Chapter 6

STRUCTURE AND EMPLACEMENT

6.1 Introduction

Several previous workers have noted the presence of localized and, to a lesser degree, regional planar features within the batholith (McKenzie, 1974; Smitheringale, 1973) and other granitoids of the Meguma Zone (MacDonald, 1981). However, most previous studies have concluded that the South Mountain Batholith is a massive, post-tectonic body that was largely unaffected by regional deformation (Taylor, 1969; Cormier and Smith, 1973; Smith, 1974; McKenzie and Clarke, 1975; Clarke and Chatterjee, 1988). The following sections present information that indicates structure played an important role in the evolution of the batholith.

Structural information was routinely collected throughout the batholith during regional mapping. Data included the orientation, size, spacing and type(s) of dykes, veins, joints, shear zones and faults. The presence and style of mineralization and hydrothermal alteration along these planar features was also noted. In addition, the orientation and degree of development of primary flow features, such as parallel mineral alignment and schlieren banding, were noted. This information was graphically portrayed on the fourteen 1:50,000 scale geological maps (see Fig. 2.1 for index). Structural data were compiled and interpreted by Horne et al. (1988, 1992) and many of the salient aspects of their work are presented in the following sections.

6.2 Primary Flow Features

Primary flow features in the batholith (Fig. 6.1) consist of megacryst alignment (Plate 6.1), schlieren banding (Plate 6.2) and biotite foliation (Plate 6.3). Megacryst alignment is the most abundant feature and consists of parallel alignment of tabular feldspar (mainly alkali feldspar) megacrysts. Elongate or tabular xenoliths are commonly oriented with long axes parallel to megacryst alignment. The smooth glaciated nature of most outcrop impedes the determination of three dimensional orientation, however, where measured, orientations were predominantly steeply-dipping. Characteristically, megacryst alignment varies slightly in orientation over single outcrops, although "swirling" patterns were also noted throughout the batholith. Measurements were only collected when a distinct preferred orientation over most of an exposed outcrop area

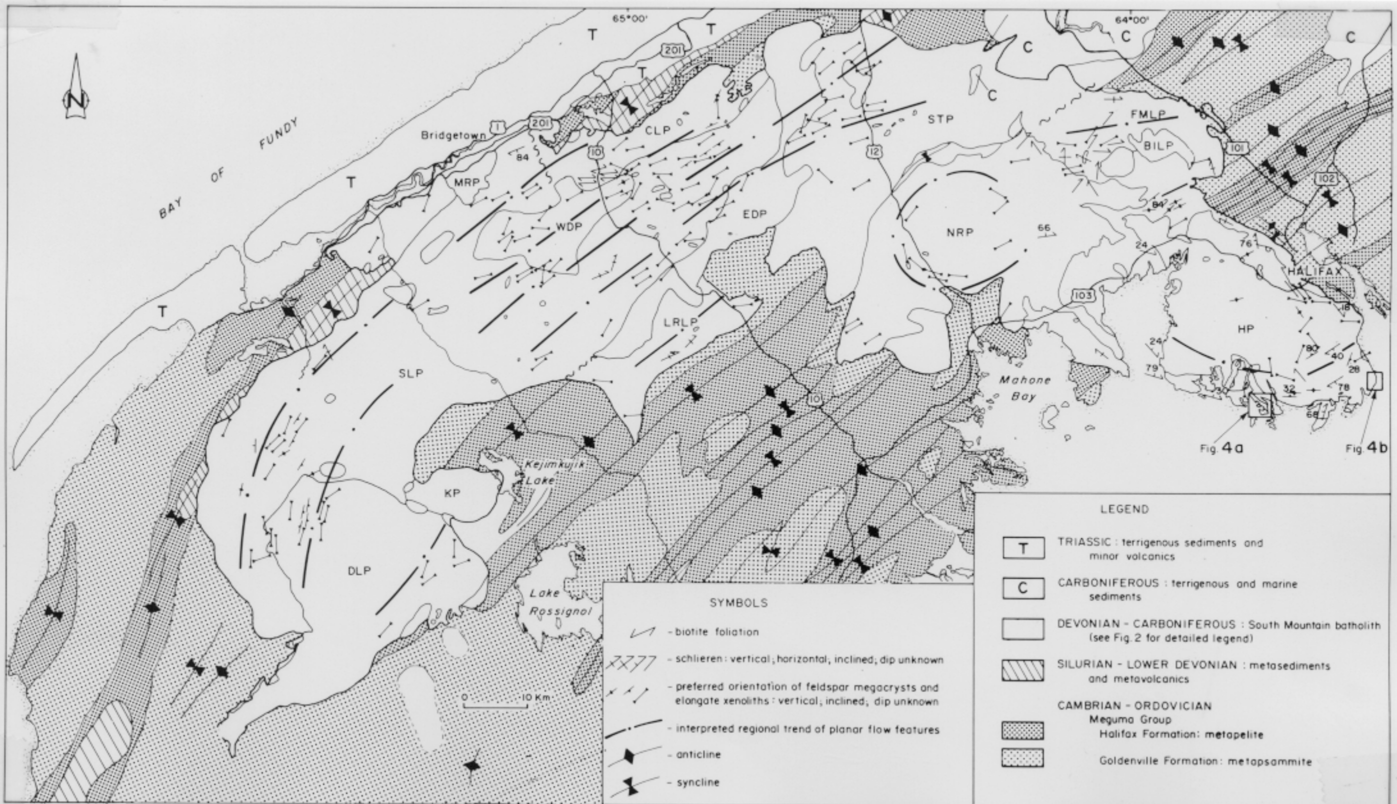


Figure 6.1 Primary flow features including megacryst alignment, schlieren and biotite foliation in the South Mountain Batholith (after Horne et al., 1992).

was evident.

Most Stage I plutons, particularly in the western portion of the batholith, and the Davis Lake and West Dalhousie Stage II plutons display weakly- to moderately-developed NE-trending megacryst alignment. Orientations in the SW part of the batholith are primarily N to NNE. These features parallel regional structural trends in the country rocks and have been interpreted as reflecting regional Late Acadian stress (Horne et al., 1988, 1992) during initial stages of magma emplacement. These features may also reflect stresses related to the emplacement of the various plutons, for example "ballooning" may explain the N-trending flow features in parts of the Scrag Lake and Davis Lake plutons (Horne et al., 1992).

The Halifax and New Ross Stage II plutons display weakly-developed circular primary flow features (Fig. 6.1) that sharply contrast with the rest of the batholith. These patterns mainly parallel the margins of the plutons, particularly in the Halifax Pluton, and are provisionally interpreted as reflecting internal stress and/or primary flow/shear within magma that was related

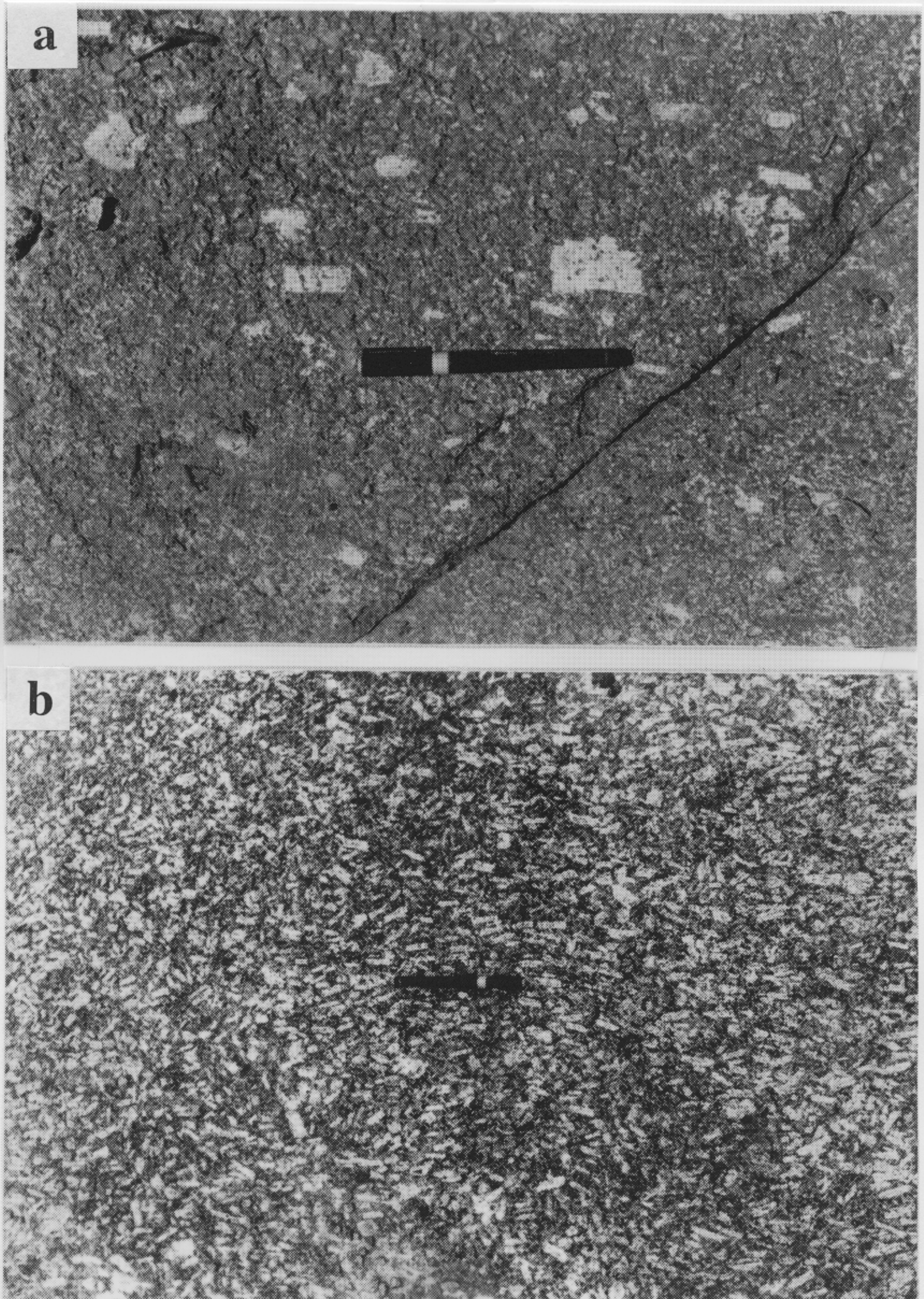


Plate 6.1 a) Parallel alignment of alkali feldspar megacrysts in the Cloud Lake biotite monzogranite. Preferred orientation, indicated by pen, is defined by euhedral megacrysts ranging from approximately 1.5->5 cm in length; b) Erratic primary flow features in the West Dalhousie coarse-grained leucomonzogranite (MacDonald and Ham, 1992). Note the erratic orientations and the uniform size of alkali feldspar megacrysts (approximately 1 x 2.5 cm).

