Geochemical characterization of the mineralized transition between the Goldenville and Halifax formations and the interaction with adjacent granitoid intrusions of the Liscomb Complex, Nova Scotia

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The mineralized transition between the Goldenville and Halifax formations of the Meguma Group was intruded by granodiorite and monzogranite of the Liscomb Complex near Eastville, Nova Scotia. Mineral and whole-rock chemical studies of samples from drillholes and surface exposures allow documentation of the chemical nature and a preliminary assessment of the magnitude of interaction between the granitoid bodies and their metasedimentary host rocks. Mg/(Mg+Fe) broadly increased, whereas Mn decreased in biotite and chlorite with increasing grades of metamorphism toward the contact with the Liscomb Complex in the eastern section of the map area. Fe and Mn, two transition elements with similar chemical behaviour, were mobilized and incorporated into Fe-rich contact metamorphic minerals such as almandine garnet and staurolite. Garnet in the granodiorite shows reversals in zoning, with Mg and Fe decreasing sharply and Mn increasing at the rim. Reversely zoned garnet crystallized with falling temperature and likely represents a highly modified xenocrystic type. Standard discriminant diagrams confirm that the Meguma metasedimentary rocks were deposited on a continental margin and that the granitoid intrusions formed as crustal melts during continental collision. Assimilation of Meguma country rock by the Liscomb granitoid intrusions is indicated by the detection of a characteristic trace element signature imparted by the transition between the Goldenville and Halifax formations near Eastville. Although not certain proof, the strong contrast between Pb/Zn ratios in the Meguma metasedimentary rocks and the Liscomb granodiorite (~0.45) and the rest of the South Mountain Batholith (1.19-2.26) suggests a variant petrogenetic process for the two granitoid bodies.

La transition minéralisée entre les Formations de Goldenville et d'Halifax du groupe de Meguma a été pénétrée par de la granodiorite et du monzogranite du complexe de Liscomb, près d'Eastville, Nouvelle-Écosse. Des études chimiques des roches et des minéraux des échantillons provenant de trous de forage et d'affleurements de surface permettent une documentation de la nature chimique du sous-sol et une évaluation préliminaire de l'ampleur de l'interaction entre les masses granitiques et leurs roches hôtes métasédimentaires. La quantité de Mg(Mg+Fe) a généralement augmenté tandis que le Mn a diminué dans la biotite et la chlorite avec les niveaux accrus de métamorphisme apparus vers la zone de contact avec le complexe de Liscomb, dans la partie orientale du secteur cartographique. Le Fe et le Mn, deux éléments de transition ayant un comportement chimique semblable, ont été mobilisés et incorporés dans des minéraux métamorphiques de contact riches en Fe comme les grenats d'almandine et la staurolite. Les grenats à l'intérieur de la granodiorite affichent des inversions de zonation avec une diminution soudaine du Mg et du Fe et une augmentation du Mn le long de la frange du secteur. Les grenats de zonation inverse se sont cristallisés lorsque la température a chuté; ils représentent vraisemblablement un type xénocristique fortement modifié. Des schémas discriminants standard confirment que les roches métasédimentaires de Meguma se sont déposées sur une marge continentale et que les intrusions granitiques se sont formées au moment de la fusion de la croûte lors de la collision des continents. La détection d'une signature d'éléments traces caractéristiques due à la transition entre les formations de Goldenville et d'Halifax, près d'Eastville, révèle l'assimilation de roches encaissantes de Meguma par les intrusions granitiques de Liscomb. Même si cela ne constitue pas une preuve certaine, le contraste marqué entre les rapports de Pb/Zn dans les roches métasédimentaires de Meguma et la granodiorite de Liscomb (~0,45) ainsi que le reste du batholithe de South Mountain (1,19-2,26), permet de supposer que les deux masses granitiques ont été soumises à un processus pétrogénétique différent.

[Traduit par la rédaction]

Introduction

Gold and base metal deposits in the Meguma terrane of Nova Scotia exhibit a close spatial association with the transition between the Goldenville and Halifax formations (GHT, Zentilli *et al.*, 1986). The GHT near Eastville, Nova Scotia, hosts the only significant known occurrence of zinc-lead mineralization in the Cambro-Ordovician Meguma Group. Petrologic interest peaked in this region with the discovery of high-grade gneisses of the Liscomb Complex (Giles and Chatterjee, 1986). The gneisses provide an important glimpse into the deep continental crust of the Meguma terrane, and offer another legitimate source region for the voluminous peraluminous granitoid rocks of the terrane (Clarke *et al.*,

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1993a). The western margin of the Liscomb Complex also warrants attention as one of the best exposures of the intrusive contact between granitoid rocks and the mineralized GHT. This unique locality represents an ideal opportunity to assess the likelihood of geochemical interaction between the granitoid rocks of the Liscomb Complex and metasedimentary rocks of the Meguma Group.

Base metals in soils and surface and ground waters reflect the chemistry of the underlying bedrock. Sulphide minerals serve as the major host for base metals, but many studies overlook the significant concentrations of base metals in silicate, oxide, and carbonate minerals. The geochemical approach of this paper, therefore, also contributes to the understanding of the distribution of base metals in the main bedrock lithologies of the Meguma terrane.

GEOLOGICAL FRAMEWORK

Deep-sea turbidites of the Cambro-Ordovician Meguma Group were deposited on the continental margin of Gondwana (Schenk, 1991). Intrusion of numerous peraluminous granitoid bodies, including the South Mountain Batholith, at ca. 370 Ma (Clarke *et al.*, 1993b) followed deformation and metamorphism associated with the Acadian Orogeny at ca. 390 Ma (Muecke *et al.*, 1988). The Cobequid-Chedabucto Fault marks the suture of the exotic Meguma terrane with the adjacent Avalon terrane (e.g., Nance, 1990).

Metawacke and slate of the Meguma Group dominate the western section of the study area (Fig. 1, lower). The Eastville Zn-Pb occurrence consists of a northeast-trending, steeply dipping, 10 km section of the GHT intruded by a granodiorite-monzogranite body of the Liscomb Complex. Heat from the intrusion has produced a contact aureole in the adjacent regionally metamorphosed Meguma metasedimentary rocks. The Liscomb Complex consists of 12 discrete plutonic bodies that include gneiss, schist, and gabbro (Clarke *et al.*, 1993a). These lithologies apparently represent the deep continental crust beneath the turbidites of the Meguma Group.

Drillholes from the western section of the study area established a simplified Meguma Group stratigraphy. Basal, massive quartz metawacke underlies interbedded metawacke and slate in nearly equal proportions. Contorted calcareous, manganiferous layers (i.e., coticules) of the GHT grade upward into graphitic black slates of the Halifax Formation. Waldron (1992) recognized unusually rapid vertical facies variations in the GHT that relate to a relative sea-level rise in the Gondwana source area of the Meguma Group. The Goldenville and Halifax formations do not show a conformable relationship in the vicinity of the granitoid intrusion. Here, the presence of a thrust fault marks the boundary between the Goldenville and Halifax formations instead of the distinctive coticule beds of the GHT.

SAMPLES

Granitoid samples examined in this study were collected from outcrops in the northwestern part of the Liscomb Complex adjacent to the GHT hosting the Eastville Zn-Pb mineralization (Fig. 1, lower). Two-mica equigranular granodiorite dominates in the southwestern part of the mapped granitoid body, whereas two-mica equigranular monzogranite forms a large volume of the granitoid intrusion to the east. Two-mica megacrystic monzogranite outcrops to the north in the map area.

Samples of the Meguma Group were taken from exploration drill holes that traverse both the regional and contact metamorphic domains, which loosely correspond to the western and eastern sections of the map area. Logs of drill holes in the western section of the study area indicate that contorted coticule beds mark the transition from basal, massive quartz metawacke to upper graphitic black slate. A limited number of samples from the regional metamorphic domain were studied to document adequately the increase in metamorphic grade from west to east in the study area. In the eastern section, a thrust fault near the granitoid intrusion has removed the contorted manganiferous beds from the stratigraphy and marks the boundary between the Goldenville and Halifax formations. Drill core encountered Meguma schist in close proximity to the granitoid plutons. Samples representative of the contact metamorphic domain that overprints the lower grade regionally metamorphosed sediments were collected from drillhole #26 in the eastern section.

