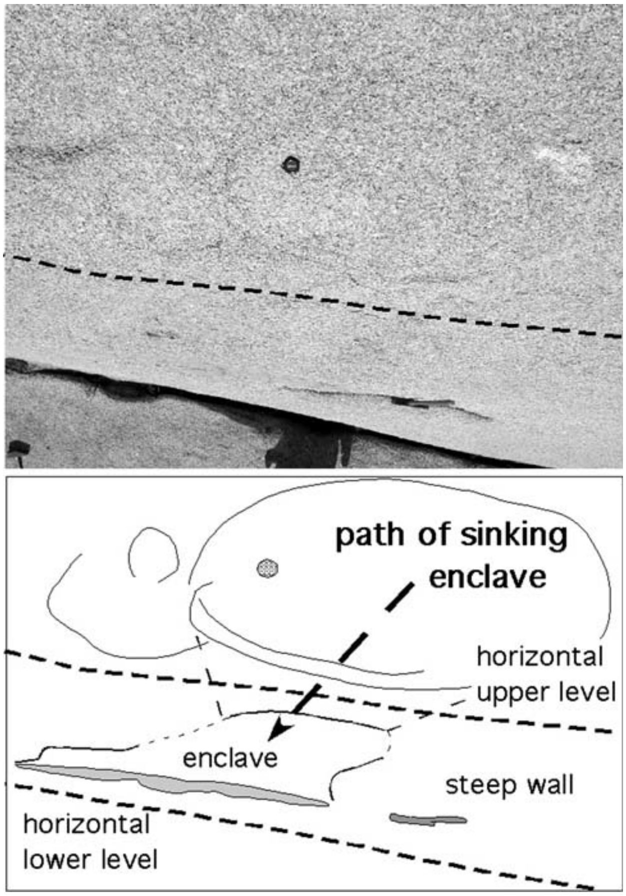


Fig. 12 Interpretation of the schlieren in Fig. 5. The *photo* shows both the delicate ellipsoidal schlieren on the upper subhorizontal surface of the outcrop and, in the lower part of the photo, a highly oblique view of the steep surface with the enclave. The *sketch* of this outcrop below shows the probable connection between the two views of the schlieren. The *dashed arrow* indicates that orientation of gravity and the path of the sinking enclave

result of the gravitational settling of the associated enclaves through the magma. The length scale of deformation preserved in the mush around the enclaves can be an important indicator of the rheology of the magma if it is non-Newtonian. Assuming that the magma through which the enclaves settled was composed predominantly of a mixture of randomly oriented equant quartz and feldspar crystals and smaller volume fraction of elongate biotite crystals, it is reasonable to expect an approximately Bingham or plastic rheology for crystal volume fractions greater than about 0.2–0.4 (Lejeune and Richet 1995; Saar and Manga 2001). A simple description of the rheology of melt-crystal mushes is a stress-dependent power law rheology, $\dot{\varepsilon} \propto \tau^n$, where $\dot{\varepsilon}$ is the strain rate, τ is the deviatoric stress and n is a dimensionless power law exponent (Burg and Vigneresse 2002). Applying this definition, perfectly plastic or Bingham rheologies with a finite yield strength and shear-thinning behavior are obtained for $n > 10$ (e.g., Jellinek et al. 2006). Newtonian viscous behavior is recovered for $n = 1$. Following the simplified analysis of England et al. (1985) and assuming that flow around the enclaves is quasi-steady, the length scale over which velocities decay from the sinking enclave into the surrounding magma by a factor of *1/e* is approximately:

$$\frac{l}{w} \approx \pi n^{1/2}, \qquad (1)$$

where l is the appropriate length scale for the enclave and w is the width of the schlieren (Table 1). From Eq. (1), the slope of a plot of l versus w constrains the power law exponent n. In the plot of l against w (Fig. 8), the scale l is taken to be the maximum measured side length for elongate enclaves and the average of the maximum and minimum lengths for equant enclaves (Kerr and Lister 1991). Slopes obtained in both plots are similar and constrain n to be in the range of 24–25. That $n > 10$ is consistent with a hypothesis that the magma had a plastic rheology with a yield strength where these enclaves were emplaced and the schlieren formed. The absolute magnitude of the yield strength implied is not uniquely constrained from the field observations owing, for example, to large uncertainties in properties such as the activation energy required for mush deformation to occur. However, a lower bound on the yield strength can be obtained from the buoyancy stress associated with the smallest enclaves associated with steep schlieren. For a 1 m diameter enclave that is 100–300 kg m^{-3} denser than the surrounding magma the yield stress, $\tau_{\text{yield}} < \Delta\rho gl < 1$–3 kPa.

Proposed model for flow

A sinking enclave will deform the mush through which it moves. In the reference frame of the enclave, flow around the enclave would generate velocity gradients from the enclave outward; the thickness of width depends on the magnitude of the stress-dependence of the mush rheology. The velocity gradient could cause crystals with the largest surface areas to migrate away from the enclave, leaving a concentration of smaller crystals at its margins (Barrière 1981; Weinberg et al. 2001). The displacement of crystals and liquid outward and upward along the margins of the sinking enclave could also generate an annular zone in which the packing of crystals is much tighter than in the surrounding crystal mush at the same level. Melt squeezed from this strongly packed, crystal-rich annular zone would probably migrate upward and outward into weaker, more porous and permeable crystal mush, away from the margin of the sinking enclave. As the enclave sinks into higher concentrations of crystals, it will encounter an increasing yield strength and cease to descend when the yield strength exceeds the buoyancy stress imparted to the mush by the enclave.

Multiple sets of schlieren are common in vertical sections, and schlieren commonly branch outward (away from the path of the sinking enclave) as they extend upward from the enclave, whereas a continuous schliere is generally present on the side toward the enclave (Figs. 4c, d, 7). This main stem appears to record the downward path of the enclave margin. The branching schlieren may record discrete pulses of flow outside of the margin in the surrounding granitic mush. As the enclave continued to sink, a strong annular zone may have caused the plane of most intense shear flow around the enclave to be displaced outward into the weaker crystal mush, generating schlieren branches. Continued downward movement of the enclave probably deformed and cut off the secondary branching schlieren. These branches therefore become younger at greater depth. Figure 13 is a schematic diagram that illustrates this hypothetical sequence of events.