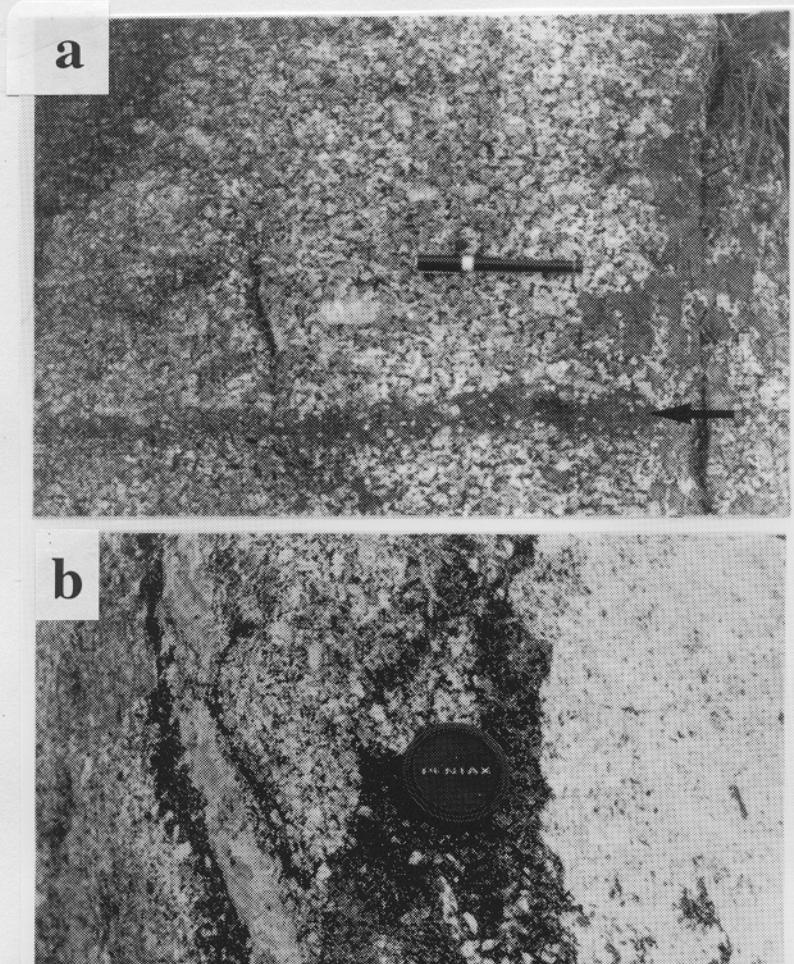


Plate 6.2 Schlieren banding in: a) Scrag Lake biotite monzogranite (NTS sheet 21A/15; MacDonald and Ham, 1992). Banding is defined by high modal amounts of biotite in gradational contact with megacrystic monzogranite. Banding parallels weakly-developed megacryst alignment; b) biotite granodiorite of the Halifax Pluton. Outcrop is located along the Bicentennial highway, near the contact with the transition zone of the Meguma Group country rocks. Note the banding consists of alternating mafic (biotite±garnet) and quartzo-feldspathic layers in contrast to the banding in a); c) close-up of schlieren in b).

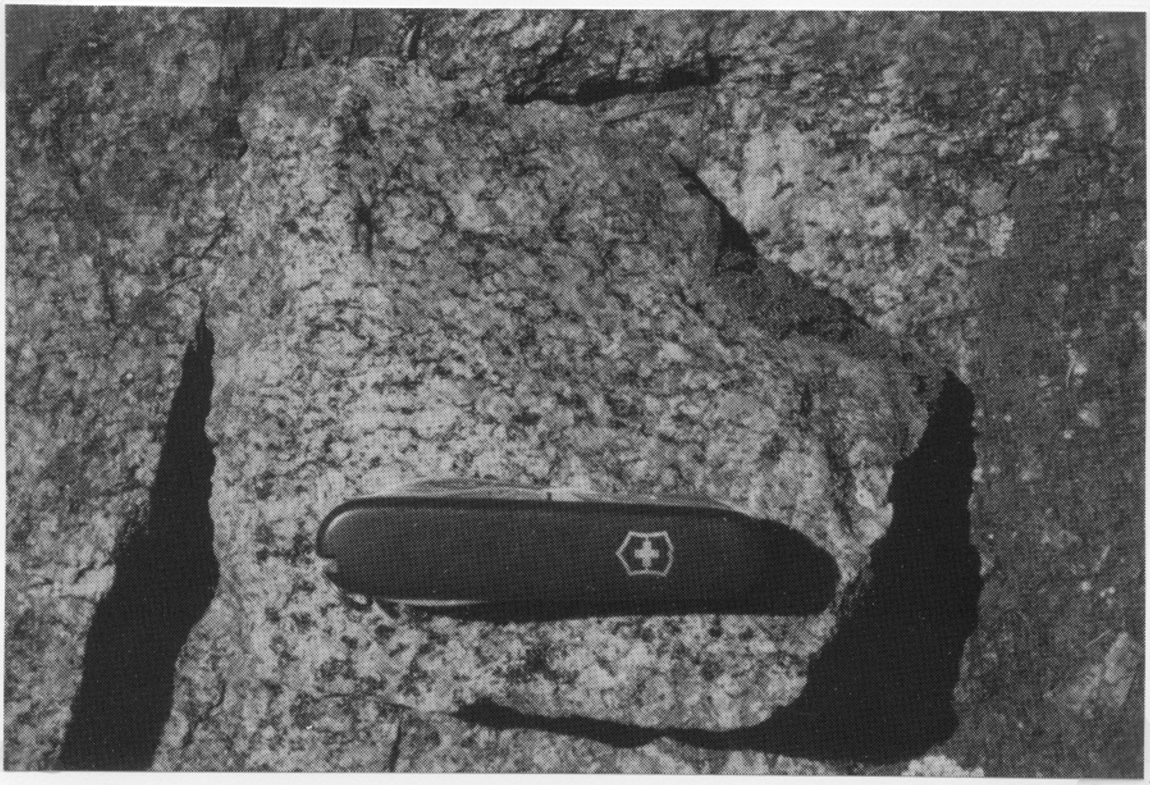


Plate 6.3 Biotite foliation with feldspar augen in the Cloud Lake monzogranite (MacDonald and Ham, 1992). (foliation is sub-parallel to pocket knife).

to the emplacement and crystallization of these plutons in accord with the conclusions of Abbott (1989) and Horne et al. (1992).

The East Dalhousie, Morse Road, Kejimkujik and Big Indian Stage II Plutons either lack primary flow features entirely or have highly erratic outcrop-scale megacryst alignments with no preferred direction. Accordingly there are no measurements for these plutons in Figure 6.1.

Schlieren, which consist of biotite-rich bands that commonly have medium-grained equigranular or seriate texture, were observed in some outcrops throughout the batholith. Most schlieren consist of "wispy" bands that rarely exceed several metres in length or width. Schlieren banding commonly is oriented parallel to other primary flow features including megacryst alignment and elongated xenoliths, as exposed in several outcrop along the southern margin of the Halifax Pluton.

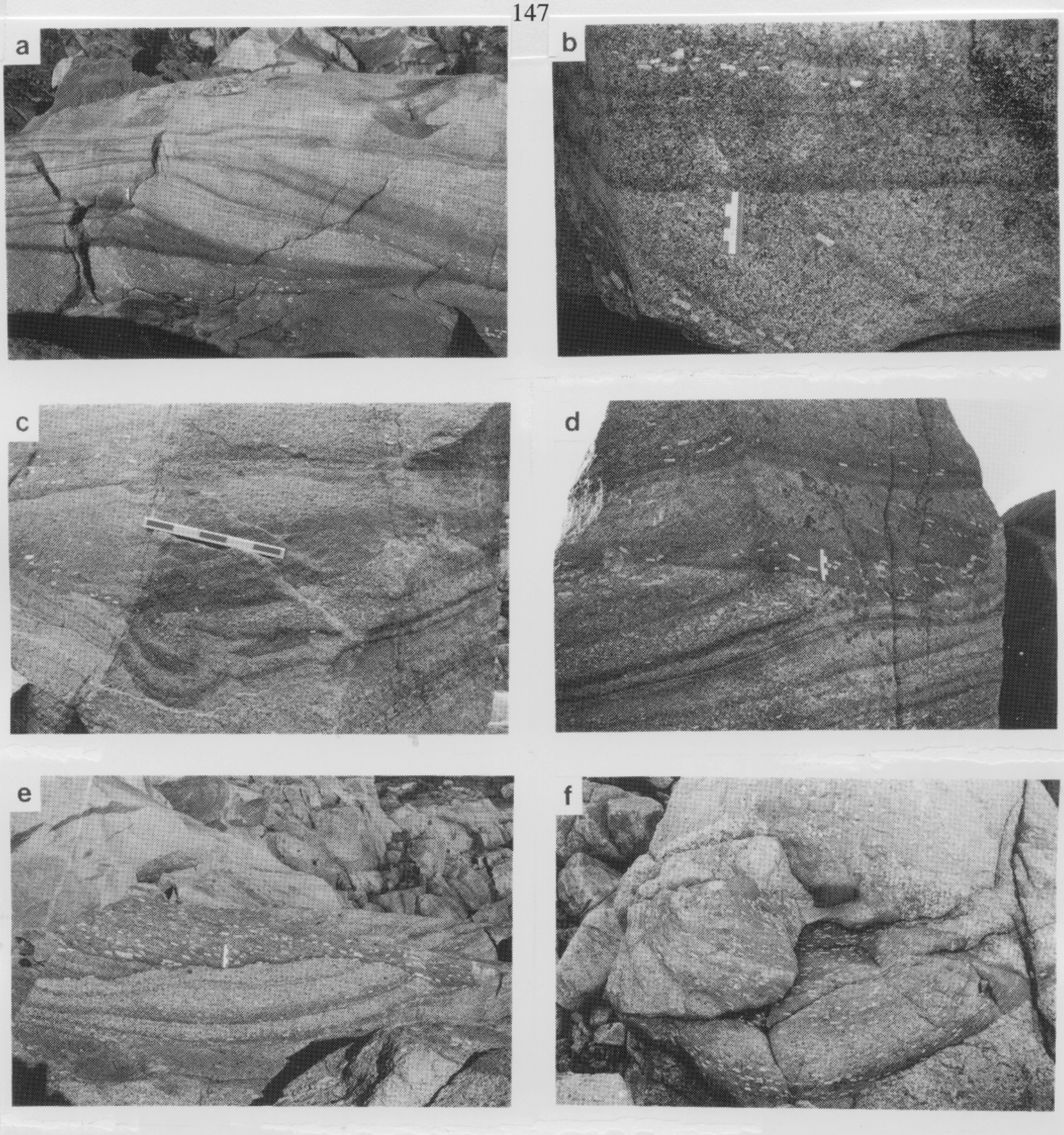
A rare occurrence of well-developed rhythmic layering, with cross- and graded-bedding

(Plate 6.4 a to h), is exposed at Chebucto Head in the Halifax Pluton (Smith, 1975; Clarke and Muecke, 1980; Abbott, 1989). The "exotic layering" is accompanied by cross-cutting dykes containing alkali feldspar megacrysts$\pm$metasedimentary xenoliths. Several contrasting models for the formation of this banding have been proposed, however, it is generally believed that formation of these features resulted from flow and/or shear within a crystal "mush" with flow segregation or filtering of fine- and coarse-grained components of a partially crystallized monzogranite magma. Clarke and Muecke (1980) concluded that the megacryst- and xenolith-rich dykes (termed `log-jam' dykes), oriented obliquely to the layered sequence, represent `feeders' for the non-megacrystic layers and were caused by influx of biotite monzogranite melt into cracks in partially solidified rock. Similar features were observed in rare outcrop throughout the batholith but nowhere was the layering as well exposed as at Chebucto Head.

