Atlantic Geoscience
Journal of the Atlantic Geoscience Society

Tectonic timing of emplacement of the South Mountain Batholith, southwestern Nova Scotia, Canada
Intervalle tectonique de mise en place du batholite du mont South, sud-ouest de la Nouvelle-Écosse, Canada

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Volume 61, 2025

URI: https://id.erudit.org/iderudit/1117524ar
DOI: https://doi.org/10.4138/atlgeo.2025.002

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Publisher(s)

Atlantic Geoscience Society

ISSN

2564-2987 (digital)

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Cite this article

Clarke, D., MacDonald, M. & McKenzie, C. (2025). Tectonic timing of emplacement of the South Mountain Batholith, southwestern Nova Scotia, Canada. *Atlantic Geoscience*, *61*, 15–75. https://doi.org/10.4138/atlgeo.2025.002

Article abstract

The South Mountain Batholith (SMB) of southwestern Nova Scotia is the largest intrusion in the Appalachian orogen. Some structures in its Meguma Supergroup country rocks pre-date emplacement of the SMB, some structures in the country rocks and batholith are synchronous with emplacement and cooling of the granite magma, and other structures in the country rocks and intrusion post-date emplacement. In this paper, we compile an inventory of all such structures, over a wide range of length scales, and evaluate each one in terms of its bearing on the tectonic conditions of emplacement of the SMB. Early structures in the country rocks may include faults that controlled the emplacement of the SMB and include folding (F1) and axial planar cleavage (S1) belonging to the Neo-Acadian orogeny. Structures in the country rocks temporally related to granite emplacement include cross-cutting relationships, annealing of cleavage, growth of porphyroblasts in the contact aureole, fabrics in contact migmatites, granite dykes cutting the country rocks, deformation aureole fabrics, late flexural slip, a putative oroclinal bend, and possibly the structures hosting the Meguma terrane gold deposits. Structures in the granites themselves include shapes of Stage I plutons, foliations in Stage I plutons, development of augen textures, shapes of Stage II plutons, foliations in Stage II plutons, “folding” in the Halifax Pluton, internal granite-granite contacts, ring schlieren, textures of immiscible sulphides in the granites, 2-D and 3-D shapes of gravity anomalies, paucity of high-T deformation microstructures, and undulose extinction in quartz. Late structures, affecting the country rocks and the granites, include joints, and barren or mineralized faults and shear zones. Not all structures have a bearing on the tectonic timing of emplacement of the SMB, but the SMB indisputably post-dates the main Neo-Acadian F1–S1 deformation. The most problematic issues concern the origin of late brittle and ductile deformation features in the SMB (augen granites, deformation aureoles, joints, faults, shear zones, and related mineral deposits) and whether they are the result of waning Neo-Acadian deformation, internal adjustments, uplift, gravitational collapse, or other regional-scale tectonics.

Tectonic timing of emplacement of the South Mountain Batholith, southwestern Nova Scotia, Canada†

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Date received: 25 September 2024 ¶ Date accepted: 8 January 2025

ABSTRACT

The South Mountain Batholith (SMB) of southwestern Nova Scotia is the largest intrusion in the Appalachian orogen. Some structures in its Meguma Supergroup country rocks pre-date emplacement of the SMB, some structures in the country rocks and batholith are synchronous with emplacement and cooling of the granite magma, and other structures in the country rocks and intrusion post-date emplacement. In this paper, we compile an inventory of all such structures, over a wide range of length scales, and evaluate each one in terms of its bearing on the tectonic conditions of emplacement of the SMB. Early structures in the country rocks may include faults that controlled the emplacement of the SMB and include folding (F_1) and axial planar cleavage (S_1) belonging to the Neo-Acadian orogeny. Structures in the country rocks temporally related to granite emplacement include cross-cutting relationships, annealing of cleavage, growth of porphyroblasts in the contact aureole, fabrics in contact migmatites, granite dykes cutting the country rocks, deformation aureole fabrics, late flexural slip, a putative oroclinal bend, and possibly the structures hosting the Meguma terrane gold deposits. Structures in the granites themselves include shapes of Stage I plutons, foliations in Stage I plutons, development of augen textures, shapes of Stage II plutons, foliations in Stage II plutons, "folding" in the Halifax Pluton, internal granite-granite contacts, ring schlieren, textures of immiscible sulphides in the granites, 2-D and 3-D shapes of gravity anomalies, paucity of high-T deformation microstructures, and undulose extinction in quartz. Late structures, affecting the country rocks and the granites, include joints, and barren or mineralized faults and shear zones. Not all structures have a bearing on the tectonic timing of emplacement of the SMB, but the SMB indisputably post-dates the main Neo-Acadian F_1–S_1 deformation. The most problematic issues concern the origin of late brittle and ductile deformation features in the SMB (augen granites, deformation aureoles, joints, faults, shear zones, and related mineral deposits) and whether they are the result of waning Neo-Acadian deformation, internal adjustments, uplift, gravitational collapse, or other regional-scale tectonics.

RÉSUMÉ

Le batholite du mont South (BMS) dans le sud-ouest de la Nouvelle-Écosse est l'intrusion la plus importante dans l'orogène appalachien. Certaines structures dans ses roches encaissantes du Supergroupe de Meguma sont antérieures à la mise en place du BMS, certaines structures dans les roches encaissantes et le batholite sont synchrones avec la mise en place et le refroidissement du magma granitique, et d'autres structures dans les roches encaissantes et l'intrusion sont ultérieures à la mise en place. Dans cet article, nous dressons un inventaire de toutes les structures en question, au sein d'un vaste éventail d'échelles de longueur, et nous évaluons la portée de chacune sur les conditions tectoniques de la mise en place du BMS. Les premières structures dans les roches encaissantes pourraient inclure des failles ayant régi la mise en place du BMS et comprendre des plissements (F_1) ainsi qu'un clivage de plan axial (S_1) propre à l'orogène néo-acadien. Les structures dans les roches encaissantes temporairement apparentées à la mise en place du granite présentent des rapports transversaux, un annelage du clivage, une augmentation des porphyroblastes dans l'auréole de contact, des éléments structuraux dans les migmatites de contact, des dykes granitiques recoupant les roches encaissantes, des éléments structuraux dans l'auréole de déformation, un glissement tardif dans le plan des couches, une courbure oroclinale hypothétique et possiblement les structures abritant les gîtes d'or du terrane de Meguma. Les structures dans les granites eux-mêmes comprennent des profils de plutons du stade I, des foliations dans des plutons du stade I, l'apparition de textures oeillées, des profils de plutons du stade II, des foliations dans des plutons du stade II, un « plissement »

†From: Atlantic Geoscience Special Series "In recognition of the geological career of Sandra M. Barr". Atlantic Geoscience, 61, pp. 15-75.

ATLANTIC GEOSCIENCE 61, 015–075 (2025) doi:10.4138/atlgeo.2025.002
ISSN:2564-2987.

dans le pluton d'Halifax, des contacts internes granite-granite, un schliere annulaire, des textures de sulfures non miscibles dans les granites, des profils bidimensionnels et tridimensionnels d'anomalies gravimétriques, une rareté de microstructures de déformation de température élevée et un motif ondulé dans le quartz. Les structures tardives, qui affectent les roches encaissantes et les granites, comprennent des diaclases ainsi que des zones de cisaillement et des failles dénudées ou minéralisées. Les structures n'influent pas toutes sur l'intervalle tectonique de mise en place du BMS, mais le BMS est incontestablement ultérieur à la principale déformation néo-acadienne F_1–S_1. Les principaux aspects problématiques concernent l'origine des particularités de déformation cassante et ductile dans le BMS (granites oeillés, auréoles de déformation, diaclases, failles, zones de cisaillement et gîtes minéraux connexes) et la question de savoir si ces phénomènes découlent d'un ralentissement de la déformation néo-acadienne, d'ajustements internes, d'un soulèvement, d'un effondrement gravitationnel ou d'autres manifestations tectoniques régionales.

[*Traduit par la redaction*]

INTRODUCTION

Regional tectonic setting

The Appalachian orogen in Atlantic Canada is the product of many collisional events that accreted a sequence of peri-Gondwanan terranes to Laurasia from ca. 500–300 Ma (van Staal and Barr 2012). The penultimate terrane to accrete was Avalonia, and the last discrete terrane to accrete, by overthrusting of Avalonia and by dextral transpression along the Minas Fault Zone (MFZ), was the Meguma terrane (Fig. 1a), the North American part of Megumia which includes equivalent rocks in Wales. The assembly of the orogen ended with the arrival of Gondwana (ca. 340–330 Ma) (Piper and Pe-Piper 2022), with the suture between Laurentia and Gondwana lying ca. 500 km to the southeast of the current terrestrial exposure of the Meguma terrane (Fig. 1b).

The Meguma terrane is exposed in Nova Scotia south of the MFZ, extending east–west from the Bay of Fundy to Chedabucto Bay and onto the continental shelf east and southwest of the terrestrial exposure. The Meguma terrane was a tectonically active region from ca. 400–300 Ma (Table 1). Its principal deformational events, collectively named the Neo-Acadian orogeny (van Staal and Barr 2012; but see Waldron *et al.* 2024), included early oblique collision resolving into a "press" component to form the folds in the Meguma Supergroup and the overlying Rockville Notch Group up to the Early Devonian (Emsian) Torbrook Formation and a "trans" component manifest as dextral motion on the MFZ (Waldron *et al.* 2015, 2022; Piper and Pe-Piper 2021), subsequently followed by transtension to continue the eastward translation of the Meguma terrane and to create the Carboniferous basins in the period from ca. 370–350 Ma (Waldron *et al.* 2015, 2022), and to ultimately bring the Meguma terrane to its present position. Assembly of the Appalachian orogen culminated with restricted far-field deformational effects of the Alleghanian orogeny caused by the terminal collision of Gondwana with composite Laurentia (Fig. 1b).

Geological setting of the South Mountain Batholith

The Meguma terrane consists of two principal lithological units (Fig. 2): (1) the Meguma Supergroup (Goldenville and Halifax groups), a thick (11 km) sequence of Cambrian–Ordovician turbidites (White 2010; White *et al.* 2012; and references within) and the overlying Silurian–Devonian Rockville Notch Group (White and Barr 2017; White *et al.* 2018). These units are deformed into tight, to open, chevron and box-style, NW- and SE-verging regional folds, termed F_1, with axial planar cleavage S_1 (Horne and Culshaw 2001; Culshaw and Lee 2006), and with Neo-Acadian deformation ages ranging from ca. 410–389 Ma (Fig. 3) (Reynolds *et al.* 1973; Kontak *et al.* 1998; Hicks *et al.* 1999). (2) many peraluminous granite plutons, including the South Mountain Batholith (SMB), which intruded the deformed Meguma Supergroup with clear cross-cutting relationships against the Neo-Acadian folds (Fig. 4), and with intrusive ages for the earliest Stage I granodiorite phases ranging from 375.9 ± 4.1 to 381.1 ± 3.8 Ma, thus covering a span from ca. 372 to 385 Ma with error bars considered (Fig. 5) (Bickerton *et al.* 2022). Zircon antecryst data from the SMB show that magma generation in the lower crust preceded emplacement in the upper crust by ca. 3–15 my.

Field relations (e.g., McKenzie 1974; MacDonald 2001) have shown two main stages of granite intrusion in the SMB, recently re-confirmed by the geochronological work of Bickerton *et al.* (2022). The five Stage I plutons (ca. 381–375 Ma) tend to be less differentiated biotite granodiorites, biotite monzogranites, and muscovite-biotite monzogranites whereas the eight Stage II plutons (ca. 375–371 Ma) are more highly differentiated two-mica leucomonzogranites and muscovite (± topaz) leucogranites.

Purpose

The SMB, adjacent country rocks, and a wider region contain a wide range of structural features. The purpose of this investigation is to determine which structures in the SMB developed internally within the cooling and crystallizing batholith, and which structures originated externally as a result of regional tectonism. To attain this objective, we have compiled a *comprehensive* inventory of structural and microstructural features that may have bearing on the problem of timing of emplacement of the SMB in the Meguma terrane. In the past, the debate concerning the timing of the emplacement of the SMB was simply a binary choice between

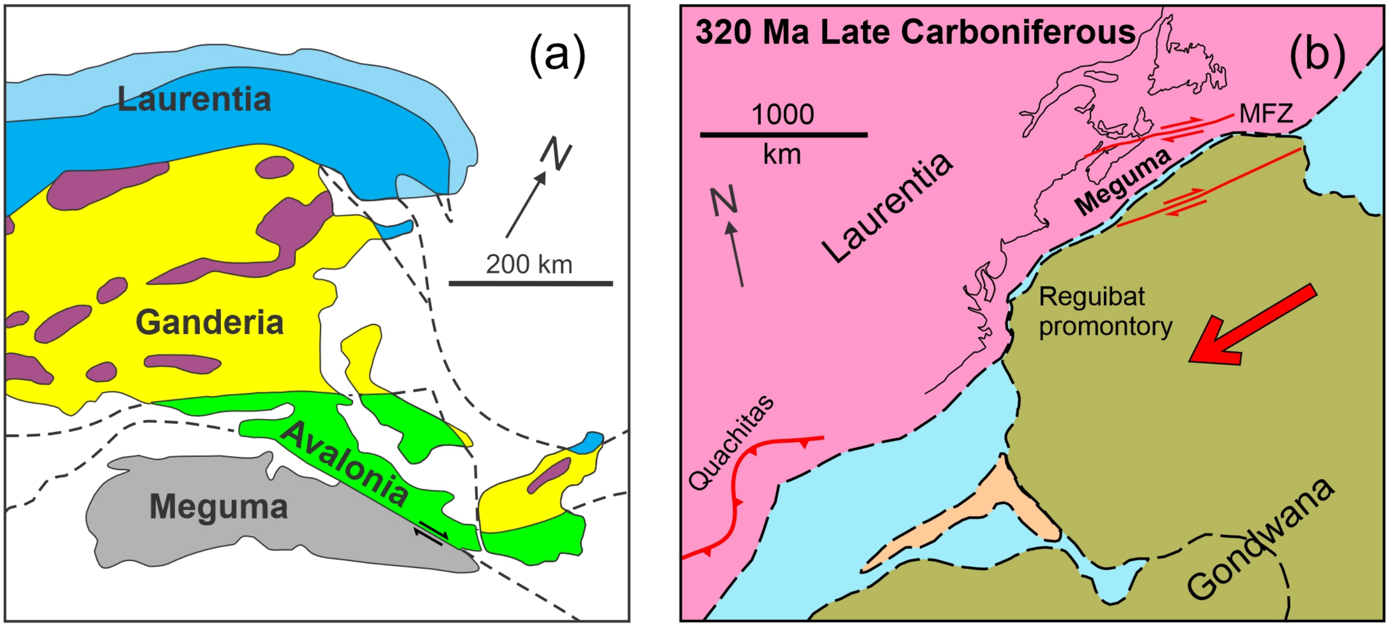


Figure 1. Terranes in the Maritime Provinces of Canada. (a) Simplified terrane map of part of the northern Appalachians. The Meguma terrane is the most recently accreted and most outboard terrane. The dextral suture between the Meguma terrane and Avalonia is the Minas Fault Zone (MFZ) (ca. 355–305 Ma) (Piper and Pe-Piper 2022). Map adapted from White *et al.* (2016). (b) The positions of Laurentia and Gondwana at ca. 320 Ma. Map after Piper and Pe-Piper 2022.

the syn-tectonic (i.e., synchronous with D_1) emplacement (Horne *et al.* 1988, 1992; Benn *et al.* 1997, 1999; Kontak *et al.* 2001; Culshaw and Bhatnagar 2001; Kellett *et al.* 2021; and Bickerton *et al.* 2022), and post-tectonic (i.e., after D_1) emplacement (McKenzie and Clarke 1975; MacDonald and Clarke 1991; Clarke *et al.* 1985; Giles 1985; and Dostal and Chatterjee 2010) scenarios. Now, we integrate the question of the timing of emplacement of the SMB more broadly, and in more detail, into the evolving regional tectonics over the ca. 80 myr interval from ca. 410–330 Ma.

Scope

To address the question of the origin of structures in the SMB, both spatially and temporally, we examine structures not only in the batholith, but also relevant features in its thermal aureole, and structures bounding the Meguma terrane over the time interval from ca. 410–330 Ma.

Claim

In general, we propose that many of the structures in the SMB are internally generated, that some are externally imposed on the SMB, and yet others are uncertain and require further investigation. In particular, the SMB shows no evidence of the transpressional deformation associated with the Neo-Acadian F_1 folding of the Meguma Supergroup but may have been affected by other tectonic events in, and bounding, the Meguma terrane.

Definitions

In this paper, we adopt the following definitions:

Deformation – the transformation from an initial to a final geometry by means of rigid body translation, rigid body rotation, strain (distortion) and/or volume change (Fossen 2016).

Acadian orogeny – a deformation associated with the ca. 440–400 Ma docking of Avalonia against Ganderia (van Staal and Barr 2012), but with no known deformational effects in the later Meguma terrane.

Neo-Acadian orogeny – deformation associated with the docking of the Meguma terrane against Avalonia, beginning about ca. 410 Ma (van Staal and Barr 2012) and ending at some uncertain time between ca. 370 and 350 Ma (Waldron *et al.* 2022) or ca. 340 Ma (van Staal and Barr 2012). The most obvious early structural expressions of the Neo-Acadian orogeny are the folding of the sedimentary rocks of the Meguma Supergroup (D_1) and the development of axial planar cleavage (S_1).

Alleghanian orogeny – the culminating collision of Gondwana with composite Laurasia beginning at ca. 340–330 Ma and extending to ca. 260 Ma (van Staal and Barr 2012, fig. 16).

Agenda

In the immediately following Methods section, we briefly describe our approach to addressing this problem concerning the origin of structures in the SMB. The next lengthy

Analysis - Observations and Discussion section is in two parts: first, we deal with relevant structures mainly in the contact aureole of the SMB but expanding our coverage of more regional structures; and second, we present all evidence from structures within the SMB itself. Finally, in the Synthesis section, we combine all the criteria to make an integrated assessment for the timing of emplacement of the SMB relative to tectonic events in the Meguma terrane.

METHODS

The authors of this paper began working on the Meguma terrane granites in the 1970s. Since then, we have variously worked episodically, or continuously, on the SMB until the present time. To prepare this paper, we have drawn on our own work, as well as on the published and unpublished work of many others and supplemented these approaches by revisiting many outcrops to check our observations and, if necessary, reassess our previous interpretations.

OBSERVATIONS AND ANALYSIS

Structures in the Meguma terrane country rocks

Annealed S_1 cleavage

Axial planar cleavage (S_1), related to the early transpressional phase of the Neo-Acadian orogeny, is well developed in slates of the Halifax Group (Fig. 6a) (Jamieson *et al.* 2012). Adjacent to the batholith, disappearance of cleavage-defining phases (muscovite, chlorite, graphite), growth of matrix minerals (quartz, feldspar), and growth of porphyroblasts (cordierite, andalusite) all contribute to physical annealing and elimination of the cleavage to produce hornfels (Fig. 6b).

According to this annealing criterion alone, the SMB and its thermal effects post-date the Neo-Acadian deformational event that produced the S_1 axial planar cleavage in the Halifax Group slates.

Cordierite and andalusite porphyroblasts

The thermal aureole in the eastern part of the SMB is 2.5–3.0 km wide (Jamieson *et al.* 2012). As noted above, porphyroblast growth is part of the annealing process, and the principal porphyroblasts in the Meguma Supergroup thermal aureole of the SMB are cordierite in the metagreywackes, and cordierite + andalusite (chiastolite) in the metapelites. Cordierite generally is present as small (mm scale) anhedral grains, and chiastolite is present as larger (cm scale) prismatic crystals. Cordierite typically overgrows both bedding and cleavage, and chiastolite prisms generally have no preferred orientations with respect to either bedding or cleavage (Jamieson *et al.* 2012).

At one locality in the Aspotogan Peninsula (N 44.50871°; W 64.10035°), well-developed cleavage in the Halifax Group slate is perpendicular to Neo-Acadian direction of maximum shortening. This locality is far enough away from the granite contact that the cleavage is not annealed, but it is close enough that well-developed chiastolite porphyro-blasts have formed (Fig. 7). As highlighted, the orientation of the chiastolite prisms bears no preferred relation to the Neo-Acadian cleavage.

The 3-D orientations of chiastolite and cordierite porphyroblasts in most of the thermal aureole of the SMB suggest that there was little or no component of directed Neo-Acadian deformation remaining at the time of their formation, demonstrating that intrusion of the SMB and associated contact metamorphism clearly post-date the main Neo-Acadian transpressional deformation that produced the S_1 fabric. Exceptions to these first-order observations and interpretation include local occurrences of aligned long axes of ovoid cordierite porphyroblasts lying in the S_1 plane (perhaps related to mimetic growth), strain shadows around cordierite in the outer thermal aureole (perhaps related to late flexural slip) and lineated andalusite in the deformation aureole, the latter two of which are discussed below.

Undeformed contact migmatites

Depending on the prevailing T-P-X conditions in the contact aureole of a pluton, partial melting of the country rock may take place. If that partial melting occurs during syntectonic emplacement of the intrusion, the regional deformation should be coaxial in the country rock, the migmatite, and the granite (Fig. 8a). Alternatively, if intrusion of the granite and development of a contact migmatite postdate the regional deformation, there should be no evidence of the regional deformation in the migmatite (Fig. 8b).

Table 1. (next page) Compilation of some of the magmatic and tectonic events in the Meguma terrane from ca. 400–300 Ma that have relevance to the South Mountain Batholith Abbreviations: BPP – Barrington Passage Pluton; LDMIs – Late Devonian Mafic Intrusions; LFS – Late Flexural Slip; MB – Musquodoboit Batholith; MFZ – Minas Fault Zone; PMP – Port Mouton Pluton; SMB – South Mountain Batholith; SP – Shelburne Pluton. References: 1 Pe-Piper *et al.* (2010); 2 Culshaw and Liesa (1997); 3 Piper and Pe-Piper (2021); 4 Waldron *et al.* (2015); 5 MacLean *et al.* (2003); 6 Shelnutt and Dostal (2012); 7 Archibald *et al.* (2018); 8 Moran *et al.* (2007); 9 Pe-Piper *et al.* (2018); 10 Murphy *et al.* (2011); 11 Horne *et al.* (1992); 12 Bickerton *et al.* (2022); 13 Kontak *et al.* (1995); 14 Keppie *et al.* (2002); 15 Horne and Culshaw (2001); 16 Clarke *et al.* (2000); 17 Tate and Clarke (1995); 18 Clarke *et al.* (2002); 19 Tate *et al.* (1997); 20 Ruffman and Greenough (1990); 21 Graves and Zentilli (1982); 22 Kontak *et al.* (1990a); 23 Chen *et al.* (2014); 24 Hicks *et al.* (1999); 25 van Staal and Barr (2012); 26 White *et al.* (2007); 27 Keppie *et al.* (2021); 28 Kontak *et al.* (2005)

Age (Ma)	Magmatic Event	Tectonic Event	Implication	References
300	German Bank Pluton			1
302				
304				
306				
308				
310				
312				
314				
316				
318				
320		Alleghanian Shear Zones		2
322		in SW Nova Scotia		
324		+	rotation(?), thrusts, oroclinal bending(?)	
326		Collision of Gondwana and Laurentia		3
328				
330				
332				
334				
336				
338				
340				
342				
344				
346				
348				
350		Appalachian (NE) and Canso (NW) Faulting?	Canso conjugate to MFZ, cutting SMB?	4
352				
354				
356	Wedgeport Pluton			5,6
358		Uplift, erosion of Kelly Brook granite	uplift and extension tectonics	7
360				
362	Seal Island Pluton		deposition of Horton Fm. directly on SMB	8,9,10
364				
366		Switch MFZ to Transtension	initiation of Maritimes Basin	3,9,10
368		Erosion/Uplift/Gravitational Collapse	jointing, faulting	11
370		Davis Lake Shear Zones, Auriferous Veins		12,13,14
372	SMB Stage II Plutons			11,15,16
374	(+ Port Mouton Pluton)	Port Mouton Shear Zone	syn-magmatic shear zone	17,18,19
375		Kelly Brook deformed granite	MFZ active syn- or post-intrusion	7
376	(+ LDMIs)	Late Flexural Slip	D_2 tightening of D_1 folds	15,17,20
378				
380	SMB Stage I Plutons			
382				
384			↑	
386			460 Ma > Meguma gold veins > 360 Ma	21,22,23
388			↓	
390				24,25
392				26,27
394	Brazil Lake Pegmatite	Neo-Acadian Oblique Collision	resolves into D_1 compressional folding	28
396			and dextral translation along CCFZ	
398				
400				

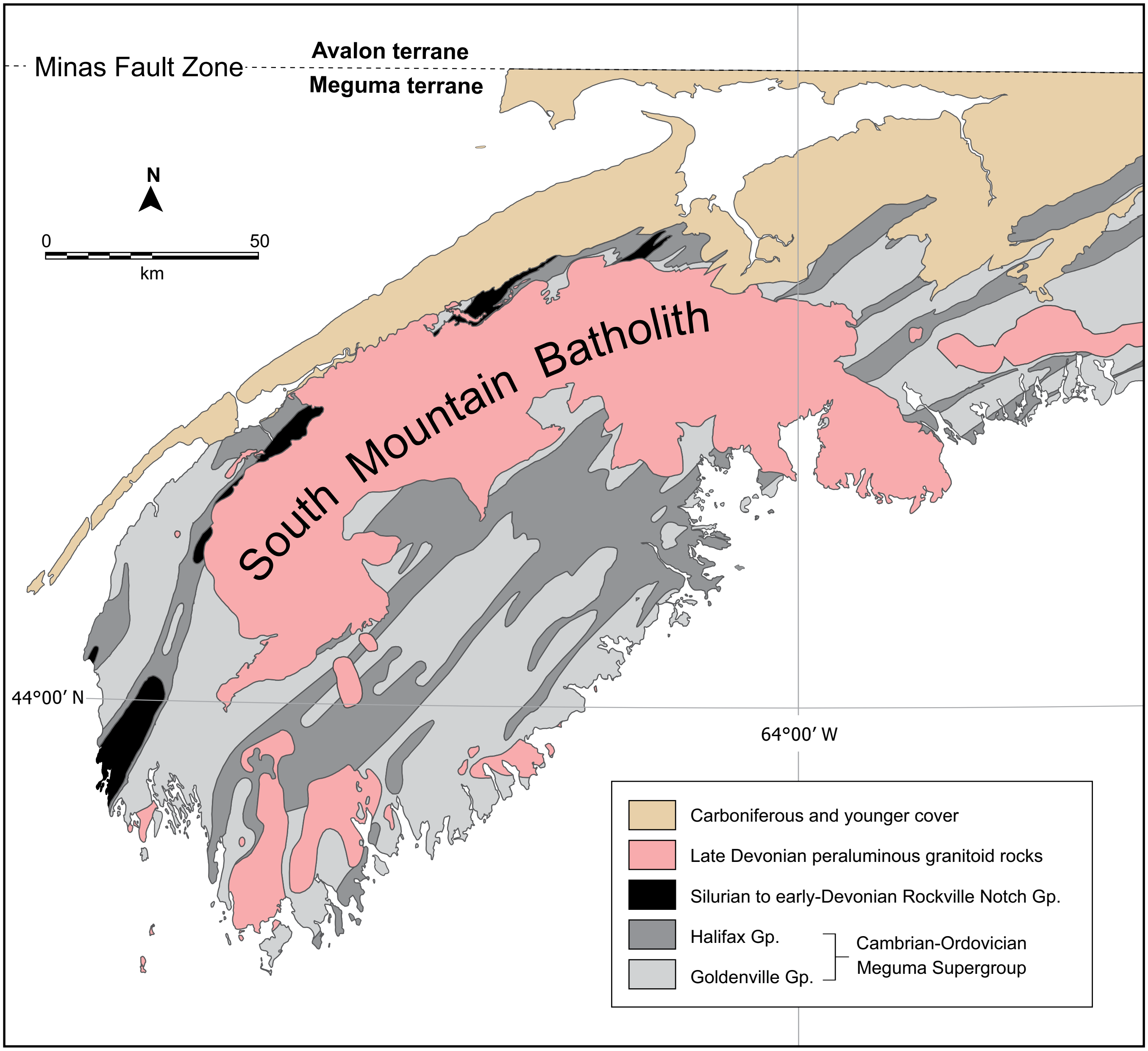


Figure 2. Geological map of the western part of terrestrial Meguma terrane (Fig. 1) showing the areal dominance of the Meguma Supergroup and the peraluminous granite plutons. The cross-cutting relationship between the SMB and the Neo-Acadian folds in the Meguma Supergroup is clear, particularly at the eastern end of the batholith.

Development of contact migmatites around the SMB is not common, presumably reflecting the relatively low temperature in the aureole (maximum 650°C; Hilchie and Jamieson 2014) of the intrusion and the refractory nature of the Goldenville Group metagreywackes. However, the combination of metapelite and H_2O degassed from the granite or released by the incongruent melting of muscovite and biotite, may have resulted in local partial melting of the country rock.

Jamieson *et al.* (2012) and Hilchie and Jamieson (2014) described examples of incipient melting in the Meguma Supergroup adjacent to the SMB, such as leucocratic patches and "elongated seams and millimetre-scale segregations enriched in quartz and K-feldspar, locally with coarse andalusite + quartz intergrowths and idioblastic cordierite". They interpreted these features as "incipient leucosomes" but made no mention of any preferred orientations in these contact migmatites. The reason for this lack of deformation may be that the migmatites occur only in the annealed, and possibly stronger, part of the thermal aureole.

We have also observed development of contact migmatites in several locations, including bedding-parallel incipient leucosomes on Dunbrack Street in Halifax (Figs. 9a, 10), a xenolith on Dunbrack Street showing somewhat more advanced partial melting (Fig. 9b), the complex combination of injected granite and in situ leucosomes on Washmill

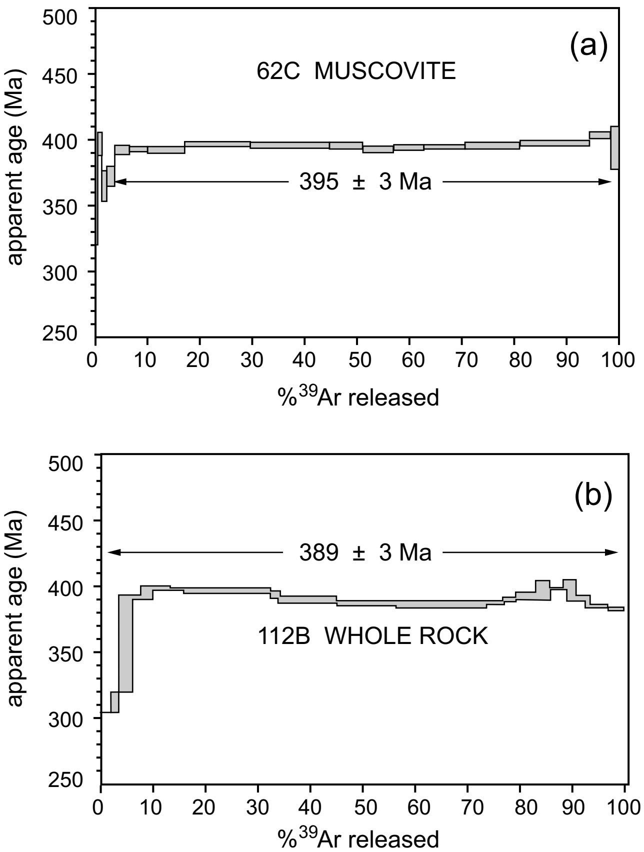


Figure 3. Geochronology of deformation of the Meguma Supergroup. (a) Muscovite from a metasiltstone in Mosher's Island Formation showing "the most reliable estimate of the time of regional metamorphism" (Hicks *et al.* 1999). (b) Slate from the Mosher's Island Formation showing the "lower limit for the time of metamorphism and cleavage development" (Hicks *et al.* 1999).

Figure 4. Vertical surface of an outcrop on Aspotogan Peninsula showing the contact of SMB cutting steeply dipping Neo-Acadian folds in the Meguma Supergroup. This stepwise contact is a microcosm for the entire batholith: in some places, the contact is perpendicular to the bedding and in other places, it is parallel, consistent with emplacement by stoping. Yellow line highlights bedding. Scale bar is 25 cm.

Lake Drive in Halifax (Fig. 9c, d) , the patchy development of leucosomes on Highway 12 in Lunenburg County (Fig. 9e) noted by McKenzie (1974), and in the roof zone of the SMB near Boot Lake in Annapolis County (Fig. 9f) (MacDonald 2001).

In the various types of migmatites in the thermal aureole of the SMB (Fig. 9), the melt fractions are low, and well below the rheologically critical melt percentage (RCMP) where evidence of externally applied deformation might not be obvious. However, even minor amounts of partial melt located along grain boundaries should have weakened the affected rocks, and made them, and any melt generated, highly susceptible to regional stresses (Rosenberg and Handy 2005). The absence of any obvious regional deformation structures in the rare contact migmatites developed locally around the sides of the SMB suggests that intrusion of the SMB post-dated Neo-Acadian D_1, unless the migmatites were protected from any putative F_1 deformation by the high-strength annealed zone of the contact aureole. The exception is the Boot Lake migmatite (Fig. 9f), located in a roof pendant, where temperatures may have been higher, partial melting was greater, and buoyant forces of the pluton resulted in significant deformation of the Meguma Supergroup country rocks (Burov *et al.* 2003).

Undeformed granite dykes

Fractures surrounding a pluton may be the product of thermal or physical expansion processes. Any magma intruded into a fracture in a deforming solid host represents a plane of extreme weakness, and it should take up all the strain of the prevailing regional deformation until the sheet is solid and at ambient temperature where its strength/rigidity has become compatible with the host. In this scenario, any dyke intruded into a deforming host should itself become deformed, and the minerals of the dyke should show evidence of high-T supra-solidus and sub-solidus deformation (features such as c-slip in quartz, S-C foliation, kinked micas, cataclasis, elongation of grains, boudinage, etc.). Alternatively, a granite dyke injected into a host that is not undergoing deformation should show no megascopic or microscopic signs of deformation.

We describe granitic dykes in the Meguma terrane host at three locations outside the deformation aureole (Fig. 11): (1) Dunbrack Street (N 44.63667°; W 63.63833°) where two shallowly dipping pegmatitic dykes with straight contacts cut the bedding (Fig. 11a); (2) Purcells Cove (N 44.61667°; W 63.57430°) where R.A. Jamieson collected aplite dyke sample PCR07-15, but the outcrop is no longer exposed; and (3) A 2 km stretch of coastline north of Portuguese Cove (Jewkes 1986), including Breakers Park (N 44.53833°; W 63.54389°), where several variously oriented pegmatite,

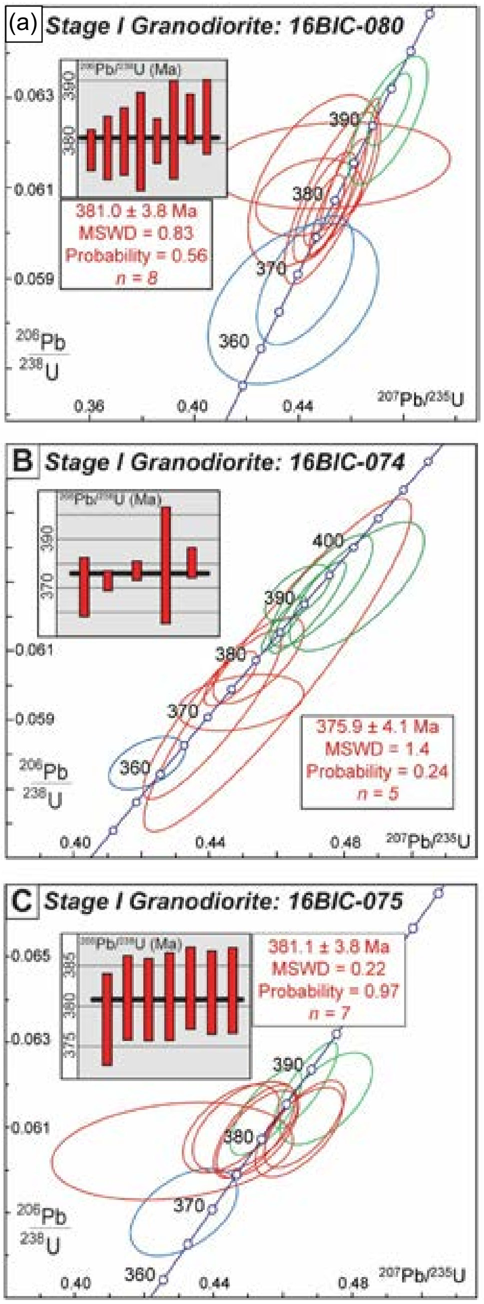


Figure 5. Zircon ages of Stage I granodiorites from the SMB (Bickerton *et al.* 2022). (Reproduced with permission of Luke Bickerton.)

aplite-pegmatite, and aplite dykes of widths ranging from centimetre to decametre scale cut the bedding and cleavage of the Meguma Supergroup at various angles (Figs. 11b, c).

In thin section, all these granite-aplite-pegmatite dykes have isotropic hypidiomorphic granular to saccharoidal textures in sharp contrast to the annealed, but strongly foliated, texture of the host rocks of the Meguma Supergroup (Fig. 12). The quartz grains show little or no undulose extinction, the micas are undeformed, and the rocks show no foliation, suggesting injection into a host experiencing minimal deviatoric stress. Assuming that the granite dykes are coeval and comagmatic with the adjacent SMB, the magmatic activity of the SMB post-dated Neo-Acadian deformation of the Meguma Supergroup, at least in this region.