ANALYTICAL METHODS

Nine granitoid and 25 Meguma Group metasedimentary rocks were analyzed at the Regional XRF Laboratory, Saint Mary's University, for 10 major and minor element oxides and 14 trace elements on a Philips PW 1400 sequential X-ray fluorescence spectrometer using a Rh-anode X-ray tube and LiF 220 analyzing crystal. Precision and accuracy are better than 5% for the major oxides, and between 5 to 10% for the trace elements (Dostal *et al.*, 1986). Loss on ignition (L.O.I.) was determined by heating samples for 1.5 hours at 1050°C in an electric furnace.

Mineral chemical data were determined from polished thin sections using a JEOL 733 electron microprobe at the Dalhousie University regional microprobe facility. All analyses were carried out using a focused beam (1 μm) with a 15-kV electron acceleration potential and a 5-nA sample current. Geologic standards were used for calibration and data were reduced using an on-line Tracor Northern matrix correction program (ZAF).

RESULTS

Petrography

The two-mica granodiorite consists of moderately large alkali feldspar grains set in a groundmass of biotite, muscovite, plagioclase (An_{24-34}), quartz, alkali feldspar, secondary chlorite, and accessory almandine garnet and zircon. The monzogranite body of the granitoid pluton consists of an equigranular and megacrystic phase. The two-mica megacrystic monzogranite has common phenocrysts

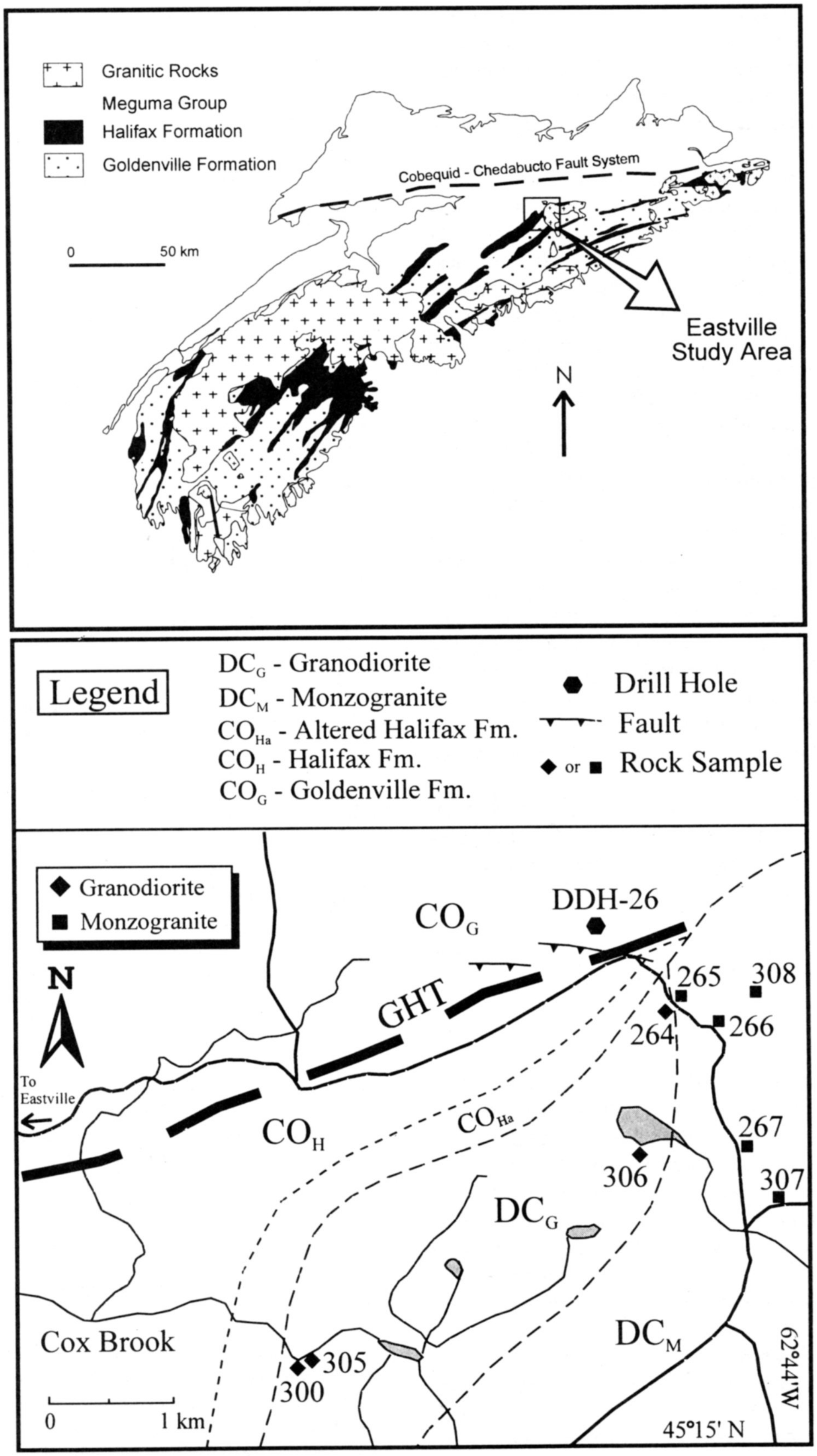

Fig. 1. Geological map of the study area near Eastville, Nova Scotia, where granodiorite and monzogranite bodies of the Liscomb Complex intruded a northeast-trending, 10-km section of the transition between the Goldenville and Halifax formations (GHT) of the Meguma Group. Metawacke, slate, and schist encountered in drillhole #26 (DDH-26) contrast chemically and mineralogically with similar lithologies from drillholes farther west, outside the influence of the granitoid intrusions in the regional metamorphic domain. The map represents a compilation of data gathered by mineral exploration companies and the authors.

of alkali feldspar in a groundmass of quartz, plagioclase, muscovite, biotite, alkali feldspar, and accessory zircon. Increased modal abundances of alkali feldspar and muscovite, less biotite, and the absence of accessory garnet distinguish the equigranular two-mica monzogranite from the granodiorite.

Porphyroblasts of quartz and xenoblastic spessartine garnet in a matrix of more elongate quartz, muscovite, and minor chlorite and plagioclase characterize the quartz metawacke of the Goldenville Formation. The contorted quartz metawacke of the transition zone has locally up to 80% small, xenoblastic spessartine garnet porphyroblasts in a groundmass of muscovite, quartz, rutile, chlorite, carbonate, and opaque oxide needles. The overlying black slates of the Halifax Formation contain small porphyroblasts of quartz, chlorite, and spessartine garnet surrounded by a groundmass of graphitic material, quartz, muscovite, and opaque oxide needles.

Biotite occurs predominantly in the more eastern drill holes, which suggests a contact metamorphic origin. Matrix biotite and muscovite likely mimic earlier phyllosilicates which define a foliation that predated the contact metamorphic aureole. Contact metamorphic mineral assemblages include: (1) a biotite zone composed of biotite with spessartine garnet; (2) an andalusite zone localized in the black slates and characterized by two varieties of andalusite and biotite; (3) an almandine zone containing almandine garnet, andalusite, and biotite; (4) an andalusite-free almandine zone; and (5) a staurolite zone containing staurolite, almandine garnet, and biotite.

Fractures control the distribution of sphalerite and galena in the contorted beds, whereas sphalerite in the cores of spessartine garnets in the black slates indicates that zinc mineralization occurred prior to the regional metamorphic event.

Mineral chemistry

(a) Garnet

Metasedimentary rocks of the Meguma Group contain spessartine garnet in the regional metamorphic domain, whereas almandine garnet exists in the higher grade metamorphic rocks of the contact aureole. MnO in garnet ranges from 29.63 wt.% in the western sections of the study area to 3.55 wt.% near the granitoid intrusion in the east. Similarly, FeO in garnet increases to 33.77 wt.% in the contact zone from 8.83 wt.% in spessartine garnet produced by regional metamorphism. The metamorphic garnet exhibits a marked increase in Mg/(Fe+Mg) ratio from 0.068 to 0.133 with increasing metamorphic grade.