Biotite foliation is restricted to a band (approx. 1.5 x 6 km) along the southern margin of the Cloud Lake Pluton, adjacent to the West Dalhousie Pluton (Fig. 6.1). Foliation of platy biotite crystals may be accompanied by alkali feldspar and plagioclase augen, encircled by biotite, and elongate xenoliths with long axes parallel to foliation (McKenzie, 1974; MacDonald and Ham, 1992). Biotite foliation ranges from 070° to 088° and thus is sub-parallel to regional megacryst alignment in the batholith and structural trends in the country rocks. The zone of biotite foliation is gradational with non-foliated Cloud Lake monzogranite to the north and is sharply truncated by the West Dalhousie Stage II Pluton. This zone of biotite foliation has been interpreted as reflecting localized stress on the Cloud Lake monzogranite during crystallization. However it is unclear whether the stress is regional tectonic or related to internal stress (e.g. "ballooning") related to emplacement of the Cloud Lake and/or West Dalhousie plutons (MacDonald and Ham, 1992; Horne et al., 1992).

Local "pods" of alkali feldspar magacrysts and xenoliths (Plate 6.5), interpreted to represent primary flow concentration features in partially crystallized granitoid magmas, are

Plate 6.4 (Following page) Rhythmic layering in the Harrietsfield monzogranite at Chebucto Head (MacDonald and Horne, 1987; photos courtesy of Barrie Clarke): a) to f) photos showing complex inter-layering of medium-grained equigranular (seriate) textured granite with biotite-rich and biotite-poor bands defining complex layering sequence. Megacrysts of alkali feldspar are restricted to specific layers in sequence and are predominantly oriented parallel to layering. Cross bedding and scour-and-fill structures are evident in several photos; g) and h) `log-jam' dykes with high modal proportion of alkali feldspar megacrysts and metasedimentary xenoliths that cross-cut layering (e.g. in h). Clarke and Muecke interpreted these `dykes' to represent feeder for the equigranular layers in the sequence.


a
b
c
d
e
f
g
h

locally developed in many megacrystic rock units of the batholith (e.g. Harrietsfield monzogranite, MacDonald and Horne, 1987; Scrag Lake monzogranite, MacDonald and Ham, 1992). These features are interpreted as resulting from flow segregation, possibly associated with convection in granitic melts. The pods have irregular, often circular, shapes that do not have a preferred orientation and hence are not portrayed in Figure 6.1. However, their occurrence is depicted graphically on the fourteen 1:50,000 scale geological maps.

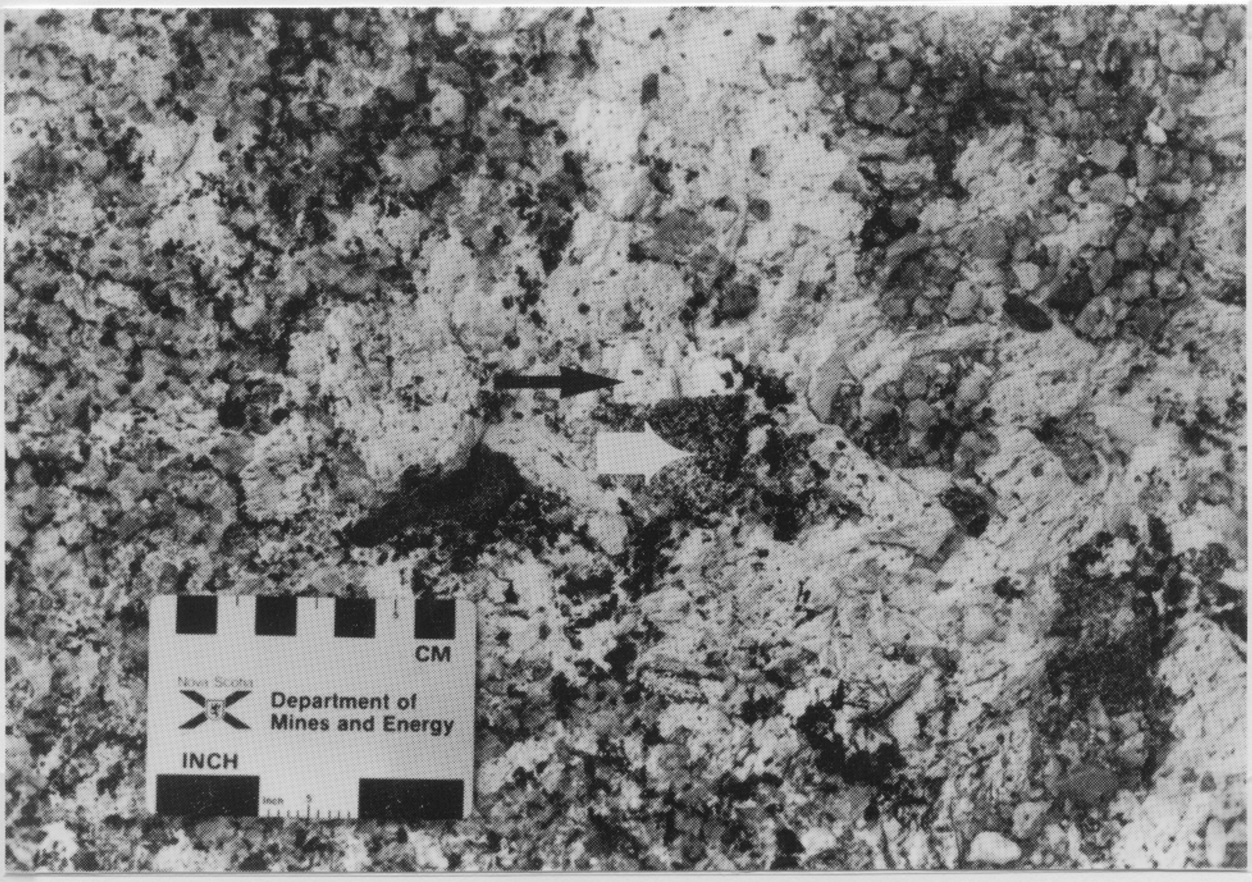


Plate 6.5 Alkali feldspar megacryst/xenolith pod in the Scrag Lake biotite monzogranite (NTS sheet 21A/15; MacDonald and Ham, 1992). Black arrow indicates euhedral K-spar megacryst. White arrow points to partially assimilated metasedimentary(?) xenolith. Note megacrystic texture characteristic of this unit is shown in lower left corner of photo. Pod has irregular outline, is gradational with megacrystic rocks and is interpreted as flow concentration in crystal/liquid "mush", possibly by local-scale convection.

6.3 Joints, Dykes and Veins

Horne et al. (1988; 1992) compiled structural data for joints, dykes and veins from approximately 2000 outcrops that were examined in detail during mapping. They prepared contoured density stereoplots for each feature in several geographic regions of the batholith and for selected Stage II plutons.

