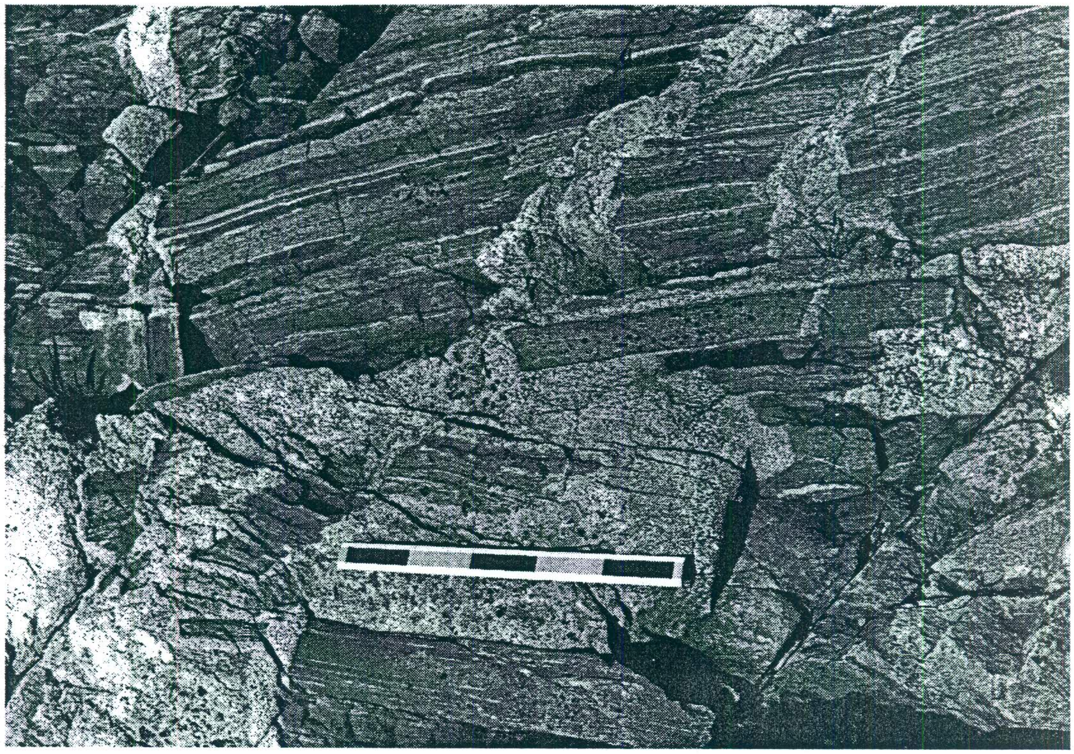
Field Trip 403, Halifax '03

FIELD TRIP GUIDEBOOK

Exploded Xenoliths, Layered Granodiorites, and Chaotic Schlieren associated with the eastern contact of the South Mountain Batholith

D. Barrie Clarke

Department of Earth Sciences
Dalhousie University, Halifax
Nova Scotia, Canada
B3H 3J5



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Department of Earth Sciences
Dalhousie University
Halifax, Nova Scotia, Canada
B3H 3J5

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Abstract

The South Mountain Batholith (ca. 375 Ma), consisting of 10-15 coalesced plutons, is the largest granitoid intrusion in the Appalachian Orogen. Its chemical composition is exclusively peraluminous (A/CNK = 1.1 - 1.3), and it contains primary magmatic biotite + muscovite ± cordierite ± andalusite ± garnet ± topaz ± tourmaline as its characteristic minerals. The batholith also displays a variety of internal physical features. At Portuguese Cove, a large exploded xenolith represents physical evidence for emplacement of the batholith by stoping. At Chebucto Head, some remarkable Skaergaard-like layered granodiorites show rhythmic layering, graded bedding, scour-and-fill, cross bedding, and slump structures, strongly resembling those in clastic sedimentary rocks. Near Prospect village are some uniform regional flow foliations, locally disrupted to produce chaotic schlieren-banded granites. At each locality, we will observe the features and try to deduce the processes responsible for their formation.

Introduction

The South Mountain Batholith (SMB) is the largest (area = 7300 km^2) body of granitoid rocks in the Appalachian Orogen (**Fig. 1**). It intrudes predominantly Cambro-Ordovician metasedimentary rocks of the Meguma Supergroup, deformed and metamorphosed in the Acadian Orogeny 410-388 million years ago. From a variety of radiometric dating techniques (Rb-Sr, ^{40}Ar/^{39}Ar, Re-Os, U-Pb), the intrusion age of the SMB is 380-372 Ma.

The SMB consists of 10-15 individual plutons – we are going to look at just one of them, the Halifax Pluton (MacDonald and Horne 1988; MacDonald and Clarke 1991). It is a concentrically zoned pluton consisting of biotite granodiorite at the outer margin, followed successively inward by biotite monzogranite, coarse-grained leucomonzogranite, and monzogranite again in the centre (**Figs. 2,3**). The central biotite monzogranite represents a reversal in the monotonic differentiation trend that began at the margin. MacDonald and Horne (1988) appealed to a late pulse of more primitive magma into the pluton to explain the compositional variation in the Halifax Pluton.

Although the primary focus of this trip is to examine three *physical* features (xenoliths, layering, and schlieren at STOPS 3, 4, and 5, respectively **(Fig. 3)**), and to consider the processes that formed these features, we are also going to consider two *chemical* aspects of the granitoid rocks: peraluminosity and chemical evolution (STOPS 1, 2, 6, 7, 8). (STOPS 2, 6, and 8 are optional, depending on available time and prevailing weather.)

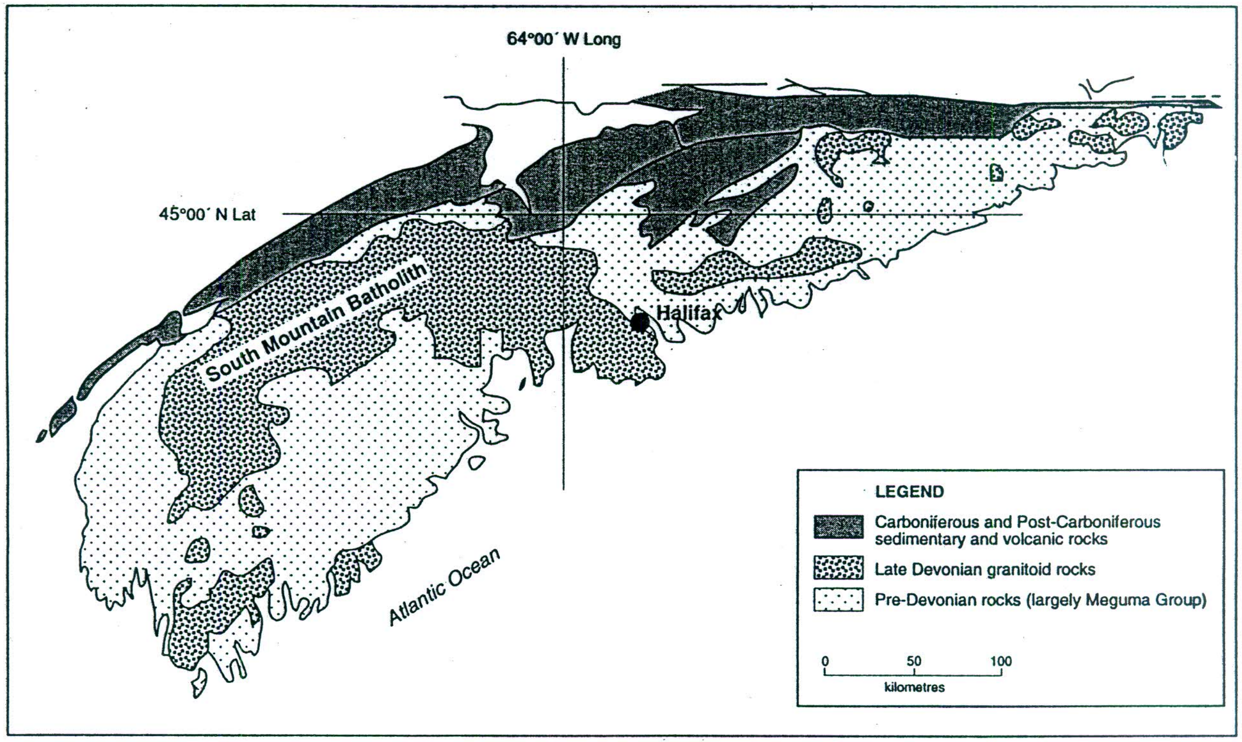


Figure 1. Location of the South Mountain Batholith in the Meguma Lithotectonic Zone.

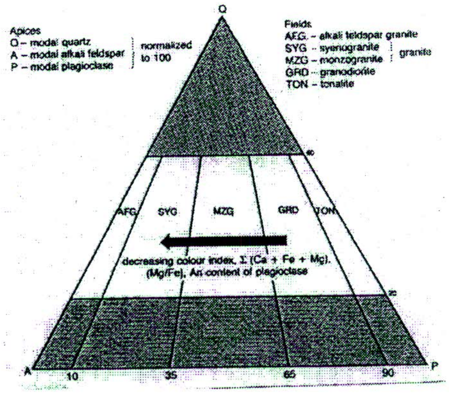


Figure 2. IUGS classification highlighting grantic rocks.