The Liscomb granodiorite hosts almandine garnet characterized by increased Fe/(Fe+Mg) ratio toward the rim. These increases occur despite Fe decreases toward the rim because of a more severe depletion in Mg near the edge. A detailed traverse across a garnet from a sample of granodiorite (ZGB-264) exhibits a reversed zoning pattern with Mn-rich rims (Fig. 2c), and Ca- and Mg-rich cores (Fig. 2a,b). An Fe-rich outer core gives way to sharp decreases at the rim (Fig. 2d). Table 1 presents the microprobe data for the garnet traverse.

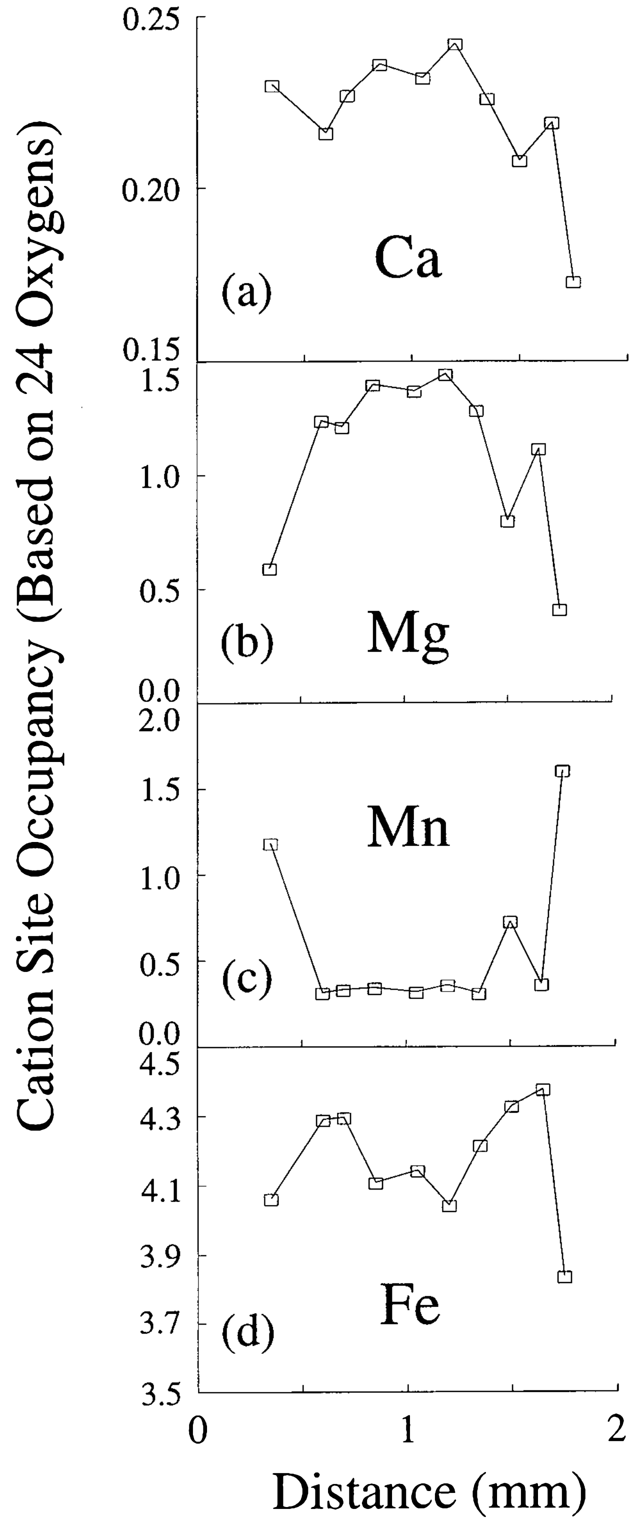

Fig. 2. Compositional zonation profiles obtained from an electron microprobe traverse of a large garnet grain hosted by the granodiorite. The garnet exhibits reversed zoning, with Mg and Ca-rich cores and Mn-rich rims. Reversed zoning in garnet suggests crystal growth during conditions of falling temperature (Allan and Clarke, 1981).

(b) Biotite

Table 2 summarizes the mineral chemical data for the metamorphic and magmatic biotite analyzed in this study.

Table 1. Electron microprobe data for garnet traverse.

Spot	312	317	319	322	326	329	332	335	338	340
SiO_2	36.82	37.04	36.98	37.09	37.04	37.68	37.53	36.48	36.79	36.03
Al_2O_3	20.96	21.16	21.50	21.35	21.38	21.54	21.34	20.70	20.99	20.84
Fe_2O_3	1.03	1.09	1.47	1.53	1.30	1.39	0.70	0.95	1.18	0.72
FeO	29.17	31.04	30.97	29.57	29.92	29.58	31.15	30.88	31.41	27.21
MnO	8.67	2.33	2.47	2.56	2.37	2.71	2.33	5.26	2.66	11.51
MgO	2.46	5.20	5.12	5.92	5.78	6.19	5.44	3.29	4.65	1.67
CaO	1.33	1.26	1.33	1.39	1.36	1.44	1.33	1.19	1.27	0.98
TiO_2	0.00	0.00	0.06	0.19	0.09	0.15	0.08	0.00	0.00	0.00
Total	100.44	99.12	99.90	99.60	99.24	100.68	99.90	98.75	98.95	98.96
(Basis 24 Oxygens)										
Si	5.94	5.94	5.89	5.89	5.90	5.91	5.96	5.95	5.93	5.93
Ti	0.00	0.00	0.01	0.02	0.01	0.02	0.01	0.00	0.00	0.00
Al	3.99	4.00	4.03	4.00	4.02	3.98	3.99	3.98	3.99	4.04
Fe^{+3}	0.13	0.13	0.18	0.18	0.16	0.16	0.08	0.12	0.14	0.09
Fe^{+2}	3.94	4.16	4.12	3.93	3.99	3.88	4.13	4.21	4.24	3.75
Mg	0.59	1.24	1.22	1.40	1.37	1.45	1.29	0.80	1.12	0.41
Mn	1.19	0.32	0.33	0.34	0.32	0.36	0.31	0.73	0.36	1.61
Ca	0.23	0.22	0.23	0.24	0.23	0.24	0.23	0.21	0.22	0.17
(Mol. % End Members)										
Alman.	66.23	70.10	69.46	66.06	67.44	68.30	69.36	70.84	71.36	63.13
Spess.	19.94	5.33	5.61	5.79	5.41	6.07	5.25	12.22	6.12	27.05

Table 2. Electron microprobe data for magmatic and metamorphic biotite.

	Z300 Gr Incl.	Z300 Gr Incl.	Z300 Gr	Z300 Gr	Z133 Low1	Z142 Low2	Z191 Low3	Z164 Med1	Z260 Med2	Z216 Med3
(wt.%)										
SiO_2	34.38	34.60	34.66	33.60	35.29	37.88	36.24	35.34	35.83	34.33
Al_2O_3	18.88	19.16	18.26	18.17	19.54	17.79	20.36	21.23	18.58	20.04
TiO_2	2.59	2.38	3.51	3.41	1.60	1.27	1.38	1.37	2.57	1.58
FeO	23.11	22.99	22.53	23.22	21.93	22.47	19.11	20.77	19.37	21.24
MnO	0.40	0.57	0.29	0.46	0.16	0.12	0.08	0.00	0.12	0.14
MgO	6.37	6.68	6.30	6.73	7.53	7.52	9.97	8.34	8.97	8.86
CaO	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00
K_2O	9.33	8.63	9.49	8.45	8.24	6.67	9.00	8.31	9.18	8.22
Total	95.06	95.07	95.04	94.04	94.29	93.72	96.14	95.47	94.62	94.41
(Basis 22 Oxygens)										
Si	5.36	5.36	5.39	5.29	5.45	5.81	5.42	5.33	5.48	5.29
Al	2.64	2.64	2.61	2.71	2.55	2.19	2.58	2.67	2.52	2.71
Al	0.83	0.86	0.74	0.67	1.01	1.02	1.00	1.11	0.83	0.93
Ti	0.30	0.28	0.41	0.40	0.19	0.15	0.16	0.16	0.30	0.18
Fe	3.01	2.98	2.93	3.06	2.83	2.88	2.39	2.62	2.48	2.74
Mn	0.05	0.08	0.04	0.06	0.02	0.02	0.01	0.00	0.02	0.02
Mg	1.48	1.54	1.46	1.58	1.73	1.72	2.22	1.88	2.04	2.04
Ca	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
K	1.86	1.71	1.88	1.70	1.62	1.31	1.72	1.60	1.79	1.62