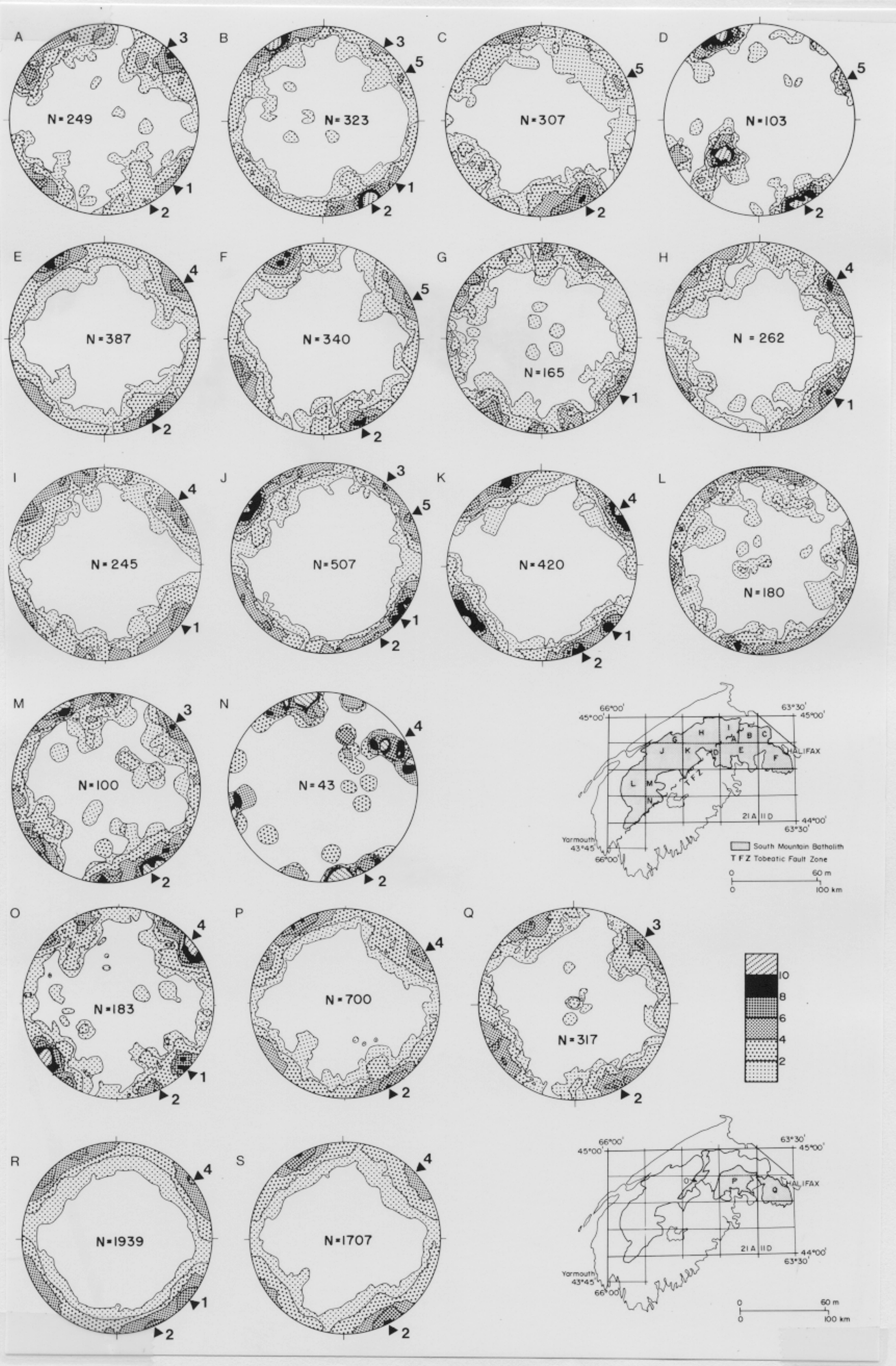

A
N=249
B
N=323
C
N=307
D
N=103
E
N=387
F
N=340
G
N=165
H
N = 262
I
N=245
J
N=507
K
N=420
L
N=180
M
N=100
N
N=43
O
N=183
P
N=700
Q
N=317
R
N=1939
S
N=1707
66°00'
45°00'
63°30'
HALIFAX
21A 11D
44°00'
Yarmouth
43°45
TFZ
South Mountain Batholith
TFZ Tobeatic Fault Zone
0
60 m
100 km
10
8
6
4
2

Figure 6.2 (Previous page) Contoured density plots of poles to joints (in 1% area) in parts of the South Mountain Batholith (after Horne et al., 1992). Stereoplots A to N are from full or portions of NTS map sheets in upper index map. Stereoplots O,P and Q are from the East Dalhousie, New Ross and Halifax Plutons respectively (see lower index map).

Stereoplots for poles to **joints** from the various map sheets and the East Dalhousie, New Ross and Halifax Stage II plutons are presented in Figure 6.2. Horne et al. (1992) concluded that "a repetitive, roughly orthogonal pattern, defined by maxima, or set of sub-maxima, representing steeply dipping NE- and NW-trending joints dominate the stereoplots of nearly all data sets." They noted that three sub-maxima (trends 3,4,5) define the NW-trending joint sets whereas two sub-maxima (trends 1,2) demarcate the NE-trending joint sets. Northwest-trending joints are, for the most part, straight-sided, evenly-spaced and form the dominant joints in most outcrop throughout the batholith (Plate 6.6a). Some joints have hydrothermal coatings (e.g. muscovite greisen) or host greisen-bordered quartz veins and may contain polymetallic Sn-W-Mo mineralization (see below and discussion in Chapter 9). In contrast, NE-trending joints are poorly developed and have curvilinear shape with irregular spacing (Plate 6.6b). The NE-trending joints commonly form narrow zones of closely-spaced fracture cleavage with variable associated hematization and/or chloritization that may host Mn or U mineralization (discussed in Chapter 9).

A compilation map showing the distribution and orientation of **granite dykes** (N=811) and stereoplots for poles to dykes for the portions of the batholith to the west and east of the proposed Tobeatic Fault Zone (Giles, 1985) are given in Figure 3.3. Dyke rock types mainly include aplite, fine-grained equigranular or porphyritic textured leucomonzogranite, pegmatite and composite or inter-banded aplite-pegmatite. Geological descriptions for dyke rocks are given above in Section 3.4. Most dykes in the entire batholith are steeply-dipping (>45°), which may be an artifact of the low-lying glaciated nature of most outcrop investigated, which decreases the likelihood of shallow-dipping dykes being exposed. The dykes from the western part of the batholith (Fig. 3.3a) are primarily oriented to the NW and correspond to joint trends 4 and 5. The dykes in the eastern part of the batholith display much more scatter (Fig. 3.3b). Horne et al. (1992) noted that dykes may locally define systematic radial or concentric map patterns that they tentatively interpreted to result from stresses associated with intrusion.

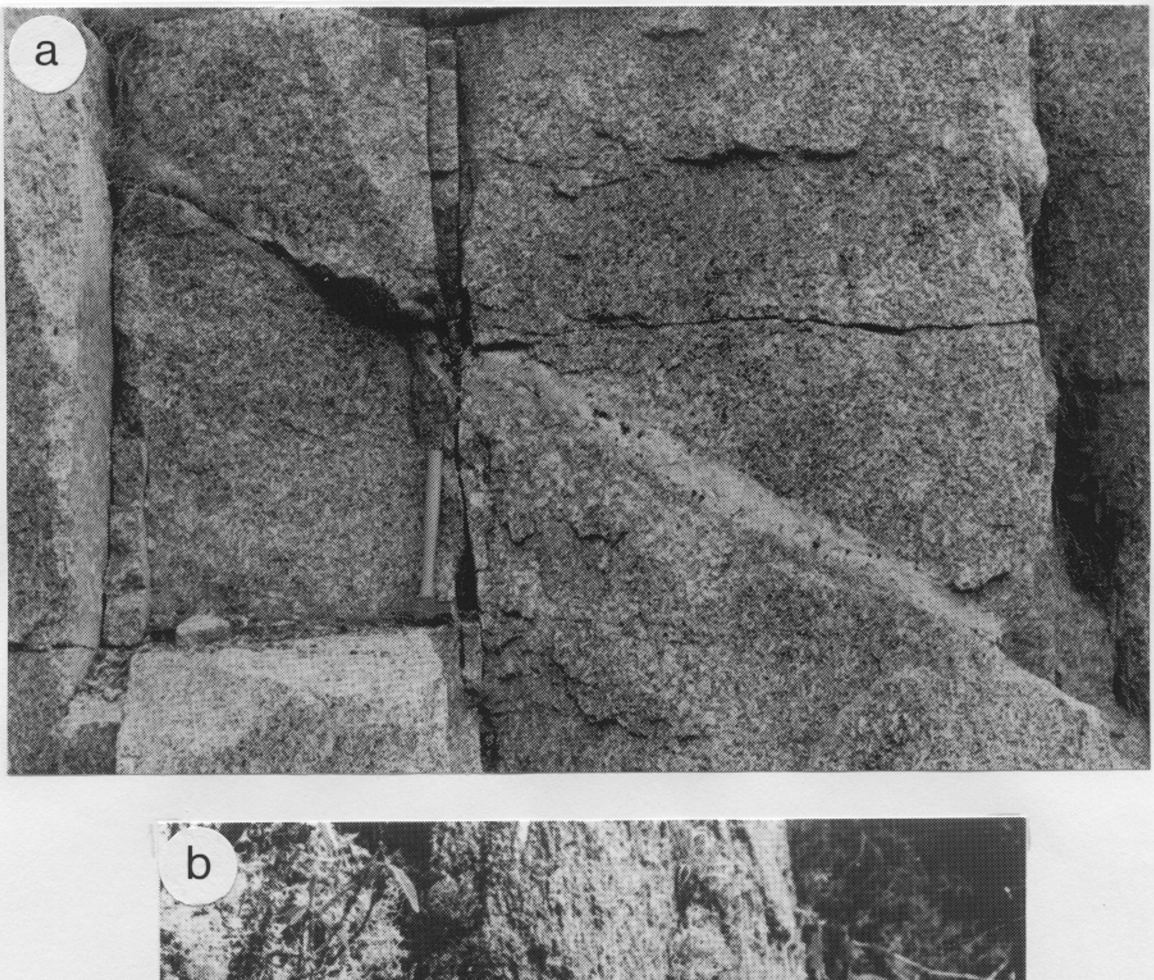


Plate 6.6 a) Outcrop of Sandy Lake biotite monzogranite from the Halifax Pluton (MacDonald and Horne, 1987) with typical straight-sided NW-trending (trend 4) joints with consistent spacing (1-2m wide). Note the presence of sub-horizontal, slightly curviplanar joints and a moderately-dipping aplite dyke. b) outcrop of biotite monzogranite (?) with closely-spaced NE-trending (trend 1?) fracture joints.

The distribution of **quartz veins** from the entire batholith (N=441) along with stereoplots for poles to veins from the eastern and western portions of the batholith are presented in Figure 6.3. Quartz veins mainly range in width from 1-10 cm, although larger veins to 1-2 m have been observed, and may occur in sheeted vein sets. Veins are dominantly NW-trending with steep dips and mainly coincide with the orientation of joint trend 4. Vein orientations appear to be unaffected by such factors as proximity to granite/granite or granite/metasediment contacts and do not define localized patterns as noted for the granite dykes.

6.4 Faults

The distribution of major fault and shear zones is given in Figure 6.4. Most of these structures were unrecognized prior to recent mapping (Horne et al., 1988, 1992; MacDonald et al., 1992; and references therein). Brittle faults predominate in most areas in the batholith and are characterized by heterogeneous deformation consisting of narrow breccia, microbreccia and cataclasite zones (generally ≤1m wide; Plate 6.7a) within wider (10-≥100m wide) moderately deformed zones containing slickensided shears (Plate 6.7b) or brittle fractures (Plate 6.7c). Most brittle faults have moderate to intense hematization and chloritization that may be accompanied by slight to intense silicification (Plate 6.7d). For example the Roxbury Brook Fault (RBF in Figure 6.4) is characterized by intensely brecciated, silicified and hematized zones with relict feldspar grains that are variably replaced by quartz (MacDonald and Ham, 1994). These zones have been previously termed "jasper breccia" by Rogers (1981) and elsewhere as "breccia zones" by Smitheringale (1973). The superposition of brecciation and alteration indicates multiple stages of deformation and fluid influx along the Roxbury Brook Fault that is typical of many brittle faults elsewhere in the batholith. Ductile shear zones are restricted to the southwestern portion of the Davis Lake Pluton. Horne et al. (1992) noted that these faults "are characterized by variably penetrative brittle-ductile to ductile deformational textures, including C-S fabrics," (Plate 6.7e) "mylonite, blastomylonite, ultramylonite and rare rodded mylonite gneiss" (Plate 6.7f). Some shear zones show late brittle deformation and associated silicification.