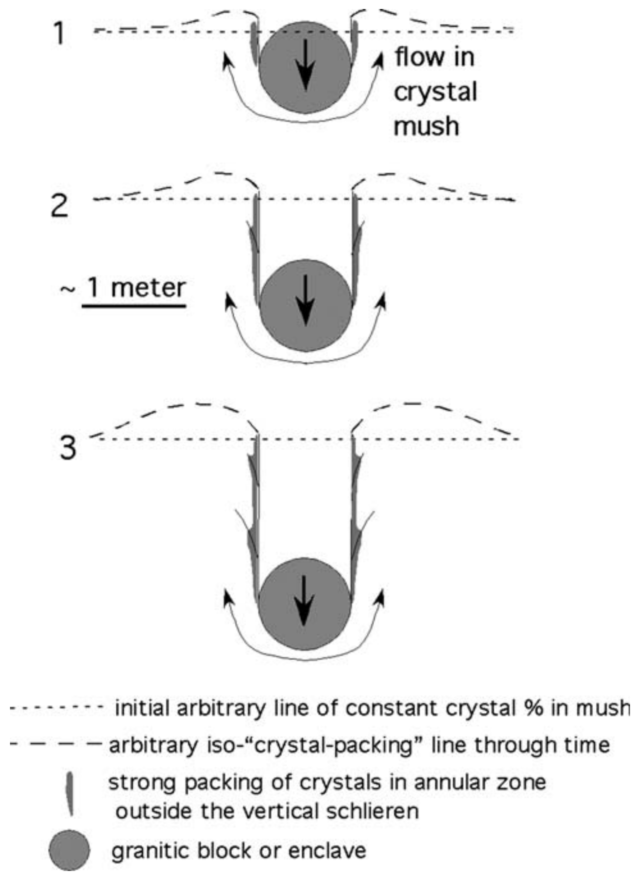


Fig. 13 Schematic diagram of a sinking spherical enclave shown at three stages as it sinks through crystal poor magma into a rheological transition to crystal-rich material at the base of a magma chamber. *Large arrows* indicates orientation of gravity; *small arrows* indicate movement of crystal and melt in response to sinking enclave

Origin of schlieren variability

In the Vinalhaven granite, natural examples of schlieren associated with enclaves vary considerably in details (Figs. 4, 5, 7). Some of this variability could be the result of the different shapes and sizes of the bodies and of different states of the crystal mush through which they sank. Nonetheless, there are several features of the schlieren that occur in most examples observed and appear to be consistent with the suggested model: (1) Schlieren typically have their sharper boundary and smallest grain size on the side toward the enclave. (2) Small enclaves of identical texture occur above the main enclave and were probably torn from its margins. (3) Larger tabular alkali feldspar crystals in granite outside cylindrical schlieren tend to be preferentially aligned parallel to the schlieren and/or dip steeply toward the schlieren (Figs. 10, 11).

The schlieren shown in Fig. 4c are unusual in being clearly visible only on one (the left) margin of the enclave. This suggests that almost all upward flow of the underlying crystal mush occurred on that margin. The orientation and shape of the enclave appears appropriate to produce such flow. The sequence of outward branching secondary schlieren is very clearly developed here, perhaps because all flow occurred on that margin. The schlieren in Fig. 4d extend upward from the upper and lower corners of the left margin of the enclave. This can be best explained if the enclave moved in a counter-clockwise rotation as it came to rest. In that light, the schlieren appear to be consistent with the sinking of a bullet-shaped enclave. Prior to rotation, the left set of schlieren would then have closely resembled the main stem and branching pattern shown in Fig. 4c.

The schlieren illustrated in Fig. 4e are unique in that the schlieren appear to close inward and meet not far above the enclave and continue upward a short distance sub-parallel to each other. Although some of this closure could be a 3D effect, it appears likely that some inward collapse of originally cylindrical schlieren has occurred. This is the smallest enclave that we have encountered associated with schlieren that extend upward from its margins. It is possible that the small size of the enclave caused it to stop settling within crystal mush that had a lower yield strength than the crystal mush into which the larger enclaves settled, so that the cylindrical walls collapsed inward.

Steep schlieren commonly connect downward to single or multiple schlieren beneath the enclaves, which commonly truncate one end of the underlying schlieren (Figs. 4b, 7). In Fig. 4b, the underlying schlieren almost certainly formed in response to the enclave sinking. Crystals may have accumulated beneath the enclave because of the irregular shape of its base. The schlieren would therefore represent shear surfaces that migrated downward as more crystals attached to its base. The truncation of their left ends would have occurred as the enclave came to rest, apparently sliding downward and to the left, truncating the lower schlieren and displacing the left steep schlieren outward.

The large granite enclave also truncates underlying schlieren and appears to have rotated away from the steep schlieren as it came to rest (Fig. 7). Very weak irregular mafic schlieren within granite above the enclave (and to the right of the major schlieren) may reflect crystal mush that rose into the overlying volume after it started to rotate.

Broader implications for magma chamber structure

There is abundant evidence that the Vinalhaven granite solidified largely by accumulation on a magma chamber floor (Wiebe et al. 2004): (1) The density inversion established by deposition of a gabbroic sheet on granite typically produces a wide range of structures which suggest the floor of a granitic magma chamber is marked by an increasing percent of crystals with depth (Wiebe and Collins 1998). (2) Gently dipping cross-bedded and graded layers occur widely and locally display erosion of earlier deposits (Figs. 2, 3). Their orientations are consistent with nearby mafic layers. (3) The granite typically has a texture of close packed quartz and feldspar, typical of cumulates. (4) The cores of feldspars and quartz crystals both have widely variable zonal histories, which suggest that, early, they crystallized in different environments and later accumulated together before crystallization of their similarly zoned rims. These observations suggest that the base of a magma chamber is a rheological transition from a crystal-poor interior downward to a crystal-rich floor.