Deformation aureole

A deformation aureole is a zone of deformed rocks adjacent to an igneous intrusion. The causes of that deformation may be related to the forceful emplacement of the intrusion, or to its subsequent structural adjustment against the host rocks during cooling. If the emplacement of the intrusion locally creates structures that overprint regional structures in the country rock, the timing of emplacement of that intrusion is post-tectonic.

Much of the perimeter of the SMB shows evidence of emplacement by passive stoping (Culshaw and Bhatnagar 2001); however, some restricted parts of the contact are more complex, and local deformation features have developed, including:

(i) deflection of the SW-trending regional strike of the Neo-Acadian folds in the Washmill Lake Drive area (Fig. 13) (White *et al.* 2008);
(ii) development of transverse anticlines near Bedford and on Aspotogan Peninsula (Benn *et al.* 1999; Culshaw and Bhatnagar 2001) (Fig. 14);
(iii) in the well-exposed deformation aureole along Washmill Lake Drive, bedding defines the prominent vertical surfaces (Fig. 15a), but cleavage is nearly parallel to bedding and shows well-defined bedding-cleavage intersection lineations on some surfaces (Fig. 15b), everywhere there is a steep mineral lineation defined by andalusite porphyroblasts (Fig. 15c), and undeformed granite dykes cut the rocks of the deformation aureole, indicating that magma was still in the SMB system after the deformation aureole had completely developed; and
(iv) elongation of cordierite porphyroblasts parallel to host-rock fabric close to the SMB contact in two localities, north of Chester Basin (McKenzie 1974) and in the railway cut in Halifax (S. Hanmer, personal communication) (Fig. 15d).

The deflected bedding (Fig. 13) and transverse anticlines (Fig. 14) are spatially closely related to the granite and consistently appear to be caused by its locally forceful (i.e., compressional) mode of emplacement and local development of a deformation aureole.

The one-time thermal metamorphism event, related to the intrusion of the SMB, is responsible for the formation of all porphyroblasts. Randomly oriented cordierite and andalusite porphyroblasts occur almost everywhere in the thermal aureole of the SMB and appear to have grown when the host Meguma terrane rocks were not deforming; however, lineated cordierite and andalusite appear to have grown in some parts of the thermal aureole undergoing local deformation.

Culshaw and Bhatnagar (2001) deduced that the local subvertical lineations in the exocontact (Fig. 15) were generated by batholith-down adjustments while regional

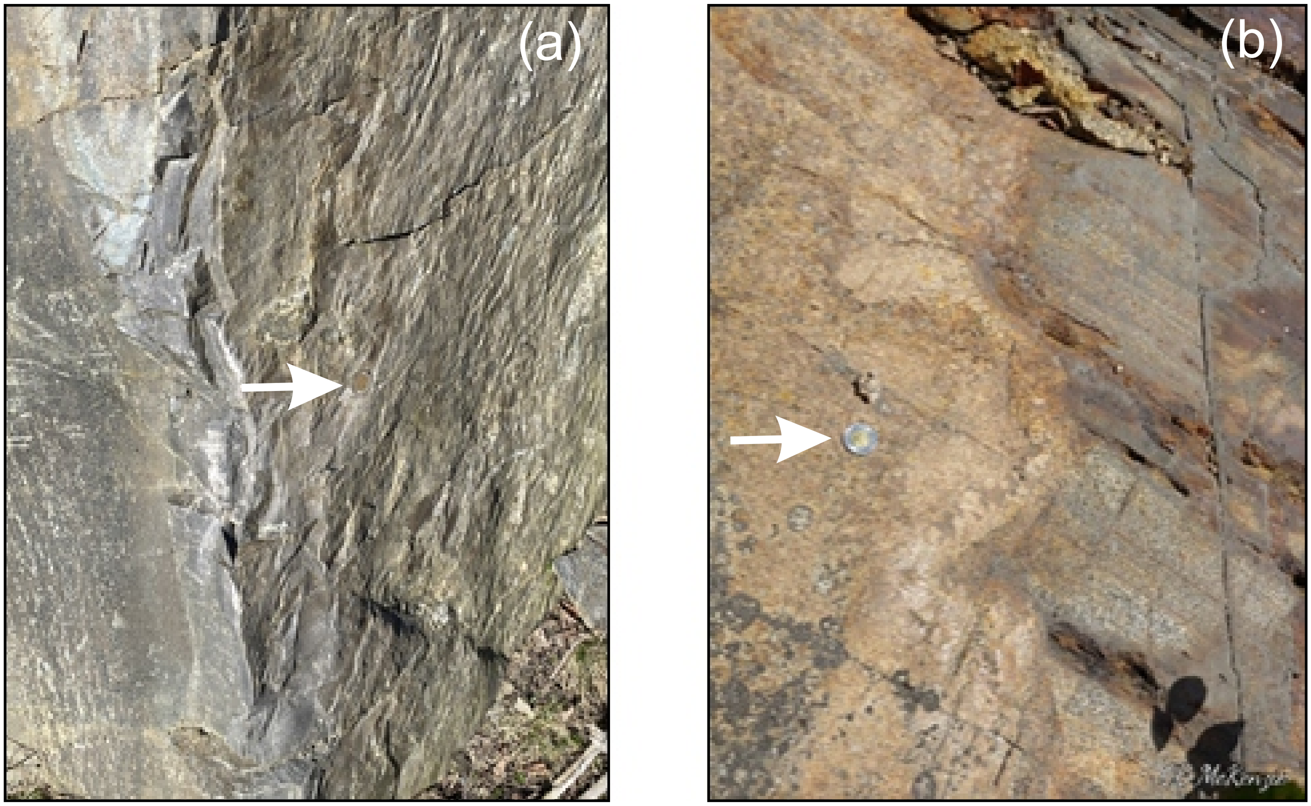


Figure 6. Cleavage in the Meguma Supergroup. (a) Outcrop approximately 200 m from the contact with the SMB that shows the contact between a psammitic bed (left) and a more pelitic bed (right). The pelitic bed shows internal cleavage roughly parallel to bedding. (b) Contact of annealed, cleavage-absent, metasedimentary rocks of the Meguma Supergroup with the SMB at Bayers Lake in Halifax. Coin (highlighted by arrow) diameter in both photos is 2.7 cm.

deformation and thermal metamorphism were still active, concluding that "magma emplacement [took place] during the latter stages of fold growth", presumably referring to late flexural slip (F_2, next section) and not Neo-Acadian F_1. It is also possible that these late overprinting vertical lineations (Fig. 15) are the products of local deformation in the thermal aureole, presumably related to forceful emplacement and/or adjustment of the enormous volume of SMB granite (ca. 70 000 km^3) against its host Meguma terrane crust.

The local development of several types of deformation features along the SMB contact show that, at least in these restricted places, e.g., where the contact is approximately perpendicular to Meguma terrane fold axes, the granite has deformed the already-deformed country rocks, thus the SMB post-dates the F_1 deformation of the Neo-Acadian orogeny.

Late flexural slip

Late flexural slip (LFS) in the Meguma terrane is manifest as offsets in quartz veins cutting the F_1 folds (Fig. 16), steepening of dips of the F_1 fold limbs, development of ramp structures, and development of metre-scale thrusts (Horne and Culshaw 2001). These features have formed outside the thermal aureole of the SMB, as well as inside where, in addition, cordierite porphyroblasts are truncated by flexural-slip structures. As such, the geological evidence states that LFS occurred during or after granite intrusion, and this deduction is supported by a ^{40}Ar/^{39}Ar date of 376 ± 2 Ma (Fig. 17) on new muscovite that appears to have formed during LFS (Hicks *et al.* 1999). That date lies within the ca. 381–370 Ma range for intrusion of the SMB (Bickerton *et al.* 2022).

As noted in the Deformation aureole section (above), intrusion of the SMB appears to be responsible for some deformation in the adjacent country rocks. One of the LFS localities studied by Horne and Culshaw (2001) is only 1 km from the SMB, but the other is 25 km from the contact, at least horizontally. The SMB represents ca. 70 000 km^3 of granite emplaced in the middle crust; how far do the structural effects of this intrusion extend into the host rocks? Could LFS be just another manifestation of forceful granite emplacement? Horne *et al.* (2007) considered that LFS was a late brittle-ductile reactivation of the Neo-Acadian F_1 fold belt and speculated that "Rapid uplift following granite emplacement may explain the change to the late, brittle, flexural-slip folding."

With so much uncertainty about the cause (reactivated Neo-Acadian, forceful emplacement of granite, uplift) and reliable timing of LFS, we leave this question unresolved until we have examined any structures in the SMB that might

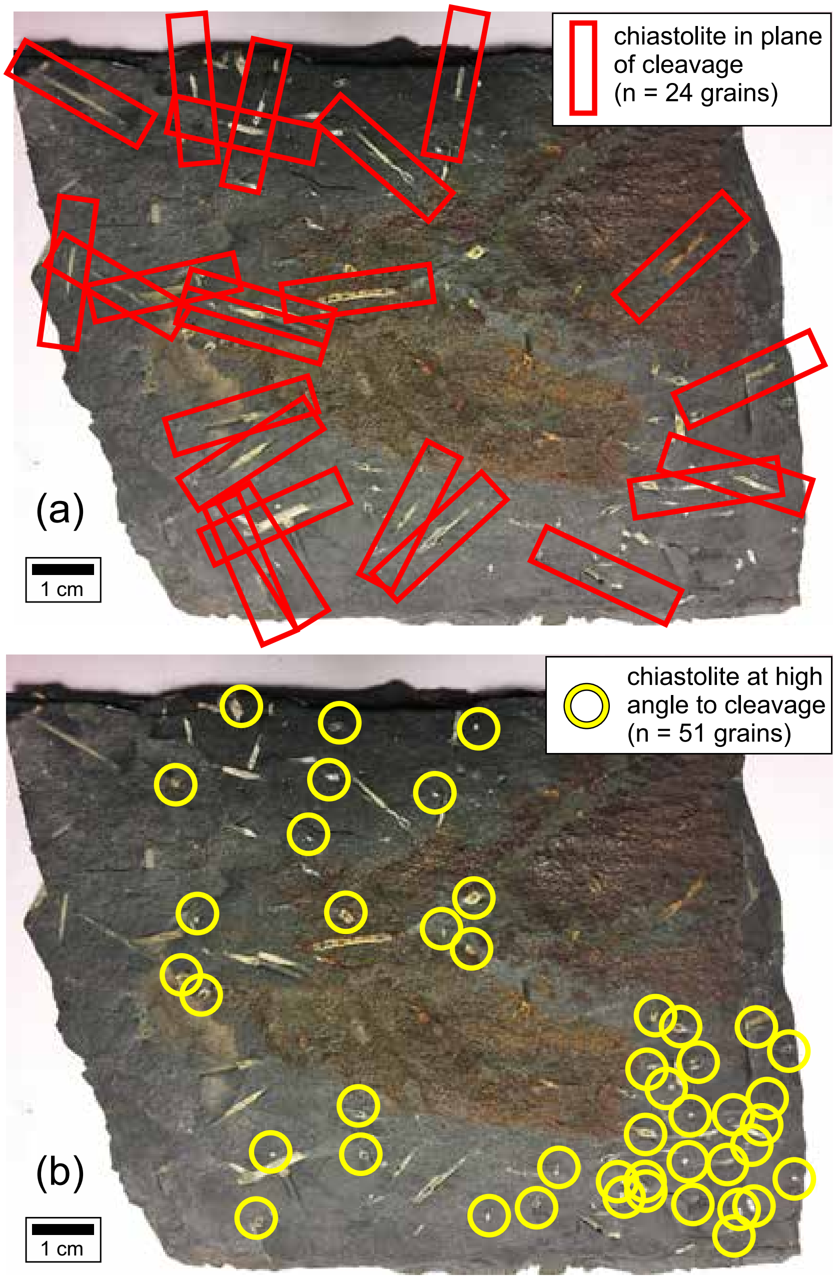


Figure 7. Cleavage-parallel specimen of slate from the Halifax Formation near Aspotogan with 75 chiastolite grains. (a) 24 chiastolite porphyroblasts (red rectangles) lie predominantly in the plane of the cleavage; (b) 51 chiastolite porphyroblasts (yellow circles) lie at high angles to the cleavage. This simplified bimodal classification of chiastolite porphyroblasts into two planes, parallel and perpendicular to the cleavage, obscures their true essentially random orientations in 3-D, but clearly illustrates that most porphyroblasts cut the cleavage at low to high angles.

be a further manifestation of LFS. In the meantime, what might LFS look like in the granite: foliations? "folds"? augen monzogranite?

Southwest Meguma terrane "orocline"

An orocline is a bend in an orogenic belt that represents buckling of that orogen about a vertical axis of rotation (Johnson *et al.* 2013). Oroclines are orogen- and plate-scale features that involve crust and lithospheric mantle. They develop after initial orogenesis, either in response to an orogen-parallel principal compressive stress oriented at a high angle to the stress responsible for orogen development, or by discontinuous compression where one plate collides at a high angle with another to produce indentation and associated escape tectonics (Bajolet *et al.* 2013).

In southwestern Nova Scotia, the strikes of the Meguma Supergroup, the overlying Rockville Notch Group, the SMB contact, and the foliation of tabular K-feldspar megacrysts in the Stage I Scrag Lake pluton and Stage II Davis Lake

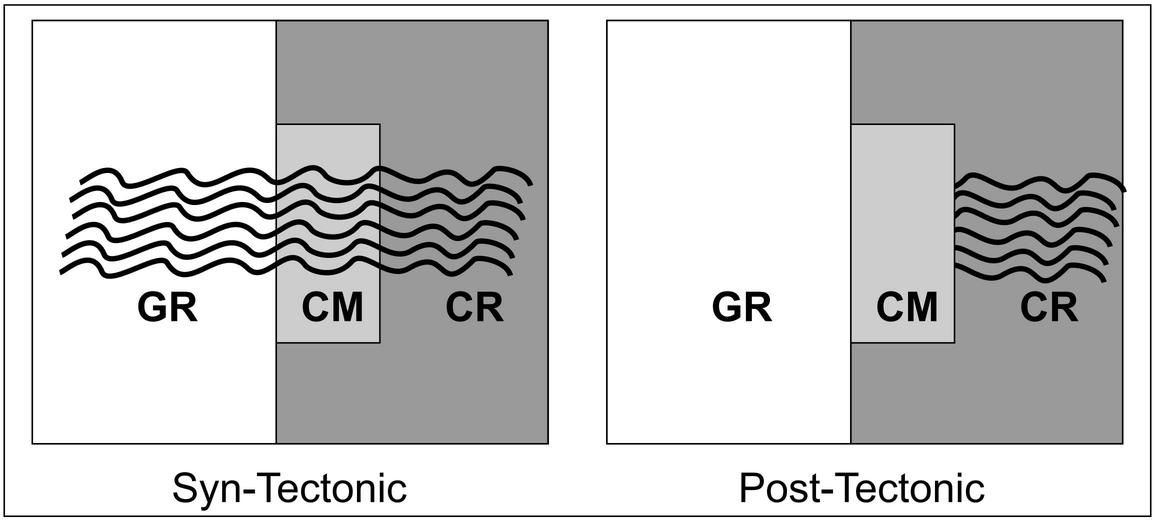


Figure 8. Schematic contrasting syn-regional deformation and post-regional deformation contact migmatites. (a) Syn-tectonic granite: regional deformation affects country rock (CR), contact migmatite (CM), and granite (GR). (b) Post-tectonic granite: regional deformation affects only country rock (CR) because granite and contact migmatite are younger.

plutons all define a distinct change in regional strike with a counter-clockwise (CCW) rotation of approximately 24° (Fig. 18). (But has the western end been rotated 24° CCW relative to the unchanged eastern end, or has the eastern end been rotated 24° CW relative to the unchanged western end by coming into alignment with the MFZ? Or has there been any rotation at all, i.e., this is just the original shape of the SMB; after all it "bends" at the eastern end also.) MacDonald (2001) considered that the observed change in megacryst alignment in the southwestern part of the SMB and coincident bend in regional structures in the Meguma Supergroup and Rockville Notch Group might represent ballooning associated with the emplacement of the Stage I and II intrusions in this part of the batholith. If so, the bend belongs in the category of structures, such as deflected bedding and transverse anticlines, that the SMB imposed on the country rocks and has some bearing on the tectonic timing of emplacement of the SMB. Alternatively, Warsame *et al.* (2021) undertook some broader paleomagnetic and tectonic studies in this region and have interpreted this bending feature as an orocline resulting from dextral transport on the MFZ during the Alleghanian orogeny, between ca. 320 and 300 Ma. Waldron *et al.* (2022) basically concur, attributing the bend to the westward translation of the Meguma terrane along the MFZ, although they do not use the term "orocline".

The current best explanation of the bend in southwest Nova Scotia is that it formed by dextral transpression during the Alleghanian orogeny and, as such, it has no relevance to the timing of emplacement of the SMB. However, it is not clear why this so-called "orocline" appears to have undergone ductile bending, because by ca. 320 Ma, the SMB was unroofed, cold, and brittle, yet there is apparently no evidence of brittle deformation to accommodate the 24º counterclockwise rotation.

Meguma terrane gold deposits

The Meguma Supergroup, especially the lower metasandstone-dominated Goldenville Group, is host to numerous orogenic-type vein-hosted gold deposits. The relative ages of gold mineralization and granite emplacement may yield insights into the tectonic setting for the intrusion of the SMB. The following summarizes the results from several geological, geochronological, and isotopic studies of the Meguma terrane gold deposits.

Kontak *et al.* (1990a) concluded that gold mineralization in Meguma Supergroup rocks occurred at ca. 370 Ma, based on $^{40}Ar/^{39}Ar$ dating of hydrothermal vein minerals, thus post-dating Neo-Acadian F_1–S_1 deformation by >10 myr. Using isotopic data, they proposed that vein-forming fluids were a combination of magmatic and sources exotic to the Meguma terrane. Henderson *et al.* (1991) questioned the suggestion by Kontak *et al.* (1990a) that all the gold veins formed at ca. 370 Ma, concurrent with granite magmatism, arguing that there was considerable evidence from previous studies that gold mineralization pre-dated widespread granite emplacement. For example, they referred to previous work by Graves and Zentilli (1982) who concluded that auriferous veins were emplaced under conditions of greenschist-grade regional metamorphism and under the same conditions of tectonic stress that later resulted in the regional Neo-Acadian F_1 folds and penetrative, axial-plane slaty cleavage, therefore pre-dating granite emplacement at ca. 380–370 Ma. Graves and Zentilli (1982) also reported that granitoid dykes cross-cut gold-bearing veins in several districts (e.g., Country Harbour and Forest Hill) and xenoliths of folded host rock and concordant sulphide-bearing quartz veins exist in the SMB near Mt. Uniacke, showing the SMB post-dates at least some Meguma terrane gold mineralization. White (2008) reported a similar field relationship at

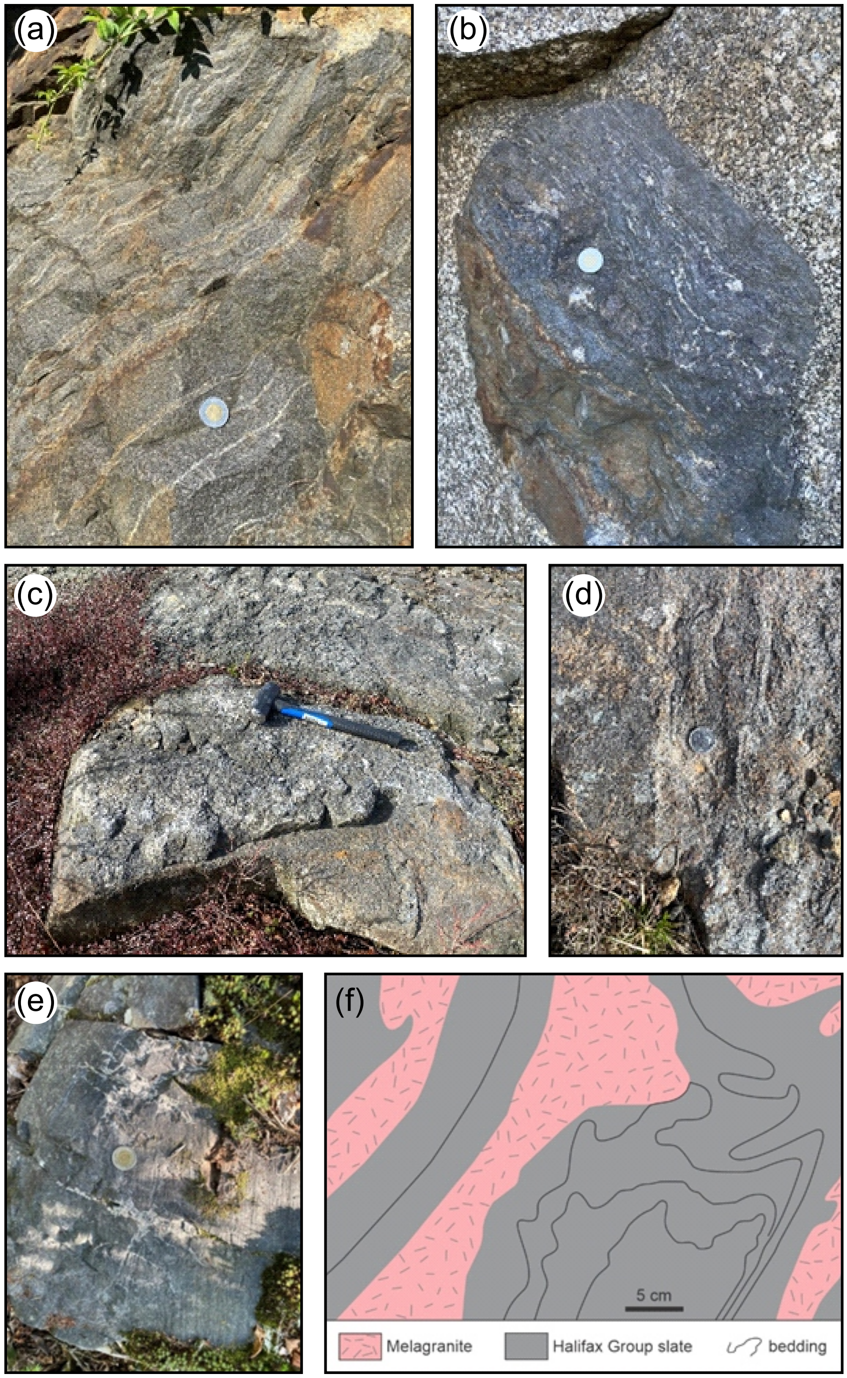


Figure 9. Field examples of contact migmatites adjacent to the SMB. (a) Dunbrack Street bedding-parallel incipient stromatic migmatites. (b) Dunbrack Street Meguma Supergroup xenolith with slightly more advanced in situ melting. (c, d) Washmill Lake Drive complex combination of granite injections (c) and in situ granitic leucosomes (d). (e) Highway 12 patchy development of migmatite in promontory of the Meguma Supergroup projecting into the SMB. (f) Locally folded roof pendant in the Boot Lake area (MacDonald 2001; sketch prepared from unoriented field photo [Plate 6.8d]) where enhanced thermal and buoyant forces may have deformed this migmatite. Coin diameter 2.7 cm. Hammer handle length 30 cm.

the Stanburne Gold District with gold-bearing quartz veins cut by several monzogranite dykes. The presence of elevated concentrations of silver and tungsten in the Stanburne deposit, however, prompted O'Reilly (1981) to suggest a possible contribution of fluids from the adjoining granitoid rocks at this gold deposit.

Subsequent work by Kontak *et al.* (1998) reported additional $^{40}Ar/^{39}Ar$ ages for several gold deposits, ranging from ca. 362 to 375 Ma, and concluded that "vein formation occurred late in the folding history of the Meguma Supergroup

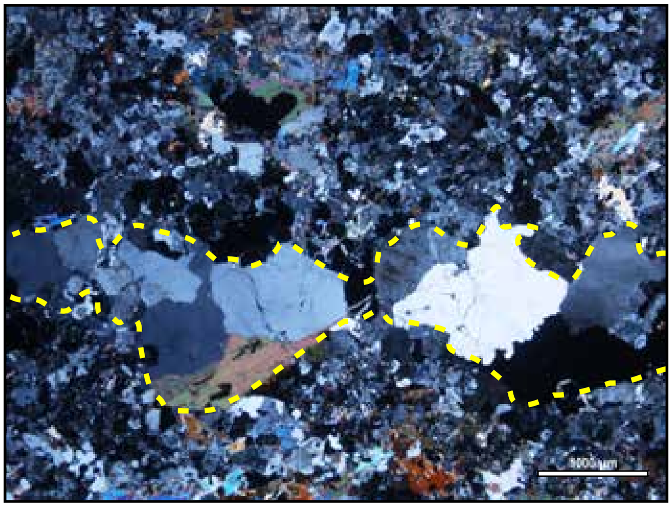


Figure 10. Photomicrograph of an incipient leucosome from Figure 9(a). The dashed lines define the irregular boundaries of the leucosome which, in many places, is only one grain wide. Other than the lobate margin of the largest quartz grain and minor undulose extinction in other quartz grains, any further deformation would have sheared or folded the margins of this leucosome.

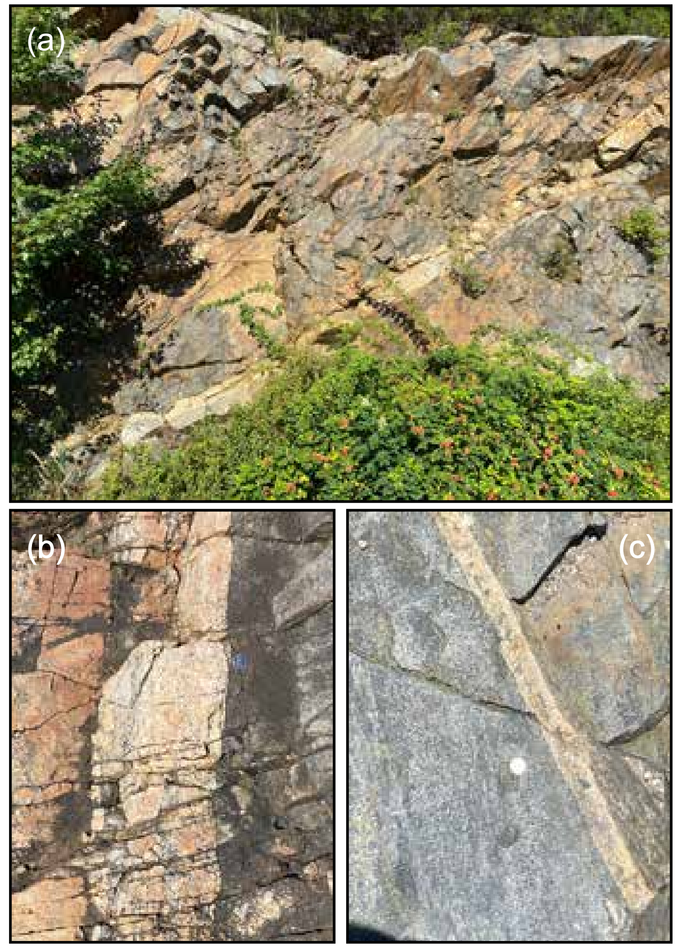


Figure 11. Granitic dykes in the Meguma Supergroup host close to the contact of the SMB. (a) Dunbrack Street prominent granitic dyke 50–75 cm wide. (b, c) Breakers Park granitic dykes cutting bedding and cleavage in the Meguma Supergroup. Coin diameter is 2.7 cm.

and was generally syn-granite intrusion (i.e., ca. 370 Ma)". Kontak and Archibald (2002) reported a $^{40}Ar/^{39}Ar$ plateau age of ca. 374 Ma for a hydrothermal alteration zone adjacent to a gold vein in the Tangier gold deposit, and they interpreted the quartz veins as having formed during flexural-slip folding during a late-stage reactivation of the regional fold belt. Kontak and Archibald (2002) proposed that gold mineralization and granite emplacement events across the Meguma terrane may be temporally and genetically related.

Rhenium–osmium geochronology for arsenopyrite from two Meguma terrane gold deposits (Morelli *et al.* 2005) present a different scenario than the previous $^{40}Ar/^{39}Ar$ data. Re–Os ages included ca. 409 ± 5 Ma and 407 ± 4 Ma for bedding-concordant and -discordant veins, respectively, from the Ovens, and ca. 380 ± 3 Ma for saddle-reef veins from the Dufferin deposit. These workers concluded that there were at least two distinct periods of gold deposition in the Meguma terrane coinciding with regional Neo-Acadian F_1–S_1 deformation and metamorphism and widespread generation of meta- and peraluminous granites and high-grade metamorphism within the basement rocks under the Meguma terrane. Morelli *et al.* (2005) concluded that the ca. 407 Ma age for The Ovens arsenopyrite provides the "best estimate for the timing of regional Neo-Acadian deformation in the Meguma terrane and is slightly older than previous estimates based solely on $^{40}Ar/^{39}Ar$ dating".

Chen *et al.* (2014) reported Re–Os ages for arsenopyrite from auriferous veins, including ca, 461 Ma, 459 Ma and 440 Ma for bedding-concordant veins from the Beaver Dam deposit, and two distinctly different ages of ca. 380 Ma and ca. 438 Ma for the Touquoy (Moose River) deposit. Re–Os model ages for arsenopyrite from a separate Touquoy sample yielded ages from ca. 400 Ma to 440 Ma. Chen *et al.* (2014) observed compositional zoning in arsenopyrite (SEM and LA ICP-MS trace element data) which they interpreted as reflecting several stages of gold mineralization, the first pre-dating the Neo-Acadian deformation and metamorphism of the host rocks. They also noted that structures containing gold-bearing quartz veins are consistent with emplacement during late-stage fold tightening of the regional F_1 folds in the Meguma terrane and formed during Neo-Acadian deformation at ca. 410–385 Ma. They reported that some veins contain cleaved wall-rock fragments and therefore post-date cleavage formation whereas rare veins "post-date hornfels related to 380 Ma granites". Interestingly, new work on orogenic gold vein deposits by Hobbs and Ord (2023) provides a model for their formation during compression and folding which would support their pre-granite formation.

In summary, $^{40}Ar/^{39}Ar$ and Re–Os geochronological data for several Meguma terrane gold deposits have yielded a wide range of ages from ca. 461 Ma to 362 Ma, suggesting

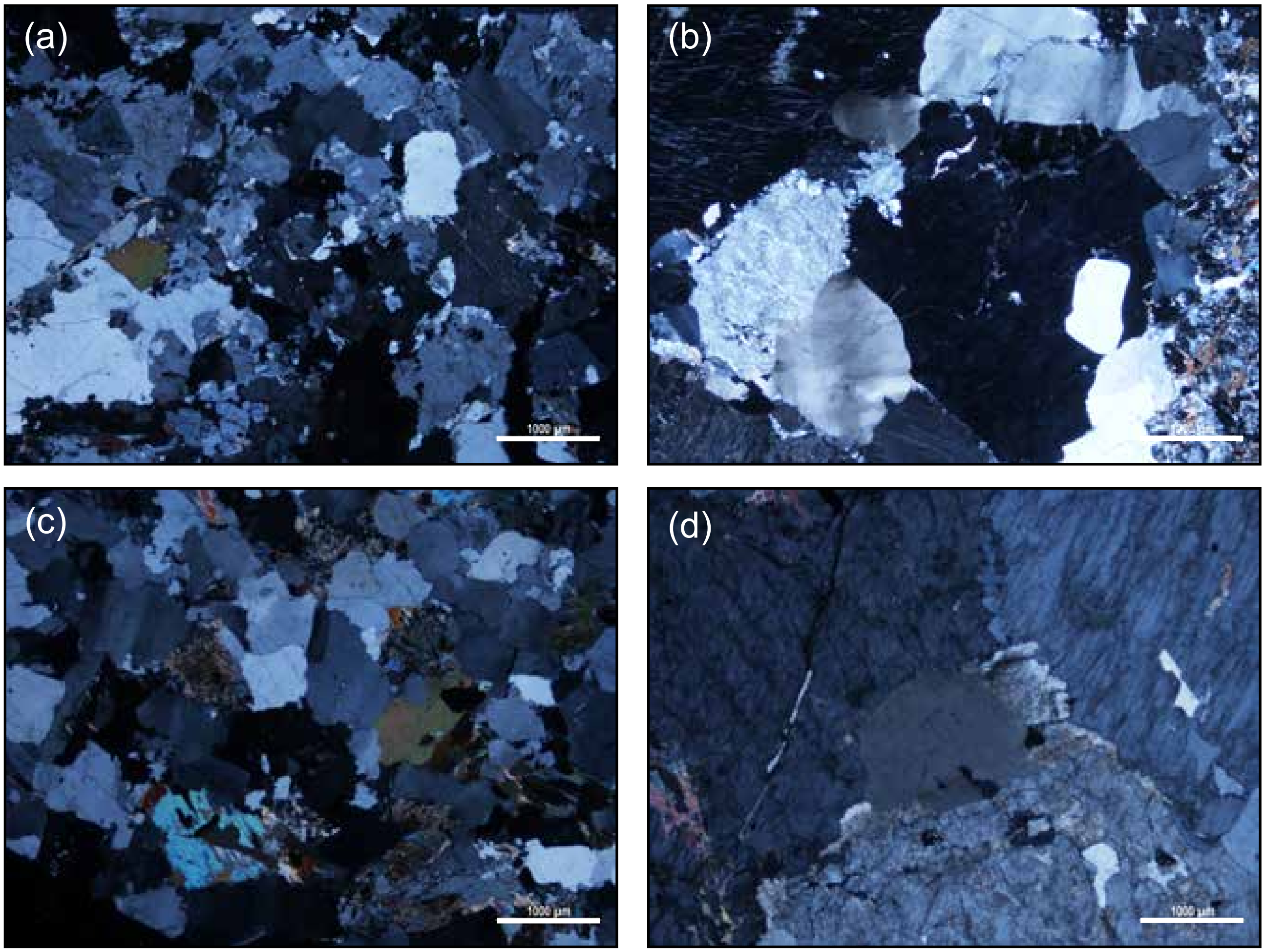


Figure 12. Photomicrographs of granitic dykes in the Meguma Supergroup adjacent to the eastern SMB contact. (a) Dyke DS-1. (b) Dyke BP-1. (c) Dyke BP-2. (d) Dyke PCR07-15. The textures of these rocks suggest that the dykes are undeformed.

that gold mineralization pre-dated, coincided with, and post-dated the main fold-forming Neo-Acadian deformation (i.e., ca. 410–385 Ma), overlapped with LFS (ca. 376 ± 2 Ma; Hicks *et al.* 1999), and overlapped with emplacement ages for Meguma terrane granitoid rocks (ca. 380–370 Ma).

The possible genetic relationship between Meguma terrane gold mineralization and the emplacement of the SMB and other peraluminous granite intrusions in the terrane is also problematic because the distances between individual gold deposits and granite intrusions varies considerably at the present level of erosion. Some gold deposits are more than 20–30 km from known granite plutons. There may be a temporal overlap between some of the Meguma terrane gold mineralization and granite emplacement but establishing a genetic link is questionable.

The approximately 100 myr time span for gold mineralization precludes the use of Meguma terrane gold deposits to provide evidence for the tectonic setting for the emplacement of the SMB.

Summary of observations and deductions from the country rocks

The best available geochronological data show that the youngest F_1 deformation age in the Meguma terrane (ca. 389 ± 3 Ma) is older than the oldest SMB intrusion age (ca. 381 ± 4 Ma) (Table 1). In many places, the SMB cuts the Meguma terrane folds at high angles showing clearly that the batholith post-dates F_1. In addition, most of the evidence from the thermal and deformation aureoles (annealing, porphyroblasts, undeformed granite dykes, undeformed contact migmatites, deflected bedding, transverse anticlines) clearly support the SMB as post-dating the F_1–S_1 deformation. The many uncertainties surrounding the putative orocline contribute nothing to the question of timing of emplacement of the SMB. Geological and geochronological data appear to show that gold mineralization pre-dated, post-dated, and even was contemporaneous with, granite emplacement from ca. 381–370 Ma, thereby not providing any clear insight into the timing of granite intrusion in the Meguma terrane. Finally, the timing of the LFS F_2 deformation and its relation to the SMB are problematic. We will keep all these certain-

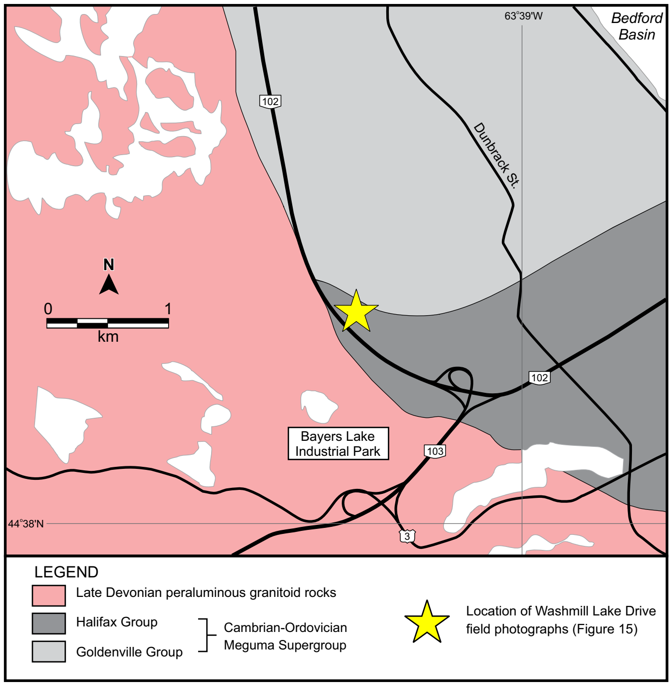


Figure 13. Deflection of the regional strike of the Meguma Supergroup strata near the contact with the SMB (after White *et al.* 2008). Star symbol is the location of photographs along Washmill Lake Drive (Fig. 15).