The absence of significant displacement of granitic map units coupled with the predominance of vertical or steeply-dipping slickensides along NE-trending faults indicate that displacement was primarily vertical. Sense of movement is indicated by the Riedel shear geometry (R' and P) of trends 1 and 2 joints that is consistent with dextral displacement along NE-trending

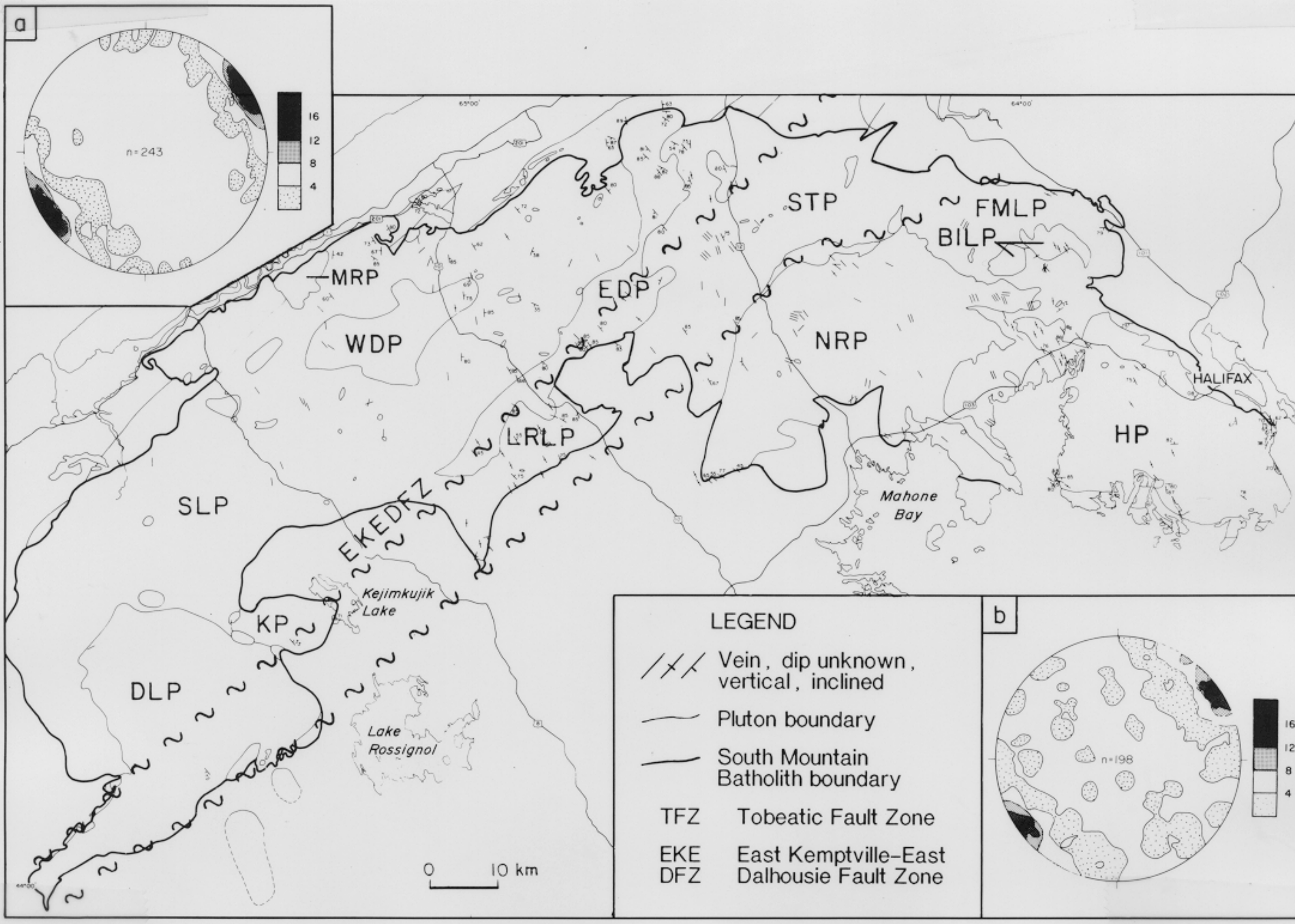


Figure 6.3 Map showing the distribution and orientation of quartz veins in the South Mountain Batholith (after Horne et al., 1992). Contoured density plots of poles to veins (in 1 % area) are for the areas of the batholith to the west (a) and east (b) of the proposed Tobeatic Fault Zone of Giles (1985). Pluton abbreviations are given in Figure 6.4.

faults (Horne et al., 1992). Similarly, C-S fabrics in the East Kemptville shear zone were interpreted by (Kontak et al., 1986) to represent dextral shear. In contrast, recent mapping at the East Kemptville Mine (Halter et al., 1993) has revealed the presence of kinematic indicators including en-echelon quartz-sulphide veins and sub-vertical fault/shear zones that signify vertical displacement along the East Kemptville shear zone during the late paragenetic stages of mineralization.

Sinistral displacement along the NW-trending Herring Cove fault and Roxbury Brook

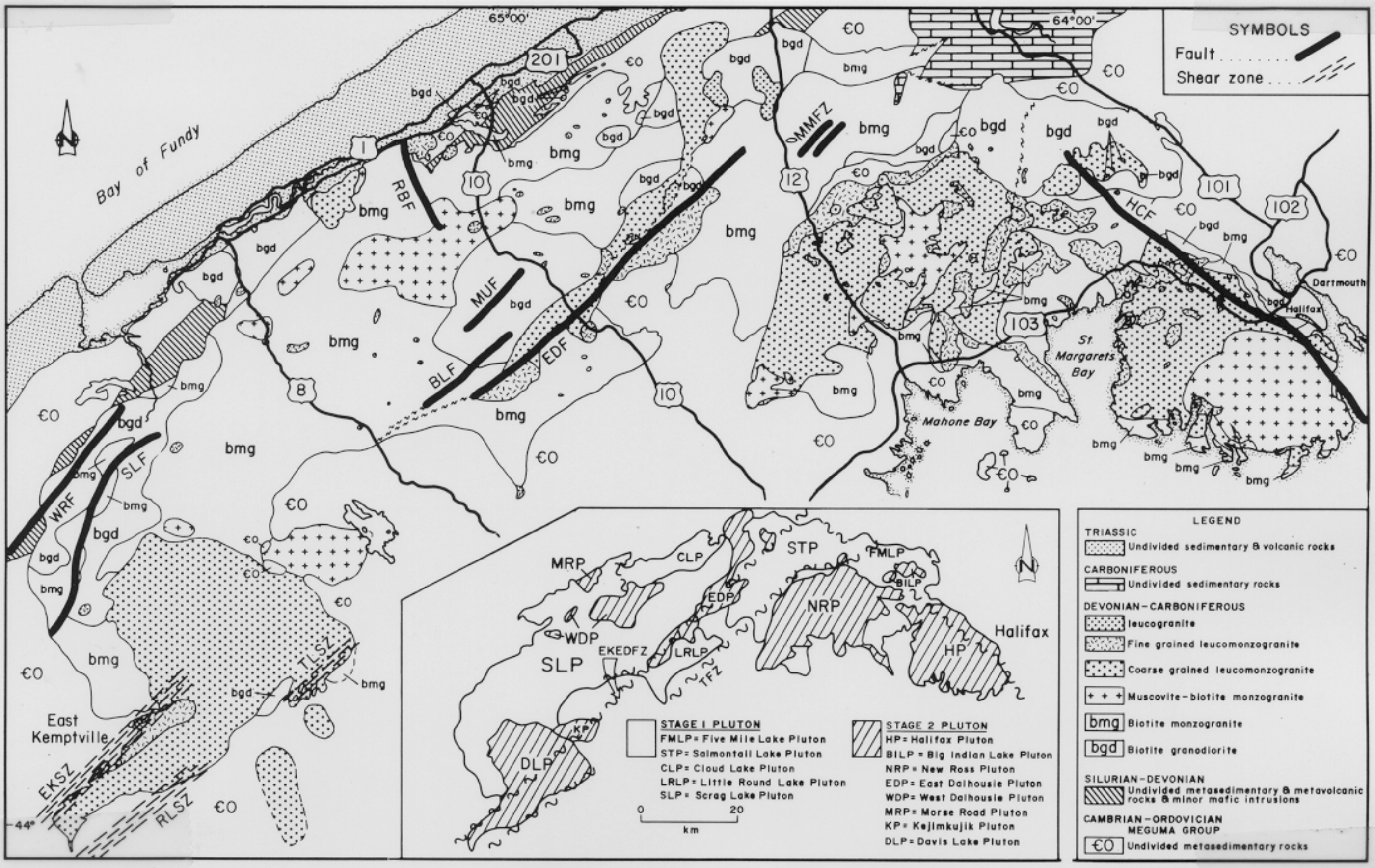


Figure 6.4 Geological map of the South Mountain Batholith showing the location of the major fault and shear zones (modified after Horne et al., 1992). Faults include: BLF - Beaver Lake fault; EDF - East Dalhousie fault; EKEDFZ - East Kemptville-East Dalhousie fault zone; EKSZ - East Kemptville shear zone; HCF - Herring Cove fault; MMFZ - Manganese Mines fault zone; MUF - Molly Upsim fault; RBF - Roxbury Brook fault; RLSZ - Rushmere Lake shear zone; SLF - Sissiboo Lake fault; TFZ - Tobeatic fault zone; TLSZ - Tobeatic Lake shear zone; WRF - Wallace River fault.

fault is indicated by the apparent displacement of granite map units in the Halifax Pluton and the margin of the West Dalhousie Pluton. However, it should be stressed that similar map unit configurations could result from a component of dip-slip movement as suggested by Horne et al. (1992).