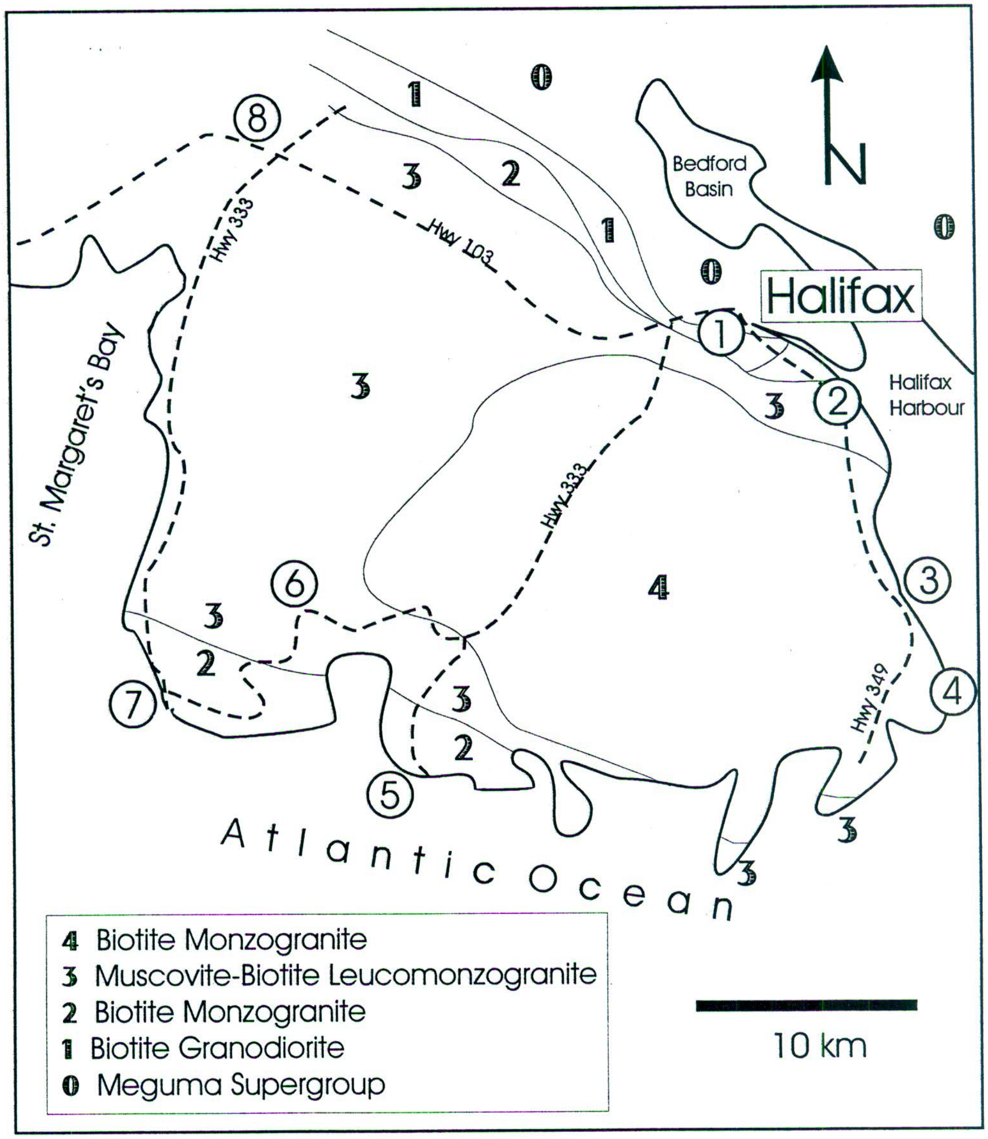


Figure 3. Geological sketch map of the Halifax Pluton (after MacDonald and Horne 1988), showing the locations of the field trip stops (circled numbers).

Physical Processes

In purely physical terms, granite magmas are hot, fluid, dynamic systems. As such, they have profound effects externally on their country rocks (thermal metamorphism, melting, thermal stress fracturing, stoping), as well as internally on their final granitic products (flow foliation, layering, schlieren, xenolith clustering).

As granite magmas cool and crystallize, they gradually change from ~0% crystals ($\phi = 0$) to 100% crystals ($\phi = 100$).
At $\phi < 55$, crystals are suspended in the melt and the magma behaves as a liquid – any structures that form in the fluid magma at this stage will probably be destroyed (**Fig. 4**).
At $\phi = 55$, crystals must interfere with one another and the magma reaches the rigidity percolation threshold (RPT) (Vigneresse and Ameglio 1999).
Between $55 < \phi < 75$, the crystals interact to the extent that the magmatic mush can flow, but it develops increasing rigidity up to $\phi = 75$, which is called the particle locking threshold (PLT) (Vigneresse and Ameglio 1999). Any structures that form in the crystal-liquid mush at this stage can be locked in permanently.
At $\phi > 75$, the crystals are completely locked together, and cannot move relative to one another by viscous flow, therefore flow foliations cannot form in this interval.

The bottom line is that granite magmas have a very narrow window ($55 < \phi < 75$) in which to *form and preserve* flow structures in granite magmas. We are going to look at several places where internal physical forces in the magma have produced some interesting magmatic structures.

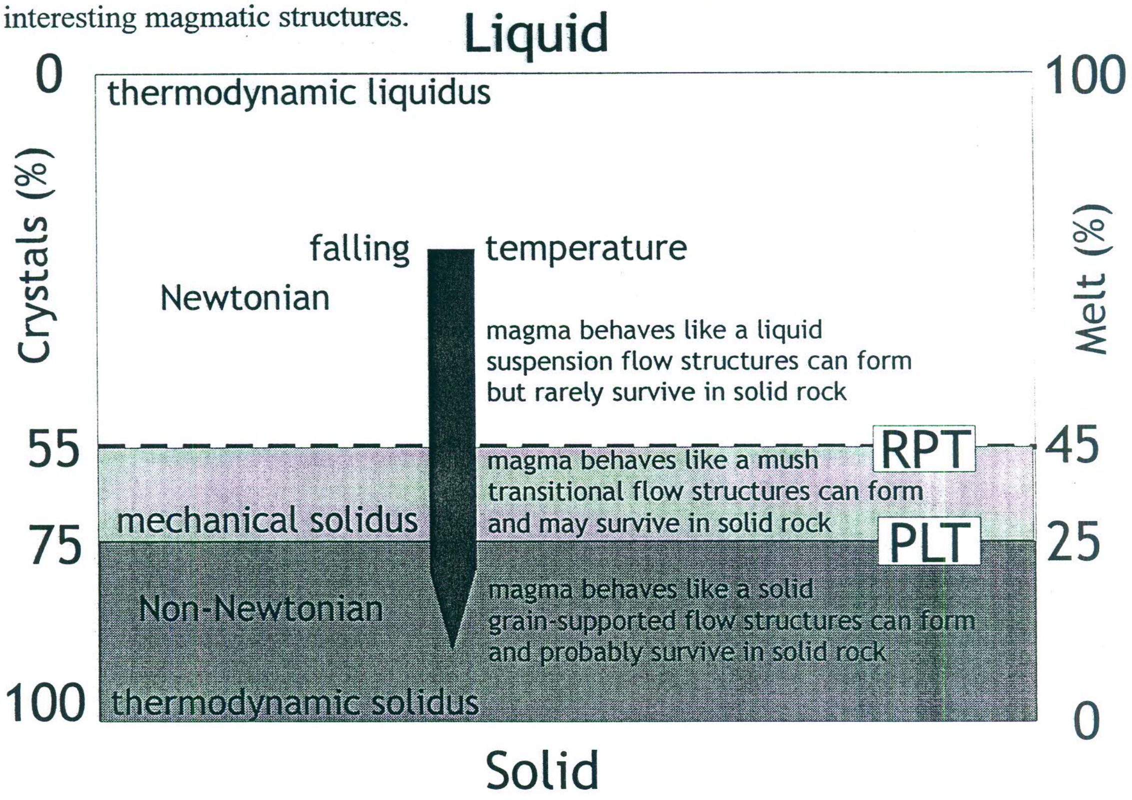


Figure 4. Variation in magma properties as a function of the degree of crystallinity.

Chemical Processes and Peraluminosity

In chemical terms, granite magmas are just enormous masses of molten, solid, and gaseous chemistry. The chemical composition of a granitic magma depends on both its source material and various physical and chemical processes acting on the crystallizing magma. During its cooling history, the SMB magma and its crystallization products undergo chemical differentiation by three main processes (Clarke and Chatterjee 1988; Tate and Clarke 1997):

(i) Crystal-Liquid Fractionation: When a magma reaches its liquidus temperature, crystallization begins and continues until it reaches the solidus temperature (where crystallization is complete). Crystals usually do not have the same composition as the surrounding melt, and any process that leads to the mechanical separation of the solid and liquid phases will create rocks of different compositions. Differences in physical properties of the liquid and solid phases, and among the various solid phases, are the main controls for crystal-liquid separation under the influence of gravity and differential (shear) flow. The widely varying proportions of biotite (~25-0 modal %) and muscovite (0-~25 modal %) in rocks of the SMB illustrate the fractional crystallization process.

(ii) Assimilation: During its ascent and emplacement, the magma inevitably incorporates fragments of the country rock. Those xenoliths must be out of equilibrium with, and must react with, the granite melt. The xenoliths that remain are just the undigested or partially digested blocks of country rock, and they represent clear evidence for the assimilation process in the SMB.

(iii) Hydrothermal 'Alteration': In the broadest sense, chemical alteration, caused by interaction of the magma and solid rocks with circulating fluids (magmatic water, metamorphic water, meteoric water, seawater), takes place at temperatures from above the granite solidus down to the weathering environment. These hydrothermal fluids are capable of adding or subtracting elements from the coexisting silicate melt or solid rocks. Some *incompatible* elements (elements that crystallizing minerals preferentially reject) are more concentrated in a late-stage melt, and have higher affinities with fluid phases. Therefore, such incompatible elements (B, Li, Cu, Mn, Mo, W, Sn, U, F, P for example) may use highly mobile late-magmatic fluids to be transported and deposited, and eventually form mineral deposits, of which there are many in the SMB (Carruzzo 2003).

All rocks of the South Mountain Batholith are peraluminous. In a haplogranite, which consists solely of quartz and feldspar, the ratio, molar ($Al_2O_3/(CaO + Na_2O + K_2O)$), equals unity, because A/CNK = 0 in quartz, and A/CNK = 1 in each molecule of feldspar (Ab, An, Kfs). If A/CNK > 1, meaning an excess alumina over that needed to make feldspars, that excess alumina must have some mineralogical expression. The main minerals to accommodate the excess alumina are: biotite, muscovite, cordierite, andalusite, and garnet (Clarke 1981, 1992) (**Fig. 5**). We will see four of these minerals in the field. Chemical analyses of more than 500 rocks from the SMB show strong inter-element correlations as a function of magma evolution (**Fig. 6a**), and an increase in A/CNK that is virtually independent of the degree of magmatic evolution (**Fig. 6b**).

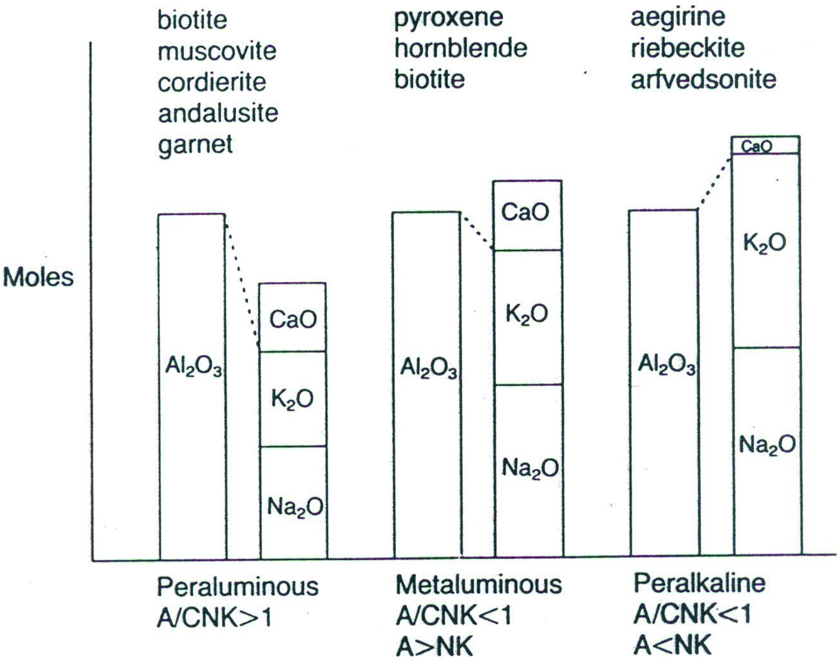


Figure 5. The relationship between alumina saturation and characteristic mineralogy of granitoid rocks.