We therefore expect that a comparable transition at the floor of a magma chamber existed when the enclaves settled downward. The preservation of schlieren extending 1–3 m above enclaves and the apparent lack of schlieren at higher levels in the granite suggest that enclaves originated at higher levels, sank through a crystal-poor magma with a potentially Newtonian viscosity (e.g., Lejeune and Richet 1995), and encountered crystal-rich magma with a stress-dependent or Bingham rheology capable of preserving a record of an enclave's passage. The lengths of steep schlieren suggest that the length scale of the transition from Newtonian magma to a strong crystal mush is on the order of meters.

Comparison with other reported examples of steep schlieren

Although steep, curved to concentric schlieren have been reported in many areas, only a small number of papers have provided detailed descriptions and specific interpretations of their origin. Abbott (1989) described what appear to be similar schlieren related to plutonic inclusions (probable autoliths) that range in size from several centimeters to 10s of meters in the South Mountain Batholith. He noted that the schlieren are more closely spaced at the edge of the inclusion and spread tangentially away from it. He proposed, as we do here, that movement of the inclusion sheared the enclosing crystal mush to produce the schlieren.

Weinberg et al. (2001) also described and illustrated several steep ellipsoidal schlieren in the Tavares pluton of NE Brazil. The paper contains some excellent field photographs of ellipsoidal schlieren in 2D. Some of the schlieren in the ellipsoids illustrated appear to have their gradational margins toward the concave (inner) side and their sharper margins on the outer convex side—opposite from that found on cylindrical schlieren related to sinking enclaves. Although they interpret these features to be rising plumes of magma (''plume heads''), they report no exposures that actually link the schlieren to mafic bodies.

Barrière (1977, 1981) provided some of the most carefully documented occurrences of schlieren in the Pluomanac'h intrusion of Brittany. The schlieren there are complex and highly variable with many examples of gently dipping and steeply dipping schlieren. We visited Ploumanac'h in 2004 to see these schlieren first hand. Many of the steep schlieren resemble those in the Vinalhaven granite and many are associated with felsic porphyry enclaves of comparable size to those in Vinalhaven. Two examples provide compelling evidence for the relationship between sinking enclaves and the formation of steep schlieren. (1) On one vertical surface, schlieren could be traced upward at least 1 m above the margins of two large rounded felsic enclaves, each about 2 m in diameter. The base of the upper enclave settled onto and deformed schlieren related to the lower enclave. (2) On another vertical surface a group of felsic enclaves has fallen through gently dipping schlieren (apparently depositional in origin), displacing them downward about 1 m (Fig. 14). The gently dipping schlieren appear to record flow and deposition of crystal mush on a chamber floor. The enclaves that sank through those schlieren provide evidence of the rheological state of that crystal mush after deposition.

Wilshire (1969) described some steep schlieren that consist of a main schliere, from which several more faint schlieren branch in a manner closely resembling the schlieren shown in Fig. 4. Harry and Emeleus (1960) described one example of a similar set of nearly vertical schlieren. For all of these occurrences, the sharp margins of the main schliere are on the side away from the branching schlieren, as they are in the Vinalhaven cylindrical schlieren. The steep rock faces that they described provide only a 2D view so that the set of steep schlieren may be straight or curved either way on a horizontal section.