It is clear from the above section that faults and shear zones were important factors in the evolution of the batholith. Field observations reveal that the intensity of deformation along some faults is more intense in Stage I than Stage II plutons, suggesting these structures may have predated the emplacement of Stage II plutons. In fact, the dyke-like shape of the East Dalhousie pluton, (65 x 1-5 km), coupled with its intimate spatial association with the East Dalhousie-East

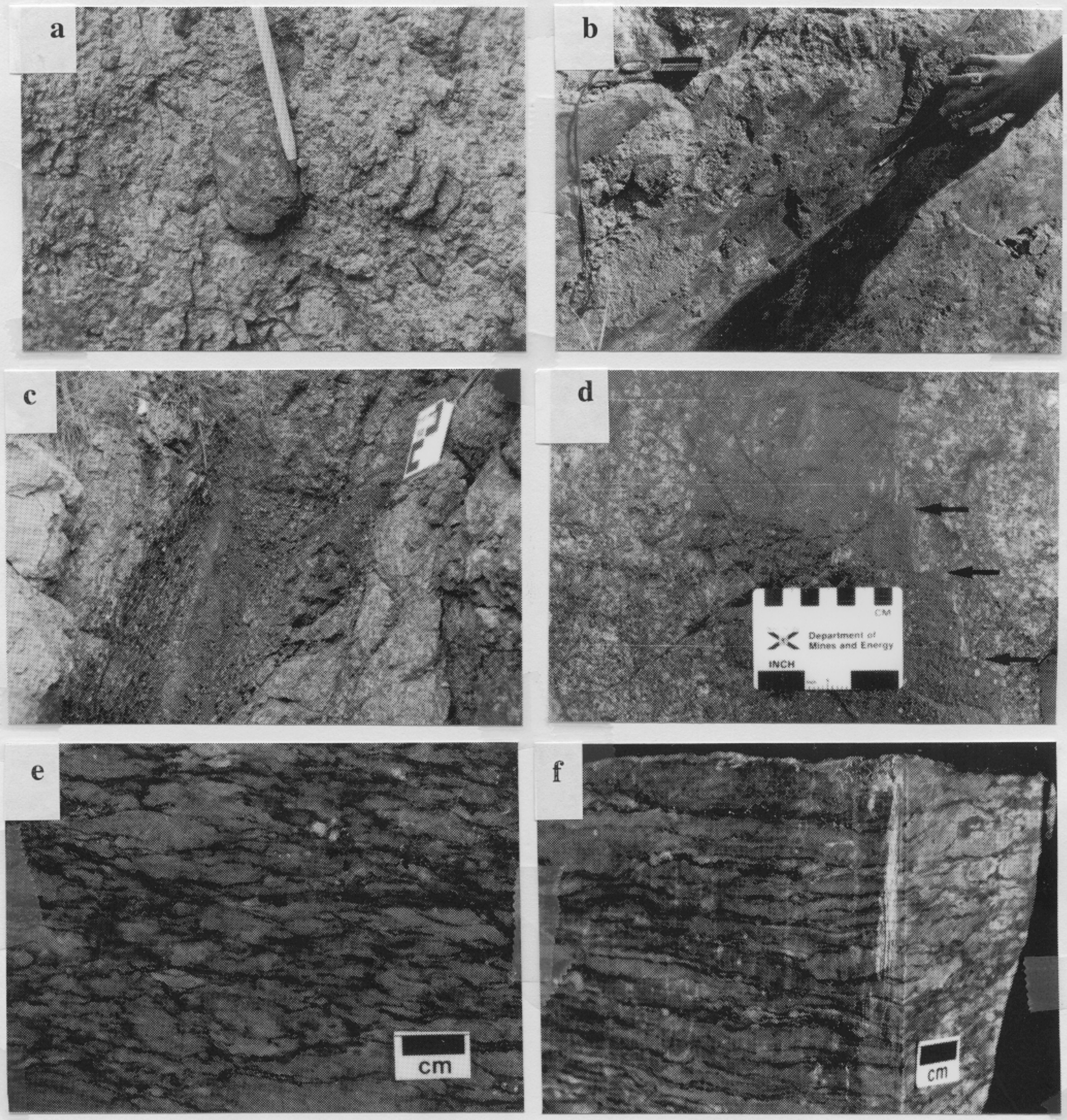


Plate 6.7 Deformation associated with faults in the South Mountain Batholith: a) cataclasite zone in the Herring Cove brittle fault zone. Note the overall grain size reduction with rounded clasts of host rock in brecciated matrix; b) hematized slickenside fault surface in the East Dalhousie brittle fault zone; c) hematized fracture/shear zone from the Herring Cove brittle fault zone at Sheehan's Cove; d) intensely hematized, chloritized and silicified breccia from the East Dalhousie brittle fault zone. Note the offset by later fractures (arrows); e) C-S fabric from the Tobeatic Lake ductile fault zone; f) rodded mylonite gneiss from Rocky Shore Lake in the East Kemptville ductile shear zone.

Kemptville fault zone, suggests emplacement along a pre-existing structure. Several contacts between Stage I and II plutons are marked by major fault zones. Several NE- and NW-trending faults cross-cut, and notably deform, several map units in Stage II plutons, including the Murphy Lake and East Kemptville leucogranites (MacDonald and Ham, 1992; Kontak et al., 1986). Halter et al. (1993) suggested that the NE-trending East Kemptville fault "exercised an important control on the location and geometry of the deposit". Similarly, fine-grained leucomonzogranite bodies and the associated Mn-P-F mineralization at New Ross Manganese Mines are localized along NE-trending fault zones. The above field-based evidence indicates protracted deformation along many NE- and NW-trending faults, from the emplacement and crystallization of Stage I and II plutons to the formation of post-magmatic mineral deposits. Various geochronological studies (Kontak et al., 1990; and references therein) reveal episodic thermotectonism along the East Kemptville-East Dalhousie fault zone that continued after the crystallization of the Davis Lake Pluton to circa 250 Ma (see further discussion in Chapter 7).

6.5 Mode of Emplacement of the South Mountain Batholith

Previous workers have concluded the batholith was emplaced by a passive stoping mechanism at the present level of erosion, primarily based on the ubiquitous distribution of metasedimentary xenoliths and the overall lack of deformation of the country rocks (Clarke and Muecke, 1985; Clarke and Chatterjee, 1988; and references therein). These observations and conclusions were largely supported by the results of recent mapping. For example, metasedimentary(?) xenoliths were observed in most megacrystic map units throughout the batholith with the relative proportions of xenoliths being proportional to the mafic mineral content of the rock as opposed to the proximity to country rock contacts (see discussion in Chapter 3). These observations support stoping throughout the entire batholith. Horne et al. (1992) concluded that the \`orthogonal' shape of the contacts in several locales supports emplacement of the batholith into pre-existing regional (\`orthogonal') structures in the Meguma Group rocks.

Granite dykes are absent in many contact zones but were noted in a few locales, where dykes could be traced for up to 100m from the batholith contact (Plate 6.8b,c). The scarcity of dykes in country rocks is somewhat puzzling if stoping were the dominant emplacement mechanism.

There is evidence for deformation of country rocks in some areas of the batholith suggesting localized forceful emplacement. These include:

1) A series of NW-trending structures termed the "transverse anticline" and "transverse

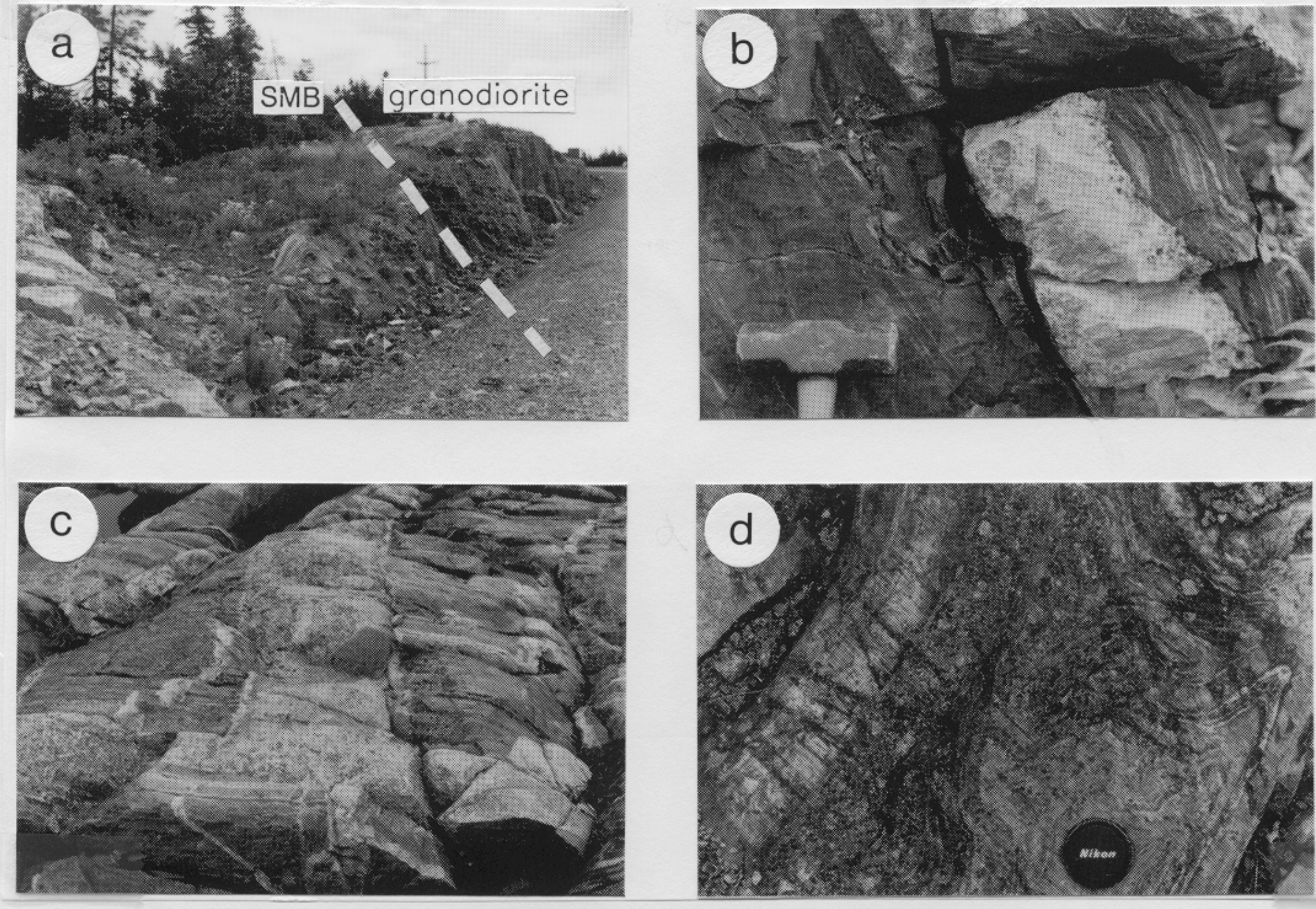


Plate 6.8 Endobatholith features: a) sharp, steeply-dipping contact between biotite granodiorite and Meguma Group transition zone rocks along the Bicentennial Highway near Halifax. Note the lack of granite dykes; b) steeply-dipping aplite dyke intruding Meguma Group rocks along Bicentennial Highway. Note the dyke is sub-parallel to bedding; c) lit-par-lit injection of monzogranite dykes in a large metasedimentary xenolith at Portuguese Cove. Dykes follow bedding planes and cross-fractures; d) ptygmatic folds in the Meguma Group metasedimentary roof pendants in the Boot Lake area.

syncline" by Faribault (1908) are developed adjacent to the margin of the Halifax Pluton near Hammonds Plains (MacDonald and Horne, 1987). These structures are perpendicular to the regional NE structures and have been interpreted by MacDonald and Horne (1987) and Horne et al. (1992) to represent forceful emplacement of the batholith resulting in reorientation of structural trends;

2) O'Brien (1988) documented the occurrence of a steeply-plunging NW-trending large-

scale antiform, along Aspotogan Harbour near Mahone Bay, that parallels the batholith margin and refolds the Indian Path Anticline. The NE limb of this antiform is comprised of NW-trending granite screens and highly strained schist that markedly contrast the NE-trending screens and variably deformed hornfelses of the SW limb. Accordingly, this structure has been interpreted by O'Brien (1988) as originating from the forceful emplacement of the batholith.