-ties and uncertainties in mind as we now examine structures in the SMB itself.

Structures in Stage I plutons of the South Mountain Batholith

In this subsection, we examine several structural features of the early Stage I plutons. Because these plutons are closest in age to the Neo-Acadian F_1 (and F_2?) deformation, we are particularly concerned about any structural features in them that could be related to regional deformation. Any structure in a granite, including its foliations, must be examined for a potential causal connection to structures in the country rocks. If structures on both sides of the contact are closely coupled, the timing of emplacement of the granite is probably syn-kinematic. If the structures in the granite are completely decoupled from those in the country rocks, they are unlikely to be the product of regional tectonism, and the granite is probably post-kinematic (Fig. 19). In the Meguma terrane, some granite intrusions are elongate and align with regional structures whereas others are more equidimensional and cut regional structures (Figure 20). Below, we examine many structures within the SMB to determine what relationships, if any, they have to regional tectonic activity.

Shapes of Stage I plutons

The three-dimensional shape of an intrusion is a highly complex function of the phtsical properties of the intrud-

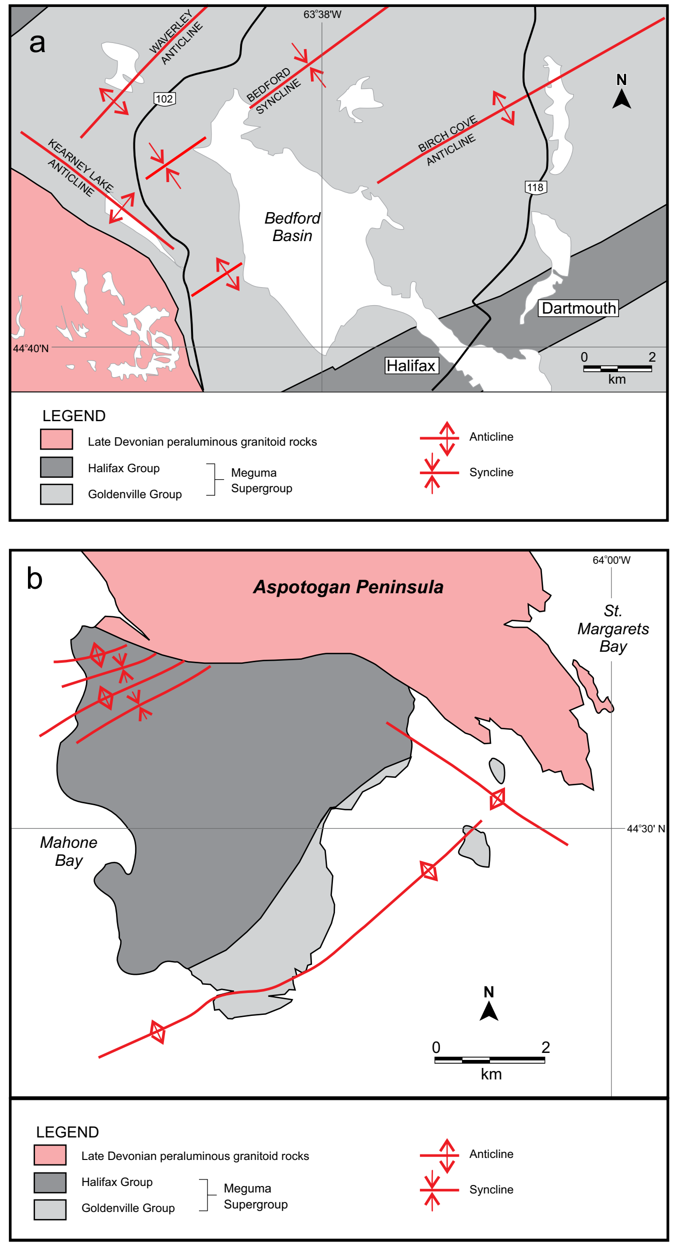


Figure 14. Transverse anticlines in (a) Bedford and (b) Aspotogan. The SW-trends of the Meguma Supergroup fold axes are truncated by transverse anticlines parallel to the contact with the SMB (after Culshaw and Bhatnagar 2001).

ing magma (e.g., temperature, viscosity, density, presence or absence of volatiles) as well as the physical properties of the intruded host rock (e.g., temperature, pressure, regional stress field, degree of anisotropy, density, strength, ductile or brittle domain) (Clarke 1992; Pitcher 1993; Ameglio and Vigneresse 1999; Nédélec and Bouchez 2019). If the two-dimensional map shape of a pluton is an indicator of the timing of its emplacement relative to regional compressional deformation, syn-tectonic plutons ideally should be roughly elliptical in plan with their long axes perpendicular to the direction of maximum shortening, whereas

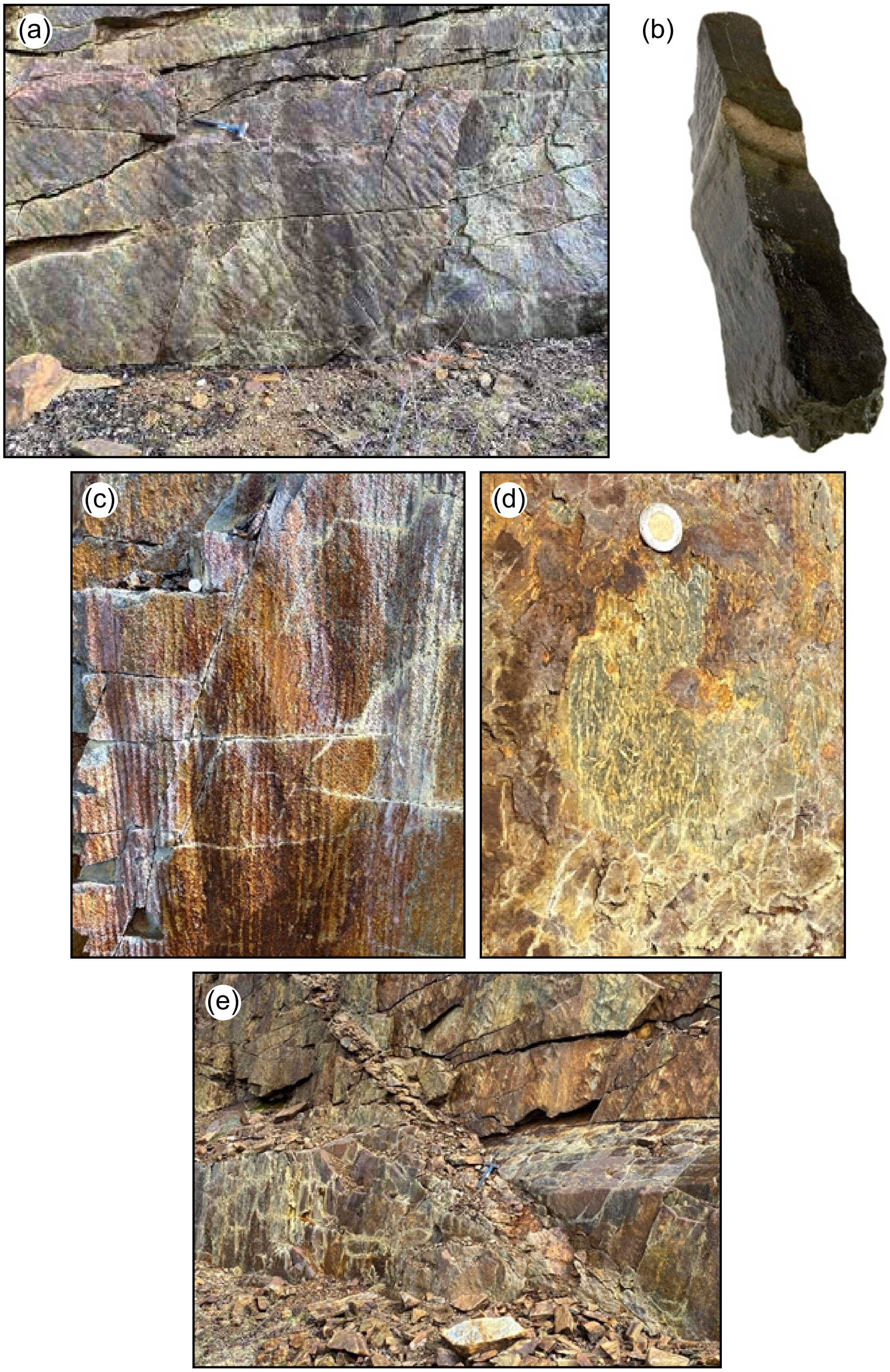


Figure 15. **Features in the deformation aureole along Washmill Lake Drive within 100–200 m of the SMB contact. (a) Near-vertical rippled bedding surface (b) Cleavage slab showing bedding at a high angle to cleavage. Exact location unknown. Slab is 4 cm wide at the leucocratic bed. (c) Vertical bedding-cleavage intersection lineations(?) elsewhere on the same vertical outcrop sur-face. (d) Vertically lineated andalusite porphyroblasts on a vertical outcrop surface, indicating that the deformation in the aureole was coeval with emplacement of the SMB. These porphyroblasts are broken along the same fabric indicating that this deformation continued after andalusite growth. (e) Undeformed granite dyke cutting rocks of the deformation aureole. Hammer handle is 30 cm long. Coin diameter is 2.7 cm.**

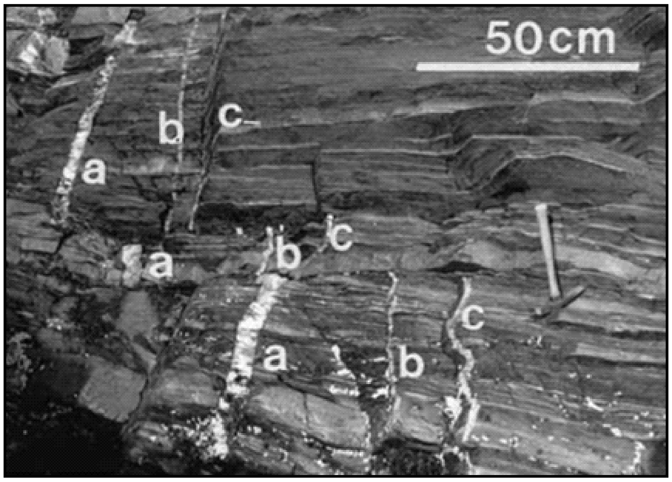


Figure 16. Three discordant quartz veins, labelled a, b, c, offset along bedding at Ovens Park (Horne and Culshaw 2001). Reproduced with permission of R.J. Horne.

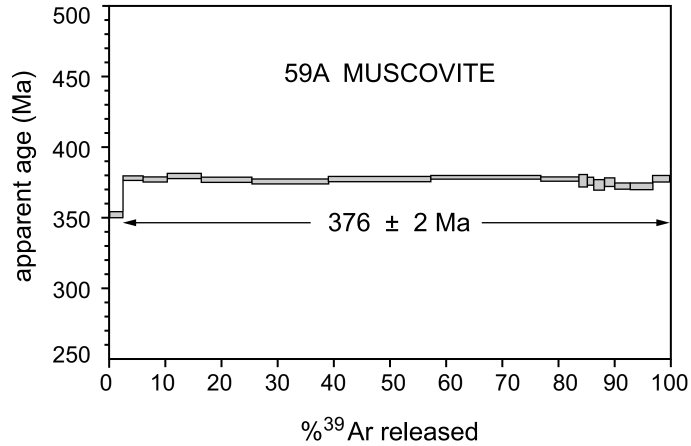


Figure 17. Muscovite from pressure shadows in hinge zone of the Ovens anticline (after Hicks *et al.* 1999).

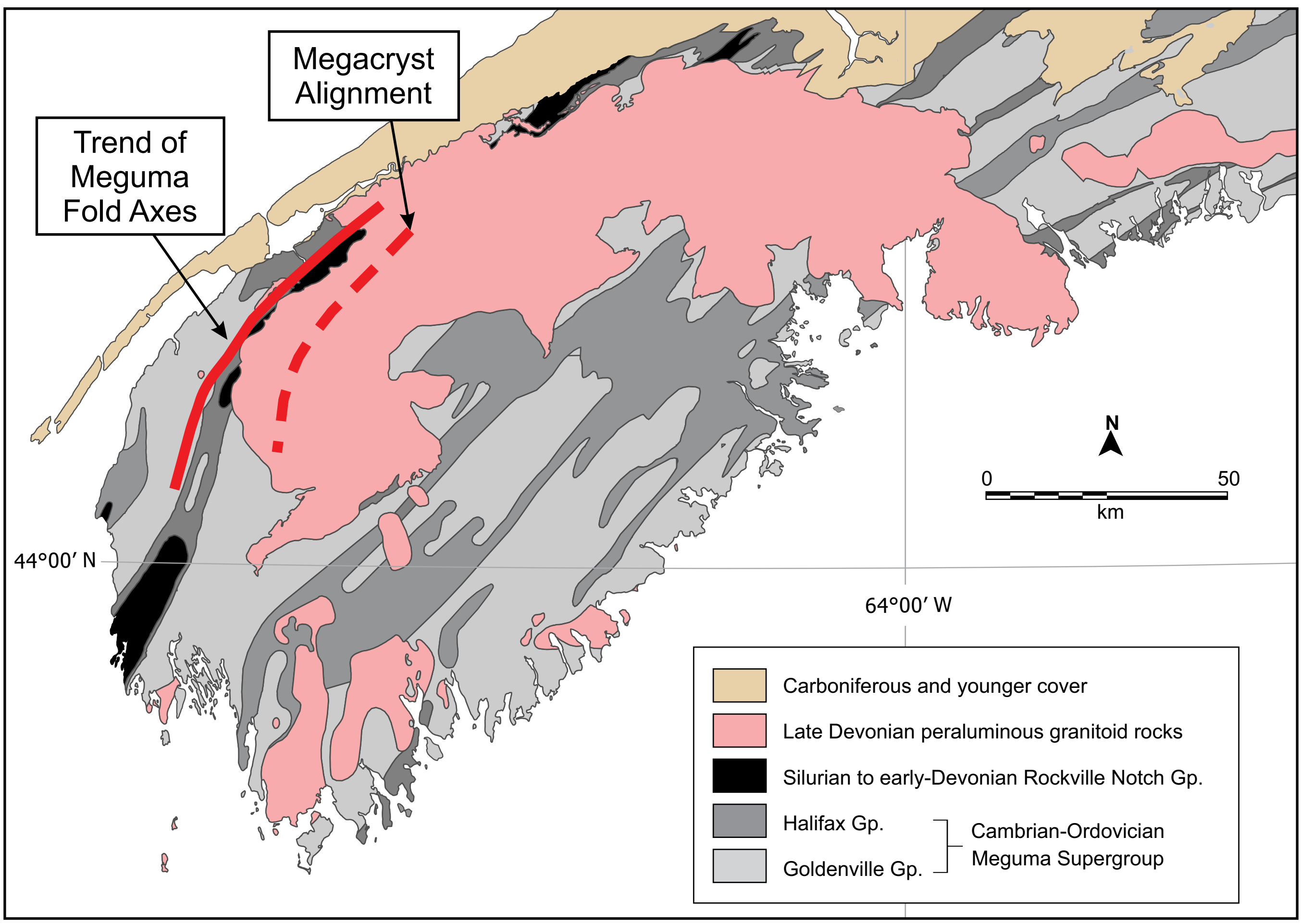


Figure 18. Geological map of southwestern Nova Scotia showing the counter-clockwise bend in the regional structural trends in the Meguma Supergroup and coincident bend in the megacryst alignments in the Scrag Lake and Davis Lake plutons.

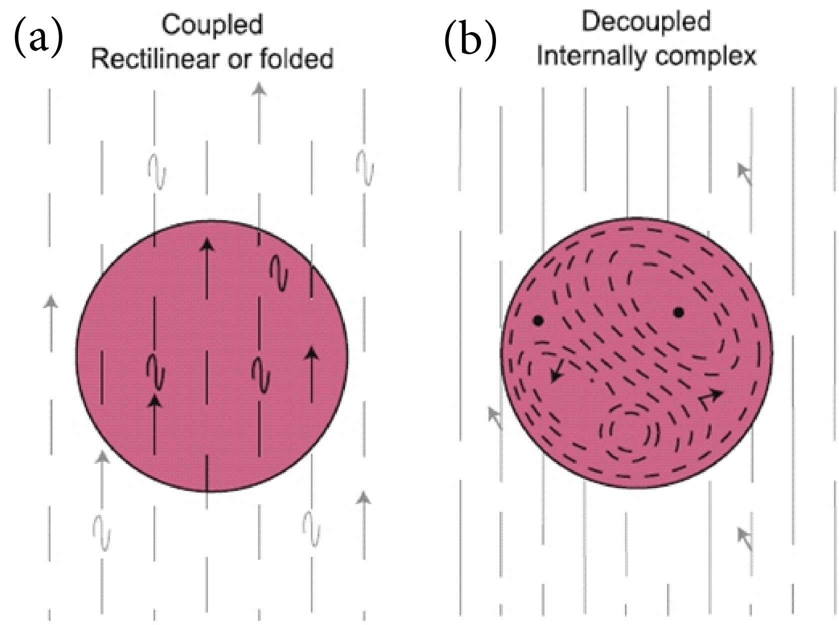


Figure 19. Relationships between structures in granite and structures in country rock. (a) Syn-kinematic – ductile (Ƨ) and brittle (↑) structures in the granite are identical to/coupled with those in the country rock. (b) Post-kinematic – complex internal structures in the granite bear no relation to structures in, and are decoupled from, structures in the country rock, except that the contact-parallel magmatic foliation, coincidentally and inevitably, is parallel, in places, to structures in the country rock, but is not necessarily pervasive throughout the granite (adapted from Paterson *et al.* 2019)

post-tectonic plutons, intruded in the absence of significant deviatoric stress, might be more equidimensional in plan. Ultimately, however, the map shape alone of any pluton is an unreliable criterion for determination of timing of emplacement of that pluton relative to regional deformation.

In the Meguma terrane, the granite bodies of similar age range from approximately circular (Kinsac, Queensport) to elliptical (South Mountain, Musquodoboit) in plan (Fig. 20). The long axes of the quasi-elliptical plutons are broadly parallel to the bedding and cleavage in the deformed Meguma terrane metasedimentary rocks.

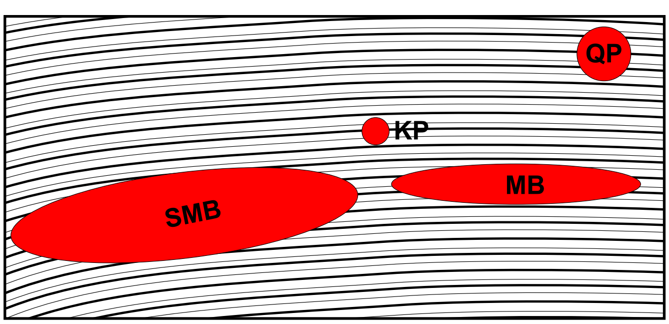


Figure 20. Schematic shapes of selected granite intrusive bodies in the Meguma terrane (not to scale). The South Mountain Batholith (SMB) and Musquodoboit Batholith (MB) are highly elliptical in plan and with their major axes parallel to trends of Meguma Supergroup folding, whereas the Kinsac Pluton (KP) and Queensport Pluton (QP) are more equidimensional in plan.

In more detail, however, the SMB is a composite batholith consisting of 13 mappable plutons. Rather than considering the SMB as a single entity, we examine the shapes of SMB Stage I and Stage II plutons separately. Figure 21 highlights the shapes of the five early Stage I plutons. Except for the Five Mile Lake Pluton (FMP), the Stage I plutons are elongate, with long axes quasi-parallel to the Neo-Acadian F_1 fold axes in the Meguma terrane country rocks.

Collectively, the five Stage I plutons largely define the overall shape of the SMB: the individual plutons are elliptical, and the entire Stage I batholith is elliptical and arcuate, coincident with regional structural trends at the west end of the batholith but highly transgressive to Meguma terrane structures at its eastern end. If these elliptical pluton shapes are externally imposed by contemporaneous Neo-Acadian stresses, there should be other supporting evidence of deformation in these Stage I plutons (examined separately). Alternatively, Horne *et al.* (1992) suggested that the shapes of the Stage I plutons were controlled by NE-trending shear zones and NW-trending faults; however, there is little evidence for pre-granite faults in the Meguma terrane itself. And finally, if a granite magma intrudes post-tectonically into host rocks with an already established strong regional fabric, that fabric may exert control on the shape of the pluton, especially if the bedding and cleavage represent major planes of weakness along which the magma can invade, and along which large blocks can be dislodged by stoping. In our view, the SMB magma probably exploited pre-existing coincident planes of weakness, such as bedding (S_0) and axial planar cleavage (S_1), especially if stoping were the predomi-

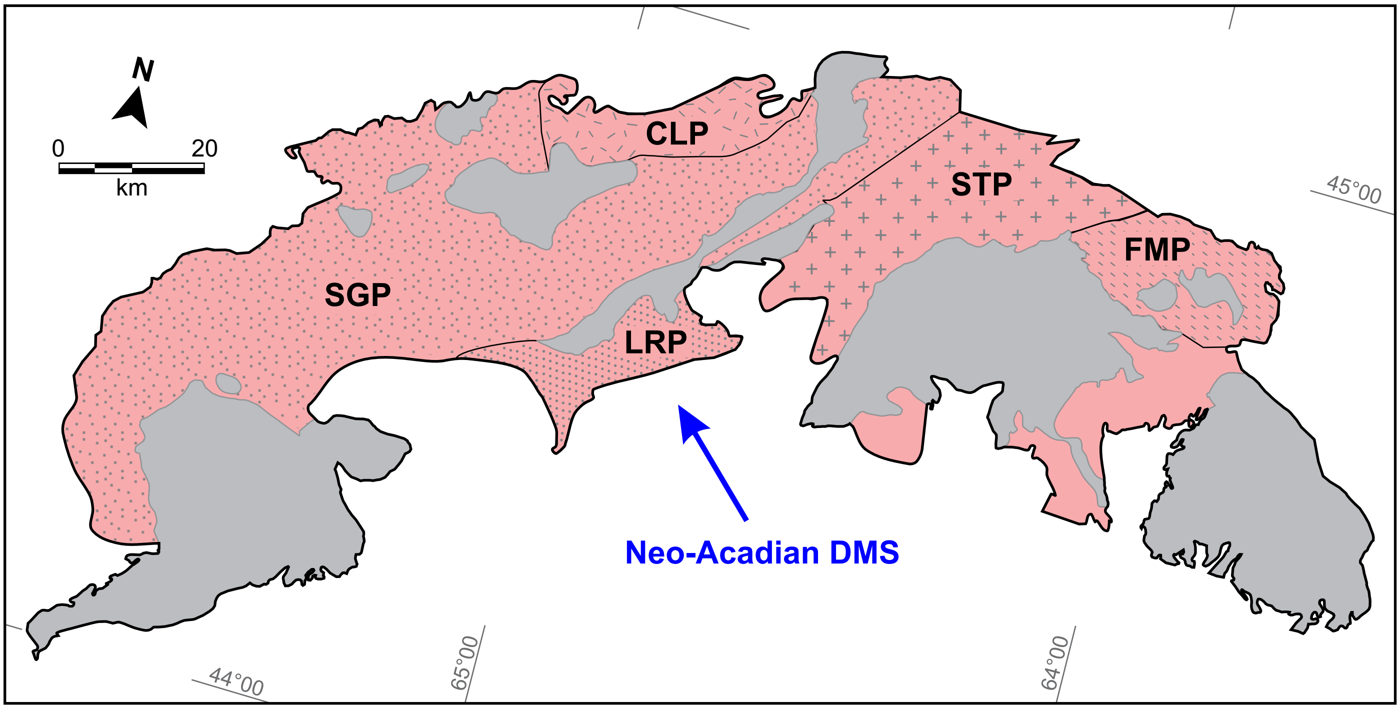


Figure 21. Shapes of the five Stage I plutons (pink and labelled) against the outline of the entire SMB. (CLP – Cloud Lake Pluton; FMP – Five Mile Lake Pluton; LRP – Little Round Lake Pluton; SGP – Scrag Lake Pluton; STP – Salmontail Lake Pluton). Stage II plutons are grey and unlabelled. DMS – Neo-Acadian direction of maximum shortening.

nant mechanism of emplacement in the upper crust. If this is true for the SMB, its overall elliptical shape has been determined by structures in the host Meguma terrane.

Foliations in Stage I plutons

The origin of the NE-SW trending megacryst-xenolith alignments (Horne *et al.* 1992; MacDonald 2001) or magnetic foliations in Stage I granites (Benn *et al.* 1997) constitutes one of the most controversial problems in the interpretation of the tectonic affinities of the SMB. Whereas NE alignment is the dominant trend (Fig. 22), in many places the K-feldspars are randomly oriented and swirling patterns and other alignment trends have developed. Benn *et al.* (1997) made field measurements of foliations defined by the tabular shapes of K-feldspar megacrysts, and in addition collected samples for laboratory determination of anisotropy of magnetic susceptibility (AMS). In ilmenite-bearing, magnetite-free, peraluminous granites, paramagnetic biotite imparts a weak magnetic signature to the rock. Thus, K-feldspar megacrysts define fabrics in the field, and biotite grains define fabrics in the magnetic susceptibility laboratory. Benn *et al.* (1997) state that, in virtually all cases, the AMS foliations and weak lineations derived from biotite are consistent with the strikes of foliations derived from tabular K-feldspar megacrysts (Fig. 23).

The distinct, but imperfect and heterogeneous, parallelism between the megacryst foliations, the weak magnetic lineations, and the Neo-Acadian F_1 fold hinges in the Meguma Supergroup led Benn *et al.* (1997) to deduce that all these structures were genetically coupled and related to the Neo-Acadian D_1 deformation. However, the NE-trending foliation of K-feldspar and biotite in this part of the SMB is also parallel to both the northern contact and the long axis of the batholith, both of which are parallel to the regional trend in the Meguma terrane country rocks.

The two relevant processes, respectively, to produce foliated granites are:

(i) external compressive and/or transpressive stress on a crystallizing batholith – For any regional compressive or transpressive stress to have had some effect on the attitude of the foliation, the granite must have reached its mechanical solidus (ϕ > PLT), where ϕ is the degree of crystallinity, and PLT is the particle-locking threshold (=CCR in Fig. 24b). If ϕ < PLT, any externally applied compressive or transpressive stresses on the magma chamber will be non-directional (magmato-static). If regional compression has created that foliation, that texture must have been developed in a mechanically solid state (ϕ > PLT), and probably also have created other high-T solid-state deformation textures, such as changes in grain size and/or shape, recrystallization, weak micas wrapping around strong feldspars, boudinage of strong minerals, recrystallized aggregates of weaker minerals (e.g., quartz and mica), local mylonite zones, and fracturing (Paterson *et al.* 2019).

(ii) internal shear stresses in a flowing magma – Dynamic currents in magmas, driven by temperature or pressure

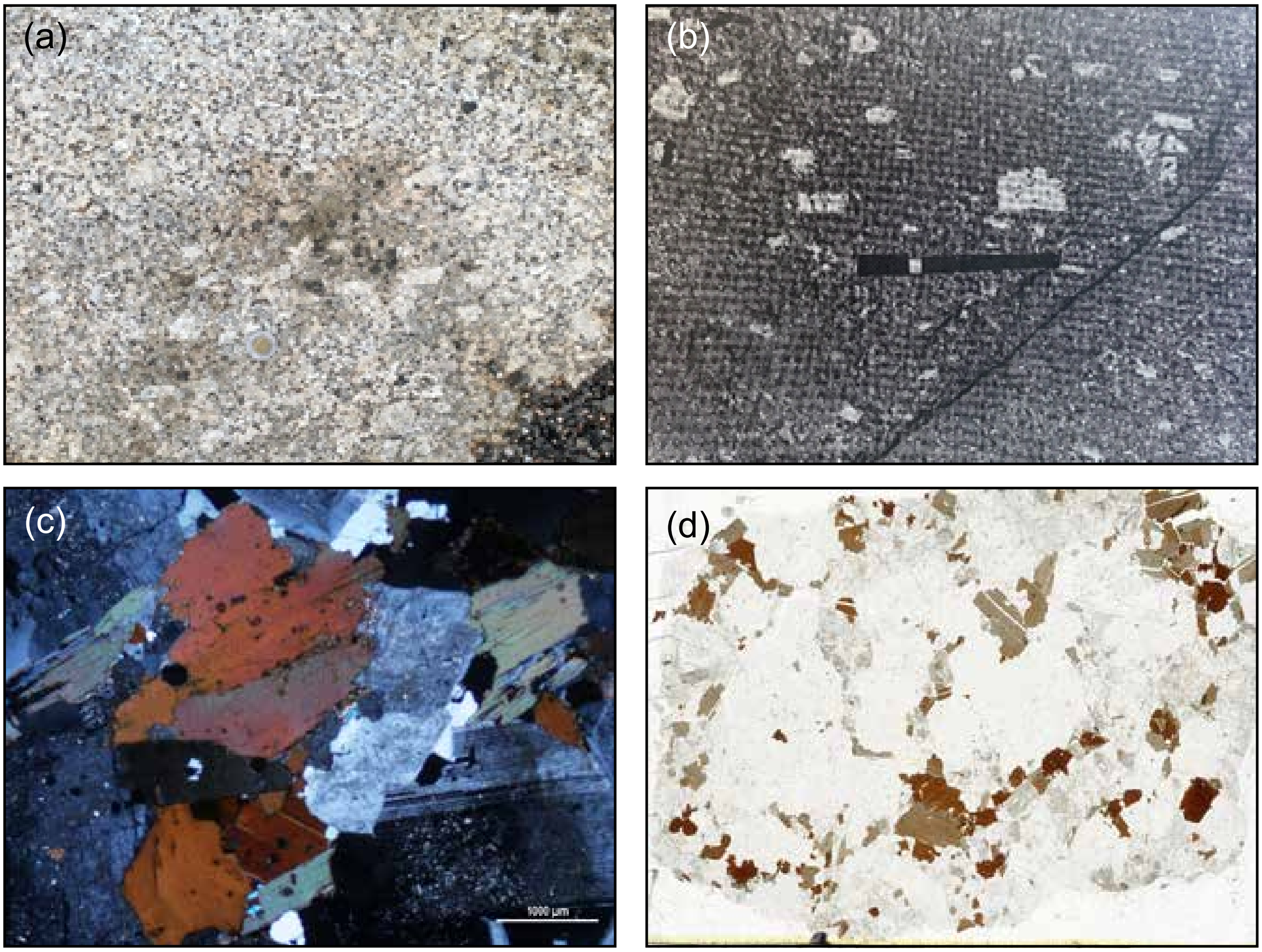


Figure 22. Fabrics in Stage I plutons. (a) NE-SW trending foliation in Stage I granite M1 on Thorne Road defined by alignment of K-feldspar megacrysts. (b) Parallel alignment of alkali feldspar megacrysts in the Cloud Lake biotite monzogranite. Preferred orientation, indicated by pen, is defined by euhedral megacrysts ranging from approximately 1.5–>5 cm in length. (c) Weak foliation of biotite in Stage I granite M72-53 (McKenzie 1974). (d) Randomly oriented biotite grains in Stage I granite M72-124 (McKenzie 1974). Image is 3.5 × 2.5 cm. Samples M72-53 and M72-124 are from biotite granodiorite from the Scrag Lake Pluton on Hwy 8 south of Annapolis Royal and the Salmontail Pluton on Hwy 12 just north of the Meguma Supergroup inlier, respectively. According to Benn *et al.* (1997), these rocks should show evidence of deformation by grain-boundary sliding, but the biotite grains are undeformed with no evidence of grain-boundary sliding, and undulose extinction in quartz is weak. Also, the weak foliation of biotite in these Stage I rocks is consistent with the small magnetic susceptibility anisotropies.

gradients, are responsible for many foliations (Fig. 24a), and this is the default interpretation for contact-parallel foliations (Ardill *et al.* 2020; Payacan *et al.* 2014) and in cases where "swirly" patterns, including closed structures, occur on an outcrop or map scale (Fig. 24a).

The fundamental conundrum with the Stage I foliations is that they are broadly parallel to Neo-Acadian fold axes in the Meguma Supergroup, but are they tectonic or magmatic or even tectono-magmatic in origin? Four interpretations are possible for this apparently "coupled" relationship:

1. The NE-trending foliation is the compound product of initial horizontal flow foliation apparently before, or during a lull in, regional D_1 deformation followed by folding by the same Neo-Acadian transpressional stresses that also deformed the Meguma Supergroup and thus the foliation and country-rock structures are causally coupled; therefore, the SMB is syn-tectonic (Benn *et al.* 1997). However, Option 1 has many problems. First, this interpretation is entirely at variance with previously presented evidence from the country rocks that clearly shows that SMB cross-cuts, and therefore post-dates, D_1 structures. Second, this interpretation appears to be the product of a default assumption that most granite intrusions are deformed laccoliths (Bouchez 1997; Nédélec and Bouchez 2019). Third, Benn *et al.* (1997) required that the Stage I foliations be formed exclusively by grain-boundary sliding without any other evidence of high-T deformation in the rocks.

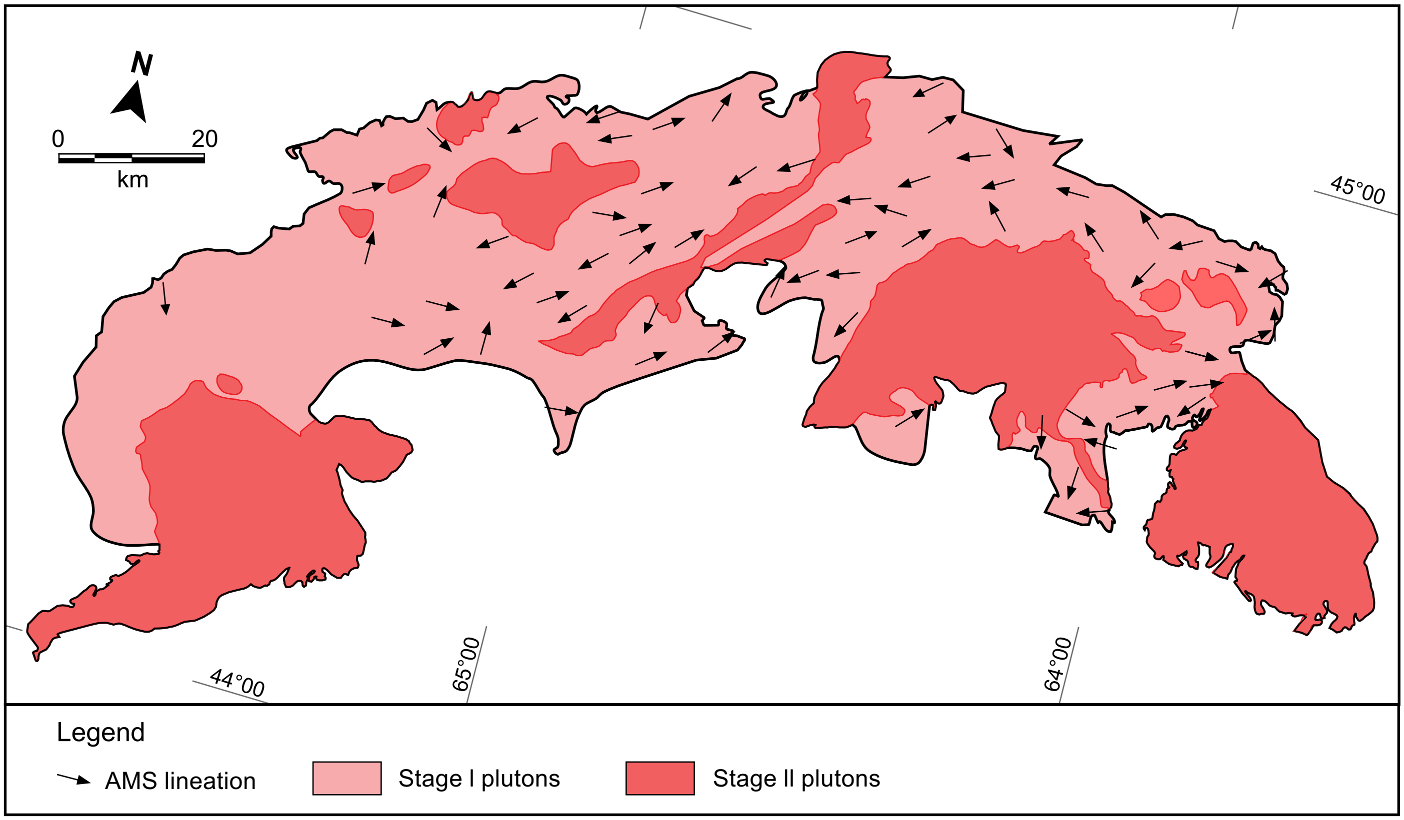


Figure 23. Magnetic lineations in Stage I plutons of the SMB (after Benn *et al.* 1997). Arrows indicate plunging direction.