Possible criteria for the origin of steep schlieren

Steep schlieren are common, though apparently sparsely distributed in many granite bodies. In spite of several careful studies there are no well-established criteria to distinguish between competing interpretations. The relatively simple, straightforward relationships between schlieren and enclaves in Vinalhaven granite provide a good opportunity to propose some criteria that might prove useful in distinguishing steep schlieren formed by a sinking body from steep schlieren formed by other unknown processes. Foremost is the direct association of an appropriate enclave closely related to the schlieren. Second, arcuate to cylindrical schlieren formed by sinking enclaves appear consistently to grade outward on the convex side and are sharp on the inner concave side. If a sinking granitic body were large and had straight margins, outcrops might also present steep straight schlieren with comparable asymmetry indicating an enclave sinking on the sharp side of the schlieren (e.g., Fig. 10). A third criterion that might prove useful is the existence of secondary schlieren that branch outward from the gradational side of the main schliere.

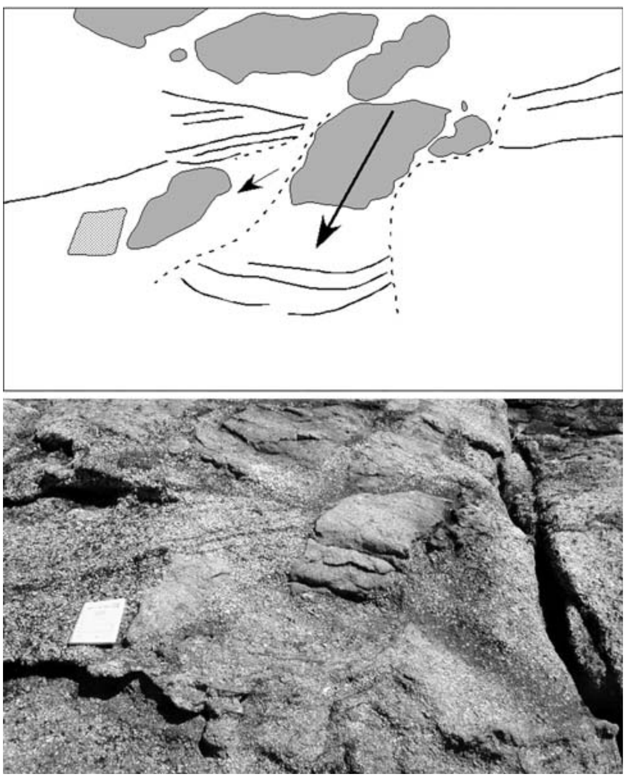


Fig. 14 Photo and traced sketch of schlieren in Ploumanac'h, Brittany, France

Conclusions

Recognition that sinking enclaves leave trails of schlieren in granite provides several important insights into how the Vinalhaven granite and possibly many other granitic bodies were produced. (1) The analysis of schlieren widths and the sizes of associated enclaves suggests that granitic crystal mush in which they settled had a plastic rheology characterized by a yield strength of the order of a few kilopascal or greater. (2) The enclaves, now enclosed in coarse-grained granite, must have existed at higher levels in a crystal-poor part of a magma chamber and settled downward until reaching material with a transitional plastic rheology before coming to rest in crystal-rich mush at the bottom of a magma chamber. The transition from a crystal-poor magma chamber to a floor of strongly packed crystal mush must commonly have been at least a few meters thick. Load-cast structures and granitic diapirs at the base of thick mafic sheets in the lower part of the Vinalhaven intrusion suggest the rheological transition could have been, at times, as much as 10s of meters thick. (3) The association of steep schlieren and enclaves may provide a means of recognizing a chamber floor within otherwise massive granite. Steep schlieren are associated with enclaves at all levels of the Vinalhaven granite. This conclusion suggests that successive magma chamber floors existed throughout the growth history of the intrusion, beginning near the base and culminating at high levels of the intrusion, and strongly supports a cumulate origin for all of the granite. (4)

Steep schlieren related to sinking enclaves appear to provide evidence for original vertical in otherwise massive plutonic rocks. In the Vinalhaven granite the axes of cylindrical schlieren appear to be sub-parallel with the axes of granitic pipes in nearby mafic sheets.

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