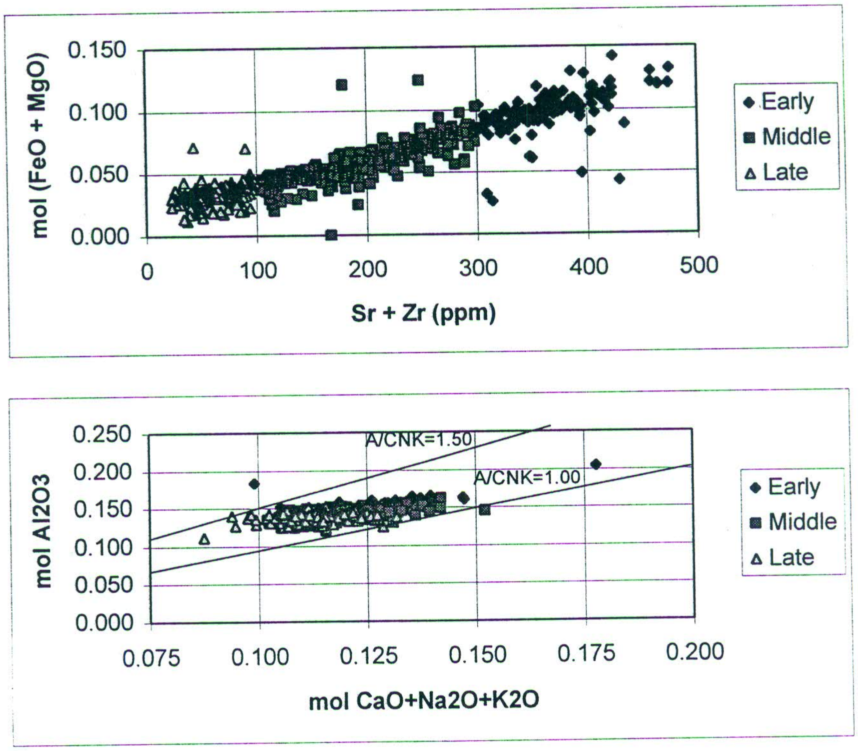


Figure 6. Chemical differentiation in the South Mountain Batholith.

Itinerary

STOP 1: Northwest Arm Drive – Introduction to the SMB

At this locality, we are ~200 metres to the west of the contact with the metasedimentary rocks (predominantly metawackes and metapelites) of the Cambro-Ordovician Meguma Supergroup (Schenk 1997). This outcrop gives us an opportunity to see the earliest and least differentiated granodioritic rocks of the South Mountain Batholith. The principal features to note here are:

- a pristine, chemically and structurally "isotropic" granodiorite, with abundant biotite as the principal mineralogical manifestation of the peraluminous character
- many elliptical enclaves (autoliths and xenoliths) with their long axes in a vertical orientation, suggesting flowage of the magma parallel to the vertical walls
- the elliptical shape of the xenoliths suggests contamination by the country rock
- some small breccia pipes/dykes containing enigmatic abundances of country rock material, and tourmaline in the pegmatitic matrix

STOP 2: York Redoubt – Cordierite-Bearing Monzogranite

A common characteristic minerals of peraluminous granites is cordierite (Clarke 1981, 1995). Of course, cordierite, garnet, and andalusite all have a stronger metamorphic connotation than an igneous one, and all three minerals do occur in the contact aureole around the SMB, so a xenocrystic origin must always be considered wherever these phases appear in the granitic rocks. Discrimination between cognate and foreign origins for these phases is based on texture (grain size, grain shape, relations with other grains) and composition (zoning, chemical equilibrium with known igneous phases). At this very short stop, the only feature we want to see is:

- subhedral to euhedral, centimeter-scale, primary magmatic cordierites (**Fig. 7**)

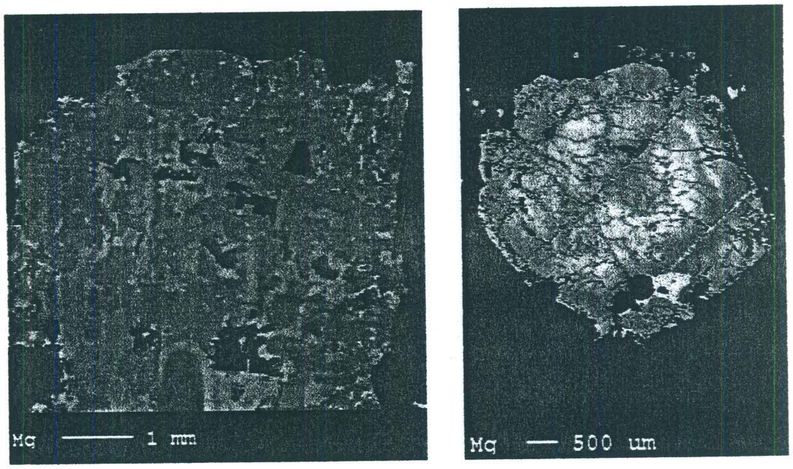


Figure 7. Magnesium X-ray maps of oscillatory zoned cordierites from the Halifax Pluton (left) and the Musquodoboit Batholith (right).

STOP 3: Portuguese Cove – An Exploding Elephant

At Portuguese Cove is a large enclave clearly belonging to the Meguma Supergroup (**Fig. 8**). Such xenolithic fragments indicate incorporation of material from the walls and roof of the intrusion. The physical process of removal is probably one of *thermal stress fracturing*, i.e., the heating, expansion, and spalling of the country rock in direct contact with the hot granite magma. The nature of the fracturing (thermal gradient cracking, thermal expansion mismatch cracking, thermal expansion anisotropy cracking) depends on the nature of the material experiencing the thermal stresses (**Fig. 9**). Once a block has spalled off to become a "free-swimming" or sinking xenolith, the process repeats itself, and the granite magma expands outwards, or moves upwards, by the process of *stoping*. The concept of stoping has been around for a long time, and the importance of stoping in granite emplacement is debatable (**Table 1**). Some geologists believe that stoping is not important in the ascent of granite magmas, because nobody ever finds floors of batholiths strewn with large sunken xenoliths, hypothetical zones known as *elephants' graveyards*. In simple terms, they say, "No elephants'graveyards, therefore no significant stoping". The large xenolith at Portuguese Cove was probably stoped from the roof of the batholith and became stuck in the granite mush as it fell (the arresting of its descent is a problem in itself!). What is remarkable about this xenolith is the large number of fractures in it (~375 over a distance of ~ 25 m), filled with granite. If this xenolith had been under a "magma-static" pressure situation, why would the melt penetrate the xenolith – what driving force, or magma-static head, would there be? On the other hand, if the xenolith were undergoing thermal stress fracturing as it descended into hotter magma, it would crack and inexorably draw the viscous magma into the vacuum of the cracks. All the fractures in this xenolith suggest that it was fragmenting during descent (**Fig. 10**), and the xenolithic shrapnel scattered around this elephant suggest that the disintegration may even have been explosive (rapid fracture propagation).

So, if xenolithic elephants disintegrate on descent, there never will be any elephants' graveyards. Instead, all one will ever find is a few elephant body parts floating around in the granite (**Fig. 11**). Their small volumes and relatively large surface areas make them ripe for reaction with, and assimilation by, the magma. In simple terms, Clarke et al. (1998) have responded to the nay-sayers, "No elephants' graveyards? No problem for granite emplacement by stoping!"

Make sure you see:

- two types of external bounding surfaces of the xenolith (straight new ones, and curved old ones)
- coarse crystal depletion zone and K-feldspar enrichment patch adjacent to the southwest corner of the xenolith
- tapered, high-aspect ratio, internal fractures filled with granite (miniature aplite-pegmatite systems a few millimetres wide)
- ductile deformation at the eastern end of the xenolith
- xenolithic shrapnel as evidence of the explosive disintegration of the xenolith
- good flow foliation and curious clusters of coarse constituents south of the elephant