Fourth, rather than the foliations in Stage I plutons having all been rotated from horizontal to vertical (Benn *et al.* 1997) at the same stage of crystallinity, with no other evidence of high-T deformation, these foliations are more simply in their original positions, although macroscopic alignments may be preserved whereas microstructures such as kinking of biotite and sub-grain growth in quartz may be annealed. The steep foliations in Stage I plutons are parallel to the vertical walls and long axis of the SMB which are, in turn, parallel to most of the exposed contacts. Benn *et al.* (1997) connected the foliation in the eastern lobe directly to the fold axes in the Meguma terrane, but it appears to us that the foliation in Stage I plutons may just have formed parallel to the contact, and that contact is parallel to the Meguma terrane fold axes.

2. The NE-trending foliation might be the product of a residual Neo-Acadian transpressional stress, such as the one responsible for the LFS F_2 deformation in the country rocks. If that stress acted on a ϕ > PLT magma resulting in parallelism of granite foliation and country-rock structures, the SMB is late syn-tectonic (Horne *et al.* 1992; MacDonald 2001). The problem with Option 2 is that the external compressive stress that forced the alignment in a (mechanically solid) magma mush had to be uniform over all Stage I plutons simultaneously and had to be strong enough to re-orient the K-feldspar megacrysts in a stiff granite mush, but perhaps weak enough not to deform the biotite crystals (although any deformation in them might have annealed).
3. The Port Mouton Pluton, outcropping to the south of the SMB, has a monazite U–Pb age of 373 ± 1 Ma (Clarke *et al.* 2000) and a long (3 km), and narrow (10–30 m), but well-defined syn-magmatic shear zone (Clarke *et al.* 2002) that is quasi-parallel to the long axes of the Stage I plutons and their NE-SW trending foliations. If syn-magmatic shearing took place in the nearby Port Mouton Pluton, it may also have occurred earlier during the emplacement of the Stage I plutons of the SMB, although similar evidence is lacking in the SMB.
4. The NE-trending foliation is the result of passive shear flow against the solidification fronts that are in turn parallel to the fold-controlled, and axial-planar-cleavage controlled, exocontact (Horne *et al.* 1988), or perhaps flowage NE and SW from the New Ross magma conduit, thus the coupling between alignments of K-feldspar megacrysts in the granites and country-rock deformation is only indirect because the Stage I plutons of the SMB are post-D_1–S_1 deformation. The problems with Option 4 are that these putative contact-parallel foliations are, in places, tens of kilometres from the nearest exocontact, and that the foliation trends cut across geochemically-defined contours in zoned Stage I plutons that probably represent solidification fronts (MacDonald 2001).

As mentioned above, the controversial origin of the

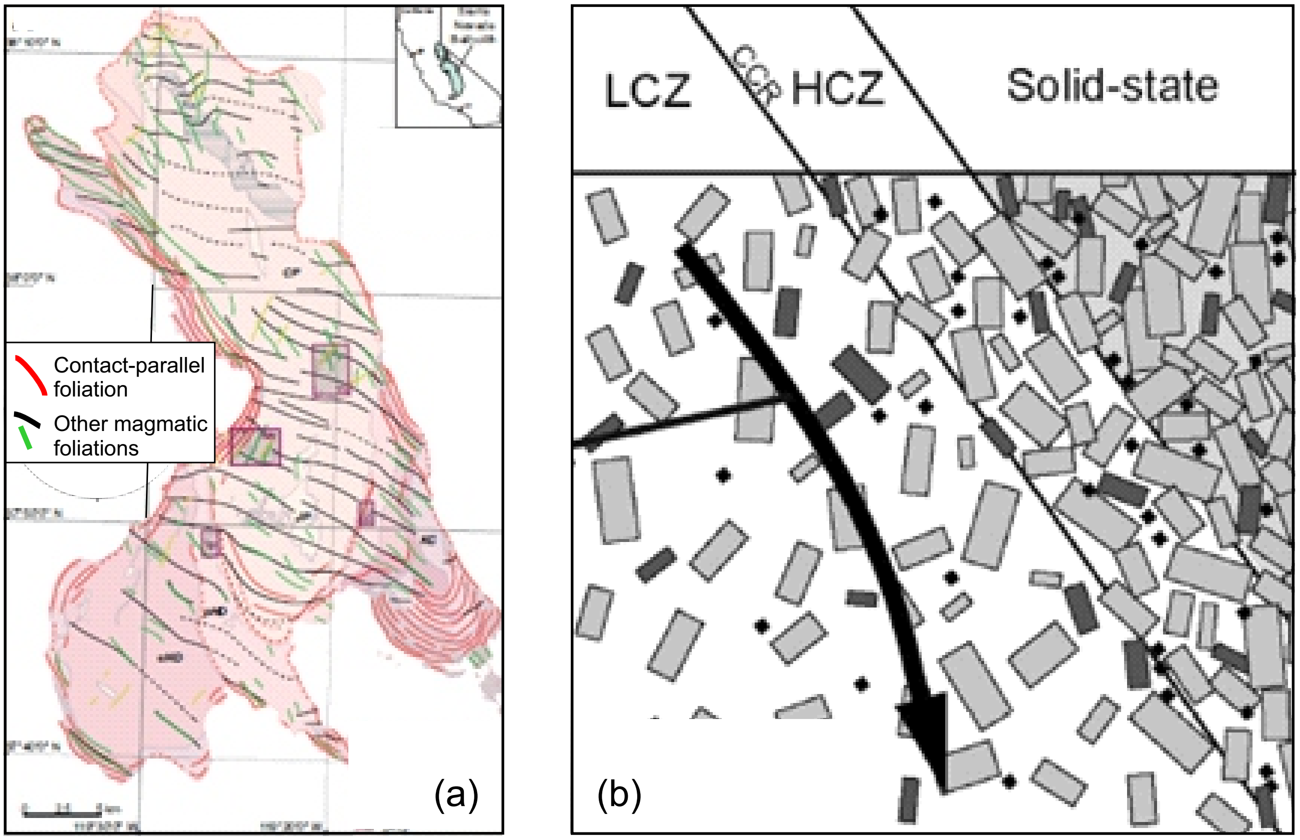


Figure 24. Examples of contact-parallel foliation. (a) Tuolumne Intrusive Complex in which contact-parallel foliation (red lines) is independent of deformation foliations in the country rocks (not shown) (Ardill *et al.* 2020) (b) Representation of the development of contact-parallel foliation as a solidification front (CCR) moves inward into the pluton (Payacan *et al.* 2014). Bold arrow indicates direction of convective side-wall magma flow. LCZ – low crystallinity zone; HCZ – high crystallinity zone; CCR – critical crystallinity region (Marsh 1996).

Stage I foliations is crucial in determining the timing of emplacement of the early granites of the SMB relative to Neo-Acadian F_1–S_1 or F_2 deformation. Not even parallelism of structural features is sufficient to infer a genetic relationship; many features can be parallel without being genetically related. Furthermore, the many departures of the foliations in Stage I plutons negate regional stresses as being responsible for any NE trend. At this stage of the investigation, we cannot make any definitive determination about the Stage I foliations. In the section on Suggestions for Future Work, we make a detailed recommendations for a resolution of this problem.

Augen monzogranite in the Stage I Cloud Lake Pluton

The term "augen" refers to the elliptical eye-shapes of normally blocky minerals that have been deformed. Commonly, the larger and stronger augened crystals (feldspars) are wrapped by platy minerals (micas) which themselves define a foliation.

Along its southern contact, the biotite monzogranite of the Stage I Cloud Lake Pluton contains a zone of foliated augen monzogranite (Fig. 25) (MacDonald and Ham 1989). This augen sub-unit is approximately 6 km long and 1.5 km wide with a moderate to weak, steeply dipping foliation defined by the alignment of biotite with minor development of augen-shaped feldspars (Fig. 26) and elongate metasedimentary xenoliths which parallel the foliation. The zone has a roughly ENE-WSW orientation with foliation orientations mostly varying from ENE-WSW to E-W, and a single outcrop having a NE-SW oriented foliation. These foliation directions dip steeply to the northwest, ranging from 74° to 80°. On the eastern side, the foliation terminates against the Stage I Scrag Lake monzogranite and, on the western and southern sides, terminates against the Stage II West Dalhousie Pluton.

Field relations (Fig. 25) show that the Cloud Lake intrusion might be the oldest Stage I pluton in this part of the SMB, confirmed by an age of ca. 378 Ma (Bickerton *et al.* 2022). Field relations also show that the augen zone formed in Cloud Lake Stage I pluton before emplacement of the adjacent Stage I Scrag Lake pluton (SGP). On the scale of the entire SMB, the unique zone of augen monzogranite is areally restricted, and represents only a minor textural variant of the Cloud Lake pluton along its southern contact. This limited geographic extent suggests this zone of augen

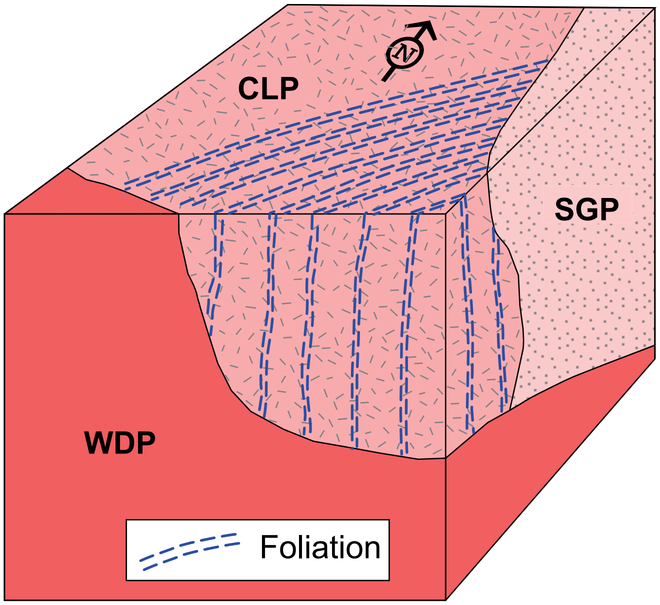


Figure 25. Block diagram showing the location of the augen monzogranite zone along the southern margin of the Stage I Cloud Lake pluton (CLP) and its intrusive relationships with the later Stage I Scrag Lake Pluton (SGP) and the even later Stage II West Dalhousie muscovite-biotite monzogranite (WDP).

monzogranite is unlikely to be the product of any regional structural deformation, such as the Neo-Acadian F_1 transpression, even though, because of its age it may be the pluton most likely to have experienced regional deformation at its margin.

The foliated biotite and deformed feldspars of this augen monzogranite appear to represent the response to stress in the latter stages (ϕ > PLT) of the crystallization history of the Cloud Lake pluton; however, its restriction to only a part of one Stage I intrusive pulse suggests local conditions may have been responsible for the structural imprint rather than regional tectonism. Thus, as with the Stage I foliations (above), the origin of this augen monzogranite may be an expression of either: LFS F_2, affecting only the SE margin of the Cloud Lake pluton; part of an early Port Mouton-style syn-magmatic shear zone truncated by later plutons; a local internal structural adjustment in the cooling and contracting Cloud Lake pluton; or a deformation aureole caused by the intrusion of the Scrag Lake pluton, especially if intrusion of the Scrag Lake Pluton closely followed that of Cloud Lake. Clearly, this enigmatic augen monzogranite merits further investigation.

Structures in Stage II plutons of the South Mountain Batholith

In this subsection, we examine several structural features of the later Stage II plutons. Because the times of intrusion of these plutons mostly post-date those of the Stage I plutons and are, therefore, temporally more remote from the

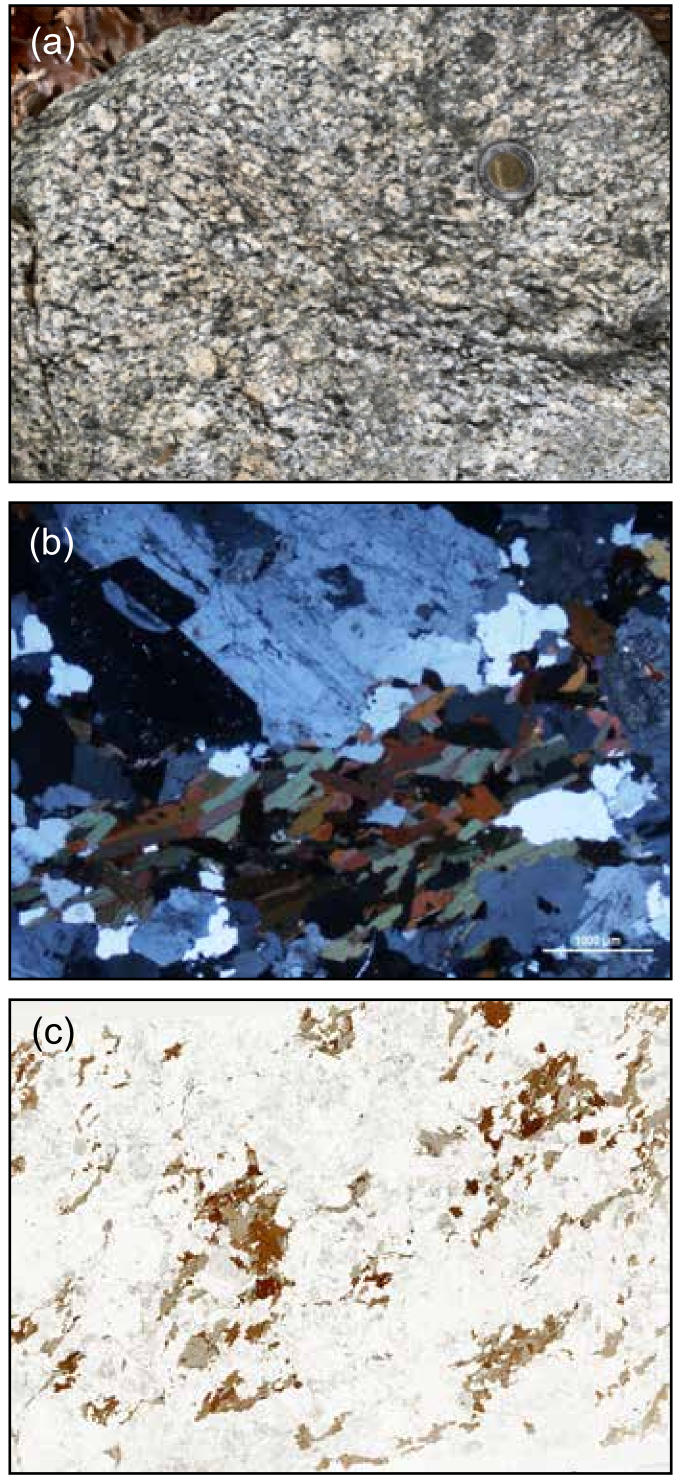


Figure 26. Textures of the augen monzogranite in the Cloud Lake pluton. (a) Appearance in the field showing distinct foliation from upper left to lower right of photograph. Coin diameter is 2.7 cm. (b) Appearance in crossed polarlized light showing feldspar augen and foliated, but undeformed, biotite grains. Either the biotite grains were never deformed as the augen monzogranite formed, or they have subsequently annealed. Scale bar is 1 mm. (c) Appearance in scattered light enhancing the foliation of the biotite grains. Image is ca. 3.5 × 2.5 cm.

main Neo-Acadian F_1 deformation, we do not expect to see any effects of it in these granites; however, LFS F_2, depending on its age, might be manifest somehow in these granites.

Shapes of Stage II plutons

Wherever they occur in the crust, bodies of magma represent zones of weakness. If the crustal host is undergoing active deformation at the time of magma emplacement, the pluton may develop a high degree of ellipticity, with its long axis perpendicular to the direction of maximum shortening. If the crustal host is relatively free of deviatoric stresses, the pluton should assume a shape dictated by a complex interplay of the physical properties of the granite magma and the host rocks (in this case, both Meguma Supergroup and early Stage I plutons). Figure 27 shows the shapes of the eight Stage II plutons against an outline of the entire SMB.

The highly irregular shapes of the Stage II plutons make any quantitative investigation difficult. In all cases, we assume the "big tank" model for emplacement, i.e., the shape of the pluton is equivalent to the shape of the magma pulse, but that simplistic model may not be true (e.g., Glazner *et al.* 2004), and MacDonald and Clarke (1991) determined that the Halifax Pluton was constructed by several roughly concentric pulses of magma. The East Dalhousie Pluton (EDP) and SW part of the Davis Lake Pluton (DLP) arguably have long axes that are essentially perpendicular to the Neo-Acadian 'direction of maximum shortening' (DMS); however, they may owe their elongate shapes to emplacement as fault-controlled dyke-shaped intrusions (Horne *et al.* 1992). Given that those putative dykes are essentially perpendicular to the Neo-Acadian DMS, it seems highly unlikely that there was any significant compression occurring at the time of their emplacement; however, there is evidence of lateral movement in the form of shearing and faulting. The reverse would be true, namely that the dyke walls would be perpendicular to prevailing σ3. Other Stage II plutons are more "blobby", suggesting that they developed in an environment characterized by weak deviatoric stresses. The generally more "blobby" shapes of the Stage II plutons, compared with those of the Stage I plutons (Fig. 27), suggest that the Stage II plutons are more likely to be post-tectonic with respect to Neo-Acadian D_1.

Foliations in Stage II Plutons

As in the Stage I plutons, alignments of K-feldspar megacrysts define foliations in the Stage II plutons; however, unlike the Stage I foliations, there is no apparently coupled alignment with respect to the Neo-Acadian F_1 deformation in the Stage II foliations. Instead, the foliation patterns in Stage II plutons tend to be more complex curving and swirling patterns indicative of magma-chamber convection (Fig. 28).

On a pluton scale, the foliations in Stage II plutons tend to be quasi-concentric with respect to the pluton shape (Fig. 29) (Horne *et al.* 1988). On a much smaller scale, Abbott (1989) showed three important features of the foliations in the Halifax Pluton (Fig 30): (i) a strong trend of the foliation in the Prospect Bay area that runs parallel to the coast-

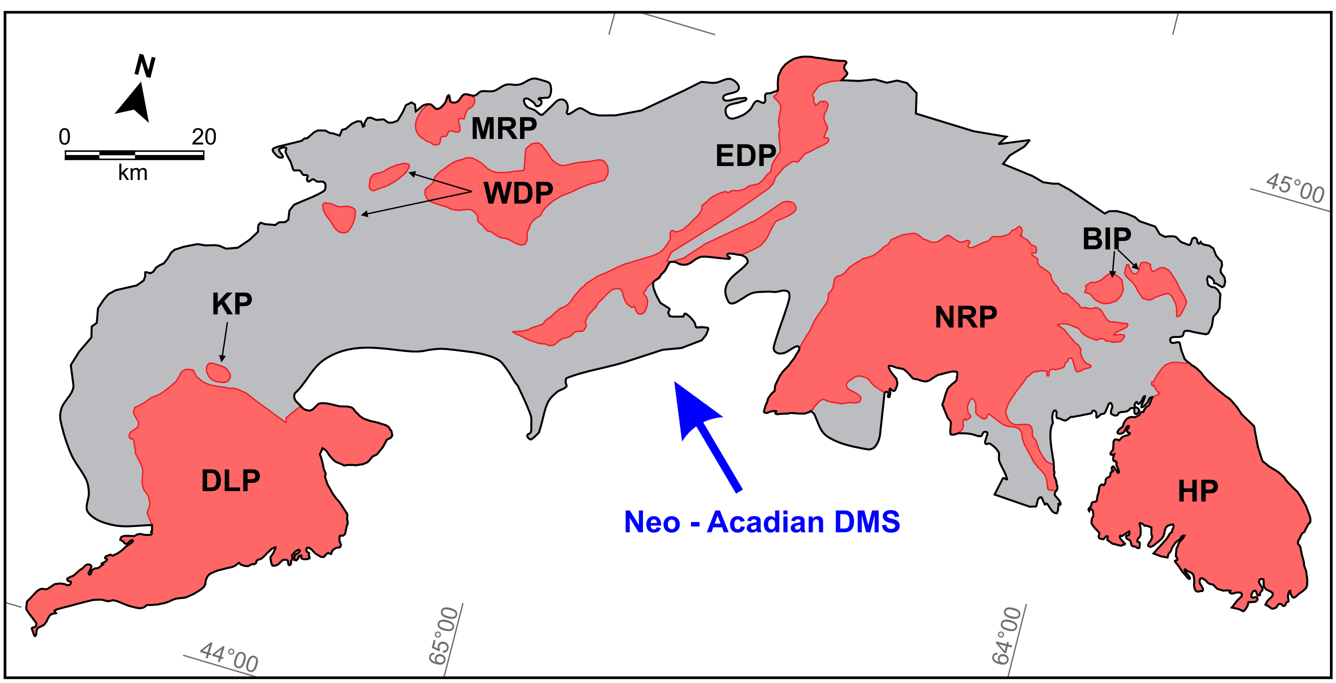


Figure 27. Outline map of the SMB with the Stage I plutons in grey and the eight Stage II plutons highlighted in red. BIP – Big Indian Lake Pluton; DLP – Davis Lake Pluton; EDP – East Dalhousie Pluton; HP – Halifax Pluton; KP - Kejimkujik Pluton; MRP – Morse Road Pluton; NRP – New Ross Pluton; WDP – West Dalhousie Pluton.

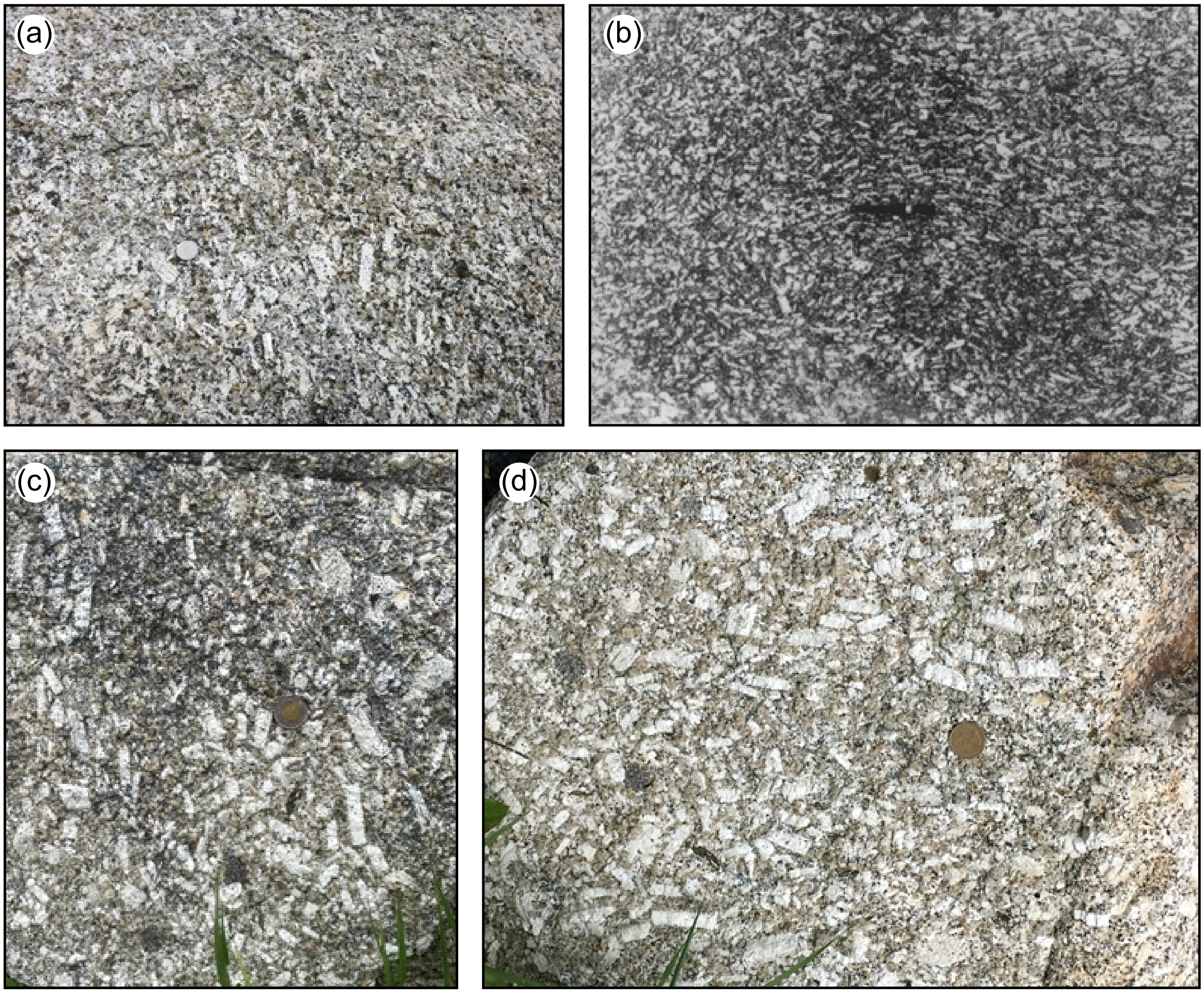


Figure 28. Foliations in the Stage II plutons. (a) Parallel alignment of contact-parallel K-feldspar megacrysts in the Halifax Pluton (b) Swirly pattern of K-feldspar megacrysts in the West Dalhousie Pluton (MacDonald 2001, Plate 6.1d). (c, d) Foliation of K-feldspar megacrysts in boulders at Herring Cove Provincial Park, Nova Scotia.

line, which in turn is sub-parallel to the contact of the SMB with the Meguma Supergroup country rocks just offshore defined by magnetic and sonographic imaging (Geological Survey of Canada 1982; Loncarevic *et al.* 1994); (ii) a less well-defined E-W trend of foliation in the Chebucto Head area aligns approximately perpendicular to the contact which aligns parallel to the coastline, but it becomes parallel to the contact ca. 1.8 km to the north where the contact is closer to the coast; and (iii) small regions of broadly closed loops of foliation occur in both areas in many places.

The strong NW-trending contact-parallel foliation in the Prospect Bay area is approximately parallel to Neo-Acadian DMS. Indeed, the one clear control seems to be flow parallel to the NW-trending contact along the Prospect–Peggys Cove coast, and the N-trending contact at Portuguese Cove. Such contact-parallel foliation is common in granite plutons (e.g., Ardill *et al.* 2020; Payacan *et al.* 2014) (Fig. 24). Even in post-tectonic circular plutons with contact parallel foliations, two places in the pluton must have contact-parallel foliations that are also parallel to structures in the country rocks, but that does not mean those foliations were formed by external tectonic forces.

The randomly distributed closed foliation structures are most likely to be the products of internal processes, such as convective overturn (Abbott 1989), or large eddies in shear flow regimes. The diverse trends of foliations in the Halifax, New Ross, and West Dalhousie plutons indicate that no single applied external, or internal, stress can be responsible for their formation, and thus the foliations in the Halifax Pluton appear to fit with the decoupled model (Fig. 19).

Finally, Stage II plutons may be as much as 7 myr younger than Stage I plutons (Bickerton *et al.* 2022), so even if the Stage I foliations were syn-tectonic with Neo-Acadian F_1, as claimed by Benn *et al.* (1997), the foliations in Stage II plutons probably do not have the same mode of origin.

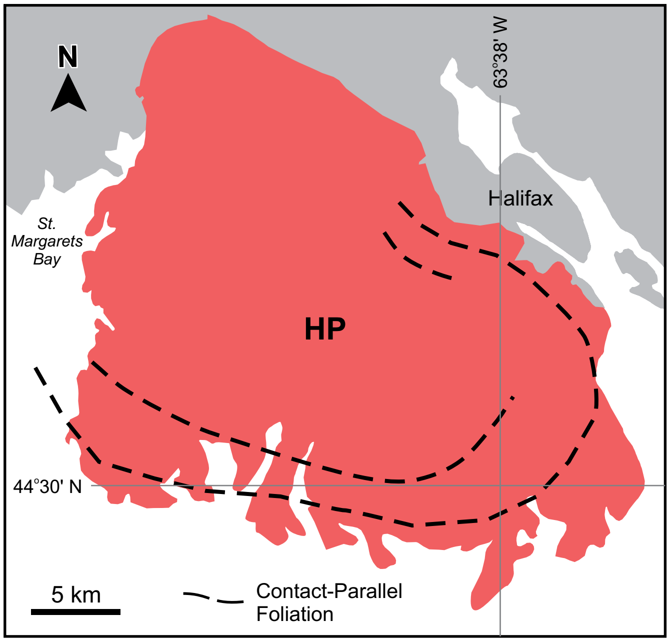


Figure 29. Schematic representation of foliation in the Stage II Halifax Pluton (after Horne *et al.* 1988, fig. 3).

Figure 30. Detail of K-feldspar megacryst foliations in the Prospect area, Stage II Halifax Pluton (after Abbott 1989).

"Folding" in the Halifax Pluton

In the absence of reliable markers, detection of folding in plutonic rocks is highly problematic. If tectonic folding in the granites of SMB exists, and if that folding is consistent with stresses associated with either the F_1 or F_2 folding of the Neo-Acadian orogeny, the SMB would be syn-tectonic. Benn *et al.* (1997) interpreted alignments of K-feldspar megacrysts in the Stage I granites as being folds of tectonic origin and Kontak *et al.* (2002) interpreted the attitudes of aplite sheets at Peggys Cove as folds related to Neo-Acadian deformation. In this section, we examine these two cases in detail.

The first area of "folding" is near Chebucto Head, where Abbott (1989) mapped foliations in part of the Halifax Pluton (Fig. 31a). Benn *et al.* (1997) made a detailed examination of the attitudes of these foliations, defined by alignment of K-feldspar megacrysts, north of Chebucto Head (Fig. 31b). Benn *et al.* (1997) defined fold axes based on oppositely dipping steep foliations (Fig. 31a) but ignored large tracts where no regular strikes to the foliations exist (poles are absent in the Schmidt plot). Abbott's map (Fig. 31a) shows that, although the predominant trend of the foliation is E-W, many other orientations exist. In fact, in nearby Portuguese Cove, the strike of the foliation is N-S, and in the ca. 20 km coastal section from Pennant Point to Peggys Cove, the predominant strike of the foliation is NW-SE.

Near Chebucto Head, Benn *et al.* (1997) made a highly selective examination of the attitudes of near-vertical foliations and locations of "fold" axes in a very small part of the larger area of foliations mapped by Abbott (1989), but without any observed fold hinges, the case for folding is weak. As a result, there is a disconnect between the map symbols and the Schmidt plot. Even if there were "folds" in this area, their axes are E-W, i.e., not parallel to Meguma Supergroup regional fold trends, and thus they are unlikely to be related to externally imposed deformation. In addition, Abbott (1989, fig. 7) showed that the dominant trend of the foliations at Terence Bay is exactly parallel to Neo-Acadian DMS. Abbott (1989) attributed these structures to magmatic flow and noted that the deformation did not affect rocks of the Meguma Supergroup, "hence the stresses that caused the folding were internal", driven by thermal convection. Furthermore, in the same area as Benn *et al.* (1997) measured "folds", there are undisturbed layered granodiorites (Fig. 32) that extend for approximately 200 m north of the main layered series and at right angles to the putative "folds", making the probability of any true folding in this area highly unlikely.

The second area of "folding" is at Peggys Cove, where Kontak *et al.* (2002) described the orientations of aplite sheets injected into early subhorizontal joints (Fig. 33). They attributed the undulating orientations of these aplite sheets to "folding of these rocks while still ductile", although apparently, the rocks had previously been brittle enough to produce the subhorizontal fractures.

At Peggys Cove, the stereogram (Fig. 33) of the "folded" aplite sheets shows randomly oriented, shallowly-dipping, undulating planes, rather than a girdle of poles in the NW-SE sectors (red ellipse) as would be expected if they had been the products of NW-SE Neo-Acadian compression. The well-exposed vertical joints at Peggys Cove range from wavy to concentric (Fig. 34), and the less-well-exposed subhorizontal joints undulate. Joints may initiate at, or be perturbed

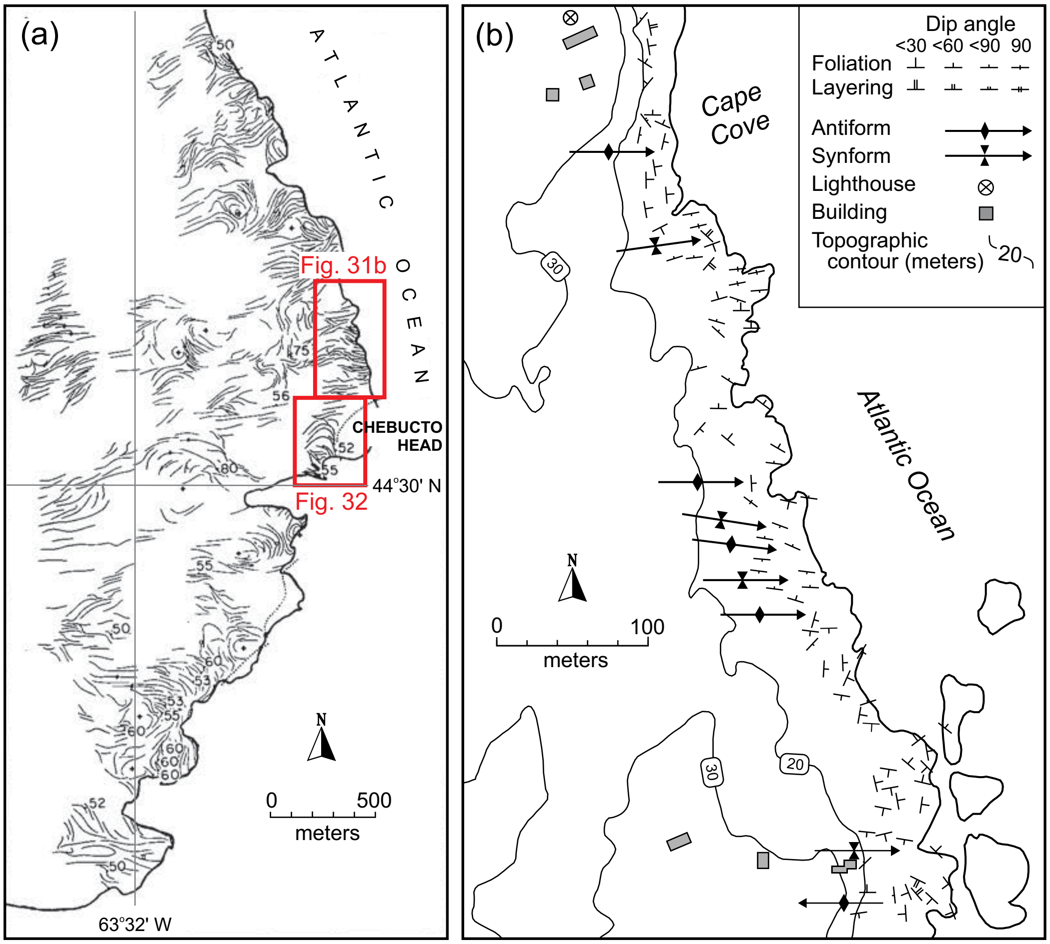


Figure 31. "Folding" in the SMB near Chebucto Head. (a) General area mapped by Abbott (1989) showing the orientations of foliation defined by K-feldspar megacrysts.(b) Detailed mapping of "fold axes" by Benn *et al.* (1997).

by, local flaws which change the stress field such that the local tensile stresses at the flaw exceed the tensile strength of the rock (Pollard and Aydin 1988; Pollard *et al.* 2004). It appears that a flaw, in this case an object with greater fracture toughness (Leblond and Ponson 2016), such as an unexposed xenolith located beneath the yellow dot on Figure 34, has caused local undulations in all the cracking fronts and joint directions. Undulations are a common manifestation of crack instability, especially when cracks propagate at seismic velocities (Pomeau 2002; Liang *et al.* 2015). Thus, we interpret the attitudes of the subhorizontal aplites (Fig. 33) as perturbations of regional joint fracturing, not folding. The sub-horizontal joints formed when magma was still available to fill them, and the sub-vertical joints appear to have been later but still subject to deviation by the flaw.

In conclusion, the "folds" near Chebucto Head, defined by steeply-dipping foliations, are the complex products of magma convection, and are unrelated to any externally applied stresses. The "folds" at Peggys Cove, defined by undulating subhorizontal aplites, are simply injections of magma into subhorizontal joints undulating around a flaw. Those features that were originally vertical (K-feldspar megacrysts, logjam feeder dyke) are still vertical, and those features that were originally subhorizontal (Chebucto Head layers, schlieren) are still subhorizontal. Thus, there is no reliable evidence of folding in the granites of the Stage II Halifax Pluton that could be used to designate the batholith as syn-tectonic with D_1.

Internal granite-granite contacts

If one igneous rock is in contact with another igneous rock, the original intrusive relationship might have been either magma (melt + crystals) against solid rock or magma (melt + crystals) against magma (melt + crystals). Both cases could occur in the presence or absence of a deviatoric stress field. Magma vs. solid rock contacts might look similar in ambient deviatoric stress and deviatoric stress-free situations; however, magma vs. magma contacts in a deviatoric stress-free environment may be fractal (DeWolfe 1994; Perugini and Poli 2000; Perugini *et al.* 2002) where magma mingling has occurred, whereas those in a deviatoric stress environment may show a fabric with preferred orientation.