Gr Incl. = Inclusion in Granodiorite; Gr = Granodiorite; Low = Low Metamorphic Grade; Med = Medium Metamorphic Grade

Subtle compositional changes in biotite accompany the textural change from small flakes in the regional metamorphic domain to coarse, xenoblastic porphyroblasts in the contact zone. The metamorphic biotites were found to decrease in Fe and Mn with increasing contact metamorphic grade, whereas Mg increased sharply. Consequently, Mg/(Fe+Mg) ratio in biotite shows enrichment with increasing metamorphic grade from west to east across the study area (Fig. 3a). Microprobe analyses of biotite in granodiorite, occurring both as inclusions in almandine garnet and in the groundmass of sample ZGB-300, differed from the metamorphic biotites in having less Mg. The relatively high Al_2O_3 content of the biotite may reflect the peraluminous nature of the granitoid rocks.

(c) Chlorite

Compositional variations were investigated in metamorphic chlorite (Table 3) occurring as laths defining the foliation, as books cross-cutting the foliation, and as large retrograde masses. Elevated Mg/(Fe+Mg) ratios above 0.25 were observed in the chlorite, with no systematic variation with increasing grades of contact metamorphism (Fig. 3b). Mn shows gradual depletion with increased metamorphic grade, except for a sharp jump in a sample with the highest metamorphic grade (Fig. 3c). Chlorite in this sample (ZGB-260) completely replaced a pseudomorph of garnet, thus helping to explain the erratic Mn increase. Elevated concentrations of Fe and Mn in the chlorite from the granodiorite (ZGB-300) approximates the composition of the anomalous chlorite replacing garnet in the high metamorphic grade sample.

(d) Staurolite

Staurolite occurs as large idiomorphic grains with sieve texture in the Meguma metasedimentary rock exhibiting the highest grade of contact metamorphism (sample ZGB-216). Staurolite-producing reactions in metapelitic rocks may either consume garnet when involving chlorite (Spear *et al.*, 1990), or produce garnet when involving chloritoid (Whitney and Ghent, 1993). Microprobe analyses of the idiomorphic staurolite summarized in Table 4 show uniform Fe-rich compositions ($X_{Fe\text{-}st}$ = 0.830-0.854 and $X_{Mg\text{-}st}$ = 0.128-0.156). Minor abundances of Zn typically reside in staurolite, but this study did not test for the presence of the base metal in this high-grade metamorphic mineral.

WHOLE ROCK CHEMISTRY

(a) Meguma Group (drillhole #26)

Table 5 presents the mean major and trace element chemistry of the metawacke, slate, and schist in drillhole #26 in the eastern section of the map area. Sandstone and mudstone from different tectonic settings possess characteristic chemical features, particularly with respect to SiO_2 content and K_2O/Na_2O ratio (Roser and Korsch, 1986). The quartz metawacke generally contains higher SiO_2 and lower K_2O/Na_2O than

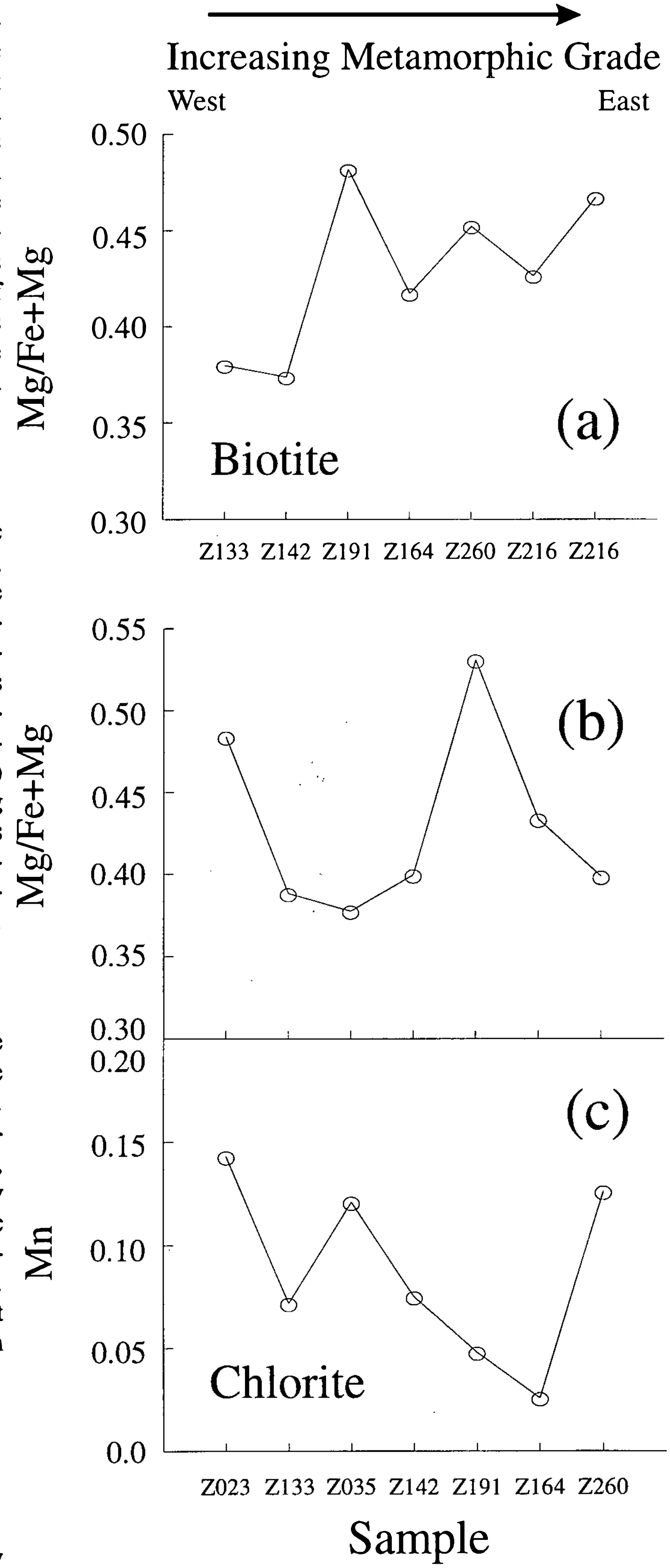

Fig. 3. Chemical changes in (a) biotite and (b,c) chlorite with increasing grade of metamorphism. Grade of metamorphism was determined petrographically based on the presence of key index minerals. Biotite shows an increase in Mg/(Fe+Mg) ratio with increasing grades of metamorphism, whereas chlorite experiences a decline in Mn up to the highest grade metamorphic schists.

Table 3. Electron microprobe data for chlorite.