3) Clarke and Halliday (1980) interpreted a weak foliation of cordierites in cleavage planes in the thermal aureole adjacent to the Halifax Pluton as representing late-syn to post-tectonic emplacement of the batholith with respect to cleavage formation. MacDonald (1981) reported similar porphyroblast foliation in a portion of the thermal aureole around the Musquodoboit Batholith and concluded that it resulted from compressive forces near the granite that were associated with buoyant forces of intrusion. Both explanations are considered to have merit.

4) Primary flow features vary from NE- to NNE- and N-trends in the SW part of the batholith and directly mirror the batholith margin and a regional warp in structural trends in adjoining country rocks (Fig 6.1). Horne et al. (1992) suggested that these features were formed by "ballooning" of the Scrag Lake and Davis Lake plutons. O'Reilly et al. (1992) presented a structural interpretation of the southern part of the Meguma Zone based upon airborne gradiometer data and geological mapping. Their data reveal that N- and intersecting NE-trending structures occur up to 100 km south of the batholith and, consequently, could not be formed by localized granite-related stresses. The southern part of the batholith is interpreted to have been emplaced into a structurally complex area where movement along faults and shears may have created "space" by local extension (Hutton, 1988), however, a component of forceful emplacement in this area cannot be ruled out.

The presence of **contact metamorphic minerals** was noted during mapping, however, the nature and extent of the aureole were not investigated in detail during the project. Taylor (1969) noted the contact aureole ranged from 0.8 to 2.5 km in width and consisted of porphyroblastic growth of cordierite and andalusite, particularly in pelitic beds, with partial to complete annealing of pre-existing cleavage in all rocks. Several workers including Taylor (1969) and O'Brien (1988) noted that porphyroblasts overgrew regional slaty cleavage with no preferred orientation. Mahoney (1996) examined the metamorphic aureole in 12 locations around the batholith and reported widths ranging from 1.5-3km. Clearly, the presence of a well-defined aureole indicates the emplacement of a relatively `hot' granite body, although does not preclude stoping as a mechanism.

As previously noted, many **contact zones** are characterized by steep granite contacts (Plates 3.2, 3.9, 6.8a). In contrast, the Boot Lake area of map 21A/15 (MacDonald and Ham, 1992) is dominated by complex outcrop patterns of monzogranite and metasedimentary rocks. Granite/metasediment contacts were not directly observed but this area was interpreted as a roof zone for the batholith by MacDonald and Ham (1992) and subsequently provides insight into the endocontact effects above the batholith. Lit-par-lit injection of biotite monzogranite, and lesser mafic porphyry, was noted in Meguma Group rocks in this area. In addition, locally-developed ptygmatic fold (Plate 6.8d) structures, that commonly have monzogranite or mafic porphyry injections with sinuous forms, were noted in restricted locales. Similar features were also documented in two roof pendants along the margin of the Kejimkujik Pluton (Horne, 1994) and are interpreted as resulting from intense heating and deformation from underlying granite magma(s). However, it should be stressed that these features are absent or rare in most areas with shallow-dipping contacts, as at the East Kemptville Sn Mine.

Contact-related features in the batholith, such as **chilled margins** and **primary flow features**, are generally absent. Notable exceptions include the chilled margin (generally 200-300m wide) along the northern margin of the Lake George leucomonzogranite (MacDonald and Ham, 1992), and the non-megacrystic or equigranular texture of biotite granodiorite units along the northern margin of the Halifax Pluton (MacDonald and Horne, 1987) and the Five Island Pluton (Corey, 1987) that may also represent large chilled margins.

6.6 Sequence of Emplacement of Granite Units

In general, the lack of chilled margins and definitive cross-cutting relationships at most granite/granite contacts (e.g. Plates 3.5, 3.10) inhibit the determination of a comprehensive sequence of emplacement for the various plutons. However, some overall points can be made based on field observations. Granite/granite contacts are predominantly sharp and clearly, although some contact zones are gradational as noted between several megacrystic units in the Halifax Pluton. Gradational contacts have largely been interpreted to represent *in-situ* fractionation (MacDonald and Horne, 1987; MacDonald et al., 1992). It was previously noted in Chapter #3 that Stage II plutons intrude, and therefore post-date, Stage I plutons.

Fine-grained leucogranite and leucomonzogranite units were noted to intrude the coarse-grained megacrystic rocks with the exception of some porphyry bodies in the New Ross Pluton that were interpreted as chilled(?) phases of megacrystic leucomonzogranite rocks (e.g. Corey, 1990). Many of the fine-grained leucomonzogranite bodies within the Stage I and II plutons have linear contacts that are crudely oriented NE or NW (Fig. 2.3 in pocket at back). These orientations correspond to the major joint directions throughout the batholith which prompted Horne et al. (1988, 1992) and MacDonald et al. (1992) to propose that the emplacement of these bodies was also structurally controlled.

Stage I plutons mainly have elliptical shapes with long axes oriented to the NE, thus mirroring the regional structures in the country rocks and the primary flow features outlined in Figure 6.1. Horne et al. (1992) and MacDonald et al. (1992) concluded that these features were indicative of regional-scale NW-oriented compression during the waning stages of the Acadian Orogeny. Stage II plutons have circular or elliptical shapes with weakly developed circular primary flow features (Figure 6.1) and have been interpreted by MacDonald et al. (1992) and Horne et al. (1992) to have been emplaced into a lower stress regime than Stage I plutons.

McKenzie and Clarke (1975) postulated that the entire batholith crystallized from a single magma with a single crystallization sequence of granodiorite-monzogranite-leucomonzogranite. Field observations indicate a much more complex sequence of emplacement. Fine- to medium-grained leucomonzogranite xenoliths were noted in biotite monzogranite and biotite granodiorite in several Stage I plutons (Plate 3.16). The exact origin of these enclaves is unclear, however, it is likely that the biotite-rich granodiorite and monzogranite units intruded crystallized leucomonzogranite units, possibly from nearby or underlying Stage II(?) plutons.

The aforementioned observations indicate the granodiorite was crystallized, cooled, cracked, was intruded by aplite which in turn crystallized, followed by further fracturing and "falling" into the leucomonzogranite in the interior parts of the pluton. Similarly there are many occurrences of granite xenoliths that are both more primitive and more evolved that the host rocks. The implications of this are that the sequence of emplacement and crystallization that is generally accepted for the batholith may in fact be somewhat simplistic.

A series of outcrops, along the coastline to the south of Crystal Crescent Beach, in the Halifax Pluton, yield insight into the emplacement of granitic rocks. Several large blocks of biotite granodiorite (DCgd), measuring up to 5-7m in diameter, occur within coarse-grained Halifax Peninsula leucomonzogranite (Plate 6.9). Several of these granodiorite `xenoliths' were bordered by, or contained, aplite dykes (<1-25 cm wide) and commonly contained metasedimentary xenoliths. Aplite dykes were frequently noted along two parallel sides of the granodiorite xenoliths but never on adjoining faces (Plate 6.9). No obvious chilled margins were noted in any of the granite phases. These features, coupled with the extremely angular shape of the granodiorite xenoliths indicate a sequence of emplacement that involves: 1) intrusion and crystallization of the granodiorite into the metasedimentary country rocks surrounding the Halifax Pluton. Metasedimentary xenoliths indicate the granodiorite was emplaced by stoping; 2) following crystallization, the granodiorite was then fractured (shrinkage feature?) and intruded by aplite dykes; 3) further fracturing in the granodiorite occurred preferentially along aplite dykes; 4) intrusion of coarse-grained Halifax Peninsula leucomonzogranite exploited the fractures and `stoped' the more mafic (i.e. more dense) granodiorite blocks into their present configuration. The lack of chilled margins suggests that the granodiorite had not cooled significantly before the intrusion of the leucomonzogranite.

In short, field evidence supports the petrological and geochemical data previously presented in Chapters 4 and 5 and indicates that the overall sequence of emplacement of the various map bodies and units comprising the 13 plutons of the batholith was very complex. However, it should be stressed that the scarcity of exposed granite/granite contacts and the absence of definitive cross-cutting field relations at many contacts prohibits the establishment of a comprehensive sequence of emplacement for the batholith.

6.7 Depth of Emplacement

The depth of emplacement can be estimated from a variety of field, textural and mineralogical evidence as outlined in the following sections.

6.7.1 Field Constraints

The batholith intruded sedimentary rocks of the Torbrook Formation along its northern margin. Taylor (1969) concluded that this Formation ranges in thickness from 1.5 to 3.0 km which gives a crude approximation of minimum thickness. However, this estimate is subject to such parameters as tectonic thickening and/or denudation prior to granite emplacement.