Exposures of internal granite-granite contacts are rare in the SMB, but some magma vs. solid rock and magma vs. magma contacts do outcrop. Figure 35 shows both types,

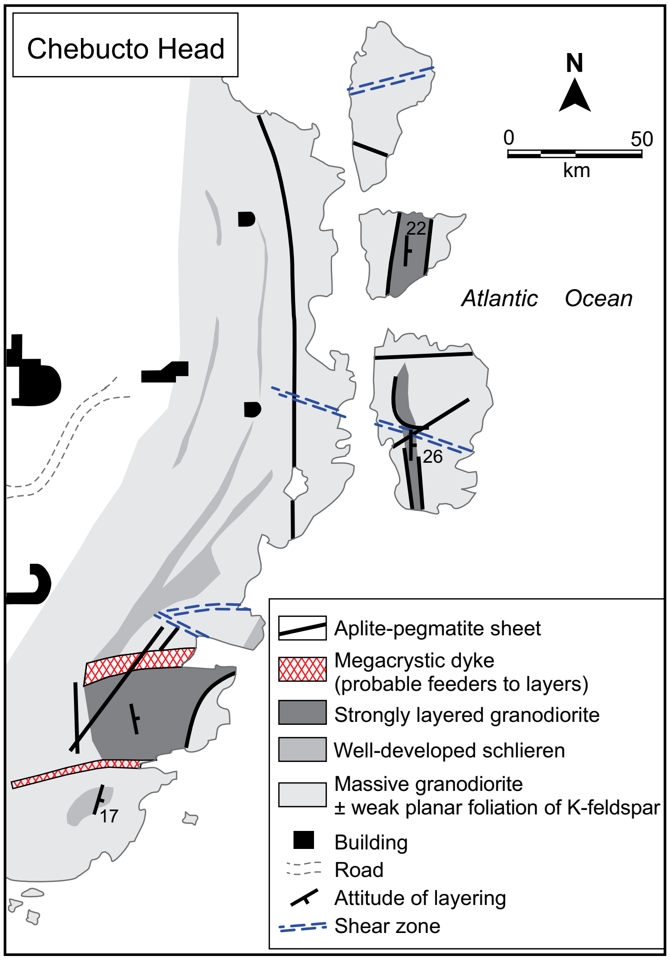


Figure 32. Undisturbed planar layered granodiorite extending 200 m north of the layered granites at Chebucto Head (after Clarke and Clarke 1998).

but concentrates on those involving mingled magmas, which show highly irregular fractal or pillowy contacts.

We conducted a deformation experiment in CorelDRAW© to simulate the effect of compressive stress on mingled fractal magma vs. magma contacts (Fig. 36). If the fractal boundary is perpendicular to the principal stress direction, the amplitude of the original fractal pattern decreases and the wave-length increases. If the fractal boundary is parallel to the principal stress direction, the amplitude of the fractal pattern increases and the wavelength of the fractal pattern decreases. The effects of simple shear are similar. In both deformed cases, strong preferred orientations develop.

As two mingled magmas cool toward their respective solidus temperatures, their degrees of crystallinity (ϕ) increase. If both mingled magmas are in the 100 > ϕ > PLT condition at the same time, they should show some effects of mechanical solid-state deformation, and the boundary between them will become modified (Fig 36). The many fractal mingled contacts in the SMB (Fig. 35) appear to be undisturbed and do not seem to have been either compressed or stretched but, of course, it is not possible to know what the original configuration of that fractal pattern might have been.

Any fractal mingled magma vs. magma contacts in the SMB would have been extremely weak and highly susceptible to deformation if the two magmas had simultaneously crystallized through their solidus temperatures under an applied deviatoric stress field. Fractal mingled magma contacts in the SMB do not appear to have been overprinted by any externally applied stresses, either by pure shear or simple shear, thus the SMB is post-tectonic relative to Neo-Acadian D_1.

Ring Schlieren

As they cool and crystallize, all granite magmas pass through a mushy state (100 > ϕ > 75), where ϕ is the degree of crystallinity of the magma, en route to complete solidification. As for the fractal contacts above, any structures formed in that relatively weak mush are highly susceptible to deformation.

Ring schlieren in granitic rocks, defined by concentric rings consisting of high modal proportions of melanocratic minerals, are metre-scale, two-dimensional expressions of three-dimensional nested cylinders (Paterson 2009; Clarke *et al.* 2013). The rings may be circular (Fig. 37a) or elliptical (Fig. 37b), and they may be concentric or eccentric. In the glaciated SMB with little vertical relief, fewer than 10% of these ring schlieren structures show a third dimension, but where they do, the cylinders are essentially and consistently vertical (Fig. 37c). If cross-cutting relationships between rings occur in a single structure, the inner rings cut outer rings, indicating successive intrusive relationships whereby the inner rings are younger (Fig. 37d).

The origin of ring schlieren structures is highly debatable (Weinberg *et al.* 2001; Paterson 2009; Clarke *et al.* 2013; Glazner *et al.* 2020), but there is broad agreement that they formed relatively late in a stiff magma mush host that was weak enough to permit their injection and yet strong enough to permit their preservation. Two important geometrical aspects of ring schlieren are critically relevant to the timing of emplacement of the Halifax Pluton.

First, the 96 rings measured in the Halifax Pluton have ellipticities ranging from 1.01 to 2.41 (mean 1.34 ± 0.25) (Clarke *et al.* 2013), and many are de facto circular in plan. It is highly improbable that so many ring structures could have been deformed into circular shapes, so they are presumably original. Figure 38 shows that orientation of the long axes of rings with ellipticities >1.1 is essentially random with respect to the Neo-Acadian DMS; thus, their shapes may also be original. Because a granite mush would have been highly deformable had that Neo-Acadian compression, or any other deformation, been taking place during their formation, we deduce that both the circular and elliptical SMB rings formed in the absence of any significant externally applied stress, or if the elliptical rings are deformed circular rings, the stresses must have been local, not regional.

Second, what seems to be common for these ring structures in granites world-wide is that they have consistently

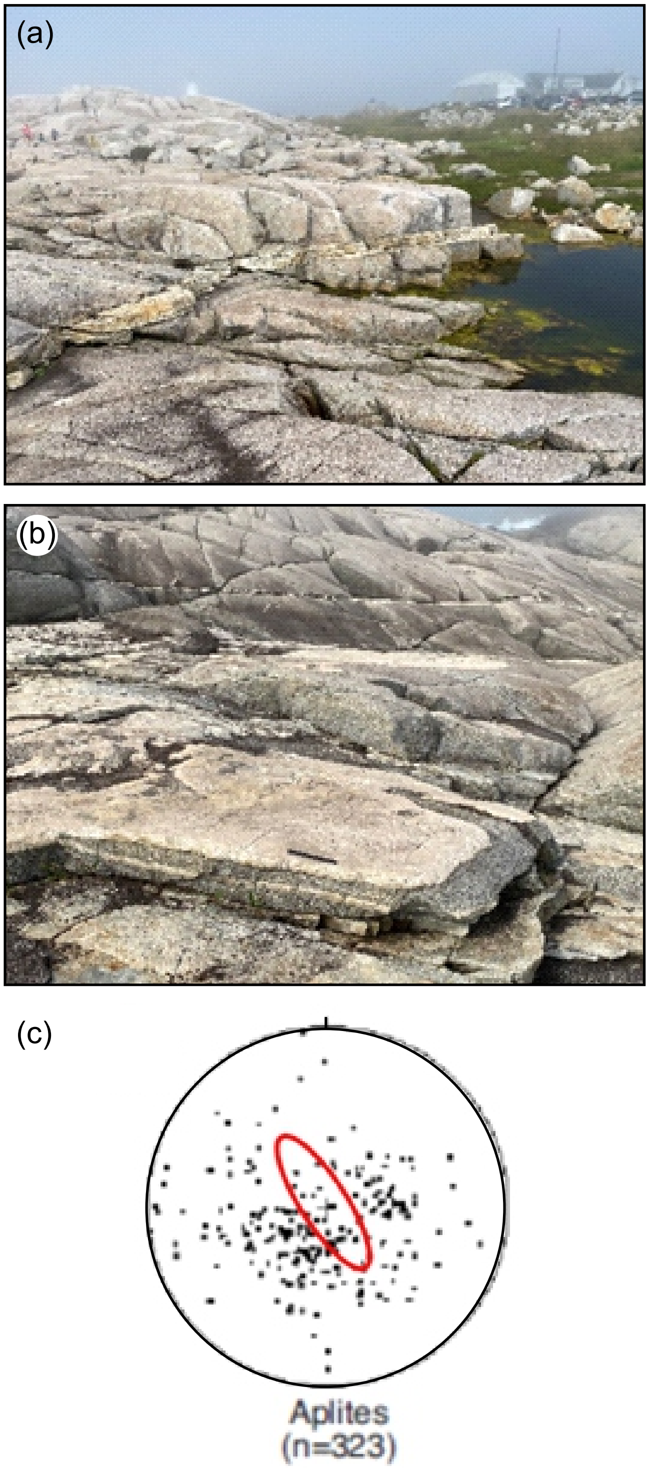


Figure 33. "Folded" aplites at Peggys Cove (Kontak *et al.* 2002). (a) Large subhorizontal composite aplite-pegmatite sheet. (b) Several parallel subhorizontal aplite sheets. Scale bar is 25 cm. (c) Stereogram of poles to the subhorizontal aplite sheets (after Kontak *et al.* 2002). Red ellipse is expected area of poles to sheets if they had been produced by Neo-Acadian F_1 deformation. Instead, the stereogram shows a predominance of shallow dips of the aplite sheets in all directions, consistent with a local perturbation of the joint pattern which some subhorizontal aplite sheets occupy.

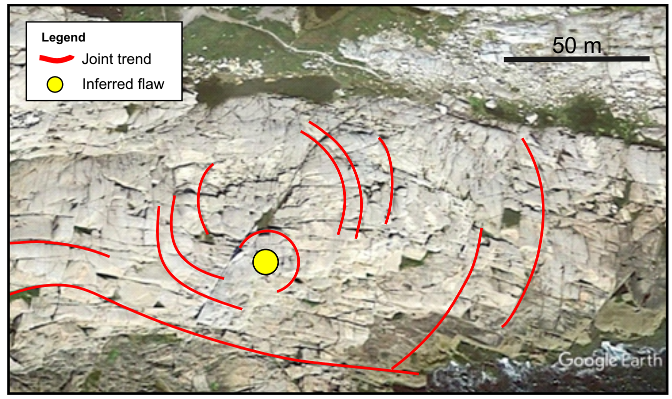


Figure 34. Irregular joint pattern at Peggys Cove. The "normal" regular NW- and NE-trending joint pattern is disturbed (red lines) in the vicinity of a possible flaw (yellow dot). In three-dimensions, the sub-horizontal joints also curve around the flaw causing irregular attitudes to the aplitic injections into these joints. Google Earth image.

steep plunges in any given pluton, strongly suggesting that gravity is an important control in their formation, caused either by material moving up (magma, bubbles) or down (xenoliths) (Clarke *et al.* 2013; Ardill *et al.* 2020; Rocher *et al.* 2018). If so, these nested cylinders can serve as paleo-plumb bobs (Paterson 2009). In the Halifax Pluton, the plunges of the cylinders are all essentially vertical, suggesting that there has been no disturbance of their original orientation, i.e., there has been no penetrative deformation of the Halifax Pluton during, or after, their formation.

Ring schlieren are mechanically weak structures that are highly susceptible to deformation at the time of their formation. Those in the Halifax Pluton appear to have retained their original three-dimensional shapes and vertical orientations, demonstrating that they formed in the absence of any externally imposed tectonic stress. Thus, the Halifax Pluton is post-tectonic relative to the Neo-Acadian F_1, and possibly even F_2, compressional deformations.

Immiscible Sulphides

Sulphide minerals, such as pyrrhotite, are rare accessory phases in granitic rocks. Pyrrhotite is mechanically soft and easily susceptible to ductile deformation (e.g., Gill 1969; Graf and Skinner 1970; Clark and Kelly 1973, 1976; Arkinson 1975) and, thus, can act as a sensitive strain gauge for any deformation that takes place in their host granite, especially at high temperatures. In deformed syn-tectonic granites, pyrrhotite should be among the easiest minerals to undergo deformation, whereas in ideally static post-tectonic granites, the sulphides may retain their original immiscible droplet shapes.

Clarke *et al.* (2009) reported the rare occurrence of sulphide minerals in the marginal facies of the SMB Stage I and Stage II granodiorites. The abundance of sulphides in these granites appears to be related to assimilation of sulphide-

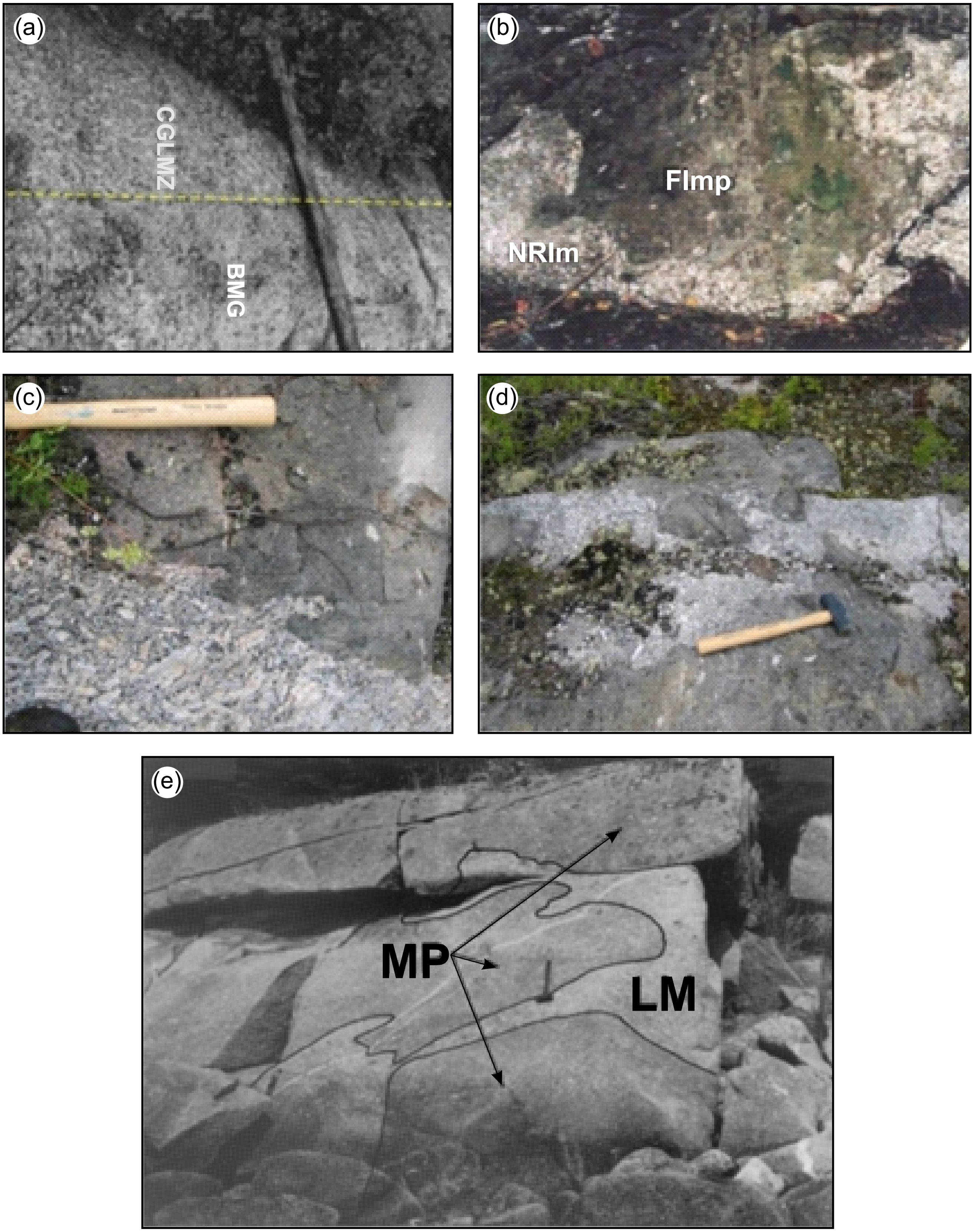


Figure 35. Endocontact relations in the SMB. (a) Typical granite magma (CGLMG) against granite solid rock (BMG) contact (MacDonald 2001, Plate 3.5). (b-d) Typical granite magma vs. granite magma fractal mingling relationship. (e) Blobby inclusions of MP (mafic porphyry, i.e., melagranite) in leucomonzogranite (LM) in the Halifax Pluton. CGLMG - coarse-grained leucomonzogranite, BMG - biotite monzogranite; NRlm - New Ross coarse-grained leucomonzogranite, FLmp – Five Mile Lake mafic porphyry (i.e., melagranite of MacDonald and Clarke 2017).

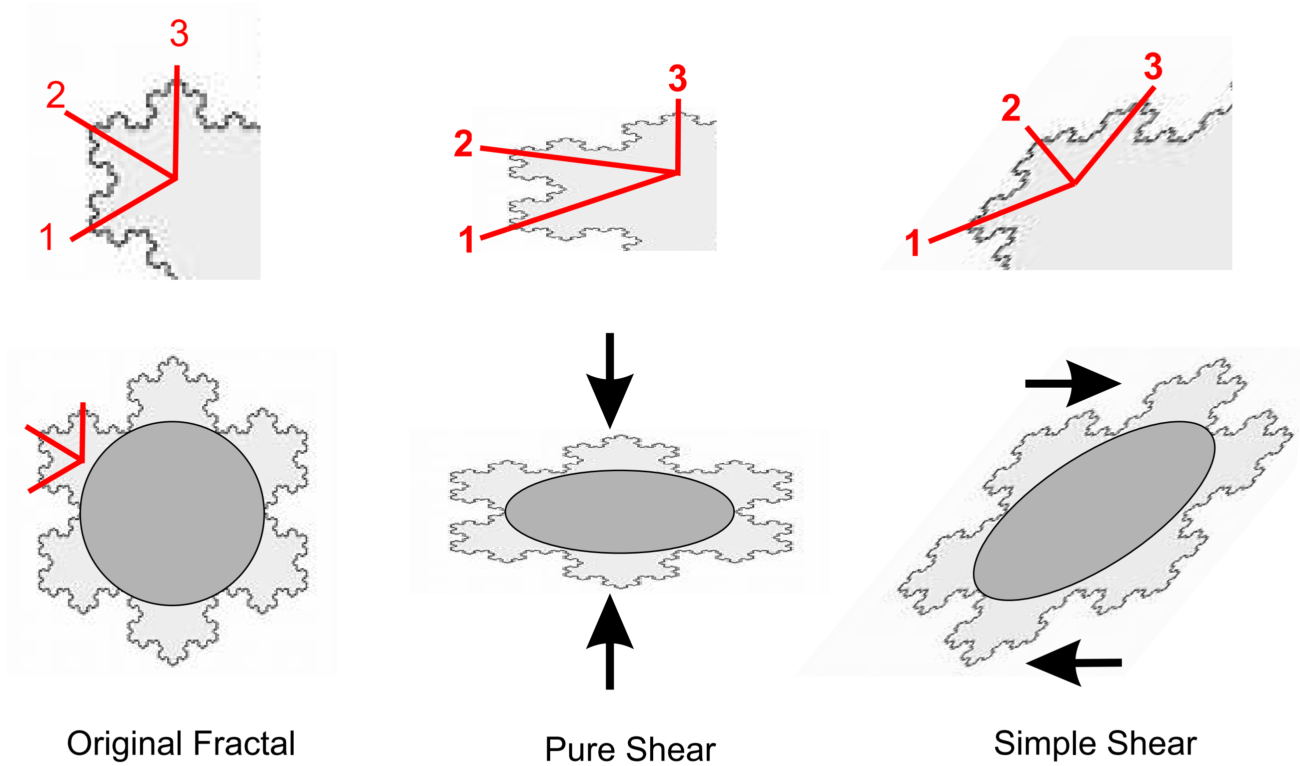


Figure 36. Effect of pure shear and simple shear on pseudo-fractal mingled contacts, showing the original fractal shape, the shape resulting from pure shear shortening of ca. 50%, and shape resulting from simple shear. The initial fractal shape has no preferred orientations (e.g., "axial planes" 1, 2, and 3 are evenly distributed), in contrast to the pure shear case in which planes 1 and 2 become more closely aligned, and the simple shear case shear case in which planes 1 and 3 become more closely aligned.

rich pelites from the adjacent country rocks (Fig. 39).

In thin section, several aspects of the shapes of these sulphide grains are important. The grains range in shape from amorphous blobs to highly irregular microdropper textures (wherein dense molten sulphide drains down and displaces silicate melt between silicate solids) or veinlets. In many cases, the sulphides also have negative grain shapes against surrounding quartz and feldspar (Fig. 40).

Clarke *et al.* (2009) deduced that the sulphide grains in the marginal facies of the Halifax Pluton began their history in the granite as anhedral sulphide xenocrysts, which then partially or completely melted to become immiscible sulphide droplets in the silicate magma. The irregular, and delicate, sulphide veinlet and microdropper textures appear to be the result of the sulphide melt passively draining down along grain boundaries between the silicate minerals under the influence of gravity and displacing the interstitial silicate melt. The negative grain shapes of the sulphides also suggest they were among the last minerals to crystallize, perhaps even at temperatures below the solidus of the silicate magma. Because minor sphalerite, galena, and arsenopyrite are part of the sulfide assemblage in some Meguma terrane country rocks, the presence of minor additional components (such as Zn, Pb, and As) in the sulfide system may have been sufficient to lower its multi-component eutectic to temperatures below the granite solidus of ca. 700°C, supporting the inference that the sulphides were the last minerals to solidify in these rocks.

If the inherently weakest, softest, most ductile minerals in the batholith, with globular shapes and delicate and fragile veinlet textures, in the outer margin of the granite most exposed to external stresses, show no evidence of deformation, we deduce that there were no strong deviatoric stresses during or after the time of emplacement of the Halifax Pluton sufficient to imprint strain markers in the granite. According to this sulphide mineral criterion alone, intrusion of the granite was post-tectonic relative to Neo-Acadian D_1.

Summary of structures in Stage II granites

Field relations and geochronology show that Stage II plutons are younger than Stage I plutons. As such, they are even further removed in time from Neo-Acadian F_1 and perhaps even LFS F_2 deformation than the Stage I plutons. Stage II pluton shapes are more "blobby", Stage II foliations bear no relation to F_1 structures in the Meguma Supergroup, Stage II plutons exhibit no folding, and Stage II plutons appear to have undeformed within-pluton granite-granite contacts, ring schlieren, and immiscible sulphides. In short, the structures in Stage II plutons show no evidence of externally applied forces and appear to have formed exclusively by internal magmatic processes.

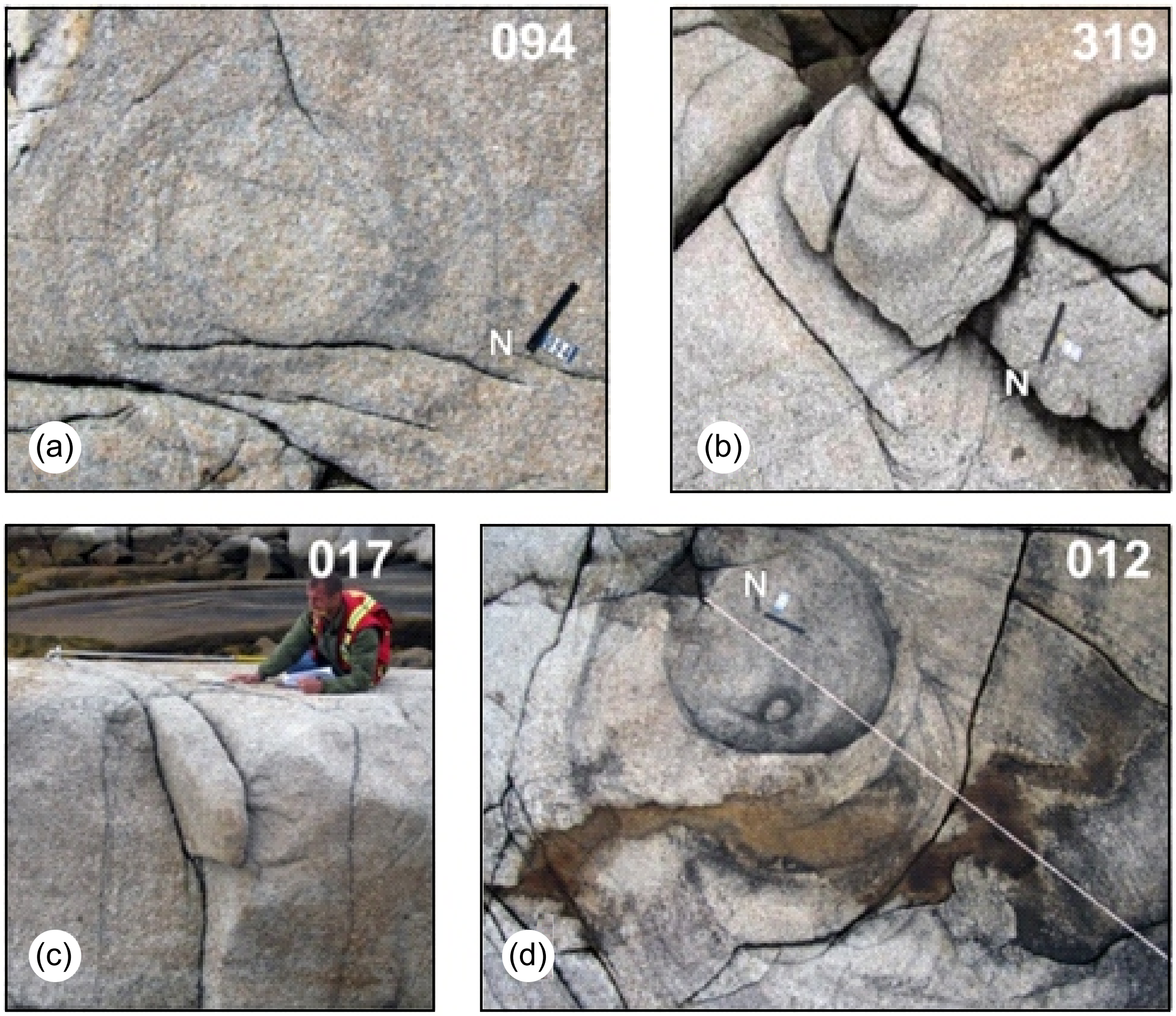


Figure 37. Ring schlieren in the Stage II Halifax Pluton. (a) Concentric circular rings. (b) Eccentric elliptical rings. (c) Vertical section through a single ring illustrating that it is a cylinder in three dimensions. (d) Central part of a large ring complex showing that inner rings cut outer rings. Three-digit numbers refer to identity of the ring in Clarke *et al.* (2013), scale bar is 25 cm, and N is north end of scale bar.

Other structures in the South Mountain Batholith

In this subsection, we examine structures that belong to the SMB as a whole and are not specific to either Stage I or Stage II plutons.

Gravity anomalies

Gravity measurements reflect the densities and thicknesses of different rock types relative to their surroundings. Granites have low densities relative to many other crustal rocks and, accordingly, if a body of granite is thick, it may produce a significant negative gravity anomaly. These gravity anomalies can be used to infer the 3-D shape of a granite intrusion, assuming that the geology and geometry of the host rocks is well known (Vigneresse and Cuney 1995; Nédélec and Bouchez 2019).

Regional gravity surveys and subsequent gravity modelling over southwest Nova Scotia (Garland 1953; Douma

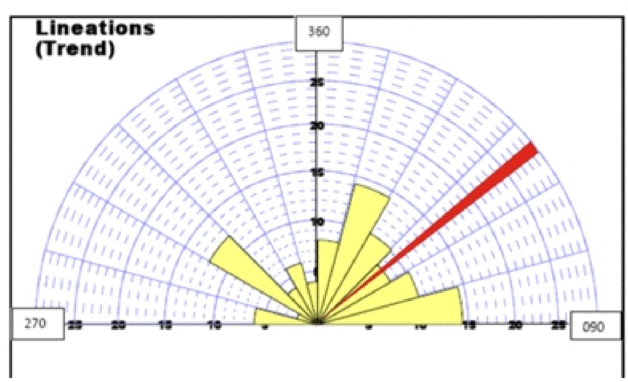


Figure 38. Orientation of the long axes of the elliptical ring structures in the Halifax Pluton. The yellow sectors show the orientations of the long axes of all 49 rings with ellipticities >1.1. The red sector is the expected orientation of the long axes if the ring structure had formed before, or during, the Neo-Acadian F_1 deformation.

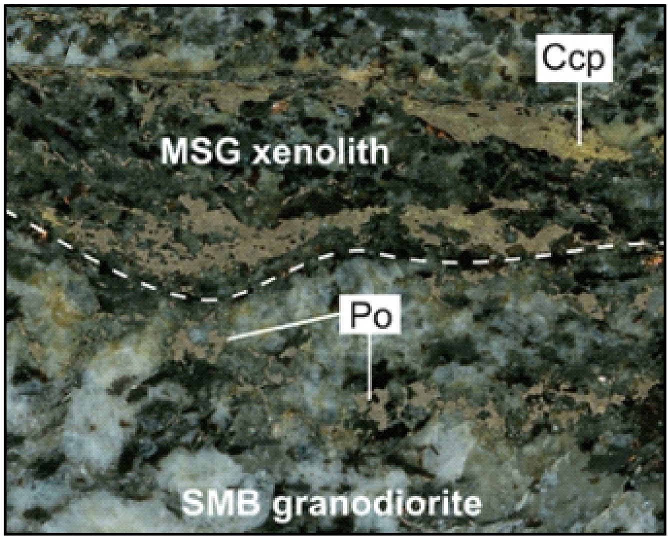


Figure 39. Macroscopic view of sulphide minerals in marginal granodiorite, showing close spatial association of sulphide grains in granite with a sulphide-rich Meguma Supergroup (MSG) xenolith. Bottom of photo is the gravitationally down direction. Po – Pyrrhotite; Ccp – chalcopyrite. Width of photograph is 3 cm.

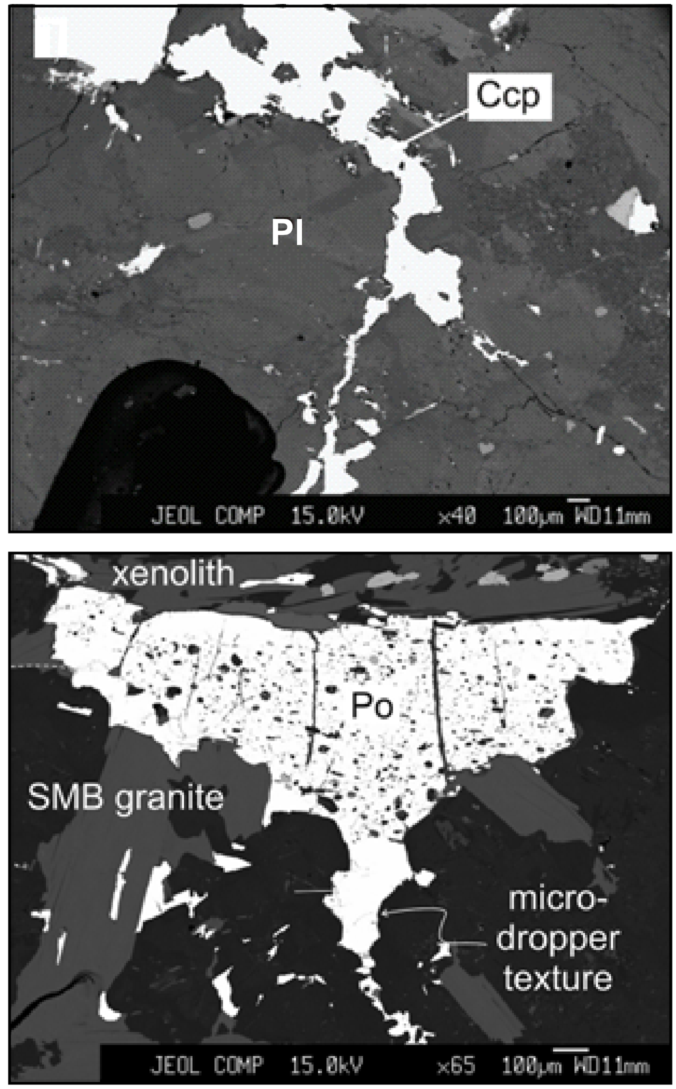


Figure 40. Microscopic view of sulphide minerals in the marginal granodiorite phase of the Halifax Pluton. (a) Delicate and fragile sulphide veinlet. (b) Complex sulphide grain showing a microdropper texture. Bottoms of photos are the gravitationally down direction. Pl – plagioclase; Po – pyrrhotite; Ccp – chalcopyrite.

1978; O'Reilly 1976; Keppie 1979; Benn *et al.* 1999) show that the SMB is characterized by a regional negative Bouguer anomaly (Fig. 41). In detail, the gravity signature of the SMB shows sub-circular anomalies centred on the Stage II Davis Lake Pluton and Stage II New Ross Pluton where the western margin is coincident with the Stage II East Dalhousie Pluton and East Dalhousie fault.

The generally accepted interpretation of these gravity data is that the SMB has a 3-D anvil or mushroom shape, relatively thin (ca. 5 km) on the margins and with two thick (ca. 29 km) "stalks" in New Ross and Davis Lake, and that those "stalks" may be the feeders for the very large volume of magma that constitutes the SMB (Garland 1953; O'Reilly 1975). More recently, Benn *et al.* (1999) modelled depths in the SMB ranging from 10 km in Stage I plutons to 20 km in Stage II plutons. Regardless, the approximately circular shapes of the gravity anomalies at New Ross and Davis Lake may be significant in assessing the timing of emplacement of the SMB, i.e., if these prominent, but physically weak, "feeders" had existed in the Neo-Acadian regional transpressive stress field, they might have been elliptical in plan. In addition, if the elongate Stage II East Dalhousie pluton and its associated gravity anomaly belatedly marks the position of a fossil feeder dyke for the Stage I plutons, that extensional dyke feature should not be oriented quasi-perpendicular to the Neo-Acadian DMS if that stress regime had been operating at the time of its emplacement. If the EDP is a dilational dyke, its σ3 direction must be parallel to the (inoperative?) Neo-Acadian DMS.

If the sub-circular shapes of the Davis Lake and New Ross gravity anomalies and the elongate East Dalhousie anomalies have any significance, they probably suggest post-Neo-Acadian F_1 emplacement of the SMB.

High-T deformation microstructures

A syn-tectonic granite magma, crystallizing in a deviatoric stress field, should show deformation features that developed during the late stages of crystallization between the mechanical solidus and thermodynamic solidus (PLT < ϕ < 100), and during high-temperature stages after the thermodynamic solidus had been reached (ϕ = 100). On the other hand, a post-tectonic granite, crystallizing in a weak to insignificant deviatoric stress regime should show few or no high-T deformation features.

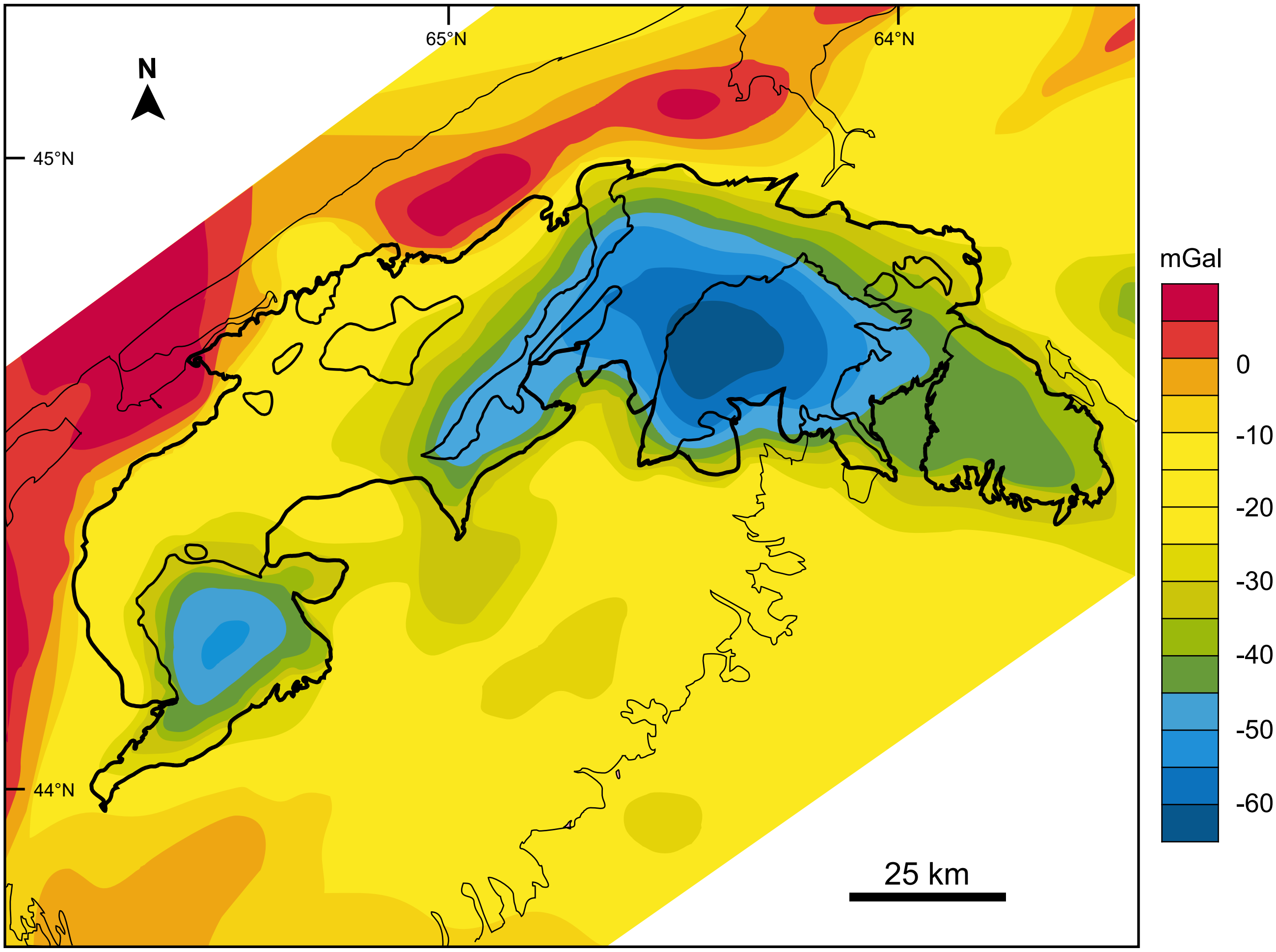


Figure 41. Bouguer gravity map of southwest Nova Scotia (after Benn *et al.* 1999).