	Z300 Gr	Z023 Low1	Z133 Low2	Z035 Low3	Z142 Low4	Z191 Med1	Z164 Med2	Z260 Med3
(wt.%)								
SiO_2	24.45	26.49	27.41	23.77	24.56	26.55	26.57	26.27
Al_2O_3	21.53	25.89	25.70	23.02	23.62	24.10	26.48	19.19
TiO_2	0.00	0.00	0.00	0.00	0.00	0.09	0.12	0.00
FeO	31.43	22.07	24.88	29.95	29.19	24.37	24.59	30.94
MnO	0.71	0.82	0.41	0.66	0.42	0.28	0.15	0.69
MgO	9.87	11.61	8.86	10.20	10.90	15.45	10.55	11.50
K_2O	0.00	0.79	1.49	0.00	0.07	0.00	0.00	0.00
Total	87.99	87.67	88.75	87.60	88.76	90.84	88.46	88.59
(Basis 28 Oxygens)								
Si	5.33	5.47	5.66	5.16	5.21	5.33	5.45	5.66
Al	2.68	2.54	2.34	2.84	2.79	2.67	2.55	2.35
Al	2.85	3.76	3.92	3.04	3.12	3.03	3.85	2.52
Ti	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00
Fe	5.73	3.81	4.30	5.44	5.18	4.09	4.22	5.57
Mn	0.13	0.14	0.07	0.12	0.08	0.05	0.03	0.13
Mg	3.20	3.57	2.73	3.30	3.45	4.62	3.23	3.69
K	0.00	0.21	0.39	0.00	0.02	0.00	0.00	0.00

Gr = Secondary Chlorite in Granite; Low = Low Metamorphic Grade; Med = Medium Metamorphic Grade

the black slate, whereas the schist falls at the low SiO_2 and high K_2O/Na_2O end of the slate field (Fig. 4). The metasedimentary rocks of the Meguma Group plot on the boundary separating active and passive continental margins (Fig. 4).

Major and trace element data for metasedimentary rocks from drillhole #26 also permit an examination of the contrasting chemistry between metamorphic rocks of variable metamorphic grade. MnO abundances increase gradually in the metawacke, and then decline in the black slate from depths of 105 to 150 m, only to increase again in the schist near the bottom of the hole (Fig. 5). Zn concentrations remain unchanged in the metawacke beds and show a two order-of-magnitude increase at the faulted contact between the Goldenville and Halifax formations (Fig. 5). Progressive declines in Zn contents characterize the higher grade metamorphic rocks at depth in the drillhole near the granitoid intrusion.

(b) Liscomb granitoid bodies

The Liscomb granodiorite body has lower SiO_2 and higher FeO_T, MgO, and CaO than the monzogranite (Table 6). The granodiorite also contains higher trace element concentrations (e.g., Ba, Sr, Zr, Nb) than the monzogranite, except for Rb which accompanies K in alkali feldspar. The peraluminous nature of the Liscomb granitoid bodies (Al_2O_3/$CaO+Na_2O+K_2O$ or A/CNK = 1.1-1.3) suggests a origin similar to that of the much more studied South Mountain Batholith of Nova Scotia (Clarke and Muecke, 1985). Silicate melt-silicate crystal equilibria generally limit A/CNK values to 1.1 to 1.2. The discriminant diagram of Maniar and Piccoli (1989) is compatible with a continental collision setting for the Liscomb granitoid rocks analyzed in this study (Fig. 6a). The discriminant diagram of Pearce *et al.* (1984) utilizes trace elements (Rb and Y+Nb concentrations) and suggests either a syncollisional or volcanic-arc setting (Fig. 6b). K/Rb ratios > 160 in the Liscomb granitoids strongly suggest control by crystal-melt equilibria rather than the involvement of an aqueous fluid phase (Clarke *et al.*, 1993b).

Discussion

The chemical data presented help document the chemical nature of the Liscomb granitoid rocks and their metasedimentary hosts of the Meguma Group. Any interaction between the two Meguma terrane lithologies was achieved by two different open system chemical exchange systems: contact metamorphism and country rock assimilation. These geological processes work separately to create chemical diversity in the Meguma metasedimentary rocks and the granodiorite and monzogranite of the Liscomb Complex.

Table 4. Electron microprobe data for staurolite.

	Z216-1	Z216-2	Z216-3
(wt.%)			
SiO_2	27.05	27.19	27.65
Al_2O_3	54.09	54.39	53.70
TiO_2	0.59	0.53	0.48
FeO	13.91	13.93	14.45
MnO	0.28	0.29	0.24
MgO	1.17	1.38	1.52
Total	97.09	97.71	98.04
(Basis 23 Oxygens)			
Si	3.79	3.78	3.84
Al	8.93	8.92	8.80
Ti	0.06	0.06	0.05
Fe^{2+}	1.63	1.62	1.68
Mn	0.03	0.03	0.03
Mg	0.24	0.29	0.32
[1]$X_{Fe\text{-}st}$	0.85	0.84	0.83
$X_{Mg\text{-}st}$	0.13	0.15	0.16

[1]$X_{Fe\text{-}st}$ = Fe/(Fe+Mn+Mg)

Contact metamorphic effects

Heat associated with the intrusion of the Liscomb granitoid rocks produced distinct mineralogical transformations in the metasedimentary rocks. Biotite, almandine garnet, andalusite, and staurolite occur only in close proximity to the granitoid intrusion. The absence of carbonate in the contact metamorphic domain suggests that Ca from carbonate breakdown went into almandine garnet and possibly plagioclase. The increase in Mg/(Fe+Mg) in garnet with increasing metamorphic grade suggests a continuous reaction by which garnet forms at the expense of chlorite (Sivraprakash, 1981): chlorite + muscovite + quartz --> garnet + biotite + H_2O. Normal zoning in garnet (Mn-rich cores) agrees with the formation of garnet by this reaction. Low Mg/(Fe+Mg) ratios (0.072-0.133) in almandine garnet favour the formation of staurolite over cordierite at higher grades. However, the high Mg/(Fe+Mg) ratios of the chlorite (>0.25) typically promote cordierite formation over staurolite. The presumed reduced thickness of the Meguma Group in the vicinity of the Liscomb Complex (Clarke *et al.*, 1993a) might yield lower pressures of metamorphism and accordingly might expand the staurolite stability field on a hypothetical AFM diagram. This would help explain the observed presence of staurolite in the contact aureole. In simple terms, the decline in Fe and Mn in biotite and chlorite with increasing grade of meta-

Table 5. Mean major and trace element data for main lithologies in DDH-26.

Rock Type	Metawacke	Slate	Schist
N	5	16	3
SiO_2	72.42	63.88	59.69
TiO_2	0.64	0.97	0.85
Al_2O_3	13.51	23.29	19.41
FeO_T	4.71	4.85	7.51
MnO	0.53	0.14	1.92
MgO	1.80	1.84	2.13
CaO	0.85	0.49	0.40
Na_2O	2.46	0.96	1.16
K_2O	2.12	2.77	3.42
P_2O_5	0.13	0.13	0.11
LOI	1.38	3.75	2.41
Total	99.15	99.19	96.59
Ba	608	839	878
Rb	76	164	150
Sr	169	207	143
Y	-	31	31
Zr	-	185	127
Nb	13	16	18
Th	17	80	18
Pb	834	5944	79
Ga	13	17	26
Zn	1918	13861	202
Cu	10	48	37
Ni	26	39	49
V	85	159	127
Cr	246	184	163

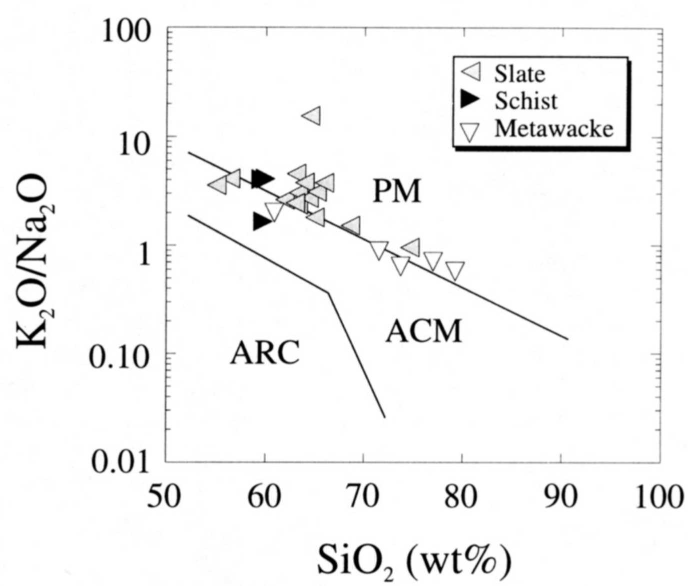

Fig. 4. The K_2O/Na_2O versus SiO_2 discriminant diagram of Roser and Korsch (1986) identifies the tectonic setting of sandstone-mudstone sequences. The metasedimentary rocks from drillhole #26 straddle the passive/active continental margin fields. PM = Passive Margin, ACM = Active Continental Margin, ARC = Continental Arc Setting.