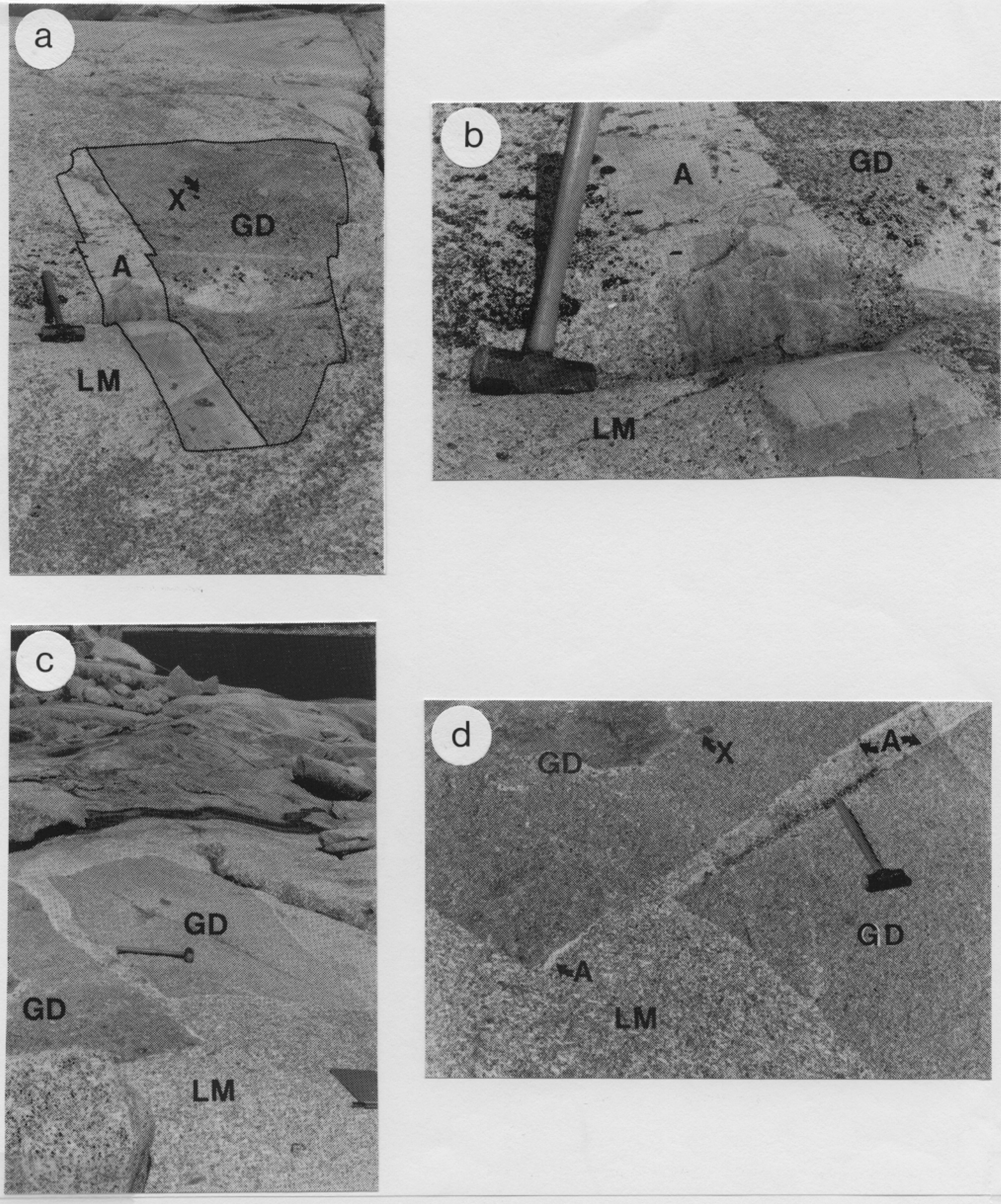


Plate 6.9 Granodiorite 'xenoliths' contained in coarse grained Halifax Peninsula leucomonzogranite near Crystal Crescent Beach along the southern margin of the Halifax Pluton. Granodiorite xenoliths commonly have Meguma Group(?) metasedimentary xenoliths and aplite dykes along one or more margins. GD - granodiorite; LM - leucomonzogranite; A - aplite; X - xenolith. Length of hammer is 40 cm.

Estimates of depth of emplacement can be determined from the metamorphic grade of the country rocks surrounding the batholith. Most of the batholith is bordered by chlorite- or biotite-grade greenschist metamorphic rocks with the exception of the SW end where metamorphic grade increases to andalusite-staurolite-cordierite and sillimanite zones of the amphibolite facies (Keppie, 1979). Miyashiro (1973) concluded that P-T estimates using metamorphic isograds was difficult because of the multitude of factors that influence stability of the various mineral species. However, he noted that biotite (i.e. greenschist grade) was stable at T ranging from 350-400°C and P ranging from approximately 2-5 kb. In contrast amphibolite grade regional metamorphism is indicative of much higher P (up to 7kb) and T (up to 600-700°C). The exact origin of the amphibolite-grade metamorphism near the SW part of the batholith is not definitively known. That is, whether this zone represents increases in regional grade or the presence of a thermal dome.

Several features are consistent with shallow epizonal intrusion (i.e. <10 km; Buddington, 1959). These include: sharp, largely discordant contacts with country rocks; presence of large stoped metasedimentary blocks; narrow contact metamorphic aureole that is commonly <100 m wide; development of granophyric textures and rare miarolitic cavities (mainly in fine-grained leucomonzogranite and leucogranite).

6.7.2 Mineralogical Constraints

McKenzie (1974) calculated normative An-Ab-Or for representative compositions from the batholith and compared these data to experimental studies. He concluded that the batholith must have crystallized between 1 and 4 kb, based upon these data.

Clarke et al. (1976) concluded that andalusite and muscovite crystallized as a primary magmatic phase in some late-stage rocks of the batholith. They concluded, on the basis of available experimental phase equilibria information, that the batholith crystallized at 3.3 to 3.9 kb and 650°C to 680°C. They employed the aluminosilicate phase diagram of Richardson (1969). Holdaway (1971) and Pattison (1992) have reported experimentally-derived aluminosilicate phase equilibria that differ significantly from the results of Richardson (1969). Their data do not allow for crystallization of andalusite in some granites. However, it should be noted that experimental studies indicate that the addition of both F and B to granitic melts has significant effect on both the granite solidus and the stability field for andalusite (Holdaway, 1971; Chorlton and Martin, 1978; Manning and Pichevant, 1983). In short, the estimation of depth of crystallization of the batholith based on the presence of `magmatic' andalusite is currently considered problematic.

Ham and Kontak (1988) concluded, on the basis of textural and chemical data, that muscovite is present as a primary magmatic mineral in much of the batholith. They noted wide discrepancies in published P-T estimates for muscovite stability which were attained using independent field evidence and experimental data. Ham and Kontak (1988) concluded that muscovite crystallized at pressures approximating 2 kb from melts with 2-3 wt. % H_2O thus placing P constraints for the batholith.

Patino Douce et al. (1993) proposed a geothermometer/geobarometer that was based upon the fugacity of O in biotite. There is currently insufficient O fugacity data for biotite in the batholith to evaluate their proposed method but definitive depth calculations may be calculated if these data becomes available in future.

As previously noted, Mahoney (1996) conducted a study of the metamorphic aureole of the batholith. She calculated P-T conditions for the formation of the thermal metamorphism associated with the intrusion of the batholith using multicomponent equilibrium geothermobarometry for an equilibrium mineral assemblage. Mahoney (1996) reported pressures ranging from 250 MPa in the western part of the batholith to 400 MPa near the eastern margin of the batholith. These pressures correspond to depths of 6 km and 10 km depth for the western and eastern parts of the batholith respectively. This work represents the first definitive estimate of the depth of emplacement for granitic bodies in the Meguma Zone.

6.8 Discussion and Summary

The South Mountain Batholith is, in general terms, massive and lacks the penetrative structural deformation that is characteristic of syn-tectonic or syn-kinematic granitoid bodies. Accordingly, it is interpreted to have been emplaced after the regional deformation associated with the Middle Devonian Acadian Orogeny. However, it is evident from the observations in the previous sections that the batholith was subject to regional stresses during, and subsequent to, emplacement and crystallization.

The NE-trending elongate shape of, and the predominance of NE-trending primary flow features in, several Stage I plutons may reflect structural control during initial stages of batholith emplacement. Conversely, their shape may reflect the exploitation of pre-existing structures in the country rocks by the intruding Stage I plutons as noted for other granite batholiths around the world (Castro, 1986 and references therein).

Some faults in Stage I plutons show evidence that they were active following crystallization of Stage I plutons and prior to the emplacement of Stage II plutons.

Granite/metasediment contacts are sharp and intrusive, for the most part, and show virtually no signs of deformation of the country rocks. The two notable exceptions include the "Transverse anticline" and the Aspotogan Harbour area where the batholith has been interpreted to have been forcefully emplaced. It is unclear whether the coincidence of north-trending regional structural and primary flow features in the batholith in the western end of the batholith represent "ballooning" or lateral forces associated with emplacement of the batholith or were generated by regional structural forces.

The East Dalhousie pluton and the southwestern extension of the Davis Lake pluton have narrow, NE-trending, dyke-like shapes and are flanked by a series of faults and/or shear zones (Fig. 6.5). In several locales these Stage II plutons have been variably deformed by movement/strain along these faults. These observations prompted Horne et al. (1988; 1992) to suggest that the entire batholith was localized along a crustal-scale structure. Results of a recent geochronological study of the East Kemptville-East Dalhousie Fault Zone, which partially forms the northern boundary of both plutons, indicates that these faults were episodically active from ca. 350 to 250 Ma (Kontak et al., 1989; Kontak and Cormier, 1991). One explanation for the coincidence of faults and pluton boundaries is that some Stage II plutons were emplaced along pre-existing structures that remained active for ca. 120 Ma subsequent to their emplacement (Horne et al., 1992). Conversely, the Stage II plutons may have intruded and crystallized and subsequently emplaced to their present configuration by displacement along the observed faults. More structural data pertaining to the movement along the sundry faults of the batholith must first be collected before this issue can be resolved.

The predominantly circular shape of Stage II plutons and the concentric primary flow trends in the Halifax and New Ross plutons, which sharply contrast the Stage I plutons, may indicate that the compressive forces on the batholith may have diminished somewhat between the emplacement of Stage I and II plutons. However, the orthogonal or dyke-like shape of some fine-grained leucomonzogranite bodies in Stage II plutons has been interpreted as reflecting intrusion along pre-existing structures in the coarse-grained megacrystic host rocks (Horne et al., 1992). These structures were presumably formed by regional compression on the batholith.

The structural data for joints, dykes, veins faults and shear zones, outlined above, demonstrate that the batholith was emplaced and crystallized in a weak regional stress regime. Horne et al. (1988, 1992) concluded that these planar features developed during northwest, horizontal compression accompanying uplift during the waning stages of the Acadian Orogenic event. The occurrence of NW-trending (315°, 325°, 335°) joints interpreted as tension joints and recurrently occupied by quartz veins or dykes, and NE-trending (040°, 062°) shear/fracture zones which are interpreted as P and R (Riedel shear geometry) are consistent with NW-directed transpression and presumably dextral displacement along NE-trending faults.

The exact origin of some of the above structural features is somewhat contentious and requires additional study, however, it is evident from the above features that the batholith was subjected to regional stresses commencing with the earliest emplacement of Stage I plutons to the terminal stages during which time mineralization occurred. These regional stresses probably relate to the waning stages of the Acadian Orogeny and also are manifest as transpressional displacement along the Cobequid-Chedabucto Fault Zone (Fig. 1.2).