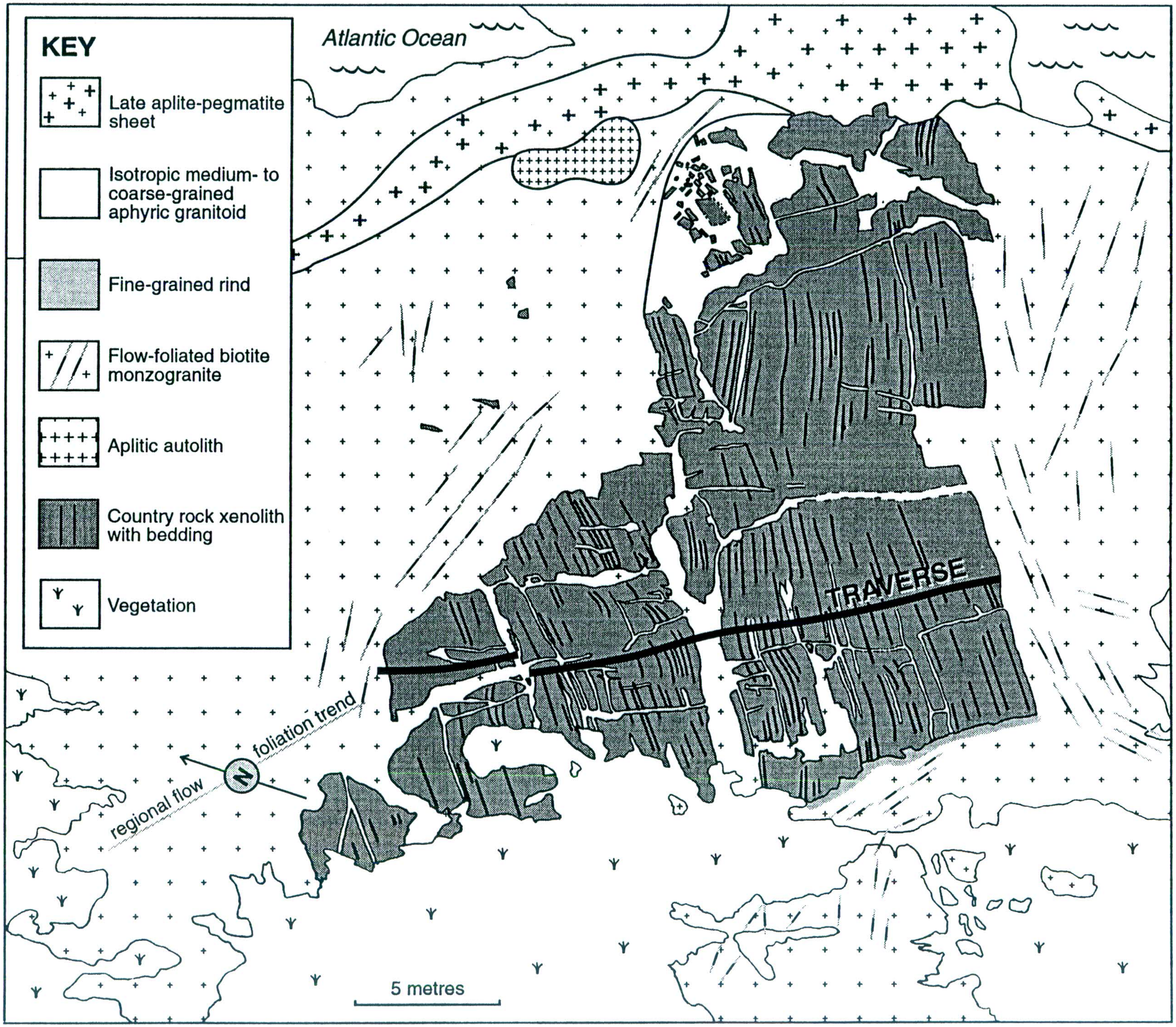


Figure 8. Sketch map of the exploding xenolithic elephant at Portuguese Cove.

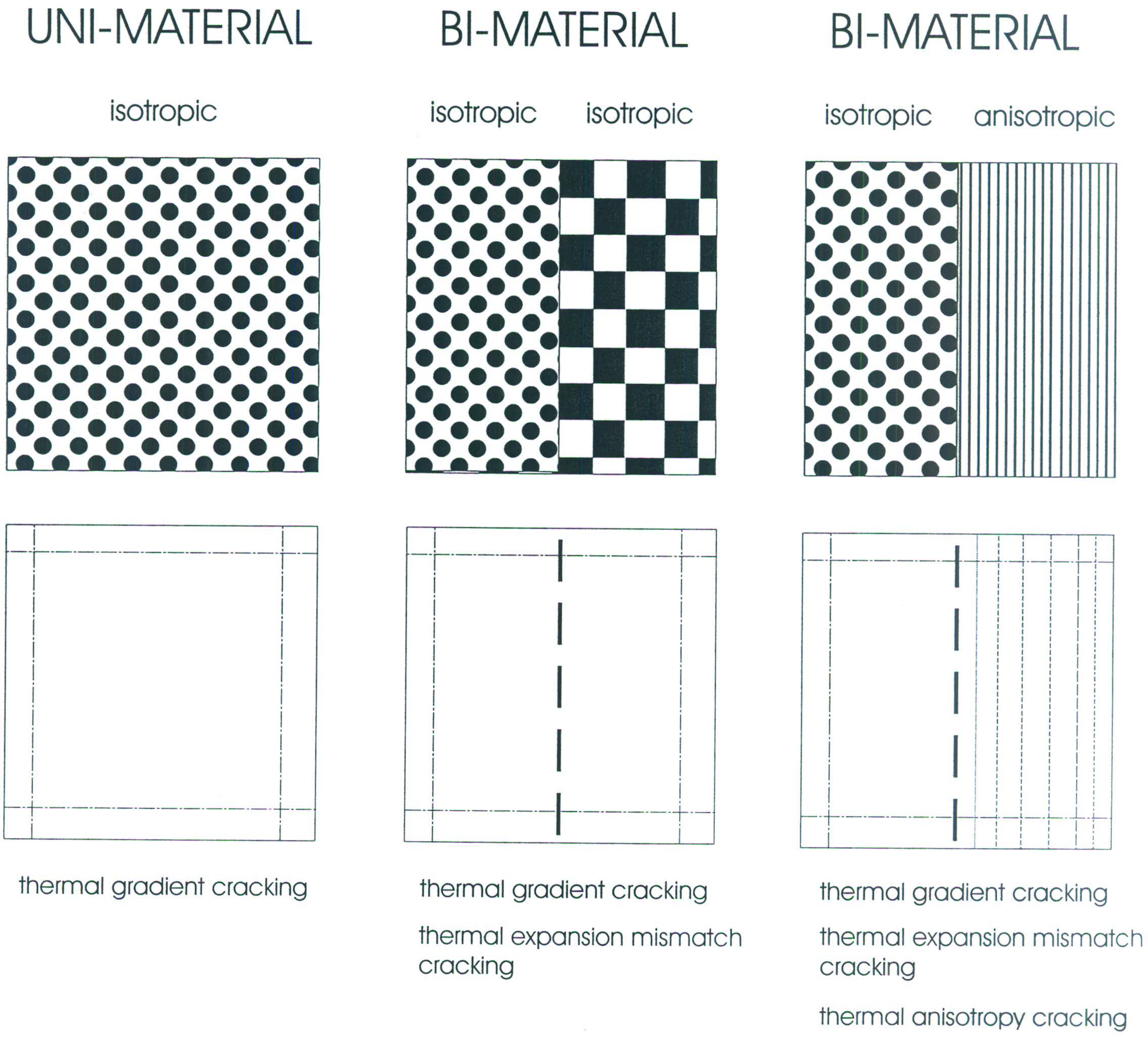


Figure 9. Types of responses of simple and complex materials to thermal stresses.

Author(s)	Role of Stoping in Magma Ascent	Fate of the Stoped Blocks
Goodchild (1892, 1894)	magmas "tend to eat their way upward in any direction of least resistance - the place of the material flowing upwards being at first taken chiefly by the colder masses of rock, which sink within the magmas fast as they are quarried" (1894)	"The inclusions appear to have been detached from the parent block…and… have quietly floated away into the molten rock, without any further change specially noteworthy." (1892)
Daly (1903a; 1933)	"It is surely unwise to try to estimate the stoping process merely by counting the visible xenoliths in intrusive bodies." nevertheless, piecemeal stoping could account for "tens, hundreds, or possibly a few thousands of meters" of ascent	"abyssal portions of plutonic magmas conspiring toward the perfect digestion of a submerged foreign rock fragment" otherwise large roof blocks just sink out of sight
Balk (1937)	just "one of the phenomena that accompany, locally and temporarily, the rise of intrusions"	
Read (1948)	"efficacy over a limited range...tens of feet"	"become incorporated in the active magma and give rise to derivatives that should be revealed in the subsequent history of the province"
Buddington (1959)		"stoping hypothesis still lacks verification in the sense that we do not have desirable supporting evidence of sunken blocks. Unless such blocks have been indistinguishably incorporated in magma, or reworked and metasomatized into new granites at depth, or have sunk to very great depths, we might expect to find more evidence of floored plutons than has been reported."
Marsh (1982)	"The congestion of the body by stoped blocks probably limits the ascent distance to a few body heights." (which could still amount to 5-10 km for large granite bodies)	"At one extreme, large blocks may spall singly from the roof and drop quickly through the magma, the block surface area relative to its volume is small, and its residence time is short. At the other extreme, small pieces of roof rock may spall in a continuous shower and thoroughly contaminate the magma in a very short time." ascent by "magmatic infoliation stoping" is "essentially undetectable by thermal and chemical contamination, if the blocks are larger than about…30 m in a granitic magma."
Castro (1987)	"stoping is a local phenomenon…usually associated to discordant plutons" and "importance of magmatic stoping in magma transport is very limited"	
Clemens and Mawer (1992)	stoping only accounts for "minor local accommodation"	
Pitcher (1993)	"piecemeal stoping plays but a minor secondary role in the emplacement process"	"...the blocks rarely enter the magma chamber! If, on occasion, they do, then it seems likely that they will sink rapidly...relative to the life of the pluton..." "we rarely see a jumble of small blocks in deeply eroded plutons"; nevertheless, Pitcher describes one ≈ 10 m block on the floor of the Tumaray pluton in Peru and states that "crystal-enclave mushes are no figment of the imagination"
Paterson et al. (1996)	"most, if not all, of the country rock in the mid- to upper crust is transported downwards in the region now occupied by the magma chamber and its aureole"	"increasing fraction of this downwards transported country rock could become assimilated by or chemically interact with magmas at deeper crustal levels"

Table 1. Evolution of ideas concerning the role of stoping and the fate of stoped blocks.