In a series of papers, Paterson *et al.* (1989, 1998, 2019) have documented the textural/microstructural features that can develop in a granite crystallizing in internally and externally applied stress regimes, calling deformations that develop during PLT < ϕ < 100, "sub-magmatic", and those that develop at ϕ = 100, "high-T solid state deformation". Below, we provide a summary list of these microstructural features.

Supra-solidus or "sub-magmatic" (PLT < ϕ < 100): In this regime, the magma has reached its mechanical solidus, but not its thermodynamic solidus, interstitial melt is still present, and strain is accommodated by a wide range of microstructures.

1. augen feldspars (described separately under Stage I plutons)
2. recrystallized K-feldspar with exsolution lamellae
3. Ca-plagioclase (oligoclase) in myrmekite
4. c-slip producing basal sub-grains in quartz and strong quartz c-axis maxima parallel to the inferred shear direction resulting from c-slip
5. change from homogeneous to heterogeneous deformation – deformation becomes localized into high-strain or melt-rich zones – rotation of sub-grains to produce smaller new grains
6. S-C foliation with same orientation and sense of shear as may have been inferred from magmatic imbrication suggests deformation was continuous from magmatic to the solid state
7. kinked micas
8. late magmatic minerals in pressure shadows or zones between fragmented grains (magmatism and deformation must be coeval) or magmatic minerals in fractures in brittle feldspars
9. cataclasis under high strain rates – high pore fluid pressure/heterogeneous distribution of fluid/high stress concentration at point contacts
10. grain-boundary sliding

sub-solidus high-T solid-state (ϕ = 100): In this regime, the magma has reached its thermodynamic solidus, melt is absent, and the strain is accommodated entirely in the solid state.

1. internal deformation and recrystallization of grains (undulose extinction of quartz, elongation of grains, microcline twinning, replacement of K-feldspar by myrmekite, kinking of biotite)

2. recrystallized tails on deformed porphyroblasts
3. elongation of recrystallized aggregates of quartz and mica forming anastomosing folia around elongate lenses of coarse and stronger crystals
4. grain-size reduction
5. development of myrmekite (in plagioclase)
6. flame perthite – flames heterogeneously distributed and related to local concentration of deformation
7. boudinage of strong minerals (feldspar) in aggregates of weaker minerals
8. anastomosing foliation passing through, rather than around, enclaves
9. highly heterogeneous strain and local mylonite zones
10. combined brittle-ductile deformation (fractured/fragmented feldspars with quartz-filled veins, and feldspar clasts in ductile folia or ribbons of quartz, mylonites to ultra-mylonites)
11. mica fish
12. a-slip in quartz producing prismatic sub-grains with c-axes normal to the shear direction at low T

This wide variety of microstructures develops as a complex function of temperature, deviatoric stresses, magma/fluid pressure, strain rate, and mineral compositions. Paterson *et al.* (2019) compiled many of these types of deformation into a single comprehensive graphic (Fig. 42).

This potential plethora of high-T microstructures should have attracted attention in the SMB, if for no reason other than their novelty, but scores of theses, starting with McKenzie (1974), government reports (e.g., MacDonald 2001), and scientific papers on the SMB mentioned virtually none of the features now formalized on the "sub-magmatic" and "high-T solid-state" deformation lists. Formalized or not, the microstructural features still should have attracted attention as unexplained anomalies. Instead, SMB rocks are almost universally undeformed hypidiomorphic granular, porphyritic, aplitic, or pegmatitic. The only possible exceptions are in localized regions of high strain (faults and shear zones, the augen monzogranite, and undulose extinction in quartz). In addition, the development of myrmekite (Vernon 2004; http://www.alexstrekeisen.it/english/pluto/myrmekite.php), and the exsolution in K-feldspar (Vernon 2004; http://www.alexstrekeisen.it/english/pluto/perthite.php),

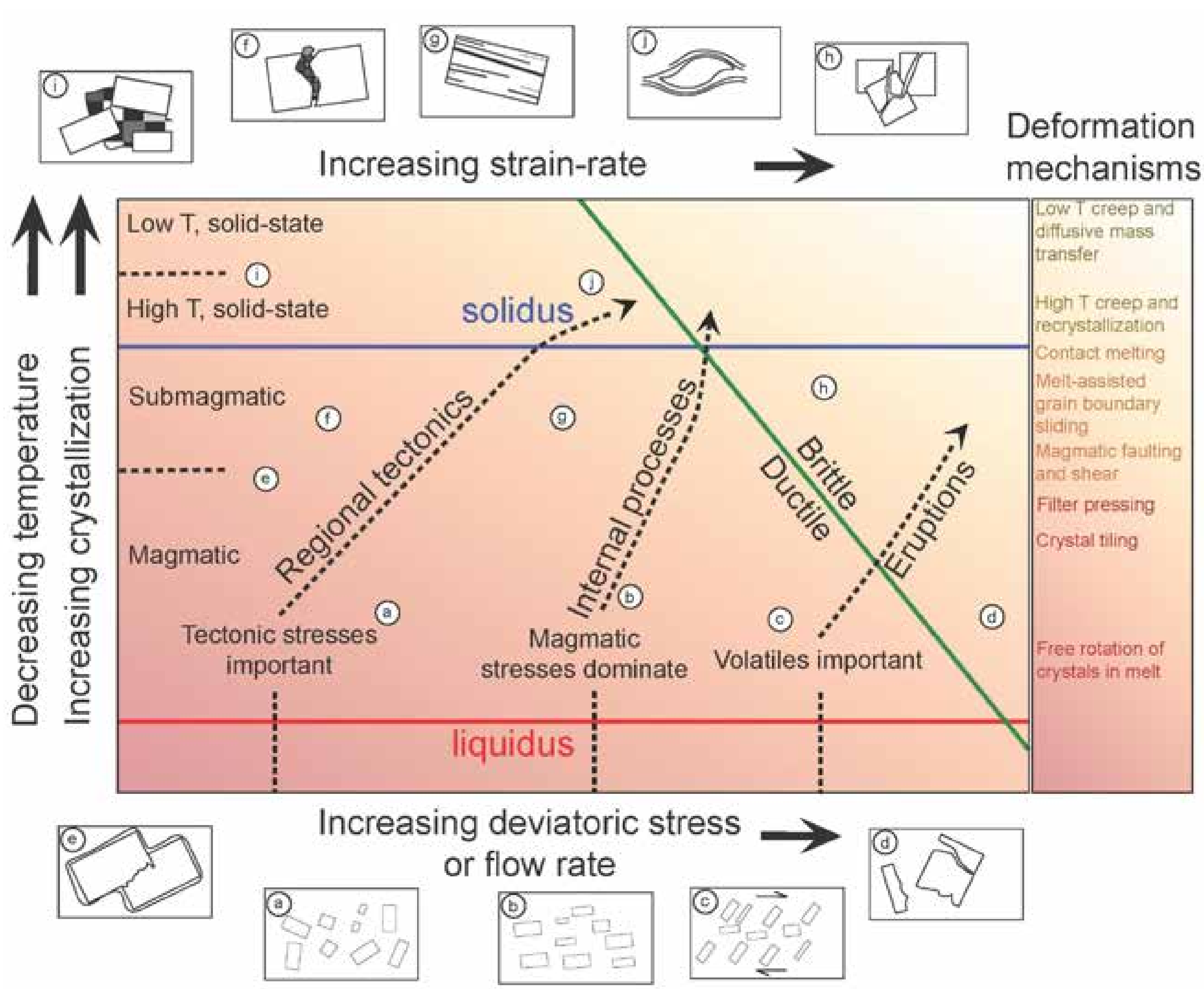


Figure 42. Composite diagram showing the development of mineralogical and textural deformation features as a function of crystallinity and strain rate in granites. (Figure courtesy of Scott Paterson).

with the possible exception of flame perthite, do not belong exclusively to deformed rocks. Otherwise, the high-T deformation features listed above are rare to absent in the SMB.

The absence of credible evidence for penetrative high-T deformation features in the SMB does not necessarily constitute good evidence for post-tectonic emplacement of the batholith; however, if the SMB were syn-tectonic with Neo-Acadian F_1, there should be more convincing evidence for high-T deformation. Thus, we reject the claim of Benn *et al.* (1997) that all the putative high-T deformation in the Stage I granites, required for their rotation, up to 90° from a horizontal to a vertical foliation, took place solely by grain-boundary sliding so there would be little or no textural evidence.

The SMB shows little to no microstructural evidence of syn-tectonic emplacement. Most rocks in Stage I and Stage II plutons are massive and undeformed, suggesting that the SMB is more likely post-tectonic with respect to Neo-Acadian D_1.

Undulose extinction in quartz

Quartz is an essential and abundant, but mechanically weak, mineral in all granitoid rocks. Undulose extinction in quartz refers to the wavy, non-uniform extinction in a single grain, owing to slight bending of the crystal. Patchy, irregular, undulose extinction in quartz can be the product of submicroscopic fractures, kinks, and dislocation tangles (Vernon 2004), and the large number of potential slip systems parallel to the a- and c-crystallographic axes in quartz makes it more susceptible to deformation than strong minerals such as plagioclase. The stresses responsible for undulose extinction in quartz in any pluton might be one or more of lithostatic loading, buoyancy, local internal adjustments, or regional tectonism. At least potentially, quartz can act as a sensitive strain gauge for deformation that takes place at any stage in the cooling history of the granite from the particle-locking threshold (PLT) in the magma, through high-temperature solid state, down to low-temperature solid state. However, large quartz grains deformed at high-T may recover to produce undeformed small ones (Trouw *et al.* 2010).

Two examples where felsic magmas crystallized in deviatoric stress-free environments include rhyolites (http://www.alexstrekeisen.it/english/vulc/rhyolite.php), and the riebeckite microgranite of Ailsa Craig (Harrison *et al.* 1987; http://nora.nerc.ac.uk/id/eprint/505002/1/Ailsa%20Craig.pdf), which intruded in an extensional environment, and in which quartz shows no undulose extinction. At the other extreme, Stipp *et al.* (2002, fig. 7) described the variable deformation in quartz over a wide range of temperatures from 250–650°C, and showed features as diverse as sutured and serrated grain boundaries, undulose and patchy extinction, elongated porphyroclasts with dominant bulging recrystallization, extremely elongated ribbon grains and dominant sub-grain rotation recrystallization, recrystallized grains, polygonization resulting from progressive sub-grain rotation, amoeboid grains with large amplitude sutures, and chessboard extinction with sub-grain boundaries parallel to prism and basal planes.

In the SMB, quartz shows almost universally weak undulatory extinction, ranging from undetectable to distinct, but weak, undulose extinction from the earliest granodiorites of Stage I plutons, including the augen monzogranite, to the latest leucogranites, aplites, and pegmatites of Stage II plutons (Fig. 43). Quartz grains in the SMB, even in the early Stage I plutons (Fig. 43c), which may have been most vulnerable to Neo-Acadian tectonic stresses, generally show only weak development of undulose extinction. Although we have not made a systematic study, there does not appear to be any correlation between undulose extinction in quartz and location or time of emplacement in the SMB.

The high susceptibility of quartz to deform is not a reliable indicator of the prevailing tectonic regime during emplacement and solidification of a bathoith. Given the uncertainties about the origin and preservation of undulose extinction in quartz, no decision about the tectonic setting of the SMB at the time of its emplacement is possible using this microstructure.

Joints

Joints are generally regular, stress-release, displacement-free, brittle fractures in solid rocks. They develop only when differential stresses are low (Fossen 2016) and can form as the result of: tectonic (compression, tension), hydraulic, and mechanical unloading conditions (Hatcher and Bailey 2020). Are the abundant and complex joints in the SMB the result of regional external Neo-Acadian compressional stresses, in which case the SMB may be syn-tectonic (Horne *et al.* 1988,1992), or are the joints the result of local or regional extensional stresses, in which case the joints have little or no relevance to the question of the tectonic timing of emplacement of the SMB?

Jointing is a prominent feature of most SMB outcrops, and Figure 44 illustrates several examples of the vertical and horizontal joint sets. Horne *et al.* (1988) published the most comprehensive data for jointing in the SMB (reproduced by Benn *et al.* 1997) (Fig. 45). In general terms, the early Stage I plutons have predominantly vertical joints for almost all azimuths, except E–W. The later Stage II plutons have more clearly defined conjugate NW-SE and NE-SW vertical joint sets, and where vertical exposure permits, an additional subhorizontal joint set exists (e.g., Fig. 45b). The NW-SE and NE-SW joint sets are not equally developed everywhere; in some places (e.g., Swissair Memorial), the NW set dominates, and in other places (e.g., Pennant Point) the NE joint set dominates. Also, at places such as Peggys Cove where the outcrop quality is excellent, the vertical joints can even be circular in plan (Fig. 34), and the aplite ± pegmatite-filled subhorizontal fractures undulate.

In addition to the NE-trending (040°–062°) and NW-trending (315°–335°) joint sets in the SMB (Horne *et al.* 1988, 1992), joints of similar orientations occur else-

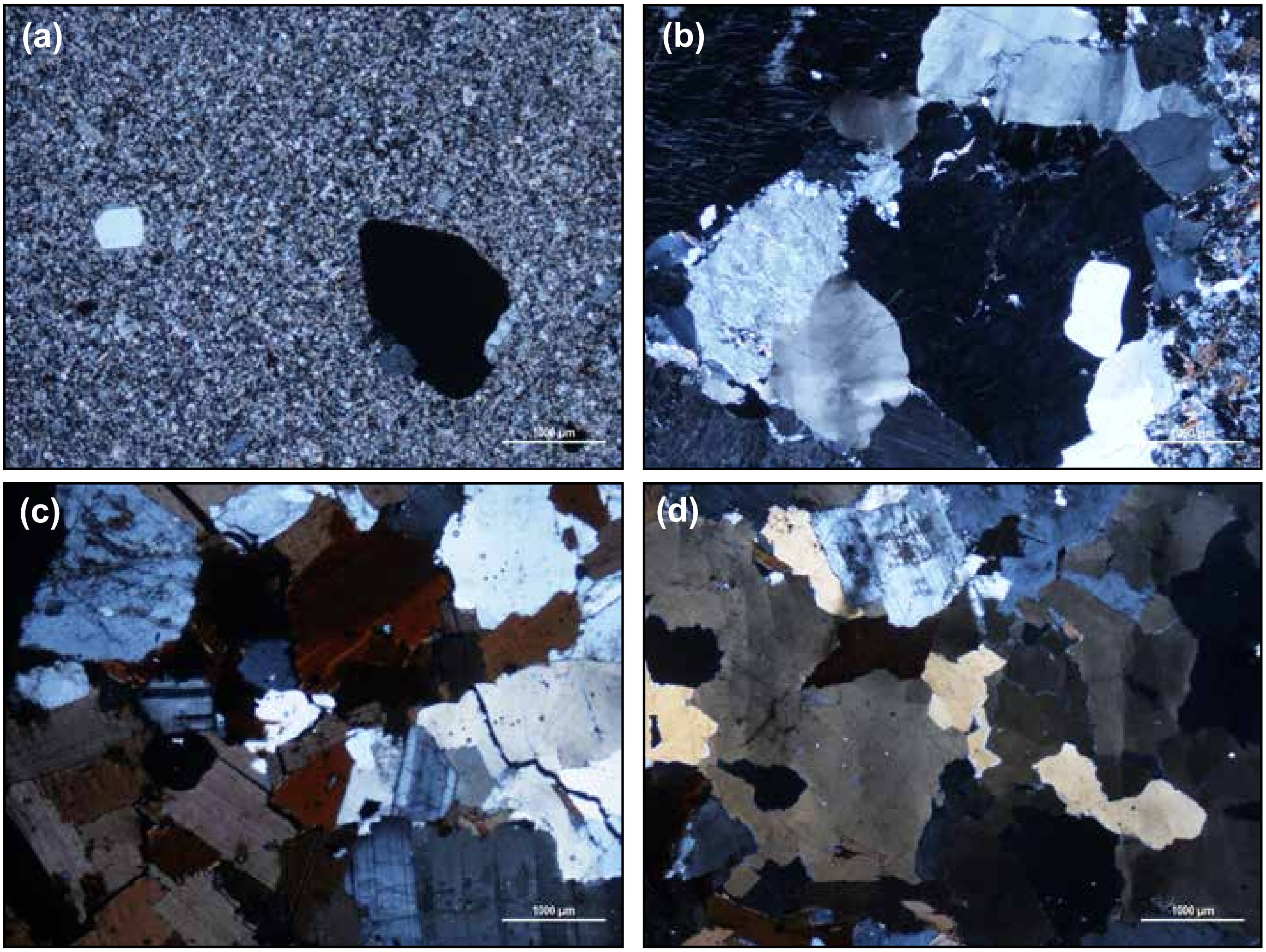


Figure 43. Examples of undulose extinction in quartz from a variety of SMB rocks. (a) Late-stage elvan (ultra-fine-grained aplite) sample 7–9 showing euhedral quartz phenocrysts with no undulose extinction. (b) Granite dyke sample BP-1 in Meguma Supergroup host showing quartz with no undulose extinction enclosed in large K-feldspar (at extinction), but the quartz grains in the surrounding matrix show undulose extinction. (c) Stage I pluton sample M72-153 showing weak undulose extinction in quartz (right side of photo). (d) Stage II pluton sample P5G1 showing weak undulose extinction in quartz.

where in the region, including:

(i) in other Meguma terrane granites, including the 315° joint set (Dickie 1978) and similarly-oriented quartz veins (MacDonald 1981) in the Musquodoboit Batholith, and a 315° set of dykes in the Queensport Pluton (Ham 1988);

(ii) in the Meguma Supergroup, where NW-trending ‘cross joints’ and NE-trending ‘longitudinal joints’ (referring to the strike of the orogen) form the prominent joint sets (Fig. 46), and the presence of granitic dykes (from SMB?) in the NW-trending joints may indicate a pre- to syn-granite origin for them (O’Brien 1988);

(iii) in the Ordovician–Silurian rocks along the northern contact of the SMB exists a prominent, steeply dipping joint set at 328°, interpreted as syn-intrusive in origin (Smitheringale 1973); and

(iv) in selected Upper Devonian to Lower Permian sandstones in southern New Brunswick and Prince Edward Island have similar joint patterns to the SMB (Lajtai and Stringer 1981), and dominant joint trends at 325° in Carboniferous rocks of the Stellarton Basin (P. Gillis, unpublished Nova Scotia Department of Natural Resources data).

If all these joints represent one fracturing event, that event had to be very late in the history of the orogen. Instead, it is more likely that the dominant existing tectonic fabric (F_1–S_1) controlled several episodes of jointing taking place after F_1 (Hatcher and Bailey 2020).

In genetic terms, the jointing in the SMB must be the product of one or more of the following processes:

(i) *cooling and contracting* – inevitable in most igneous bodies (a granite coefficient of thermal expansion =

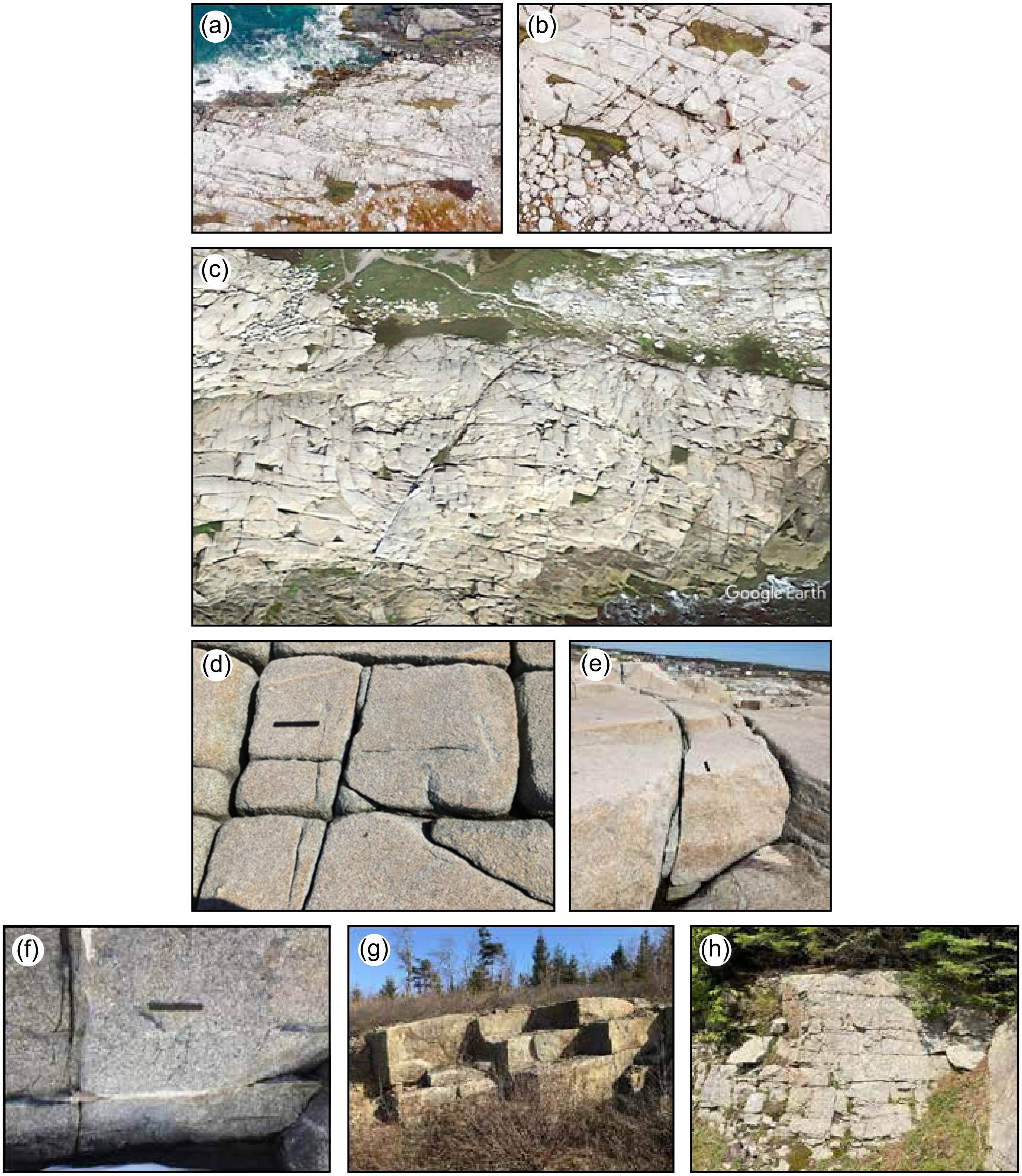


Figure 44. Jointing in the SMB. (a) Dominant unevenly-spaced NW-SE joint set at Swissair Memorial. (b) The dominant NW joint set bisects an additional conjugate set mutually at 60–120° at Swissair Memorial. (c) Complex joint pattern at Peggys Cove (cf. Fig. 34). (d) Detail of quasi-orthogonal vertical joint set at Peggys Cove. (e) Detail of arcuate/circular vertical joint set at Peggys Cove. (f) Subhorizontal joints filled with aplite at Peggys Cove. (g, h) Late, topographically-controlled, unroofing joints on Hwy 103 and Otter Lake, respectively.

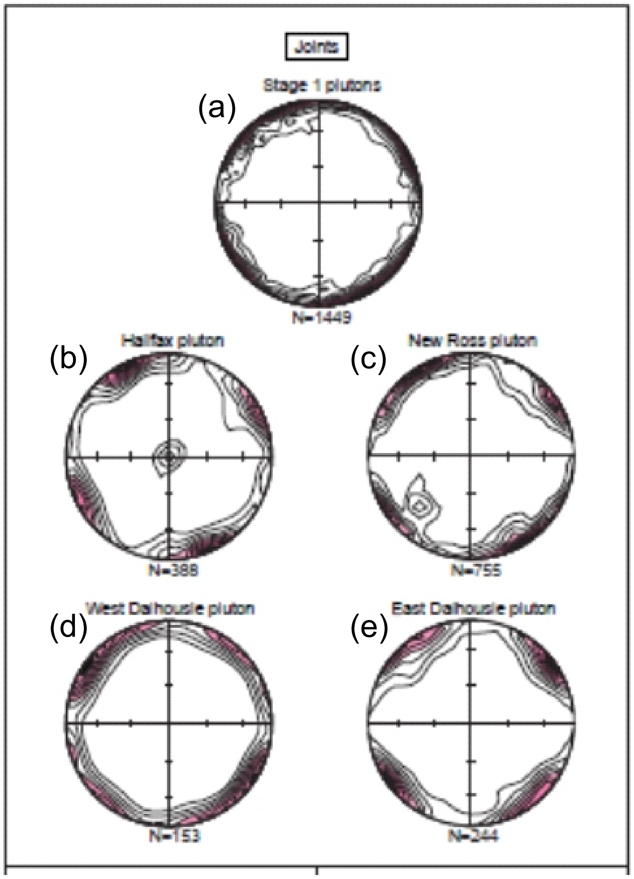


Figure 45. Joint data for the SMB. A – Stage I plutons showing no strongly preferred orientations. b-e Stage II Plutons showing better-developed conjugate NW- and NE-trending joint sets (after Horne *et al.* 1988).

0.0000044% per degree, and a cooling of 500°C, produces a volumetric shrinkage of 0.0022% which, for a pluton that is 100 km (100 000 m) across, represents a shrinkage of 220 m in that direction, and if the joints are only 1 mm wide, there would be 22 000 of them across that 100 km pluton, equivalent to one 1 mm wide joint approximately every 0.5 m);

(ii) *magma overpressure* – caused by repeated injection of magma into a pluton, and/or the release of volatiles during advanced crystallization (hydraulic fracturing) – in such cases, magma may intrude along these planes of fracturing, both vertical (Horne *et al.* 1992, fig. 7) and horizontal (Fig. 44f);

(iii) *sheeting/unroofing/membrane effect* – the circumference of an annular ring at the surface of the Earth is 0.08% greater than an annular ring at 10 km depth, and this expansion is equivalent to 800 1 mm wide joints per kilometre (i.e., one joint every 1.25 m), in mutually perpendicular directions, and this jointing could affect the country rocks as well as the granites (Fig. 46);

(iv) *gravitational collapse* – joints form as a result of relaxation where the orogen spreads laterally under its own weight after the compressional tectonic forces that formed the orogen have ceased (Dewey 1988) – this lateral spread implies expansion which can be accommodated by brittle fracturing (jointing);

(v) *externally applied tectonic stresses* – in syn-tectonic plutons where externally applied compressional stresses operate on a pluton during and after solidification, a conjugate joint set would be related to one or more shear planes in the strain ellipsoid and the principal stress

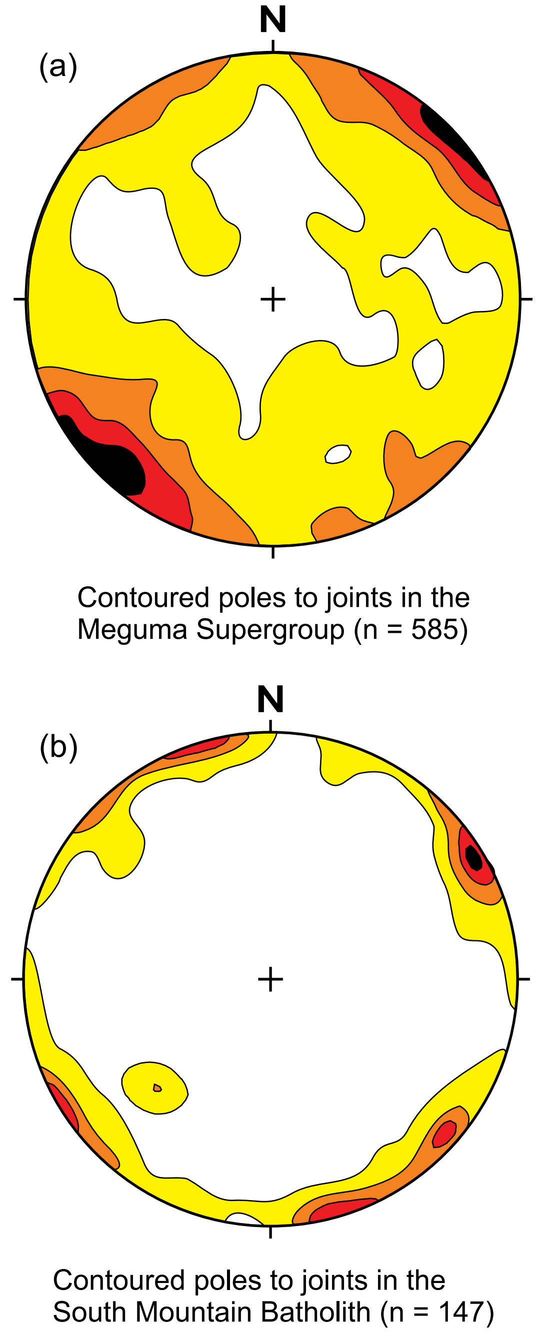


Figure 46. Comparison of jointing in (a) Meguma Supergroup and (b) South Mountain Batholith (after White 2008, with permission). In both stereograms, the darkest shading indicates the highest concentration of poles to the jointing.

direction would bisect the angle between the joints, but why would expansional joints develop instead of faults and shear zones? And

(vi) *release of stored elastic strain energy* – solids under stress store elastic strain energy that can be released when the stresses are removed to cause fracturing.

The first four items in the list above must apply, at least to some extent, to the formation of vertical joints in the SMB, and perhaps the country rocks as well. Contraction upon cooling of the granite is unavoidable, magma overpressure is evident in the aplite ± pegmatite-filled vertical (and subhorizontal) fractures, sheeting/unroofing/membrane effect is inevitable, gravitational collapse must also happen and can result in similarly oriented joints forming in the granite and the Meguma Supergroup country rocks. In all these processes, jointing in three directions is the product of extension and expansion that is incompatible with compressional forces.

Subhorizontal joints in the SMB are of two distinct types, and their origins are much less controversial. Those at Peggys Cove, and elsewhere in the SMB, are occupied by aplite ± pegmatite, so these fractures are clearly coeval with magmatism. They must be the products of a combination of contraction, and perhaps magma overpressure, wherein weak shrinkage in planes parallel to the roof of the pluton was followed by injection and pressure-quenching of magma. At Chebucto Head, there were multiple, passive, normal granite magma injections into a widening subhorizontal fracture before the final injections which were forceful aplite injections resulting from fluid-oversaturated magma (Clarke and Clarke 1998). The combination of -ΔV in the solid rocks and +ΔV in the fractionating magma must cause jointing in the roof rocks of the SMB. This pressure from magma below, either by repeated pulses of magma injected into the pluton, or by build-up of fluid pressure in a single magma batch, can potentially fracture the solid carapace not only horizontally but also vertically.

Thus some, if not all, of the jointing in the SMB can form without any external stresses being applied. Of the genetic types of joints (Hatcher and Bailey 2020), tension (cooling, gravitational collapse, membrane effect), hydraulic (melt-filled horizontal and vertical joints) and unloading (empty sub-horizontal joints) processes all apply to the SMB and regional rocks. Only one genetic type, externally applied tectonic stress, is in question. If we assume that the predominant NW-SE and NE-SW joint sets are the conjugate products of Neo-Acadian DMS (Horne *et al.* 1988), those joints should intersect at 60/120°, not at 90/90°, and they might also show systematic signs of shearing on the joint surfaces if differential stresses were large (Fossen 2016). Neither is true for the vertical joints in the SMB (Fig. 47). Alternatively, if the NW-SE joints in the SMB were the result of compression-parallel axial splitting in the absence of confining pressure caused by Neo-Acadian DMS stresses, the NE-SW joints should not have opened at all, because their strikes would have been normal to Neo-Acadian DMS. The NE and NW trending joints are, for the most part throughout the batholith, different in character (planar (NW) versus curvilinear (NE)) and therefore may have formed at different times. As noted below in the Mineralized structures section, NW-trending greisen-bordered quartz veins, which may be mineralized (Sn, W, Cu, As) are oriented NW-SE throughout the batholith and presumably exploited NW-trending joints whereas NE-SW joints, which may be mineralized (U, P, Mn), commonly have close-spaced fracture cleavage and associated hematization. The different mineralization and alteration styles associated with NW- and NE-trending joints support a time difference for these structures. Rocks cannot separate along planes of maximum compression (Pollard and Aydin 1988). Instead, the strikes of joints are always perpendicular to the prevailing σ3, and yet the perpendicular to the NE-SW joint direction is parallel to the inferred Neo-Acadian σ_1. The NW-SE joint direction cannot be simultaneously parallel to σ_1 to produce axial splitting <u>and</u> be parallel to σ_3 to allow the opening of the NE-SW joint set. How does the NE-SW joint set open in this scenario, unless the NE-SW joint set is demonstrably and consistently younger? Perhaps the only way to apply the compressional syn-tectonic model, at least partially, for joint formation in the SMB is to have the NW-SE joint set form by Neo-Acadian DMS axial splitting, and the NE joint set form by subsequent gravitational collapse/relaxation/release of stored elastic strain energy. However, if this were the case, everywhere in the batholith the NE-SW joint set should be demonstrably younger than the NW-SE joint set, but the problem is that there are no offsets to establish relative timing of the joints. Alternatively, as the Meguma terrane docked along the Cobequid–Chedabucto Fault, the principal stress direction may have changed from compressional to trans-tensional when dextral motion on the structure became dominant. It is not clear if any such new translational stresses had any effect on joint formation in the region.

In summary, similarly-oriented joint patterns occur regionally in pre-SMB, syn-SMB, and post-SMB rocks. The presence of granitic dykes in some of the NW-trending joints in the SMB and adjacent Meguma Supergroup shows that some of the jointing pre-dated, or was synchronous with, granite magmatism. That rocks as young as Carboniferous and Permian share similarly oriented joint sets shows that a late regional component was involved, most likely caused by some combination of gravitational collapse and the membrane effect and/or regional transtension that formed the Maritimes Basin. The principal joints in the region are orogen-parallel and orogen-perpendicular, and the bottom line is that jointing is a space-making process that is unlikely to occur in a compressional regime. Indeed, Hatcher (1990) notes that "Release joints form late in the history of an area and are ultimately oriented perpendicular to the original tectonic compression …" and maintains that compressional jointing can take place only at depths of less than 3 km where confining pressure is low, but the SMB intruded at a depth of 10 km. Finally, an explanation for the nearly random orientations of joints in the Stage I plutons and focused NW- and NE-trending joints in Stage II plutons is that

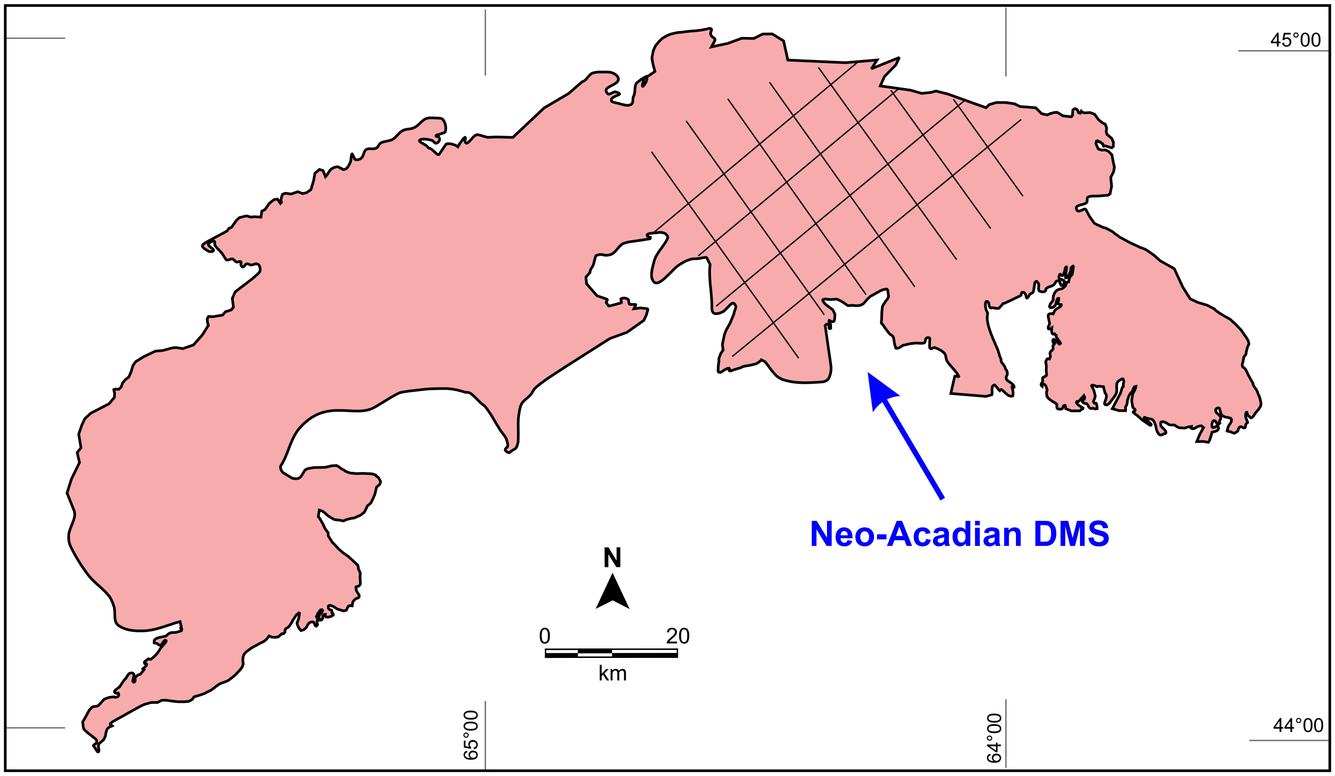


Figure 47. Schematic representation of the dominant orthogonal NE- and NW-trending vertical joint directions in the SMB and the direction of the Neo-Acadian DMS).

cooling and contracting produced the relatively randomly oriented joints in Stage I but other processes are responsible for producing the more regularly oriented joints in Stage II.