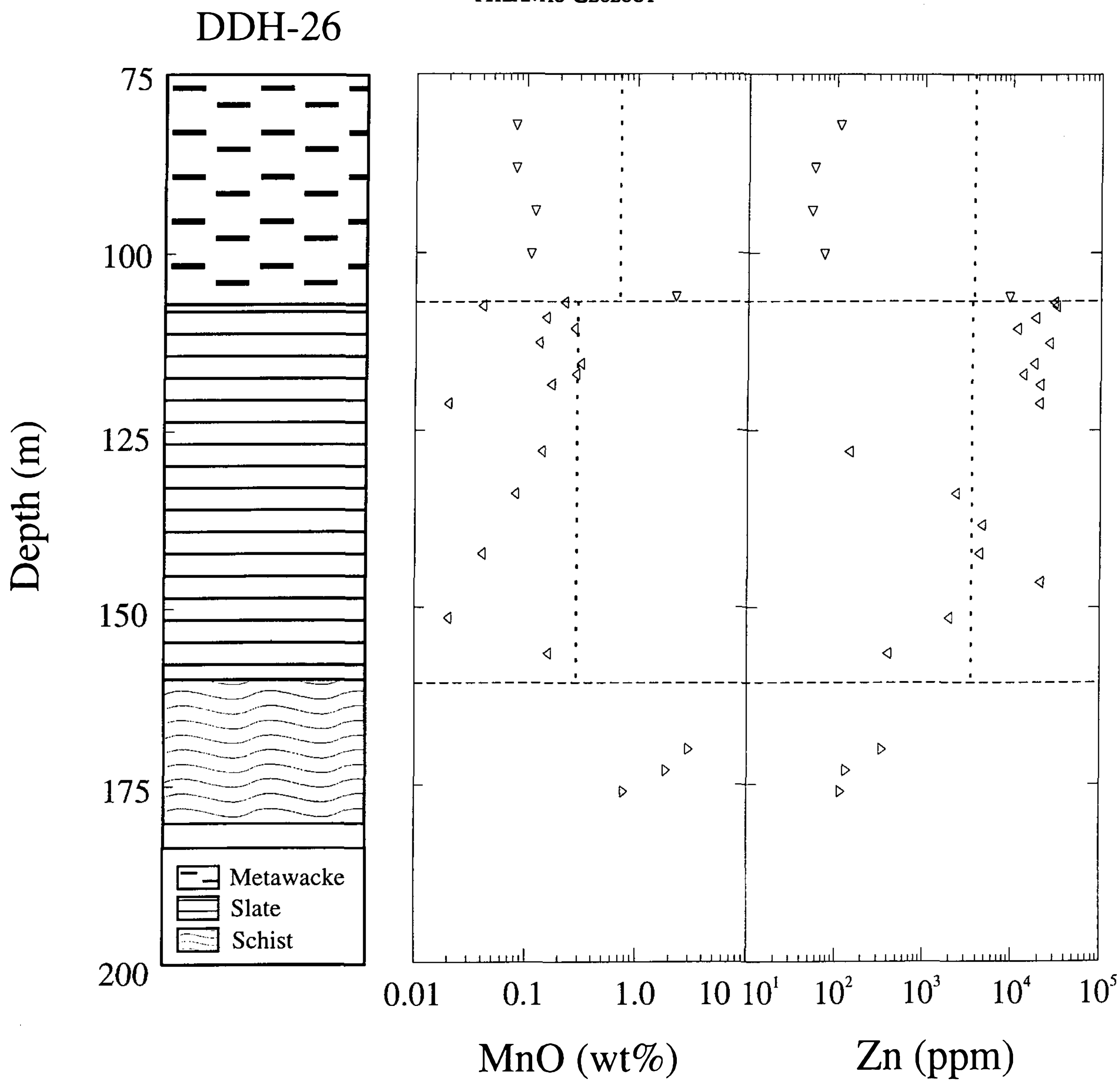

Fig. 5. MnO (wt.%) and Zn (ppm) contents vary with depth in drillhole #26. Horizontal dashed lines mark lithologic boundaries between metawacke, slate, and schist. Vertical dotted lines indicate mean composition for regionally metamorphosed equivalent lithologies taken from MacInnis (1986). Symbol shapes as in Figure 4.

morphism likely accounts for the occurrence of Fe-rich minerals like staurolite and almandine garnet in the contact aureole. The absence of chlorite in the highest grade contact metamorphic zone and garnet compositional profiles suggest the discontinuous reaction of chlorite + garnet + muscovite = staurolite + biotite + quartz + H_2O (Spear *et al.*, 1990; Whitney and Ghent, 1993).

Origin of garnet

In terrains displaying prograde metamorphism, temperature controls the distribution coefficient (K_D), which in turn governs the concentration of Mn in the cores of the growing garnet. Assumptions for the normal zoning models include equilibrium conditions, perfect diffusion in the surrounding matrix, and negligibly slow growth (Jamieson, 1974). The zoning pattern observed in the garnet of the metasedimentary rocks of this study confirm their origin by progressive metamorphism. Garnet-biotite geothermometry using garnet rim and biotite mineral chemical data suggests that temperatures of approximately 580°C were reached in the contact aureole. Such calculations incorporate errors of ± 50°C and assume a pure binary system (Ferry and Spear, 1978).

The reversed zoning in garnet in the granodiorite might indicate either a magmatic origin or a highly modified xenocrystic type. Immersion of the garnet in a relatively high-temperature magma would cause rapid crystallization, contrary to the initial assumptions of the zoning model outlined above. Rapid growth of the garnet produces a Mn-depleted zone in the core where diffusion lags behind crystallization (Edmunds and Atherton, 1971). Reestablishment of equilibrium accompanies a decreased growth rate and the K_D again controls the Mn concentration of the rim. The presence of pyrite adjacent to the garnet, biotite and musco-

Table 6. Major and trace element data for Liscomb granitoids.

Sample	Z264 Gr	Z300 Gr	Z305 Gr	Z306 Gr	Z265 Mg	Z266 Mg	Z267 Mg	Z307 Mg	Z308 Mg
SiO_2	66.18	63.93	64.56	64.28	77.72	72.38	72.98	73.23	71.93
TiO_2	0.82	0.82	0.82	0.49	0.08	0.17	0.17	0.18	0.19
Al_2O_3	16.30	17.70	17.47	15.31	14.56	15.75	15.71	15.71	15.51
FeO_T	4.84	5.35	5.39	3.08	0.73	1.08	1.16	1.19	1.11
MnO	0.12	0.13	0.11	0.06	0.02	0.02	0.02	0.03	0.02
MgO	1.55	1.68	1.72	1.15	0.21	0.36	0.34	0.41	0.33
CaO	2.04	2.31	2.18	1.46	0.31	0.43	0.42	0.45	0.38
Na_2O	3.51	3.78	3.89	4.07	3.67	3.64	4.14	4.00	3.89
K_2O	3.71	3.55	3.28	3.91	3.57	5.63	4.48	4.77	4.82
P_2O_5	0.32	0.29	0.31	0.26	0.34	0.37	0.34	0.34	0.36
LOI	0.69	0.92	1.23	0.85	0.77	0.77	0.85	0.85	0.85
Total	99.40	99.56	99.73	94.07	101.22	99.82	99.76	100.31	98.53
Ba	963	869	819	563	82	346	468	406	331
Rb	147	149	139	191	160	223	215	206	231
Sr	217	248	228	148	24	58	73	65	50
Y	30	29	21	17	7	8	8	9	6
Zr	232	259	263	155	17	68	60	71	71
Nb	14	16	15	11	11	8	9	9	8
Th	11	8	13	11	-	7	6	6	7
Pb	37	25	18	27	19	24	31	31	22
Ga	20	22	23	21	22	21	19	17	23
Zn	107	106	79	77	27	50	46	52	35
Cu	2	6	4	-	-	-	-	-	-
Ni	10	8	8	8	4	4	5	5	6
V	51	73	69	33	1	5	4	9	2
Cr	22	26	25	27	4	13	2	8	6

Gr = Granodiorite; Mg = Monzogranite

vite inclusions, and the localization of small modal abundances of almandine garnet to the granodiorite near the intrusive contact, all favour a metamorphic origin.