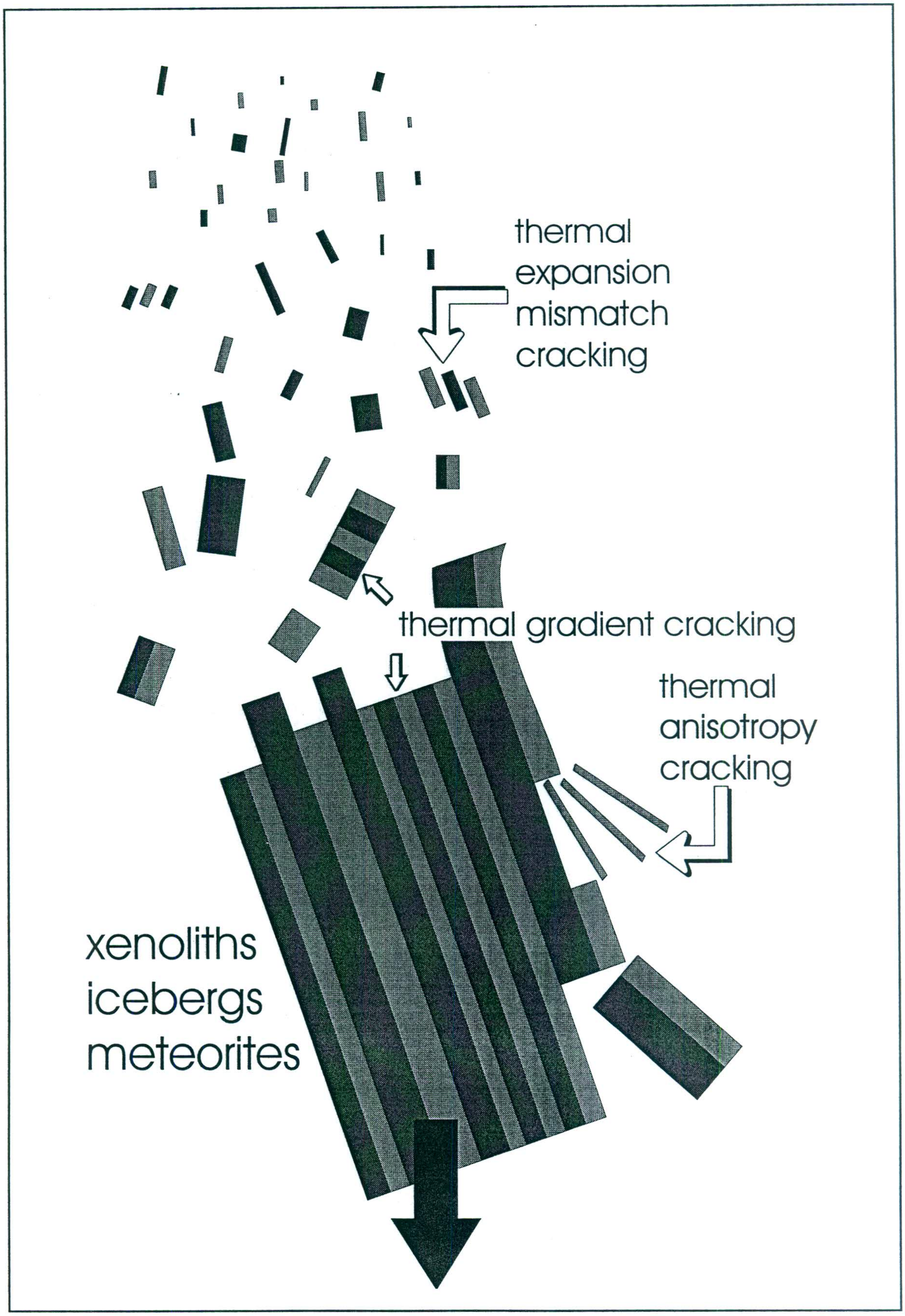


Figure 10. Falling and spalling. Several types of objects undergo thermal stress fracturing in nature. The result can be complete disintegration of the material down to the level of individual grains.

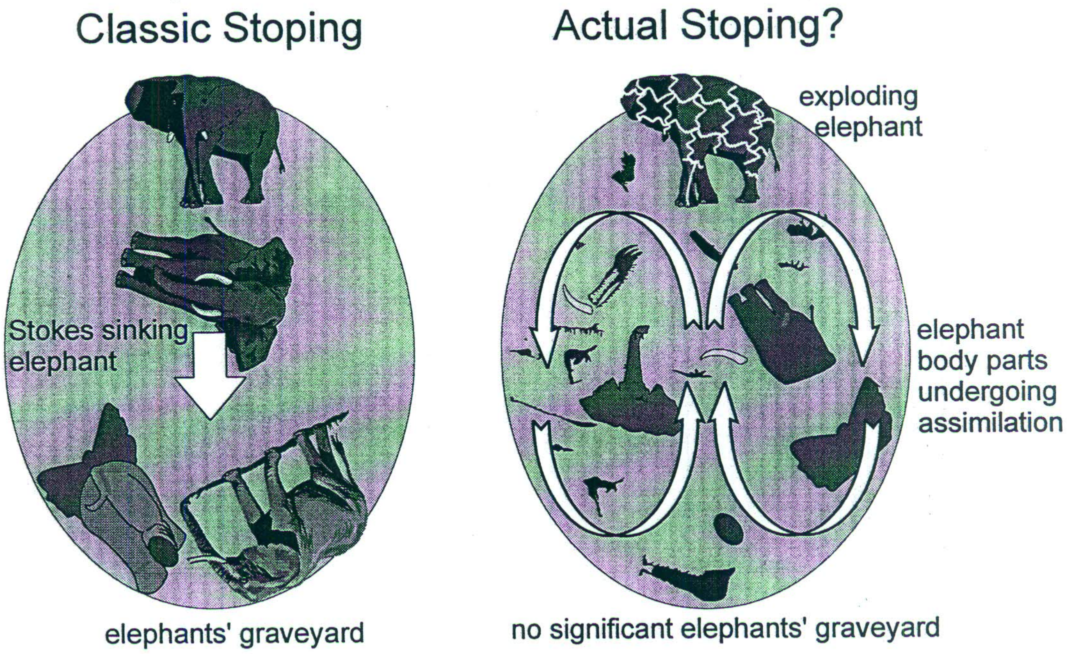


Figure 11. Contrasting models for stoping.

STOP 4: Chebucto Head – Granites Mimicking Sedimentary Structures

Layering, graded bedding, cross-bedding, scour-and-fill structures, and slumping are features normally associated with sedimentary rocks. For early workers, it was difficult to convince others that such structures could form in gabbroic magmas (10^3 times more viscous than water) to produce the Skaergaard intrusion. Another three orders of magnitude in viscosity may appear to stand in the way of such structures forming in granites, but they form nevertheless.

At Chebucto Head, we are going to look at a remarkable 7-metre thick layered granite sequence (Clarke and Clarke 1998) (**Fig. 12**). We will move systematically from the bottom of the layered sequence to the top, looking at:

- the razor sharp lower contact of the layered sequence
- scour-and-fill structures
- K-feldspar foliation without lineation
- K-feldspar megacrysts in the lower parts of the lowermost layers, but generally absent from the upper layers
- slump structures
- rhythmic layering with melanocratic biotite bases and leucocratic quartz-feldspar tops
- sharp contacts between layers, but gradational variation within layers
- inverse graded bedding (fine on bottom, coarse on top)
- bifurcating layers
- cross-bedding
- diffuse top of the layered sequence
- diapir from layers penetrating the overlying granodiorite
- log-jam dyke, its termination at the top of the layers, and its connection to the lowermost layer

Then we will try to understand how this layered sequence formed by a process of multiple injection from the log-jam dyke into a sub-horizontal fracture above a block sinking from the roof of congealed granite (**Fig. 13**). The roof material must have been crystallized sufficiently to be able to fracture like a solid (razor sharp lower contact), and yet not have been crystallized enough to prevent flowage of the diapir into the material above the layers (cf. Fig. 4). Repeated rocking downwards of the roof block can explain the multiple layers, the depositional stratigraphy (youngest on top), the scour-and-fill structures, the bifurcating layers, and the slump structures. Gravity settling can explain the modal and grain-size variation within the individual layers. Filtering of the coarse constituents (phenocrysts and xenoliths) from the thin layers can explain their concentration in the log-jam feeder dyke.

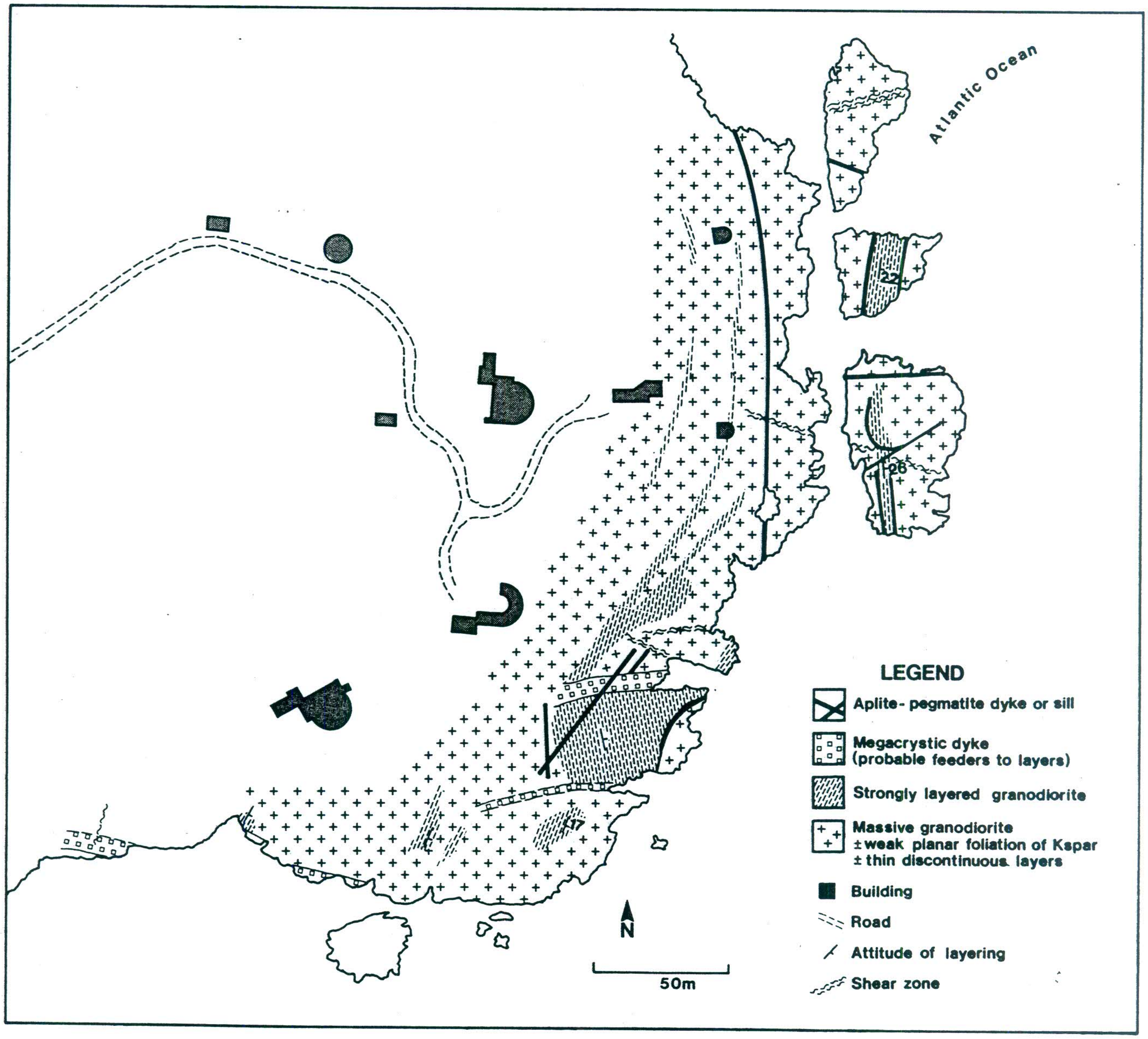


Figure 12. Map of the layered sequence at Chebucto Head.