Jointing in the SMB is probably the result of several processes, the least likely of which is compressional tectonic stresses, and, as such, jointing is irrelevant to the question about the prevailing tectonic regime at the time of its emplacement.

Faults and shear zones

A fault is "a discontinuity with wall-parallel displacement dominated by brittle deformation mechanisms" whereas a shear zone is a "tabular zone in which strain is notably higher than in the surrounding rock" and "ductile shear zones can involve both plastic and brittle deformation mechanisms" (Fossen 2016). In this section, we document the orientations, displacements, ages, and origins of faults and shear zones affecting, or relevant to, the SMB.

In general, the relationship between faults, shear zones, and granite emplacement is complex where the structures may:

1. pre-date, and perhaps even act as channel-ways for ascending magmas prior granite emplacement (granite is post-tectonic relative to the age of the structures);
2. contemporaneous with granite emplacement, possibly acting as channel-ways for ascent of magma (granite is syn-tectonic); and/or
3. post-date granite emplacement (granite is pre-tectonic).

Some long-lived faults and shear zones may be active during all three stages.

The SMB hosts faults and fracture zones distributed throughout the batholith. Horne *et al.* (1992) mapped eight prominent faults within the SMB and three ductile or ductile-brittle shear zones near the margins of the Davis Lake Pluton (DLP) in the southwestern end of the batholith (Fig. 48). In their more recent 1:50 000 mapping, White and Horne (2012) and White (2019) recorded other faults, both within the granites and offsetting the SMB/Meguma Supergroup or the SMB/Carboniferous cover contacts, the latter being clearly post-granite emplacement.

NE-trending faults: Seven prominent NE-trending faults cut the SMB. The Wallace River and Sissiboo Lake faults cut the Stage 1 Scrag Lake pluton in the extreme western part of the SMB. The former may be a continuation of an Alleghanian deformation zone, described by Culshaw and Liesa (1997) as a high-angle thrust within the Meguma Supergroup and Rockville Notch Group along strike to the southwest. The Molly Upsim and Beaver Lake faults are NE-trending structures that occur near the centre of the SMB and are confined to Stage I lithologies. Horne *et al.* (1992) measured vertical slickensides on fractures in both zones suggesting "at least some component of vertical motion", possibly related to the Alleghanian thrusting event. The NE-trending Manganese Mines fault zone (MMFZ) is also in

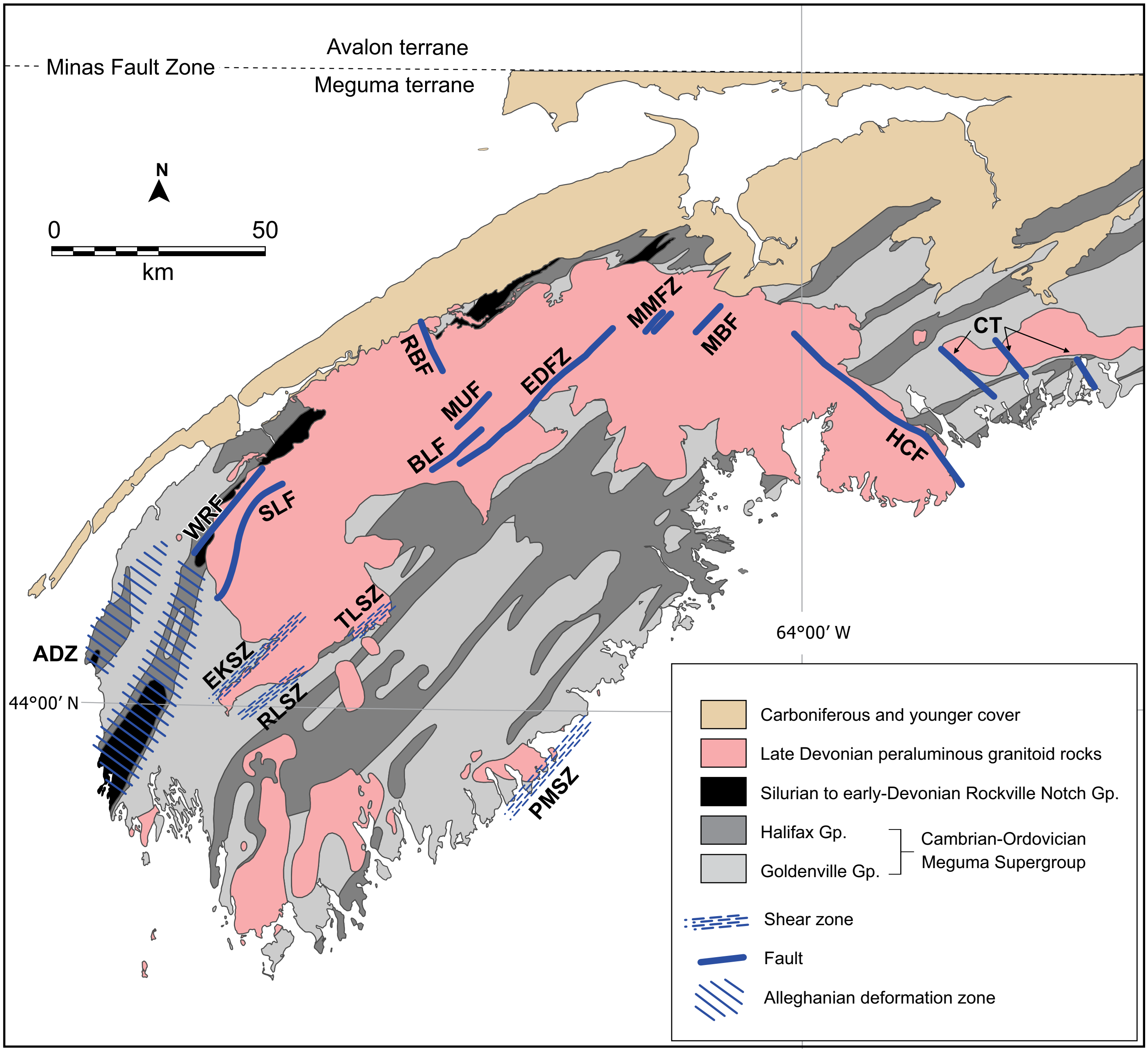


Figure 48. Geological map of the South Mountain Batholith showing the distribution of the principal lithologic units and the location of the major fault and shear zones (after Horne *et al.* 1992). ADZ – Alleghanian deformation zones; BLF - Beaver Lake fault; CT – Canso trend faults; EDF - East Dalhousie fault; EKSZ - East Kemptville shear zone; HCF - Herring Cove fault; MMFZ - Manganese Mines fault zone; MUF - Molly Upsim fault; MBF – Millet Brook fault; PMSZ – Port Mouton shear zone; RBF - Roxbury Brook fault; RLSZ -Rushmeer Lake shear zone; SLF - Sissiboo Lake fault; TLSZ - Tobeatic Lake shear zone; WRF - Wallace River fault.

Stage 1 biotite monzogranites. The zone comprises at least two short, parallel faults which have controlled the emplacement of manganese mineralization (Horne et al. 1992). A swarm of small, leucomonzogranite plutons and dykes adjacent to the manganese deposits intrude, and are in fault contact with, the Stage I monzogranites (O'Reilly 1992) suggesting that the NE-trending faults also controlled the emplacement of the small plutons. Thus, the structures may have predated intrusion of leucomonzogranite plugs. Finally, undat-ed uranium mineralization at Millet Brook is controlled by NE fault and breccia zones with similar alteration mineralo-gy to the MMFZ (Fig. 48).

The East Dalhousie fault zone (EDFZ) is the longest and most prominent NE-trending structure in the SMB. It is up to 1.5 km wide, 65 km long, and appears to control the northeasterly elongate shape of the Stage II East Dalhousie pluton (EDP). Deformation has placed the Stage II lithologies in fault contact with Stage I granodiorites along at least 20 km of strike. The Stage I rocks have been more strongly affected by the deformation suggesting that the EDFZ may pre-date the Stage II emplacement. Despite the dyke-like shape of the Stage II EDP and its association with the EDFZ, the rocks do not show any textural features (e.g., K-feldspar alignment, groundmass foliation) typical of syn-emplacement shear strain (MacDonald 2001).

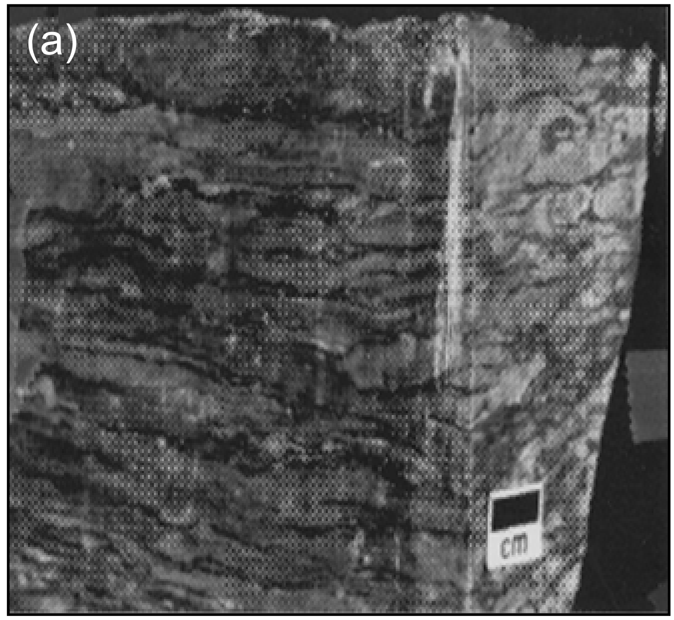
Horne *et al.* (1992) and later Bickerton *et al.* (2022) also attributed regional northeast trending faults as controlling the emplacement of the SMB, but such structures are unsubstantiated by previous field studies within the batholith (e.g., MacDonald 2001) and the lack of any pre-granite northeast faults in the wider Meguma terrane. The current evidence indicates northeasterly trending faults may have played a role in localizing the emplacement of some Stage II plutons. Any structural controls of the initial emplacement of the SMB remain, at this point, speculative.

NE-trending shear zones: Horne *et al.* (1992) identified three NE-trending shear zones, with uncertain ages, at the western end of the SMB (Fig. 48): the East Kemptville shear zone (EKSZ), the Rushmeer Lake shear zone (RLSZ), and the Tobeatic Lake shear zone (TLSZ). The RLSZ occurs mostly in Meguma terrane metasediments and trends northeasterly towards the TLSZ which is situated along the southern contact of the DLP. Despite their connection not having been confirmed in the field, Giles (1985) considered them as part of the proposed Tobeatic fault zone; however, subsequent detailed studies (MacDonald 2001) across the entire batholith have been unable to verify the existence of this structure.

The EKSZ affects both granites and metasediments on the north side of a dyke-like protuberance at the west end of the Davis Lake Pluton (DLP). It trends towards the East Dalhousie fault zone, but it has not convincingly been connected to the brittle structures to the northeast. According to Horne *et al.* (1992), the shear zones show penetrative brittle-ductile and ductile deformation with such diagnostic features as C-S fabrics and various styles of mylonitization. Typically, the shear zones also record later brittle deformation with zones containing deformed and mylonitized granite and metasediment fragments (Fig 49).

Kontak *et al.* (1990b) speculated that the elongate, dyke-like shape of the western side of the DLP could have been controlled by pre-existing structures. Nevertheless, ductile deformation continued after emplacement as evidenced by the strongly deformed granites in the central part of the Davis Lake Pluton (Fig. 49) and structural control of mineralization in the former East Kemptville Mine. Geochronological work on muscovite from the East Kemptville leucogranite within the EKSZ (Kontak *et al.* 1995) also indicated variable resetting of $^{40}Ar/^{39}Ar$ systematics from the Late Devonian into the Permian (i.e., 240 Ma).

Shear zones outside the SMB include the NE-trending, subvertical Port Mouton Shear Zone (PMSZ), (Clarke *et al.* 2002), a structure about 50 km long and 10–30 m wide that appears to be syn-magmatic with the 373 ± 1 Ma Port Mouton Pluton (Fallon 1998). Kinematic indicators imply



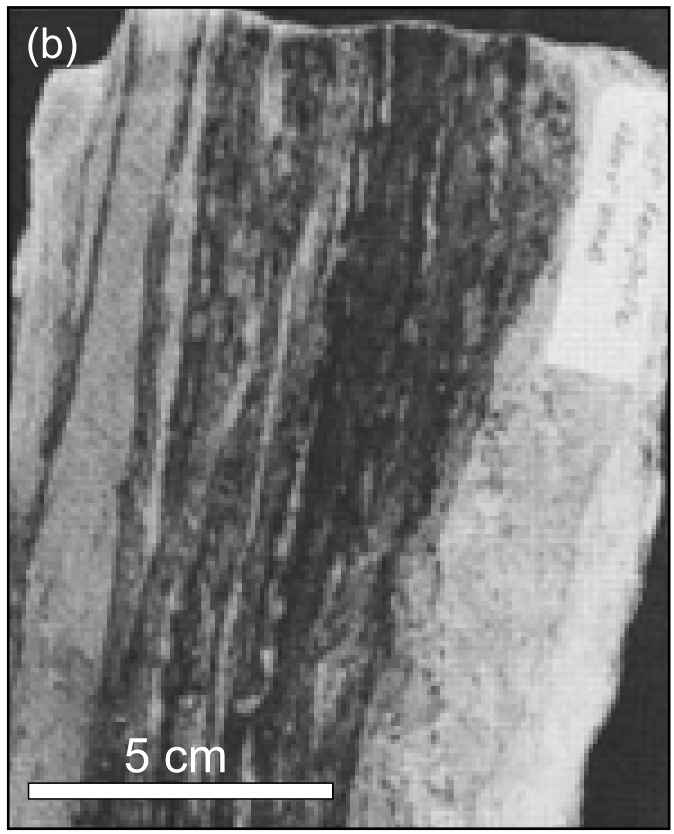


Figure 49. Mylonitic textures in the SMB. (a) Intensely deformed and greisenized granite from East Kemptville (after Kontak and Cormier 1991.) (b) Protolith of Davis Lake leucomonzogranite converted into a rodded mylonite gneiss from the Rocky Shore Lake in the East Kemptville ductile shear zone (MacDonald 2001, Plate 6.7f).

dextral motion across the zone which extends over 3 km within the Port Mouton pluton. Clarke *et al.* (2002) deduced that, because this shear zone is spatially related to occurrences of LDMIs, it may be crustal in scale and even regional in extent. Elsewhere in southwest Nova Scotia, to the west and north of the SMB, Culshaw and Liesa (1997) recognized shear zones as belts of strong high-angle thrust D_2 deformation along lithological contacts in the tight, 040° trending Neo-Acadian synclines. Dating of muscovite grains in D_2 pyrite pressure shadows (Culshaw and Reynolds 1997) yielded Carboniferous cooling ages. This observation is significant for faults in the SMB as one of the shear zones appears to extend into the SMB as the Wallace River fault (Horne *et al.* 1992).

Northwest-trending faults: Horne *et al.* (1992) documented two NW-trending faults, the Herring Cove fault (HCF) and the Roxbury Brook fault (RBF). These faults strike over tens of kms and are steeply dipping. Horne *et al.* (1992) suggest movement appears sinistral although they note dip slip could also explain the observed map patterns. More detailed mapping of the batholith (e.g., White and Horne 2012) also outlined numerous other offsets in this orientation, showing either sinistral or dextral sense of motion. The ages of the NW-striking structures, like the prominent NW joints throughout the SMB, are uncertain, although the presence of extensive quartz veining along portions of both faults indicates some hydrothermal activity took place after deformation.

East-trending fault: The most important regional structure is the MFZ, recognized as the suture between the Meguma terrane and Avalonia (Murphy et al 2011; van Staal and Barr 2012). The MFZ consists of an anastomosing network of sub-parallel E-W faults representing a transfer zone within a NE-trending orogen-parallel shear system. Collision between the Meguma terrane and Avalonia began as oblique overthrusting in the period from ca. 410–390 Ma and resulted in the F_1 deformation in the Meguma Supergroup. The combination of crustal thickening and subduction-related LDMI magmatism (Tate and Clarke 1995) created extensive lower crustal melting resulting in enormous (ca. 70 000 km^3) volumes of peraluminous granite magma. There had certainly been a cessation of the compressional F_1 deformation during the emplacement of the granites, but there must also have been a lull in the dextral translation of the Meguma terrane along MFZ because the granites at the time of their emplacement would have been ultra-weak elements in the crust, yet they show no signs of high-T deformation in the E-W, or any other, direction; however, in the NE part of the terrane there is deformation of granite bodies (e.g., Cranberry Lake and Lost Lake plutons) close to the MFZ and the development of C-S fabrics which increase in intensity approaching the MFZ (van Rooyen *et al.* 2025). Following the oblique collision and lull, regional deformation continued as episodic transtensional dextral movement on the MFZ from ca. 350–315 Ma, resulting in up to 1000 km of westward dextral movement of the Meguma terrane at ca. 3 cm/y (Fig. 50) and the formation of pull-apart basins that were filled with sediments eroded from Avalonia and the Meguma terrane (Murphy *et al.* 2011; Waldron *et al.* 2015; Piper and Pe-Piper 2021).

We now consider the origins of these sets of faults and shear zones in the Meguma terrane:

NE-trending faults: Brittle-ductile structures in the Meguma terrane in general, and the SMB in particular, may be the result of either local stresses or of much broader regional stresses. For instance, some of the NE-trending faults and shear zones in the SMB may be related to the major, regional, orogen-parallel, NE-trending, Appalachian shear zones (Fig. 50); however, those large structures are completely outside the Meguma terrane and, based on orogen reconstructions, are unlikely to have correlatives within the terrane. Instead, the vertical movement along these NE-trending structures may be late, as implied for the Molly Upsim and Beaver Lake faults and related to intra-batholithic processes permitting the linear Stage II East Dalhousie Pluton to ascend along existing zones of weakness. A similar interpretation applies to the MFZ.

Most other NE-trending faults do not show any significant horizontal movement which would be expected if they were related to the regional Appalachian trend of continental-scale dextral faults. Exhumation accompanied by transtensional movements along the MFZ in the Late Devonian and Carboniferous exposed at least the eastern end of the terrane by ca. 359 Ma (Archibald *et al.* 2018) and created pull-apart basins (Murphy *et al.* 2011). Under this stress regime both the NE-trending joints and larger faults zones could be release structures formed by extension and the rapid unroofing of the SMB.

Alternatively, these NE-trending faults may be related to Alleghanian compression and thrusting (Culshaw and Liesa, 1997) during the final positioning of the Meguma terrane against Laurentia (Waldron *et al.* 2022). Westward movement of the terrane along the MFZ during this period of dextral transpression, (i.e., ca. 330–320 Ma) was potentially hundreds of kilometres (Waldron *et al.* 2022) and would have been accompanied by NE-trending reverse faulting.

NE-trending shear zones: Two sets of shear zones occur in southwest Nova Scotia. Ductile shear zone deformation occurs at the southwestern end of the SMB, associated with the ca. 373 Ma Davis Lake Pluton where proto-structures may have controlled the emplacement of the dyke-like part of the intrusion. Evidence for protracted (dextral) motion on the shears includes strong foliation and mylonitization of the DLP and the structural imprint on granophile mineralization (Halter *et al.* 1996). The other shear zones in the Yarmouth–Meteghan area, with Carboniferous ages (ca. 320 Ma), are related to Alleghanian deformation associated with the arrival of Gondwana (Muecke *et al.* 1988; Culshaw and Reynolds 1997).

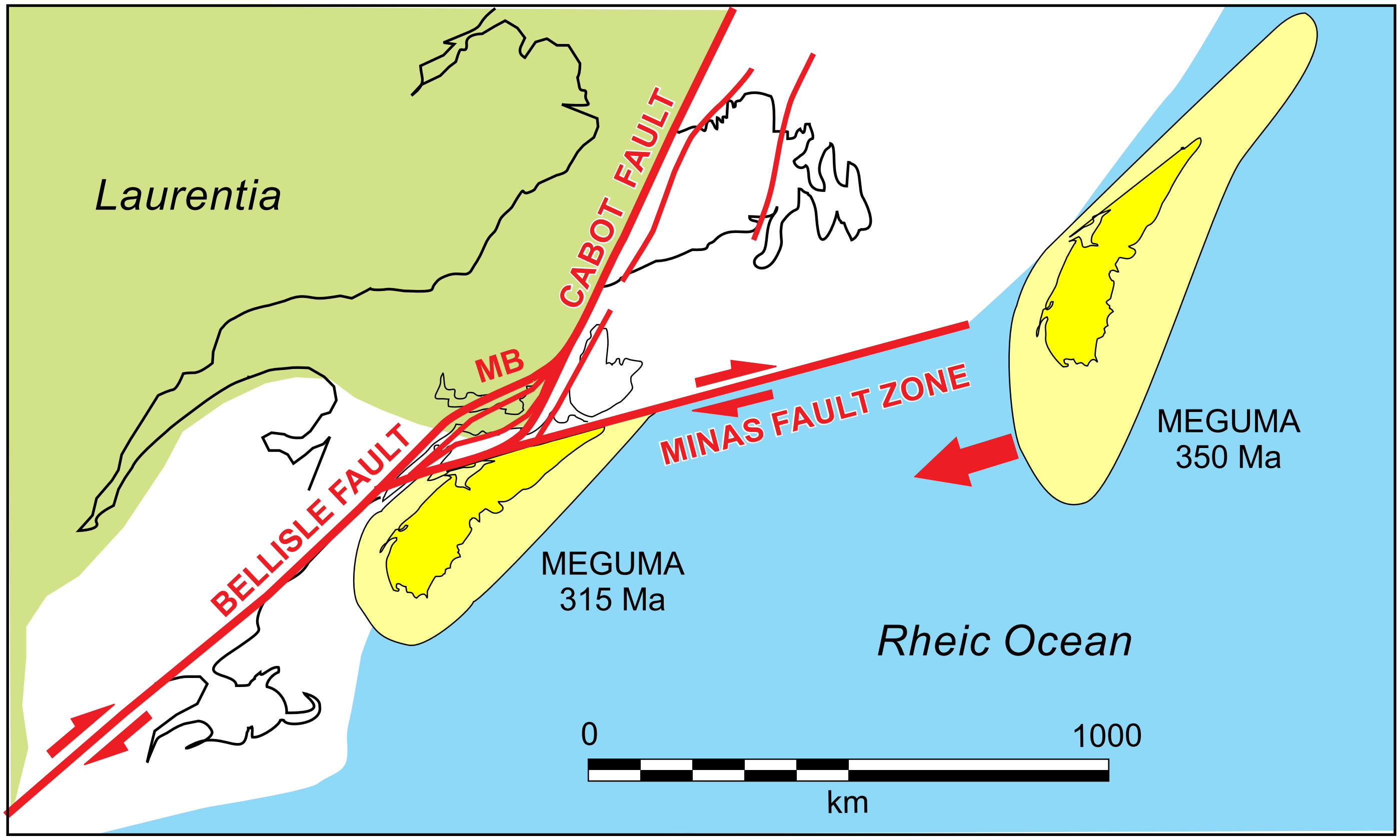


Figure 50. Dextral movement of the Meguma terrane along the MFZ from ca. 350–315 Ma (after Waldron *et al.* 2015).

NW-trending faults: The NW-trending faults are similar in orientation to a series of offsets within the Meguma Supergroup east of the SMB, called the Canso trend (Waldron et al 2015). These latter faults appear to be sinistral conjugates of the dextral, terrane-bounding, MFZ. This interpretation implies transpression during the docking of the Meguma terrane which, according to Culshaw and Lee (2006), happened no earlier than granite magmatism (ca. 380–370 Ma). In this sequence of events, it is unlikely the NW-trending faults had any syn-emplacement influence on the intrusions; however, the Roxbury fault forms the boundary between the Scrag Lake and Cloud Lake Stage I plutons, the western boundary of a lobe of the West Dalhousie pluton and the eastern margin of the Inglisville Stage II intrusion, so it may have played an important role in the emplacement of several Stage I and II plutons. Also, the NW-trending faults within the SMB may instead be related to cooling and uplift as there is evidence for both sinistral and dextral motion on the smaller NW offsets. Horne *et al.* (1992) also note the evidence for sinistral movement on the RBF and HCF is not convincing because the observed offsets could be explained by dip slip as well. Furthermore, Mesozoic extension, to open the Atlantic Ocean, may have reactivated some of these faults and even reversed their displacements (Waldron *et al.* 2015).

In summary, some small faults may just be local and intra-batholithic, such as the Molly Upsim, Beaver Lake, Manganese Mines, and Millet Brook faults. On the other hand, the larger NE- and NW-trending structures in the SMB are co-planar with the principal joint sets in the batholith. In many cases they occur entirely within the batholith, affecting both Stage I and Stage II plutons, although this may be a consequence of limited mapping and poor outcrop exposure. Also, at least some of the major NE-trending shear and fault zones, e.g., the East Kemptville shear zone and the East Dalhousie fault zone, indicate that faulting and deformation were active during emplacement of the Stage II granites. These structures may have controlled the emplacement of some Stage II magmas as evidenced by the dyke-like protrusion on the west side of the Davis Lake Pluton and the overall elongate shape of the East Dalhousie Pluton. It is less clear that any of the major structures were contemporaneous with or pre-dated emplacement of the Stage I granites. The previously described augen monzogranite in the Stage I Cloud Lake Pluton suggests an early stage of shearing, at least on a local scale, but there is no evidence of any other high-T deformation in Stage I plutons. Other NE- and NW-trending brittle structures in the SMB are post-emplacement and probably related to the oblique docking of the Meguma terrane against Laurentia in the Late Devonian/Carboniferous. The competing local and regional explanations for late brittle and ductile structures in the Meguma terrane require substantial further investigation to resolve.

Mineralized structures

The deposition of economic minerals (Sn, W, U, Mo, Cu, Zn, Ag, and Mn) in the SMB is generally restricted to the late-magmatic to hydrothermal stages within individual plutons. These polymetallic mineral deposits are associated with fine grained muscovite-biotite leucomonzogranite and muscovite-topaz leucogranite (Carruzzo *et al.* 2003, 2004).

In the absence of significant deviatoric stress, the orientations of any planar features within individual mineralized zones would be controlled by factors such as fluid pressure, existing structures, and proximity to, and morphology of, either granite-country rock or granite-granite contacts. The presence of preferred structural orientations of mineralized zones across one or more plutons could indicate external stresses were present during the mineralizing event(s).

The three styles of mineralization in the SMB (MacDonald 2001) include, in approximate order of formation: late magmatic rare metal aplite-pegmatites, late magmatic/hydrothermal greisen zones, and hydrothermal veins, discussed in detail below. Each mineralization type developed at specific stages in the evolution of the SMB and may, therefore, have formed during different structural/strain conditions.

1. Late magmatic aplite-pegmatite (Li, Cs, Ta, Nb, Be) - Aplite-pegmatite dykes are common features throughout the Stage I and Stage II plutons of the SMB, with many containing tourmaline as an accessory mineral. Individual pegmatite bodies are present as small (<10 m) pods, lenses, and dykes. The only significant lithium-cesium-tantalum (LCT) bearing pegmatites, which may also contain niobium and beryllium minerals, are present in the Stage II New Ross pluton where they are hosted by muscovite-biotite leucomonzogranite and muscovite ± topaz leucogranite.

Horne *et al.* (1992) noted that dykes in the eastern part of the SMB, including the LCT pegmatite occurrences in the New Ross pluton, "do not show any well-developed [structural] trends" and are, therefore, not considered to have been affected by external stresses. The lack of consistent orientations for mineralized dykes in the New Ross area was confirmed by Carruzzo (2003) who noted the orientations ranged from 035°/60°SE for Morley's pegmatite, 065°/steeply NW for the Reeves pegmatite, and roughly N-S/shallowly W for the Keddy's pegmatite.

Carruzzo *et al.* (2000) documented the presence of low salinity fluid inclusions (0–9 wt. % NaCl) in several polymetallic mineral occurrences in the Stage II New Ross pluton and interpreted these fluids as meteoric in composition. The mixing of meteoric and hydrothermal mineralized waters in some mineral occurrences indicates the presence of permeable fractures acting as channel-ways for both mineralizing and meteoric fluids in late magmatic times.

Horne *et al.* (1992) noted that unmineralized aplite-pegmatite dykes in the western portion of the SMB displayed a weak NW-trending sub-maxima on stereographic projections, which are similar to the orientations of hydrothermal quartz veins in the same are (see below), suggesting their orientations may have been structurally controlled.

2. Late magmatic/hydrothermal greisens (Sn, W, Cu, Pb, Zn, F, Ag, Au, As) - Greisen-type mineralization is present in both Stage I and II plutons throughout the SMB and is hosted by rocks ranging in composition from granodiorite to monzogranite, fine- and coarse-grained leucomonzogranite, and muscovite ± topaz leucogranite. The polymetallic mineralization is associated with greisen alteration (muscovite-quartz ± tourmaline) of host lithologies.

The three types of greisen mineralization in the SMB, each with its characteristic geological setting, include:

(a) *Massive greisen zones,* ranging in length from tens of metres to greater than 1 km, which are developed in embayments at the margins of Stage II plutons, including the East Kemptville, Long Lake, and Upper New Cornwall deposits (MacDonald 2001). The main controlling factor for mineralizing fluids is the presence of an impermeable(?) country rock contact; however, several workers have proposed structural controls on mineralization at the East Kemptville deposit. Halter *et al.* (1993) reported mylonite zones and en-echelon mineralized quartz veins at the East Kemptville Mine and noted that the mineralized greisens are spatially associated with, and localized around, sub-vertical faults. This feature indicates that there was movement along the East Kemptville shear zone during the post-crystal-lization mineralizing event.

(b) Greisen-bordered quartz veins, with quartz-muscovite alteration selvages (<1 cm–1 m) in all rocks ranging from granodiorite to leucogranite in both Stage I and II plutons throughout the SMB. A stereographic plot of 381 greisen-bordered quartz veins from the entire SMB (Fig. 51a) shows the predominant NW trend which corresponds to joint set #4 from Horne *et al.* (1992; Fig. 51b). The significance of this preferred orientation is discussed below.

(c) Sheeted quartz veins and quartz muscovite greisen zone hosted by coarse-grained leucomonzogranite with pegmatite segregations near the eastern contact of the Stage II Halifax Pluton at Sandwich Point (MacDonald 2001; Kontak and Kyser 2011). The zone consists of a series of N-S (180–190°/60–85° NW) quartz veins bordered by quartz-muscovite ±tourmaline ±arsenopyrite greisen. The nearby contact with the Meguma Supergroup rocks is also oriented approximately N-S and presumably had some influence on vein orientations. Kontak and Kyser (2011) interpreted the vein structures at Sandwich Point as representing Riedel shear geometry.

3. Hydrothermal Veins (U, Cu, Ag, Mn, Fe) - Hydrothermal vein type mineralization is mostly present in Stage I plutons and hosted by biotite monzogranite and biotite granodiorite, although a few occurrences are hosted by leucomonzogranite in Stage II plutons (MacDonald 2001). Mineralization and associated alteration, consisting mostly of intense

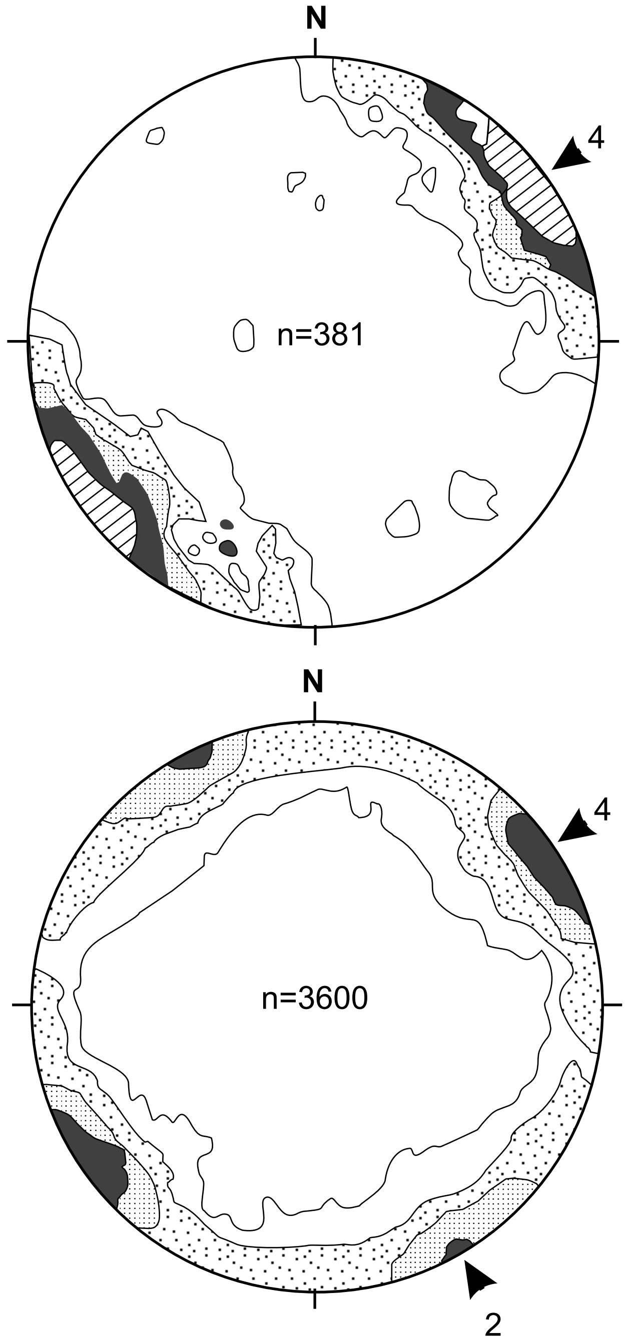


Figure 51. Contoured density plots (after Horne *et al.* 1988, 1992) of poles to: (a) quartz veins (in 1% area; n=381) from the entire SMB; and (b) all joints from the eastern part of the SMB (n=3600). Hematized joints, fractures and shear zones are mostly restricted to joint trend #2 whereas the highest density of NW-trending quartz veins coincide with joint trend #4.

hematization, are developed along NE-trending/steeply dipping structures including faults, fractures and shears corresponding to the trend #2 joints of Horne *et al.* (1988; Fig. 52b).

Mineralization at the New Ross Manganese Mines (Mn-Fe-P) vein deposits (Fig. 52) consists of Mn-oxide veins with intense hematite alteration selvages and associated calcite veins in biotite monzogranite of the Stage I Salmontail Lake pluton (O'Reilly 1992). Mn-bearing veins are present in a series of seven NE-trending/steeply NW dipping subparallel faults and are associated with hematite-ochre breccias, indicating shearing/brecciation along the NE structures. Several plugs of Gold River fine-grained leucomonzogranite (<1 km^2) are proximal to the Mn deposits, and several leucomonzogranite dykes are present at the Dean and Chapter Mine. These leucomonzogranite bodies are in both fault and intrusive contact with the host biotite monzogranite and are interpreted as having been intruded along pre-existing structures (O'Reilly 1992).

Vein-type mineralization at the Millet Brook U-Cu-Ag deposit (Fig. 52) consists of a series of NE-trending/steeply dipping uraniferous veins in en-echelon fracture zones, hosted in biotite granodiorite with cross-cutting veinlets and dykes of muscovite leucogranite (Chatterjee *et al.* 1985). Uranium mineralization is associated with carbonate breccias, indicating shearing along the NE-trending structures.

The preferred orientations of NW-trending quartz veins (mineralized and barren) from throughout the batholith, coupled with evidence of coeval deformation and mineralization at East Kemptville and the strong NE-trend for U-P-Fe and Mn-Fe vein deposits at Millet Brook and Manganese Mines, indicate that the batholith was subject to regional stresses during the late magmatic and hydrothermal stages of its evolution.

It is unlikely that greisen-bordered quartz veins infilling joints, which were formed by processes related to either cooling and contracting, magma overpressure, unroofing, or membrane effect, would have a preferred NW-SE/steep orientation. The strong NW-trending quartz vein orientation indicates NE-SW dilation, which is perpendicular to the main Neo-Acadian DMS. The restriction of vein deposits to NE-trending structures with associated(?) shearing and brecciation indicates a structural control on mineralization. The presence of meteoric fluids associated with the pegmatite deposits in the New Ross area (Carruzzo, 2003) indicates the presence of pre-existing (?) deep-seated structures, capable of circulating surface fluids during late magmatic conditions, or perhaps the Stage II plutons were emplaced at higher crustal levels. We discuss the possible tectonic conditions that controlled the distribution of the various types of mineralization in the SMB in the Synthesis section below.