Felsic peraluminous granitoid rocks serve as the most common igneous hosts to magmatic garnet. Euhedral, inclusion-poor to inclusion-free, almandine-spessartine solid solution garnet characterizes the magmatic variety (Miller and Stoddard, 1981). Magmatic garnet typically crystallizes from Mn-rich magmas. Supportive evidence includes garnet with a spessartine component in excess of 10% and coexisting biotites containing MnO > 0.75 wt.%. In this study, the garnet occurs in peraluminous granodiorite. The spessartine component of the garnet cores falls well below 10%, although the rims exceed this critical value. Furthermore, coexisting biotite in the granodiorite averages only 0.43 wt.% MnO, whereas secondary chlorite contains 0.71 wt.% MnO.

Country rock assimilation

Metasedimentary enclaves in the South Mountain Batholith have Nd and Sr isotopic compositions intermediate between those of the batholith and the country rocks, and provide clear evidence of contamination (Clarke *et al.*, 1988). Thus, in addition to the physical evidence of rounded Meguma enclaves in the Liscomb granitoid plutons, we propose equivocal lines of chemical evidence for assimilation. Mineral chemical zoning in garnet in the granodiorite seems to favour a metamorphic origin, as does the occurrence of pyrite in the granodiorite phase.

The probable derivation of the Meguma sediments from a granodiorite source terrain severely hampers efforts to utilize trace element chemistry to identify significant contamination (i.e., little difference exists between the contaminant and the assimilating body). The best hope, excluding isotopic data, lies in detecting some trace element signature of the Meguma metasedimentary rocks that is unique to the GHT in the Liscomb granitoid rocks. The Pb/Zn ratio of 0.45 in the Meguma metasedimentary rocks from drillhole #26 falls very close to the ratio found in the numerous drillholes from the western section. The Pb/Zn ratio of the Liscomb Complex (mean 0.47) mimics the diagnostic ratio in the Meguma rocks of the Eastville occurrence. Moreover, the

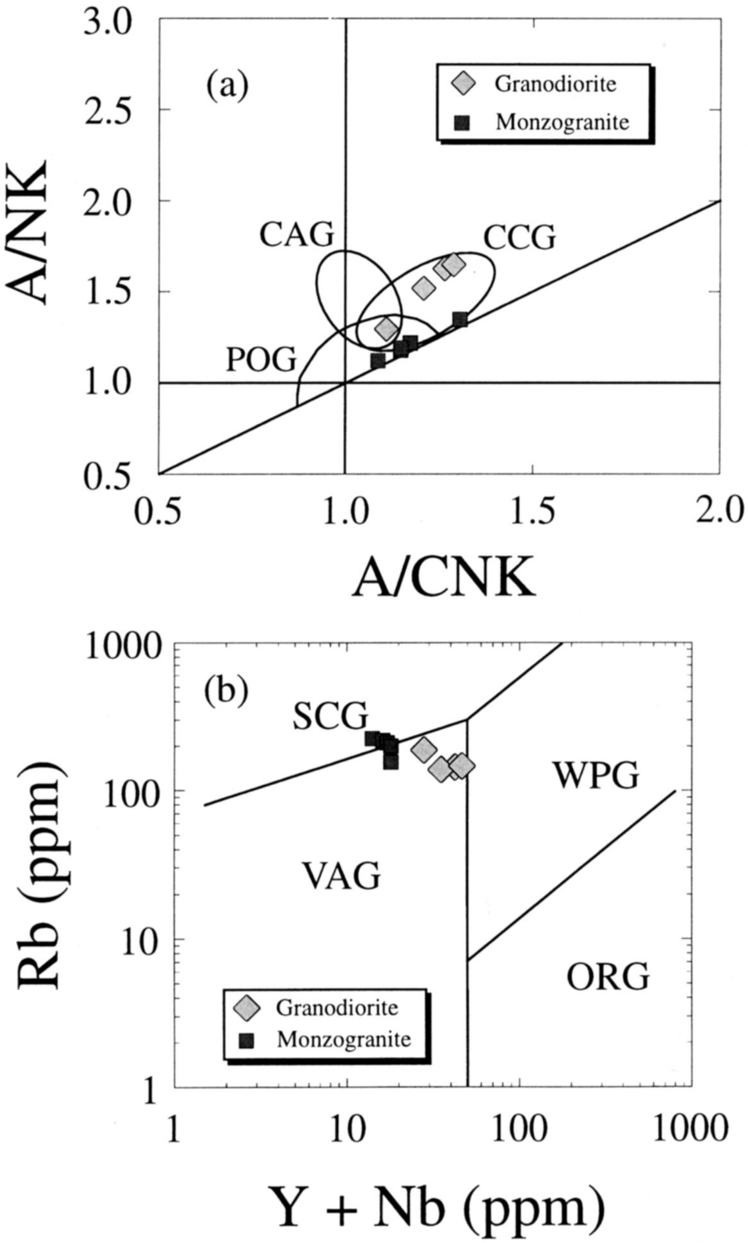

Fig. 6. (a) The A/NK versus A/CNK discriminant diagram of Maniar and Piccoli (1989) affirms the peraluminous nature of the Liscomb granitoid rocks and suggests that the chemistry supports a continental collision setting. A = Al_2O_3; C = CaO, N = Na_2O; K = K_2O. CCG = Continental Collision Granite; CAG = Calc-alkali Granite; POG = Post Orogenic Granite. (b) The Rb versus (Y+Nb) trace element discriminant diagram of Pearce *et al.* (1984) indicates either a syncollisional or volcanic-arc tectonic setting for the Liscomb granitoid rocks. SCG = syncollisional granite, VAG = volcanic arc granite, WPG = within-plate granite, ORG = orogenic granite.

Pb/Zn ratio of various phases of plutons from the South Mountain Batholith ranges from 1.19 to 2.26 (Smith, 1979), substantially higher than those of the Liscomb Complex (Fig. 7). Small differences in the composition of the Liscomb granitoid rocks and the South Mountain Batholith were attributed to source rock variations and subsequent processes such as fractional crystallization and crustal assimilation (Clarke *et al.*, 1993a). Source rock differences and fractional crystallization seem less likely candidates to control the Pb/Zn ratio in the Liscomb granitoid bodies. Instead, we suggest that the lower Pb/Zn ratio highlights the role of country rock assimilation in modifying the trace element character of the Liscomb granitoid rocks. Moreover, the monzogranite has a less extreme Pb/Zn ratio compared to the Liscomb granodiorite (i.e., more similar to the South Mountain Batholith), suggesting less interaction with the Meguma metasedimentary rocks. Rigorous mass balance calculations were not undertaken, but would assist in the quantification of the degrees of country rock assimilation.