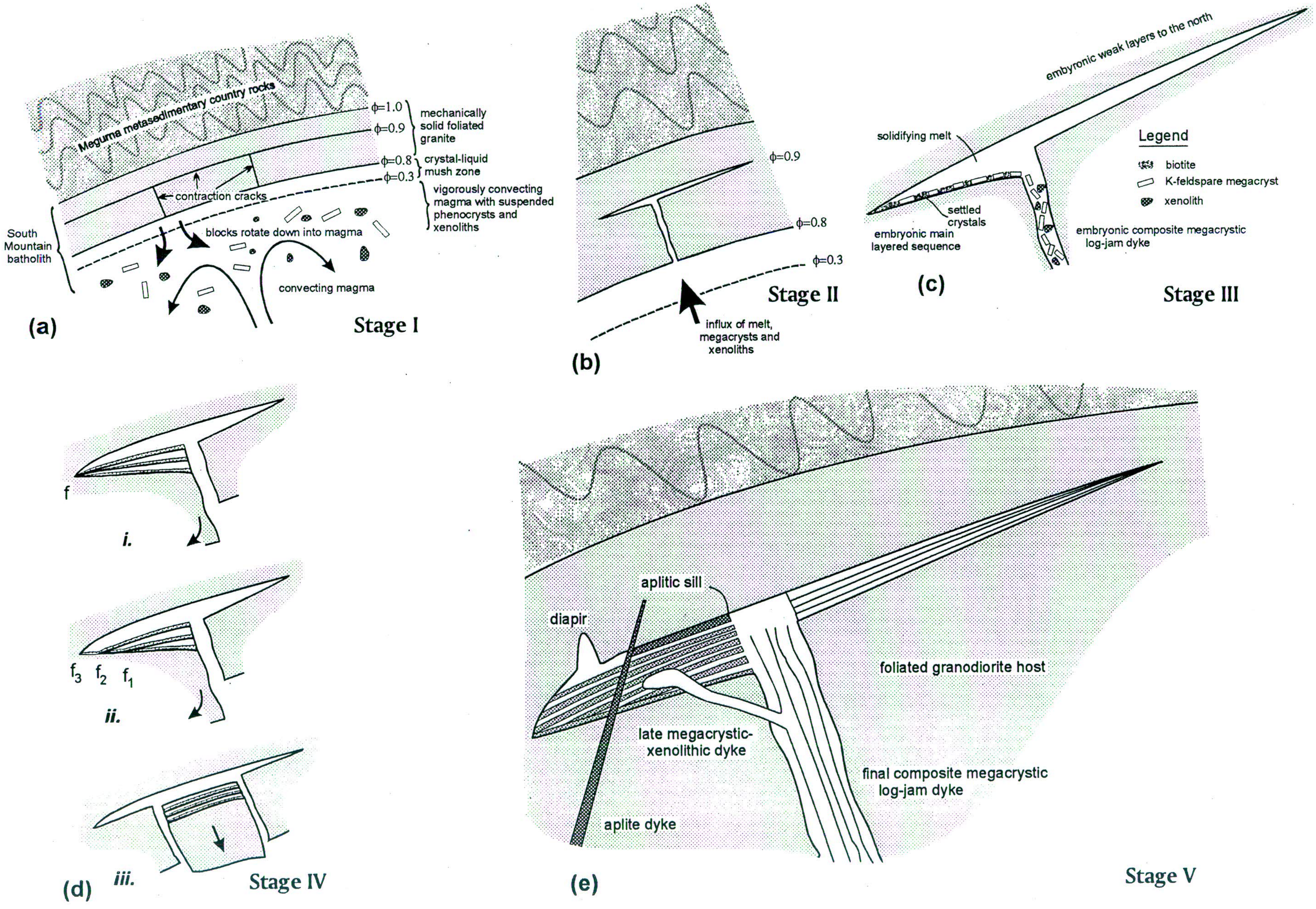


Figure 13. A model for the development of the layered sequence at Chebucto Head.

STOP 5: Prospect – Chaotic Schlieren in Ordered Flow Foliation

Schlieren are dark streaks in granites with many possible origins. As we walk out to this locality, we will note the roughly constant orientation of the flow-foliated K-feldspar phenocrysts (dents-de-cheval) and absence of schlieren (**Fig. 14**), similar to patterns mapped by Abbott (1989). However, in a relatively small area, something disrupted this regular regional pattern – the regular alignment of the Kspar and biotite disappears, and a chaotic development of biotite schlieren appears (**Fig. 15**).

	Regional Pattern (Figure 14)	**Local Disruption** (Figure 15)
Kspar phenocrysts	flow foliated regular alignment	clustered
Biotite schlieren	absent	prominent chaotic alignment

Make sure that you see (**Fig. 16**):

- relatively sharp discontinuity between the regional flow foliation and the chaotic zone
- random orientation of schlieren, size sorting of minerals, and clusters of K-feldspar
- the strange spider-shaped schlieren patterns that we call 'arocknids' – check out (http://www.dal.ca/~granite/arocknid/arocknids.htm) – circular arocknids, and randomly oriented elliptical arocknids, are problematic for those who believe that the SMB is syntectonic

What process(es) caused the local K-feldspar clustering and formation of biotite schlieren? Probably the best explanation is some type of shear flow. If one part of the magma is flowing faster than another, then a velocity gradient exists in the melt. If the sheared liquid contains large isotropic blocky solids (e.g., Kspars), those blocky solids will migrate to zones of minimum shear stress and may form clusters (cf. slurry pipes). If the sheared liquids contain small anisotropic flaky solids (e.g., biotite), those flaky solids may also become concentrated by shear flow and develop strong shape-preferred orientations, which we see as schlieren. Overall, the modal proportion of minerals in the locally disrupted area seems to be about the same as that in the regional area, suggesting that there has only been a local sorting of mineralogical constituents, largely on the basis of size and shape.

What caused the local shear flow that disrupted the regional flow pattern? It could be some sort of convective overturn in the $55 > \phi > 75$ mush, caused by differences in density or temperature. Alternatively, the local turbulence might be the pathway of a large xenolith – remember the elephant at STOP 3? – that fell through this locality producing vortex structures in its wake (**Fig. 17**).

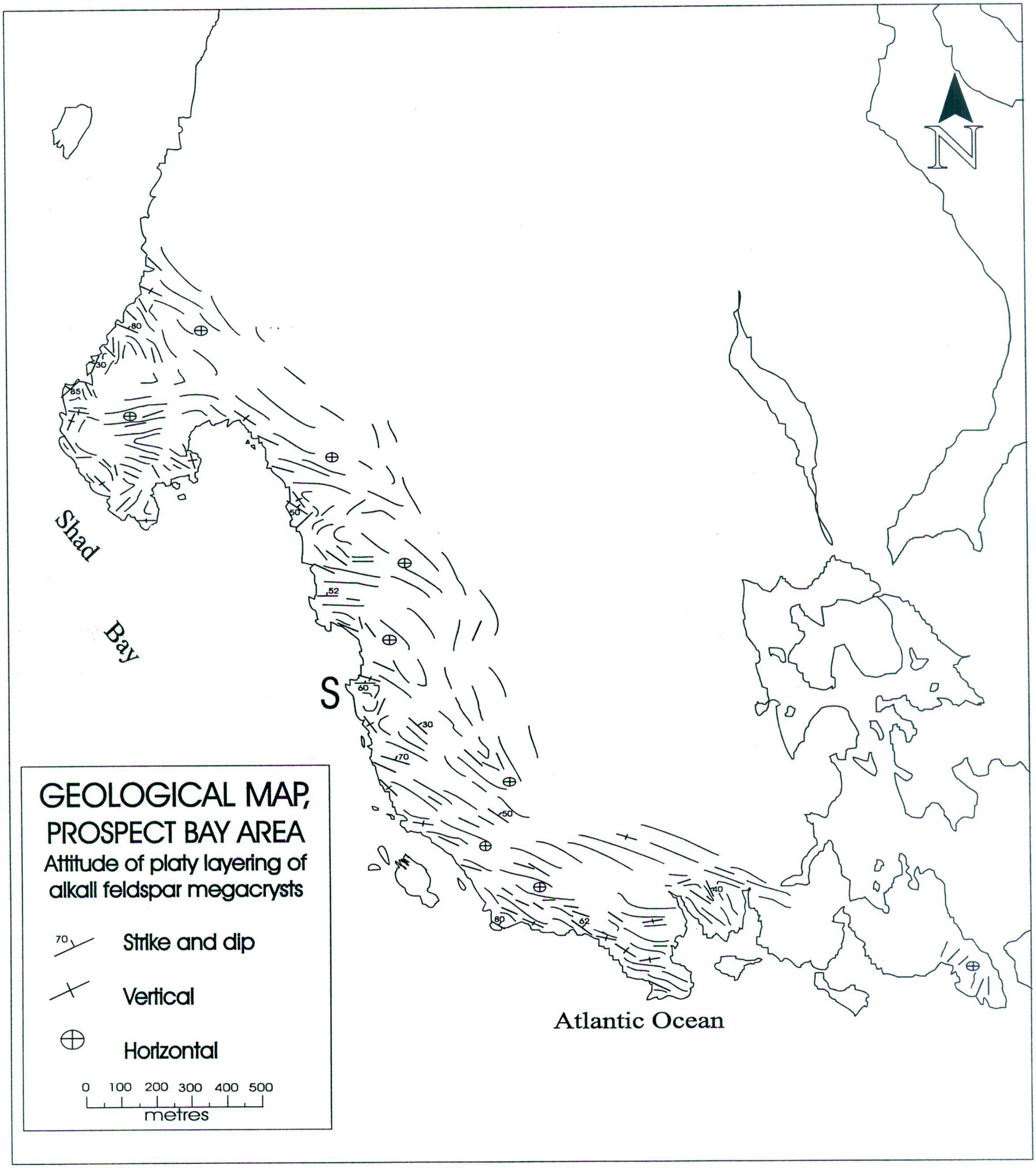


Figure 14. Regional map of the Prospect area showing foliation of K-feldspar phenocrysts. Position S marks the location of the chaotic schlieren.