Summary

Benn *et al.* (1997) claimed "Importantly, the outline of the SMB and its internal features (e.g., faults/shear zones, jointing) combined with gravity, seismic, and aeromagnetic studies support a syn-tectonic model for its emplacement." We disagree. The elongate shapes of the Stage I plutons are most likely controlled by pre-existing F_1–S_1 structures in the country rocks. The foliations in the Stage I plutons have several possible origins, the least likely of which is regional deformation. The augen monzogranite is local, not regional.

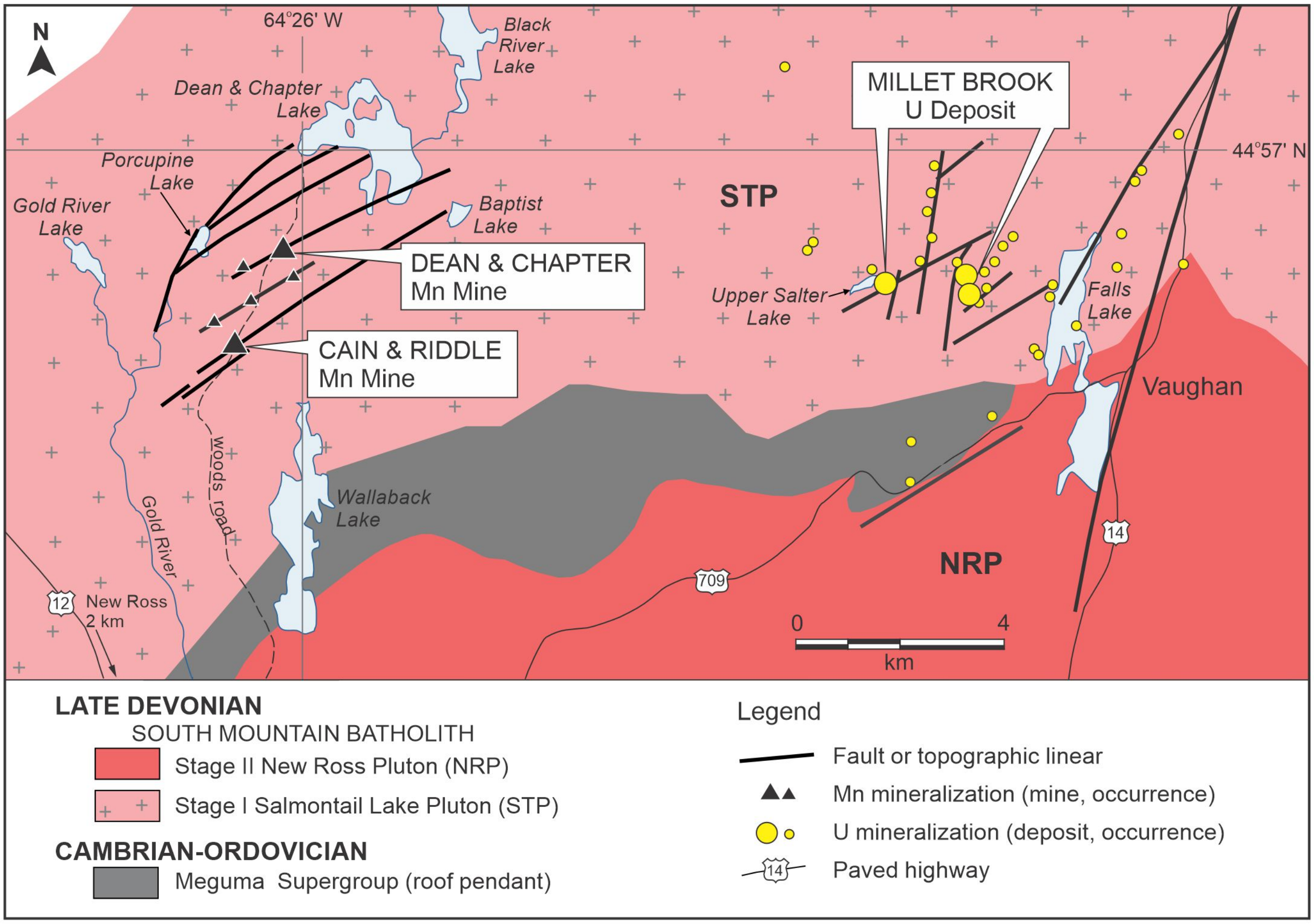


Figure 52. Geological map showing the location of the Millet Brook (U-Cu-Ag) deposit and the New Ross Manganese Mines (Mn-Fe-P) (after O'Reilly 1992). Vein mineralization at both locations is restricted to NE-trending faults, fractures and shears.

The irregular shapes of the Stage II plutons do not support their formation in a regional stress field. Foliations in Stage II plutons are broadly concentric and decoupled from structures in the country rocks. Folding is non-existent. Weak features such as internal mingled granite-granite contacts, ring schlieren, and sulphide blobs show no evidence of any significant deviatoric stress. If anything, the quasi-circular gravity anomalies suggest post-D_1 emplacement of the SMB. High-T deformation microstructures are essentially absent in the SMB, and undulose extinction in quartz is not a reliable indicator of prevailing tectonic conditions. Joints are late structures and are the product of several processes, least likely of which is compressional deformation. Barren and mineralized faults and shear zones are local (i.e., confined to the SMB), not regional. The consistent NW trend for barren and mineralized quartz veins in both Stage I and II plutons throughout the batholith suggests a prolonged period of NE-SW dilation, although the structural regime responsible for this dilation remains unclear.

SYNTHESIS

Overview of the deformation history of the Meguma terrane

Collisional orogens, including the Appalachian orogen, typically develop over long periods of time (ca. 10^8 years), under a wide range of effective viscosities (10^5 to 10^{20+} Pa s), and show a great variety of compressional, tensional, and tangential (shearing) stresses, the effects of which vary in length scale (10^{-6} to 10^6 m), intensity, and direction over time (Attia *et al.* 2022). Within the Appalachian orogen, the Meguma terrane is a discrete peri-Gondwanan terrane that collided obliquely with composite Laurentia, resulting in a wide range of structural and magmatic events.

Figure 53 is a qualitative graphic history of the tectono-magmatic events in the Meguma terrane, derived in part from Table 1. Initially, Iapetus oceanic crust subducted beneath Avalonia (Tate and Clarke 1995) and then the leading edge of the Meguma terrane collided with Avalonia (Keen *et al.* 1991), thereby thickening the crust. This oblique collision involved the F_1–S_1 transpressional folding of the

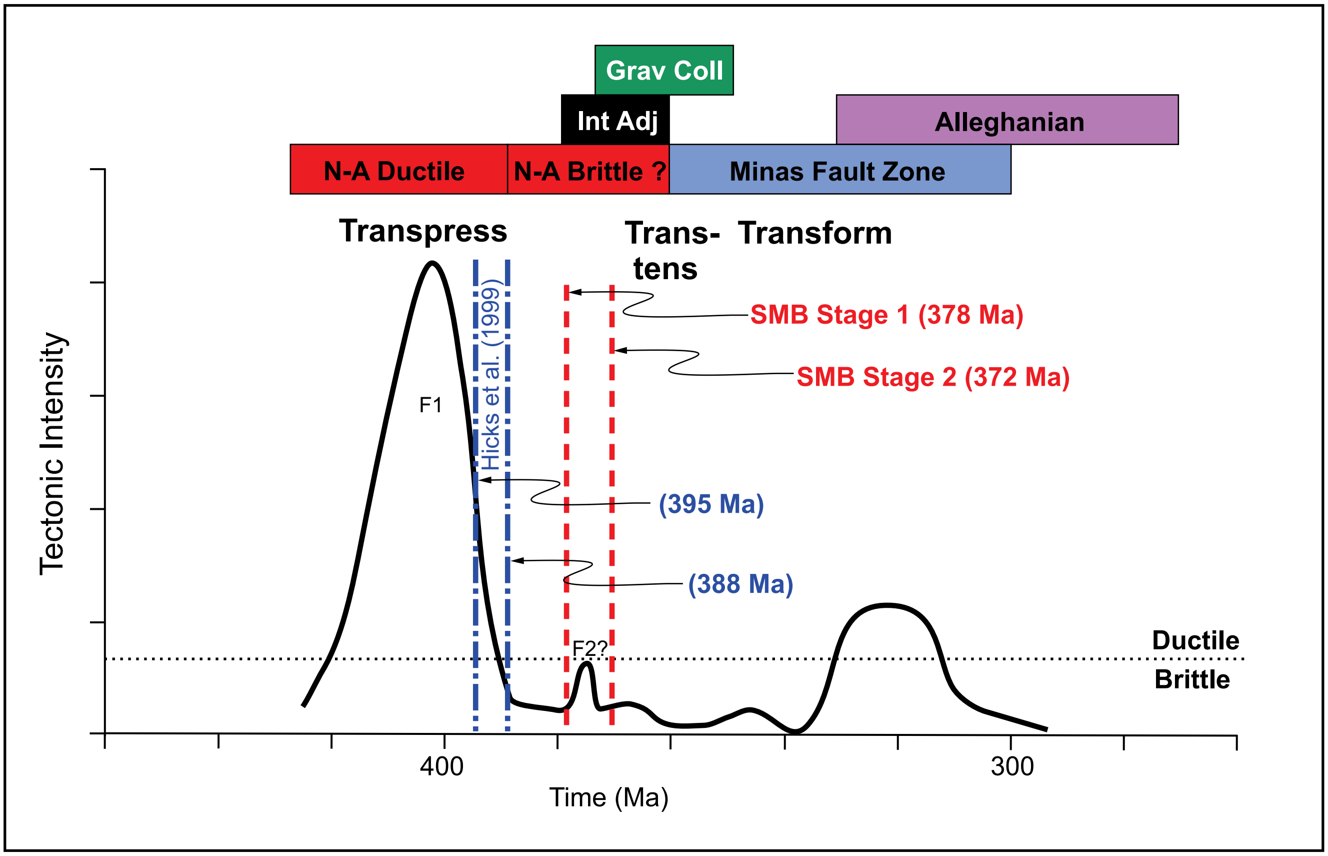


Figure 53. Summary of the deformation history of the Meguma terrane. Details in text. Abbreviations: Grav Coll – Gravitational Collapse; Int Adj – Internal Adjustments; N-A – Neo-Acadian.

metasedimentary Meguma Supergroup from ca. 410–389 Ma, subsequently intruded by large volumes of peraluminous granites and small volumes (at least at the current level of erosion) of Late Devonian mafic intrusions, from ca. 381–370 Ma, and continued with the transtensional dextral motion on the MFZ. which may have had some brittle manifestations in the SMB such as jointing and faulting. Determining when the Neo-Acadian transpressional stresses effectively stopped having any effect on the Meguma terrane (perhaps F_2) is difficult. However, we know that during, and shortly after, the intrusion of the SMB, there must have been a lull in compressional deformation, followed by development of internal thermo-mechanical adjustments in the SMB and immediately adjacent rocks, as well as gravitational collapse affecting the entire northern Appalachian orogen (Hillenbrand and Williams 2021). These effects are temporally stacked upon any putative waning Neo-Acadian stresses, meaning that structures created during this time have uncertain origins. Internally, the Meguma terrane was tectonically relatively quiet from about ca. 360–330 Ma, except for the dextral transtension partitioned along the MFZ, resulting in the formation of the Maritimes Basin. Finally, at ca. 330 Ma, collision of Gondwana with the Meguma terrane resulted in local Alleghanian deformation, such as the brittle-ductile shear zones in SW Nova Scotia (Waldron *et al.* 2015, 2022).

Figure 54 is a schematic compilation of the late joints, faults, and shear zones in the SMB, and all the regional and local stresses that may have been responsible for their formation. In general, these structures belong to two groups aligned NW and NE. Most faults and shear zones post-date granite emplacement; however, a few might be earlier. The known principal *external* regional stresses responsible for their formation are transpressional Neo-Acadian, translational MFZ, transtensional formation of the Maritimes Basin, and transpressional Alleghanian deformation. In addition, conventional internal orogen-parallel and orogen-perpendicular collapse might account for the joint and fault patterns in the SMB. We explore these possibilities in more detail below.

All ductile and brittle structures in the SMB are the result of Neo-Acadian stresses

Ample evidence shows that the SMB was emplaced after the main Neo-Acadian, brittle-ductile, fold-forming, transpressional deformation event F_1–S_1, but were there any residual Neo-Acadian transpressional stresses operating on the batholith during its emplacement?

The earliest interpreted, but nevertheless debatable, manifestations of Neo-Acadian stresses in the SMB, during its magmatic stages, are the elliptical shapes of the Stage I

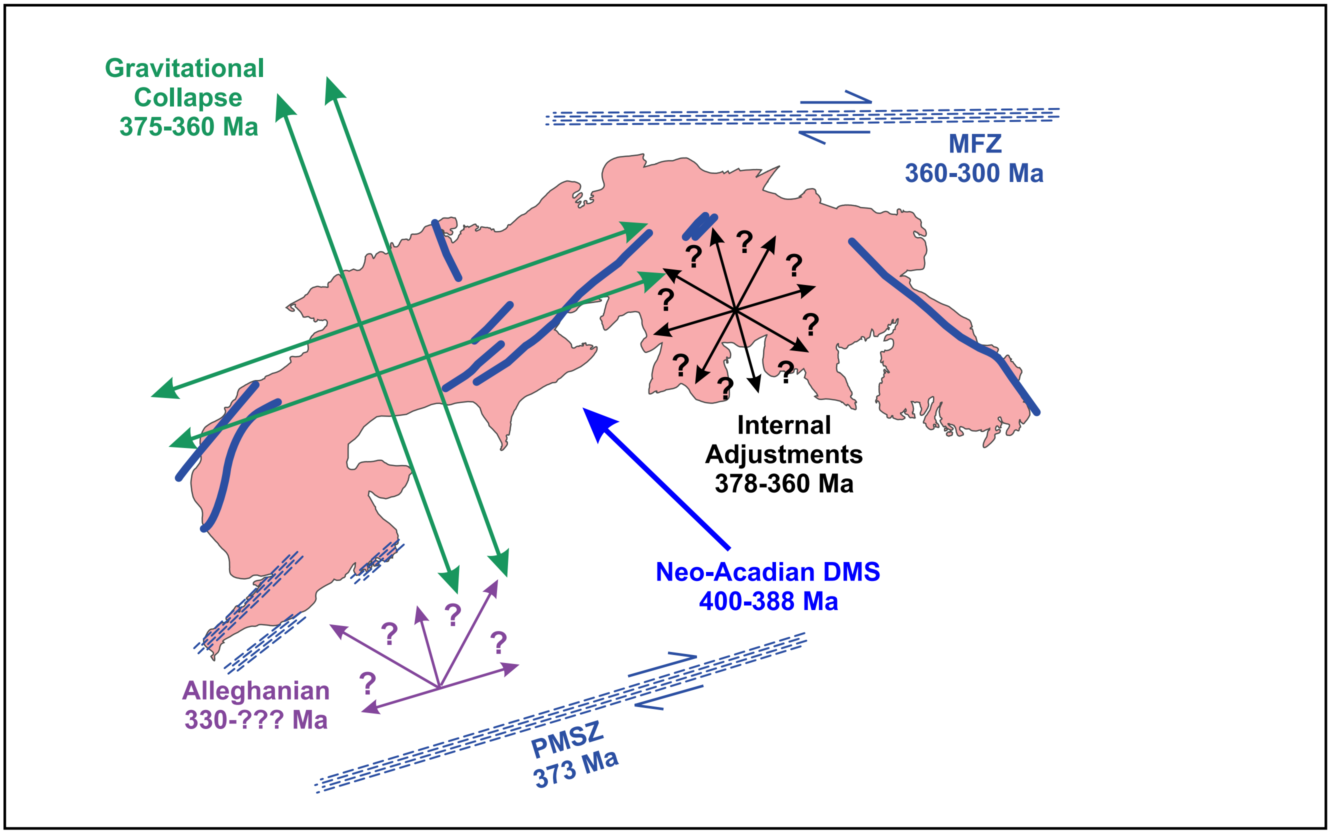


Figure 54. Colour-coded compilation of stresses in the Meguma terrane, in the vicinity of the SMB (bold blue lines – faults; dashed lines – shear zones; light blue arrow – Neo-Acadian compression; blue – simple shear; black – internal adjustments; green – gravitational collapse; purple – Alleghanian transpression;). Note that the Neo-Acadian compression may have ended before intrusion of the SMB, that no clear evidence exists for any effect of the MFZ the SMB, and that the orienta-tions of Alleghanian transpressional stresses are largely unknown.

plutons and the NE-trending foliations in Stage I plutons (Horne *et al.* 1988, 1992; Benn *et al.* 1997). At some later stage, "folding" occurred in the granites, presumably while the granitic rocks were still ductile (Benn *et al.* 1997; Kontak *et al.* 2001). And further evidence of ductile deformation occurs in the form of the augen monzogranite in the Stage I Cloud Lake pluton (MacDonald and Ham 1989; MacDonald 2001).

The phenomenon of late brittle deformation is common in many granite intrusions, and in many cases, it is tempting to attribute the stresses to a continuation of the same compressive stresses that deformed the host rocks. Horne *et al.* (1988, 1992, 2007) and Horne and Culshaw (2001) suggested that waning Neo-Acadian stresses were responsible for the late brittle structures, such as LFS, joints, faults, and mineralized quartz veins. "The Late Devonian (ca. 375 Ma) South Mountain Batholith (SMB) postdates the main folding event; it however records subtle internal strain consistent with folding accompanying transpression on the terrane-bounding fault." (Horne *et al.* 2007). Independently, Culshaw and Bhatnagar (2001) concluded that the deformation aureole along part of the exocontact of the SMB was consistent with "magma emplacement during the latter stages of fold growth".

Collectively, these observations and interpretations constitute a substantial body of evidence in favour of emplacement of the SMB while Neo-Acadian F_1 or F_2 was still taking place in the Meguma Supergroup country rocks, and that waning Neo-Acadian deformation continued to affect the batholith well into the subsolidus region. Some structures reflect deformation at the highly ductile magmatic stage, and others represent structures developed in the brittle subsolidus stage. However, can a transpressional stress directed at approximately 330° adequately explain these later structures, when there are other plausible interpretations for them? Specifically:

- the elliptical shapes of Stage I plutons were probably controlled by structural weakness (cleavage) in the host rocks.
- the NE-trending foliations in Stage I plutons cannot be the product of external stresses on a magma, unless the degree of crystallinity was uniformly greater than ca. 75%, and it is more likely that these foliations represent the same flow-driven convective or contact-parallel orientations as they do in the Stage II plutons.
- the reported "folds" are not folds and do not require compression to form them.
- the augen monzogranite is the product of weak duc-

tile deformation, but it may be too local to have been caused by any broad regional deformation.

- the deformation aureole may simply represent a local adjustment of the batholith against its host rocks.
- the timing of the LFS (F_2) is uncertain, and this structural feature might even be attributable to forceful emplacement of the SMB.
- the joints and faults are extensional features and have directions and displacements that are unlikely to be the product of NW-directed compression. The NE-trending structures are perpendicular to Neo-Acadian DMS and could not open under compression, and the NW-trending structures would have to represent axial splitting, but that process is impossible under confining pressure conditions (Fakhimi and Hemami 2015).
- the shear zones could be the products of internal adjustments, gravitational collapse, or Alleghanian deformation.
- the mineralized quartz veins are dilational, so they are unlikely to have formed in a compressional stress regime (but see Hobbs and Ord 2023).

These alternative interpretations avoid the dual problems of having to arbitrarily invoke Neo-Acadian deformation on demand (a tectonic toggle switch) and having to explain why the granites and contact aureoles show so many undeformed features. For instance, if the porphyroblasts, annealed cleavages, granite dykes, etc. demonstrate that there are no significant remaining Neo-Acadian stresses, how can these stresses subsequently be responsible for late deformation in the SMB (joints, faults, shear zones, etc.) unless conveniently reactivated? However, it is possible that regional strain can be taken up in restricted zones, such as ductile shear zones, while the surrounding rocks remain essentially undeformed. Thus, the locally undeformed porphyroblasts may not necessarily be evidence of absence of contemporaneous strain within the broader system. The only late or waning syn-tectonic case is to postulate that, by 380 Ma, the Neo-Acadian tectonic stresses have waned to the point that they can no longer deform the Meguma terrane, but they can still affect the relatively weak SMB as it cools from supra-solidus (750°C) to sub-solidus (300°C) temperatures, and they can still be transmitted through the rigid Meguma block to deform it, at least along its northern margin (Archibald *et al.* 2018; Piper and Pe-Piper 2021).

Some ductile and brittle structures are the result of internal adjustments in the SMB

Emplacement of ca. 70 000 km^3 of granite over ca. 11 myr represents enormous physical (density, viscosity) and thermal anomalies in the crust. The emplacement of this much granite cannot occur without any mechanical adjustment whatsoever. First-order adjustments between the relatively heterogeneous country rock and homogeneous granite will be driven by density differences as well as cooling and contracting. Second-order adjustments can occur because the SMB itself is not a monolithic block, but rather it contains internal compositional (density) differences, structural (foliations) differences, and even temporal differences that make it vulnerable to local, relatively minor structural adjustments as each pluton cools and contracts. These types of deformation can dominate over any externally applied, weak, deviatoric stresses, and if we have concluded that by the time of intrusion of the SMB, there are no residual regional Neo-Acadian stresses that are strong enough to deform the crust, we must explain deformation aureoles, augen granite, faults, and shear zones in terms of more local internal processes.

Karlstrom *et al.* (2010) detailed several internal thermomechanical stresses in magma chambers, including:

(i) initial filling of the magma chamber and associated stresses on the host rock (whether metamorphic or earlier granite) – the fluid-filled magma chamber is surrounded by a visco-elastic shell surrounded by an infinite elastic medium, e.g., the deformation aureole where the SMB contact is perpendicular to the Meguma Supergroup fold axes.
(ii) over pressurization resulting from magma pulses (ballooning) or volatile release
(iii) solidification resulting in a reduction in volume "Because of the assumed 15% volume change that accompanies melting or solidification (Dobran 2001), large pressures are induced by melting and freezing of magma, and this acts in concert with rheological effects to amplify or damp elastic pressurization stresses."
(iv) migrating isotherms with consequential expansion and contraction.
(v) dynamic convection and advective heat transfer.
(vi) evisceration of magma chamber during possible eruption.
(vii) cooling and contraction of solid granite from the solidus to ambient temperature.
(viii) buoyancy differences between melt, solid granite, and country rocks create internal stresses

In the SMB, possible effects of these entirely internal stresses include:

- the undulose extinction in quartz might be related to the rate of temperature decrease.
- the deflected bedding and transverse anticlines (deformation aureole) in the Meguma terrane host rocks might be the result of magma overpressure.
- the deformation aureoles could be the result of shrinkage on solidification.
- the faulted and sheared pluton-pluton contacts might be the result of volume adjustments, and the faults in the SMB are almost entirely confined *to* the SMB. If those faults were driven by external stresses, they might be expected to extend well beyond the confines of the SMB, such as the Wallace River fault. Adjustment movement, to seek mechanical equilibrium, can take place along inherent planes of weakness, especially extra- and intra-contacts (becoming the shear zones that define some contacts in the SMB).
- the augen monzogranite could be a mechanical adjust-

ment in a cooling pluton.

- the joints must be at least partly the result of contraction in the solid state.
- the sub-horizontal aplites at Peggys Cove could be the result of over pressurization.
- the hypothetical McKenzie Caldera (Clarke and Bogutyn 2003) could be the result of magma chamber evisceration and subsequent collapse.

In conclusion, the SMB was constructed of many plutons over ca. 11 myr. During that period, the SMB could not have behaved as a uniform body. Only after all components of it had reached the same temperature and strength would it begin to deform relatively more homogeneously. Some of the late brittle structures in the SMB must be the result of internal adjustments, independent of any applied regional stresses. It is not possible that these intrinsic and internal processes have had no structural effects on the SMB. Which ones is the question. We suggest, at a minimum, these include the deformation aureole, the augen granite, and some inevitable contribution to the jointing, faults, and shear zone contacts.

Some ductile and brittle structures are the result of gravitational collapse of the Neo-Acadian orogen

Most of the gravitational collapse occurs in collisional orogens when compression has ended and where the thickened and elevated crust is not strong enough to support its own weight, especially if it is underlain by hot and ductile material at depth (Fossen 2016). This so-called free-boundary collapse is normally manifest as extensional faults in the upper crust, and as shear zones at deeper levels (Fig. 55) (Rey et al 2001).

Collapse of the Neo-Acadian orogen in the Meguma terrane must be considered as an explanation for some late structures. Intrusion of the SMB, and its associated enormous advective transfer of heat, could have weakened the entire orogen and led to simultaneous brittle deformation at higher levels and ductile deformation at greater depths. We also know that the SMB, emplaced at a depth of ca. 10 km, was exposed at the Earth's surface by ca. 360 Ma, so that an average erosion rate of 1 mm/y would have been necessary, and this rapid rate of exposure might have been enhanced by gravitational collapse.

In detail, some of the structural features that might be attributable to gravitational collapse are:

- the conjugate orogen-parallel and orogen-perpendicular joints and faults inside and outside the SMB.
- the shear zones, especially those in the more deeply exposed parts of the Meguma terrane in southwest Nova Scotia.
- the NW-trending (extensional) quartz veins.

Some ductile and brittle structures in the SMB are the result of translation on the MFZ

The dextral strike-slip MFZ is the first-order terrane boundary between Avalonia and the Meguma terrane. It comprises an anastomosing network of sub-parallel faults related to movement in the vicinity of the terrane boundary (Murphy *et al.* 2011). This family of faults strikes predominantly either E-W or ENE-WSW and is characterized by mylonites, fault breccias, and hydrothermal alteration (Pe-Piper *et al.* 2018). Although there is a consensus that many of these faults are part of a larger system, kinematically linked during the Late Paleozoic, great uncertainty exists as to how much earlier this structural relationship existed.

Reconstructions by Waldron et al (2015, 2022) suggest that up to 1000 km of westward movement of the Meguma terrane took place along the MFZ beginning in the Late Devonian/Early Carboniferous, after emplacement of the various Meguma terrane granites, including the SMB (Culshaw and Lee 2006). Initial motion may have been oblique transpressive, evolving to transtensive, resulting in the formation of pull-apart basins that collected continental detritus from the Meguma terrane and Avalonian highlands.

Specifically, some structural features in the SMB that might be attributable to strike-slip movement on the MFZ include:

- prominent NW-trending structures entirely within the SMB, e.g., the Roxbury and Herring Cove faults, also appear to show evidence of sinistral motion and may be related to the Canso group of faults (Waldron *et al.* 2015). Timing for these structures, however, is unclear although Waldron et al (2015) prefer a Lower Carboniferous age. This picture is further complicated by the Weekend mafic dykes which are the same age as the nearby granites (Kempster 1988; Ruffman and Greenough 1990) and are aligned with the Canso structures.
- the westward translation of the Meguma terrane may have provided the stress regime for the regional jointing patterns on both sides of the MFZ, and suggests that at least some jointing occurred very late in the assembly of the orogen.
- mineralized NE-trending faults, such as the Manganese Mines and Millet Brook faults, in the SMB could also be related to motion on MFZ, in particular those structures that host late, low-temperature hydrothermal mineralization.
- northeast-trending shear zones in the southwest of the SMB appear related to syn-emplacement structures in Stage II plutons and were likely formed before the docking of the Meguma terrane.
- northwest-trending quartz veins in the SMB may represent extension perpendicular to σ_3 in the strain ellipse related to dextral shear on the MFZ.

Some ductile and brittle structures in the SMB are the result of Alleghanian deformation

The Alleghanian orogeny began when the Rheic Ocean completely closed and Gondwana collided with composite Laurentia to form Pangea. The Gondwana–Meguma terrane suture was ca. 500 km to the south of present-day Nova Scotia, and thus the structural effects of this terminal

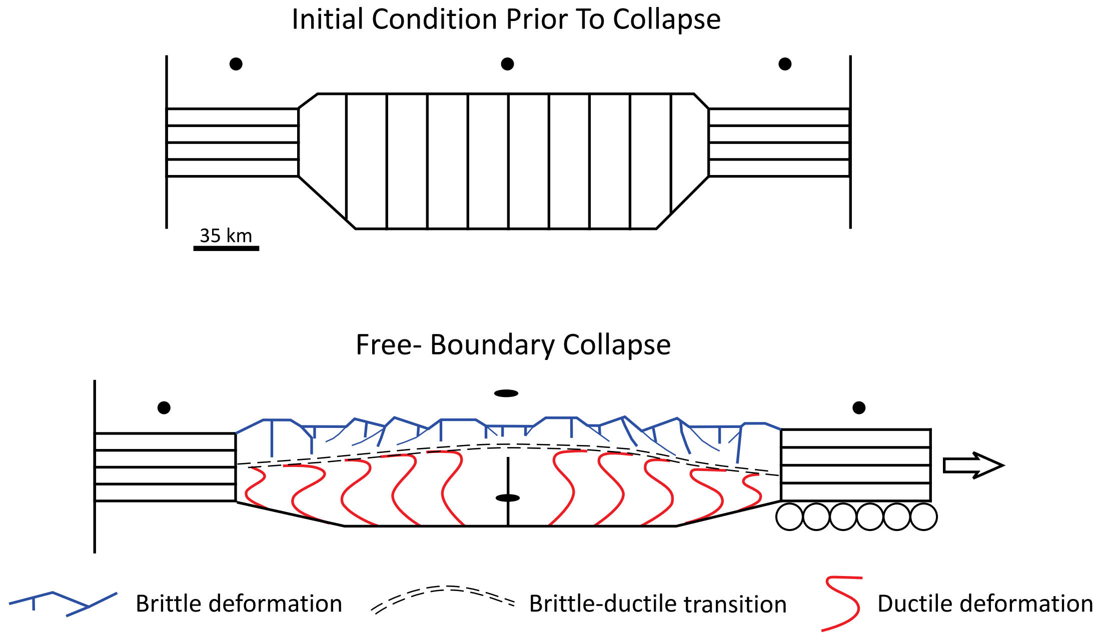


Figure 55. Gravitational collapse (after Rey *et al.* 2001). Brittle features (blue) occur at high levels, and ductile features (red) occur at deeper levels, in the orogen.

collision are far-field, generally local, and commonly minor. Nevertheless, specific examples of Alleghanian deformation include:

- the development of shear zones in SW Nova Scotia (Culshaw and Liesa 1997).
- the reactivation of Neo-Acadian folds (Culshaw and Liesa 1997).
- the forcing of further dextral movement along the MFZ (Piper and Pe-Piper (2021).
- the development of the putative orocline (Warsame *et al.* 2021).
- final movements became transpressive during the Alleghanian orogeny which brought the Meguma terrane into its current configuration against the Laurentian margin.
- high-angle reverse faults in the Meguma terrane of southwestern Nova Scotia are related to the Alleghanian and may extend as NE-trending brittle structures into the SMB.

and no doubt some (further) evidence of Alleghanian deformation in the SMB will be discovered.

Summary

To summarize, the folded Meguma terrane sequences, previously intruded by the ca. 381 to 370 Stage I and II plutons, moved as a rigid block outboard from Avalonia, along the MFZ, to dock against the assembled Laurentia continent. Transtension along the boundary structure formed Tournaisian pull-apart basins which subsequently received detritus from the Meguma terrane, including granitic material, an indication that the plutons were cooled, uplifted, unroofed and eroded within 10 Ma (Archibald *et al.* 2018). Later transpression during the Alleghanian orogeny tightened and sheared Meguma Supergroup structures in western Nova Scotia which may have continued as NE trending dip slip faults in the SMB.

Previous interpretations of structural features in the SMB relied heavily, or even exclusively, on Neo-Acadian transpressional stresses (Horne *et al.* 1988, 1992; Benn *et al.* 1997). We have shown, however, that the contribution from internal adjustments in the SMB cannot be zero, the contribution from gravitational collapse of the orogen cannot be zero, the contribution of movement on the MFZ may not be zero, and the contribution from Alleghanian deformation may not be zero. So, after D_1–S_1, how much deformation is left for Neo-Acadian transpression to explain? As should be clear from the extensive discussion above, we do not believe that any single explanation can account for all the highly problematic late structural features in the SMB and host rocks.

Recommendations for future work

So much evidence shows that the SMB intruded into a weak Meguma Supergroup host experiencing insignificant deviatoric stresses, and yet there are many ductile and brittle structural features in and around the batholith that seem to require additional internal, gravitational, MFZ, and Alleghanian explanations. Our work has resolved some questions, but many issues remain. Here we make some recommendations to further the understanding of the timing and origin of structural features in the SMB.

1. Stage I foliations. Explain the combination of heterogeneous development (strain partitioning?), yet in a generally NE-trending direction. Texturally investigate the

apparent correlation between macroscopic foliation of K-feldspar megacrysts and weak AMS lineations from biotite grains.
2. Quantitative comparison of Stage I and Stage II foliations with a view to determining if more than one process is involved. We suggest a double-blind, digital (e.g., Gerik *et al.* 2010), examination of textures from each of 10 samples from Stage I and 10 samples from Stage II granites, followed by objective classification by discriminant function analysis. Is there any systematic difference between a known local magmatic foliation in Stage II plutons and a putative regional deformational foliation in Stage I plutons?
3. A much closer examination of each class of late structures (joints, faults, shear zones), paying particular attention to the kinematics of each type of structure with a view to understanding the causative compressional, tensional, or shearing driving forces, and including radiometric dating these structures, if possible.
4. A systematic search for high-T deformation features in the SMB.
5. A detailed structural/petrological investigation of the SMB and host rocks in the putative orocline. Is there any recognizable ductile or brittle deformation associated with this bend in the orogen, e.g., are there extensional features on the outside of the hinge and compressional features on the inside?
6. A detailed examination of the augen monzogranite in the Stage I Cloud Lake Pluton, especially regarding kinematic indicators and spatial variation in intensity of deformation.
7. A new detailed gravity survey to learn more about the three-dimensional geometry of the SMB and what structural controls may have been important in its emplacement.
8. Each generation of researchers has attempted to create a comprehensive temporal-structural-petrogenetic-metallogenic model embracing all types of mineralization in the SMB (e.g., O'Reilly *et al.* 1982; MacDonald 2001). The considerable accumulation of relevant data in the last two decades suggests that another attempt at a comprehensive model is overdue.

CONCLUSIONS

Over many decades, the SMB has been referred to in the literature as either syn-tectonic or post-tectonic with respect to Neo-Acadian D_1, usually with only one line of evidence, or no cited evidence at all. This paper is the first comprehensive investigation of the timing of emplacement of the SMB with respect to the D_1 phase of the Neo-Acadian orogeny. We have used geochronology, cross-cutting relationships, porphyroblasts in the contact aureole, annealing of cleavage, undeformed contact migmatites, undeformed granite dykes in the country rocks, shapes of Stage II plutons, foliation in Stage II plutons, internal granite-granite contacts, ring schlieren, immiscible sulphides, gravity anomalies, and the absence of high-T deformation features to support, and even strengthen, the case for a post-D_1 emplacement of the SMB. In addition, we have reinterpreted the deformation aureoles, the shapes of Stage I plutons, the foliation of Stage I plutons, the so-called folding in granites, and the augen granite as being consistent with post-D_1 emplacement of the SMB. Also, we have provided credible alternative post-D_1 interpretations for late brittle and ductile structures in the SMB, including joints, faults, shear zones, and structures hosting mineral deposits. Finally, some lines of evidence, such as undulose extinction in quartz, and so-called folding in Stage I and Stage II granites appear to have nothing to offer in the way of solution to the question about the timing of emplacement of the SMB, and only the origin and timing of LFS remains problematic.

If Neo-Acadian tectonism effectively ended with transpressional deformation D_1 at ca. 389 Ma, the SMB is post-tectonic in the historical/classical sense. Alternatively, if tectonism, including transpressional, translational, and transtensional, in the Meguma terrane extended from before ca. 400 Ma until after ca. 300 Ma, the SMB is syn-tectonic in the current sense (as, therefore, are most granite intrusions in arcs and collisional orogens). Finally, if granite intrusion took place during a lull in Neo-Acadian deformation in the Meguma terrane (Fig. 53), the SMB is simply inter-tectonic.

ACKNOWLEDGEMENTS

For valuable discussions about many aspects of structures and orogens, we wish to thank Sandra Barr, Djordje Grujic, and Jiří Žák. For a personal short course on AMS, we thank Andrea Biedermann. For their detailed reviews of an early version of our manuscript, we are greatly indebted to Rebecca Jamieson and Scott Paterson who significantly raised the level of our observation and analysis. Any remaining errors of omission or commission are entirely ours. We also thank Sarah Carruzzo and Anne Jähkel for the use of their samples, Lucas Evans for his preparation of high-quality thin sections, and Janet Webster for the most professional of our graphics. We are grateful to David West for editorial handling, to Michael Dorais and Brendan Murphy for helpful peer reviews, and to Chris White for valuable additional scientific comments. Finally, we dedicate this paper on the SMB (South Mountain Batholith) to SMB (Sandra M. Barr) for her unparallelled contributions to the understanding of the geology of Atlantic Canada.

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Editorial responsibility: David P. West, Jr.