CONCLUSIONS

New mineral and whole-rock chemical data contribute to the understanding of the chemical nature of the GHT and

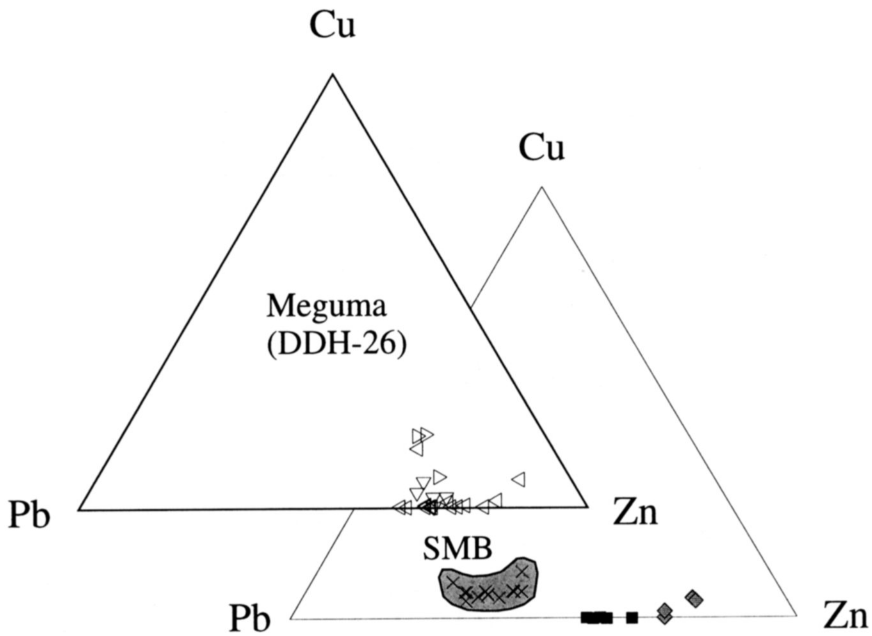

Fig. 7. The Pb-Zn-Cu triangular diagram highlights the contrasting Pb/Zn ratio in the Liscomb granitoid rocks and the South Mountain Batholith (Smith, 1979). The Liscomb granodiorite and metasedimentary rocks of the Meguma Group near Eastville share a common Pb/Zn ratio of approximately 0.45. Intrusive phases of the South Mountain Batholith possess a much higher Pb/Zn ratio of 1.19 to 2.26. Symbol shapes as in Figures 4 and 6. SMB = South Mountain Batholith.

the processes that produce secondary chemical variability. This geochemical study draws the following conclusions:

(1) The chemical data affirm the tectonic setting for the deposition of the Meguma metasedimentary rocks on a continental margin and the origin of the peraluminous Liscomb granitoid rocks as crustal melts related to continental collision.

(2) The progressive decline of Mn content in garnet, biotite, and chlorite with increasing grades of metamorphism reflects dispersion of the transition metal Mn, rather than economic concentration.

(3) A metamorphic origin best explains the reverse zoning patterns in garnet hosted by the granodiorite. Whether the garnets were derived from the Meguma schists in the contact aureole or from the deeper gneisses of the Liscomb Complex warrants further investigation.

(4) Similar Pb/Zn ratios in the Liscomb granodiorite and Meguma metasedimentary rocks of the Eastville Zn-Pb occurrence suggest, but does not prove, some role for assimilation of the Meguma metasedimentary rocks by the ascending granitoid intrusions.

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ALLAN, B.D. and CLARKE, D.B. 1981. Occurrence and origin of garnet in the South Mountain Batholith, Nova Scotia. Canadian Mineralogist, 19, pp. 19-24.

CLARKE, D.B. and MUECKE, G.K. 1985. Review of the petrochemistry and origin of the South Mountain Batholith and associated plutons, Nova Scotia, Canada. *In* High Heat Production (HHP) Granites, Hydrothermal Circulation and Ore Genesis. Institute of Mining and Metallurgy, London, pp. 41-54.

CLARKE, D.B., HALLIDAY, A.N., and HAMILTON, P.J. 1988. Neodymium and strontium isotopic constraints on the origin of the peraluminous granitoids of the South Mountain Batholith, Nova Scotia, Canada. Chemical Geology, 73, pp. 15-24.

CLARKE, D.B., CHATTERJEE, A.K., and GILES, P.S. 1993a. Petrochemistry, tectonic history, and Sr-Nd systematics of the Liscomb Complex, Meguma Lithotectonic Zone, Nova Scotia. Canadian Journal of Earth Sciences, 30, pp. 449-464.

CLARKE, D.B., MACDONALD, M.A., REYNOLDS, P.H., and LONGSTAFFE, F.J. 1993b. Leucogranites from the eastern part of the South Mountain Batholith, Nova Scotia. Journal of Petrology, 34, pp. 653-679.

DOSTAL, J., BARAGAR, W.R.A., and DUPUY, C. 1986. Petrogenesis of the Natkusiak continental basalts, Victoria Island, Northwest Territories, Canada. Canadian Journal of Earth Sciences, 23, pp. 622-632.

EDMUNDS, W.M. and ATHERTON, M.P. 1971. Polymetamorphic evolution of garnet in the Fanad aureole Donegal, Eire. Lithos, 4, pp. 147-161.

Ferry, J.M. and Spear, F.S. 1978. Experimental calibration of the partitioning of Fe+Mg between biotite and garnet. Contributions to Mineralogy and Petrology, 66, pp. 399-414.

Giles, P.S. and Chatterjee, A.K. 1986. Peraluminous granites of the Liscomb Complex. Nova Scotia Department of Mines and Energy, Tenth Annual Open House and Review of Activities, Program and Summaries, Information Series 12, pp. 83-89.

Jamieson, R.A. 1974. The contact of the South Mountain Batholith near Mt. Uniacke, Nova Scotia. Unpublished B.Sc. thesis, Dalhousie University, Halifax, Nova Scotia.

MacInnis, I.N. 1986. Lithogeochemistry of the Goldenville-Halifax transition (GHT) of the Meguma Group in the manganiferous zinc-lead deposit at Eastville, Nova Scotia. Unpublished B.Sc. thesis, Dalhousie University, Halifax, Nova Scotia.

Maniar, P.D. and Piccoli, P.M. 1989. Tectonic discrimination of granitoids. Geological Society of America Bulletin, 101, pp. 635-643.

Miller, C.F. and Stoddard, E.F. 1981. The role of Mn in the paragenesis of magmatic garnet: An example from the Old Woman Piute Range, California. Journal of Geology, 89, pp. 233-246.

Muecke, G.K., Elias, P., and Reynolds, P.H. 1988. Hercynian/Alleghanian overprinting of an Acadian terrane: $^{40}Ar/^{39}Ar$ studies in the Meguma Zone, Nova Scotia, Canada. Chemical Geology, 73, pp. 153-167.

Nance, R.D. 1990. Late Precambrian-early Proterozoic arc platform transitions in the Avalon terrane of the Northern Appalachians; review and and implications. *Edited by* A.D. Socci, J.W. Skehan, and G.W. Smith. Geological Society of America, Special Paper 245, pp. 1-11.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology, 25, pp. 956-983.

Roser, B.P. and Korsch, R.J. 1986. Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. The Journal of Geology, 94, pp. 635-650.

Schenk, P.E. 1991. Events and sea-level changes on Gondwana's margin: the Meguma Zone (Cambrian-Devonian) of Nova Scotia, Canada. Geological Society of America Bulletin, 103, pp. 512-521.

Sivraprakash, C. 1981. Zoned garnets in some Scottish Dalradian pelites. Mineralogical Magazine, 44, pp. 301-307.

Smith, T.E. 1979. The geochemistry and origin of the Devonian granitic rocks of southwest Nova Scotia. Geological Society of America Bulletin (II), 90, pp. 850-885.

Spear, F.S., Kohn, M.J., Florence, F.P., and Menard, T. 1990. A model for garnet and plagioclase growth in pelitic schists: implications for thermobarometry and P-T path determinations. Journal of Metamorphic Geology, 8, pp. 683-696.

Waldron, J.W.F. 1992. The Goldenville-Halifax transition, Mahone Bay, Nova Scotia: relative sea-level rise in the Meguma source terrane. Canadian Journal of Earth Sciences, 29, pp. 1091-1105.

Whitney, D.L. and Ghent, E.D. 1993. Prograde reactions and garnet zoning reversals in staurolite schist, British Columbia: significance for thermobarometric interpretations. Journal of Metamorphic Geology, 11, pp. 779-788.

Zentilli, M., Graves, M.C., Mulja, T., and MacInnis, I. 1986. Geochemical characterization of the Goldenville-Halifax transition of the Meguma Group of Nova Scotia: preliminary report. *In* Current Research, Part A. Geological Survey of Canada, Paper 86-1A, pp. 423-428.

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