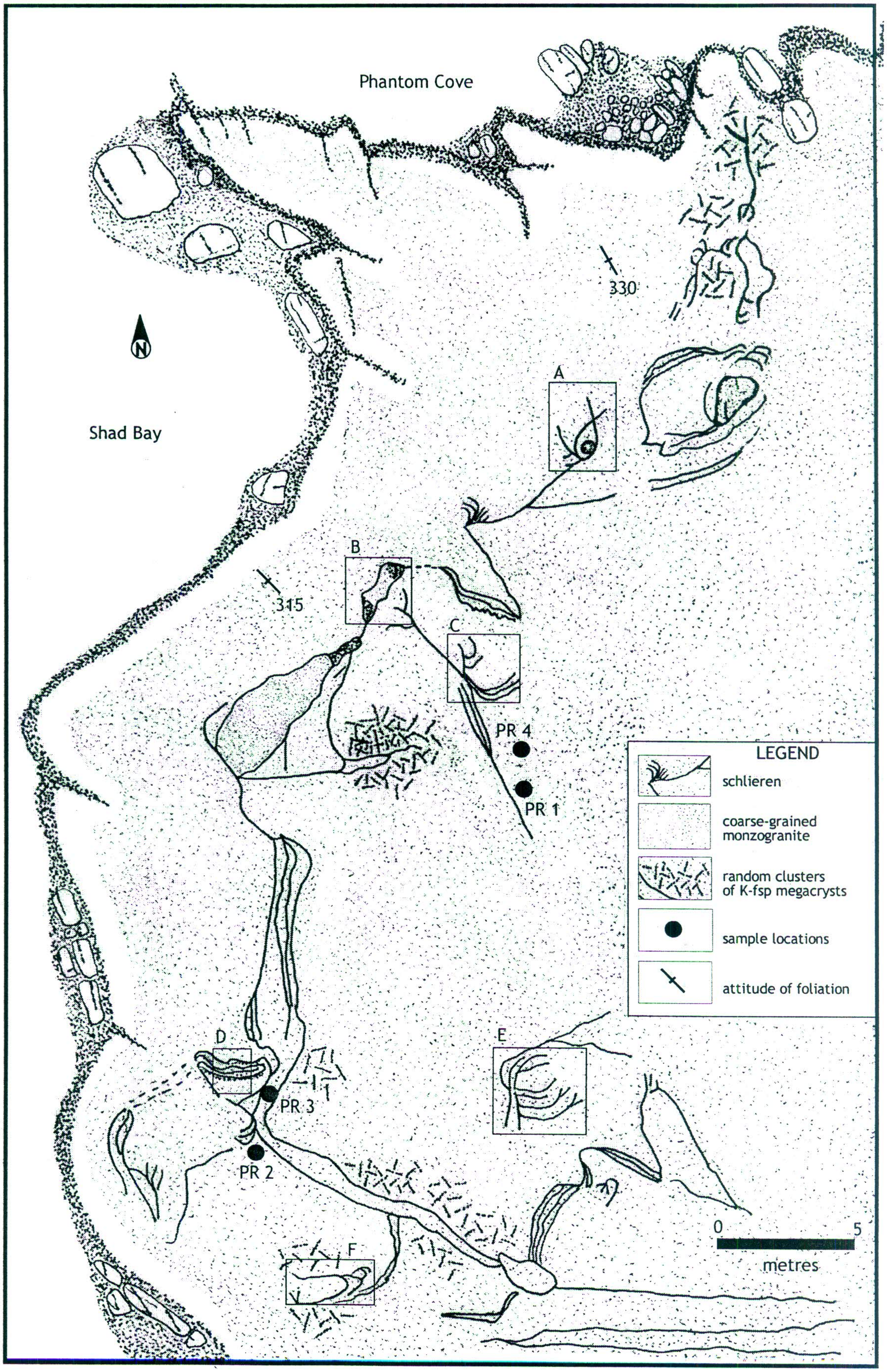


Figure 15. An enlarged map of the Prospect study area. The boxes marked (A) to (F) correspond to the photographs in Figure 15 (A) to (F). (From McCuish 2001, with permission.)

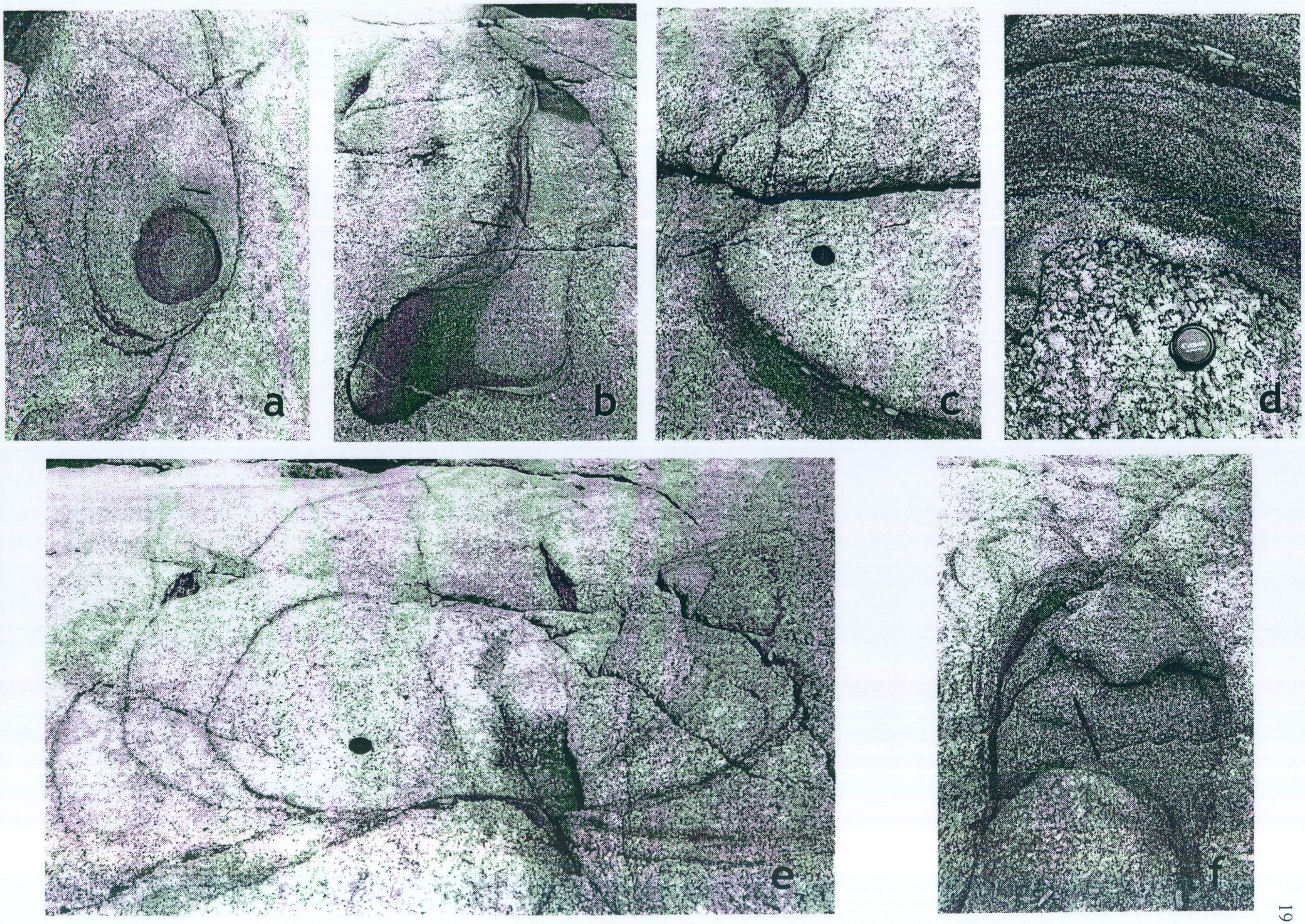


Figure 16. (a,b) Biotite-rimmed margins coarsening inwards surrounded by random clusters K-feldspar phenocrysts. (c) Aligned K-feldspar phenocrysts with (010) faces parallel to biotite layering. (d) Biotite layers bordered by a cluster of K-feldspar megacrysts. (e) Eccentric rings of biotite schlieren constituting an "arocknid". (f) Semi-circular structure with wispy biotite margins. (From McCuish 2001, with permission.)

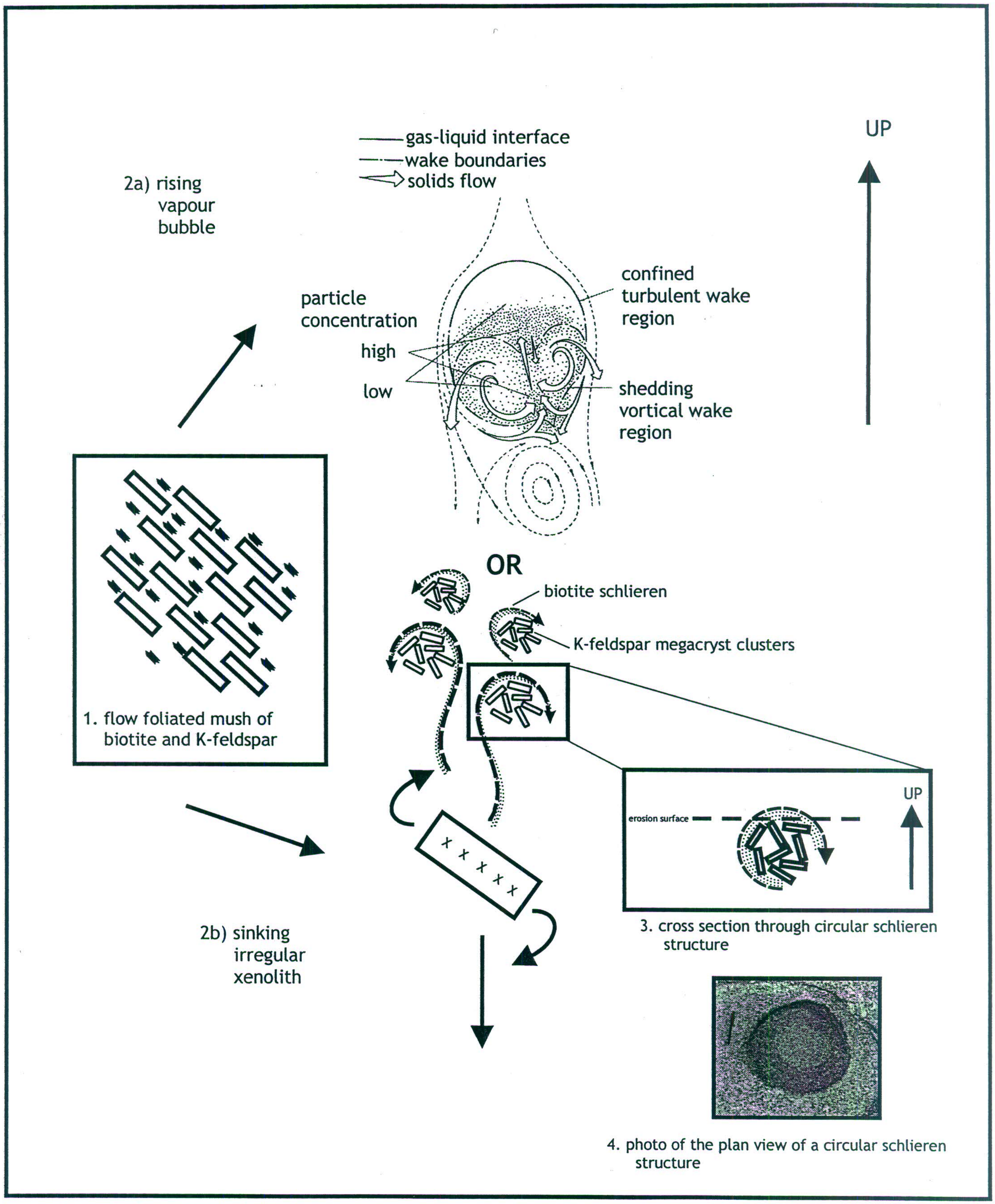


Figure 17. Schematic diagram illustrating the possible physical process responsible for schlieren development at Prospect. Stage 1. Flow-foliated mush of crystals and melt. 2a) Rising vapour bubble 2b) Sinking irregular xenolith block forming complex flow patterns in its wake. 3. Cross section through circular schlieren structure showing fine-grained margins and coarse-grained interior. 4. Photo of plan view of circular schlieren structure showing fine-grained biotite margins coarsening inwards. (From McCuish 2001, with permission.)

STOP 6: East Dover Road – Garnet-Bearing Monzogranite

Time permitting, we will stop here to see a new mineralogical expression of the peraluminosity of these granitic rocks. Garnets in granites can be either: (i) relict metamorphic grains (xenocrysts) from the country rock – anhedral because they are out of equilibrium with the granite melt, and having normal chemical zoning (Mn-rich cores); or (ii) primary magmatic minerals crystallized from the silicate melt – euhedral because they are in equilibrium with the granite melt, and having reverse chemical zoning (Mn-rich rims) (Allan and Clarke 1981).
The only observation here is:

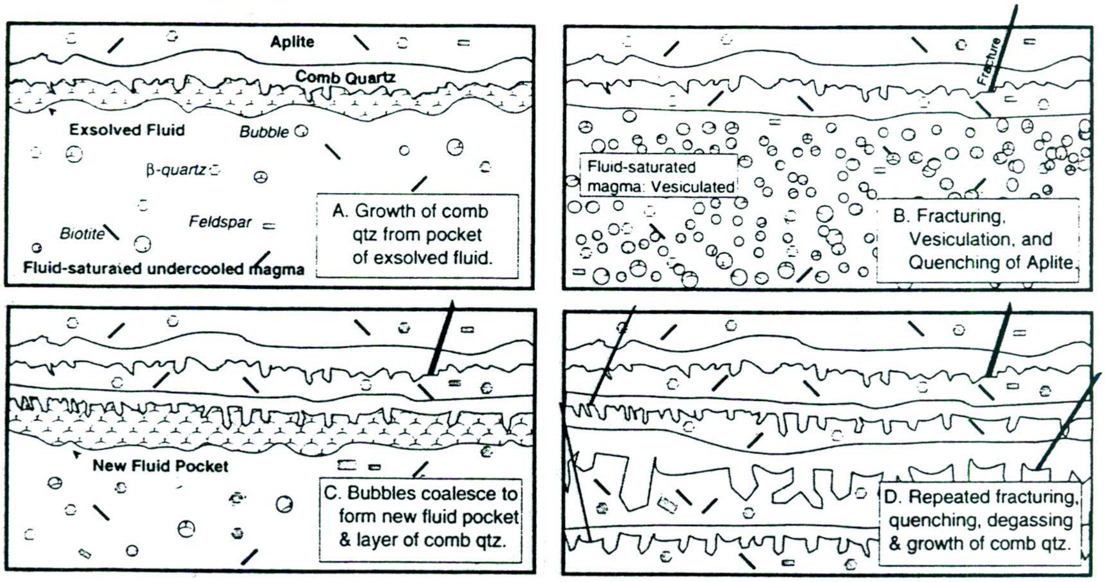
- discrete, euhedral, primary magmatic pinhead garnets

STOP 7: Peggy's Cove – Flowage, Jointing, and Pegmatites

CONSIDERABLE DANGER AT THIS LOCATION FROM SLIPPERY ICY ROCKS!
PLEASE STAY FAR AWAY FROM THE WATER!

Peggy's Cove is a quaint working fishing village, and one of Canada's best-known scenic icons. On a busy day in the summer, cars in the parking lot carry license plates from every political jurisdiction in North America. This stop is more cultural and culinary than geological, but the rock exposures here are outstanding. Some of the features we can see are:

- contact-parallel magma flowage from the preferred orientations of the xenoliths (recall STOPS 1 and 5)
- excellent jointing of the granites in three directions (NE, NW, and sub-horizontal), and occupation of the sub-horizontal set by aplite-pegmatite indicating that these joints developed while magma was still in the system (reminiscent of STOP 4, Chebucto Head)
- asymmetrical distribution of aplite and pegmatite in the sub-horizontal sheets, with banded aplite toward the bottom and pegmatite toward the top. Kontak et al. (2002) have detailed the origin of these pegmatites at Peggy's Cove, and Lowenstern and Sinclair (1996) offered a general model of alternating build-up of volatiles (precipitation of the pegmatitic top) and release of volatiles (quenching of the banded aplitic base) of volatiles in the sub-horizontal sheets as a way to produce such textural variations (**Fig. 18**). These pegmatites, are not very evolved chemically, so the pegmatites do not contain much in the way of exotic elements other than boron in tourmaline-rich pockets.



Sequence of events during growth of comb-layered textures

I Bubble coalescence and collapse of vesiculated magma produces a pocket of exsolved magmatic fluid adjacent to rhyolitic magma that contains phenocrysts of two feldspars and quartz (β-form) + minor mafic and accessory minerals

II Prismatic quartz grows from pocket of exsolved magmatic fluid to produce comb-layered bands. Little to no growth of phenocrysts occurs in subjacent undercooled magma. Continued degassing of melt and accumulation of fluid results in significant overpressures

III Overpressures cause fracturing of previously deposited comb layers. The pocket of fluid is drained as fluid flows out towards cooler country rocks, creating quartz-rich mineralisation, often accompanied by molybdenite. Precipitation of quartz and feldspar results in system sealing. Melt/aplite often enters the veins, forming dyke-like bodies (vein dykes; White *et al.* 1981)

IV Initial reduction in pressure, associated with fracturing, causes vesiculation of magma, even at great distances from the comb layer–magma interface. A thin layer of magma is quenched to phenocryst bearing aplite along the comb-layered quartz. Aplite crystallisation may be caused by loss of H_2O from the melt, the negative heat of vaporisation, conduction of heat into the comb quartz and adiabatic depressurisation, all of which should promote crystallisation of the melt. Growth of dendrites within the aplite layers also occurs during undercooling associated with this stage

V Return to stage I for repetition of events

Figure 18. Formation of alternating comb layering and aplite in sub-horizontal sheets (Lowenstern and Sinclair 1996).

STOP 8: Upper Tantallon – Flowage, Cordierite, and Fluorite *(time permitting)*

For reasons of time and logistics, we are not likely to be able to visit this locality. If we do, there are several interesting features to observe, but we must *be very careful about the instability of the outcrop*:

- as a reminder that the magma was a physically dynamic system, we can readily see evidence of strong flow foliation of the Kspar phenocrysts at this locality, but note the sub-horizontal attitude (compare with STOP 1)
- general absence of xenoliths (compare with STOP 1), although we may see a surmicaceous clot containing garnet (compare with STOP 6)
- weathered surfaces of this monzogranite have large rectangular holes that were once occupied by euhedral cordierite
- prominent fluorite-rich veins – high fluorine contents characterize the most evolved leucogranites in the SMB, and the halides are important ligands for metal complexing in fluids of various origins (**Fig. 19**) – in the centre of the batholith, we can see evidence of precipitation of Li, Cu, Mn, Mo, W, Sn, and U, but all we see here is CaF_2 deposited from the fluid that passed through

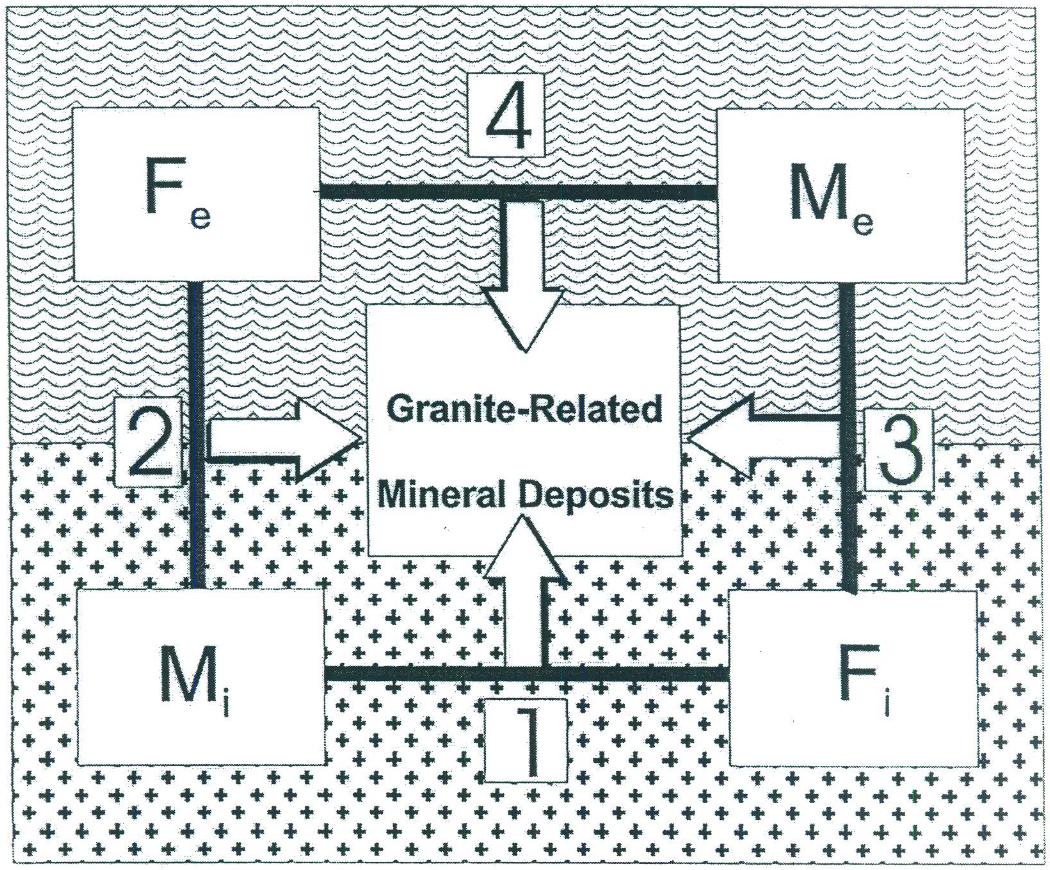


Figure 19. Simple model illustrating the possible fluxes of metals and fluids through a granite and its country rock. (F = fluid, M = metal, e = external, I = internal)
A hydrothermal granite-related mineral deposit may originate in one of four ways:
1 – F_iM_i; 2 –F_eM_i; 3 – F_iM_e; 4 – F_eM_e.

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