Epizonal I- and A-type granites and associated ash-flow tuffs, Fogo Island, northeast Newfoundland

Hamish A. Sandeman and John Malpas

Abstract: Magmatic activity of Silurian–Devonian age is widespread in the Appalachian–Caledonian Orogen. A marked characteristic of this magmatism is the composite nature of the igneous suites, which range from peridotite to granodiorite in single plutonic bodies. The origin of these suites is still enigmatic, and the assumption that all are the same not proven. Such a suite of intrusive rocks, ranging in composition from minor peridotite to granodiorite, intrudes an openly folded sequence of Silurian volcanogenic sandstones and ash-flow tuffs on Fogo Island, northeast Newfoundland. Two units, the Rogers Cove and Hare Bay microgranites, consist of fine-grained hastingsite granites with spherulitic and flow-banded textures, and exhibit drusy cavities and microfractures that contain the mineral assemblage hastingsitic hornblende + plagioclase + magnetite + zircon. These rocks are characterized by elevated high field strength element contents (e.g., Zr = 74–672 and Y = 21–103 ppm), very high FeO*/MgO ratios (FeO*/MgO = 2.4–93.5), and 10 000 Ga/Al ratios of 1.67–10.52, indicating an A-type granitoid affinity. A third and the most voluminous granitic unit, the Shoal Bay granite, is an alkali-feldspar-phyric, medium-grained, equigranular biotite–hastingsite granite with hastingsite and annitic biotite interstitial to euhedral plagioclase, anhedral quartz, and perthite crystals. The Shoal Bay granite exhibits mineral parageneses similar to the microgranites, but chemical characteristics more typical of calc-alkaline, I-type granitoids. Volcanic–sedimentary sequences spatially associated with the granitic rocks include dense, welded, high-silica, hastingsite-bearing ash-flow tuffs with compositions that suggest they represent erupted equivalents of fractionated end members of the Shoal Bay granite. The rocks making up the Fogo Island batholith have been directly equated with the bimodal, calc-alkaline Mount Peyton batholith of northeast Newfoundland, but the specialized A-type nature of the Fogo granites suggests differing source conditions for the two suites.

Résumé : L'activité magmatique d'âge Siluro-Dévonien est amplement répandue dans l'orogène appalachien–calédonien. Une caractéristique de ce magmatisme est la nature composite des suites ignées, variant de péridotite à granodiorite dans les corps plutoniques individuels. La source de ces suites demeure énigmatique, et la thèse qu'elle serait la même partout n'est pas démontrée. Une de ces suites de roches intrusives, dont la composition varie d'une petite masse péridotitique à une granodiorite, pénètre dans une séquence de plis ouverts formée de grès volcanogéniques et de coulées pyroclastiques de cendres, d'âge Silurien, sur l'île Fogo, dans le nord-est de Terre-Neuve. Deux unités, les microgranites de Rogers Cove et de Hare Bay, constituées de granites à hastingsite, à grain fin, avec des textures d'écoulement rubanée et sphérulitique, et exhibant des cavités drusiques et microfractures recouvertes par l'assemblage minéralogique de hornblende hastingsitique + plagioclase + magnétite + zircon. Ces roches sont caractérisées par des teneurs élevées en éléments à forte intensité de champ (ex., Zr = 74–672 et Y = 21–103 ppm), des rapports très élevés de FeO*/MgO (FeO*/MgO = 2,4–93,5), et des rapports 10 000 Ga/Al de 1,67–10,52, indiquant une affinité granitoïde de type-A. Une troisième et la plus volumineuse unité granitique, le granite de Shoal Bay à hastingsite et biotite équigranulaire, à grain moyen, et à feldspath porphyrique alcalin, incluant de l'hastingsite et de la biotite annitique en position interstitielle dans le plagioclase automorphe, et des cristaux xénomorphes de quartz et de perthite. Le granite de Shoal présente une paragenèse similaire à celle des microgranites, mais les caractéristiques chimiques se rapprochent plus des granitoïdes calco-alcalins de type-I. Les séquences volcano-sédimentaires associées spatialement aux roches granitiques incluent des coulées

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pyroclastiques de cendres avec de l'hastingsite, elles sont denses, soudées et très siliceuses, leurs compositions suggèrent qu'elles représentent les équivalents éruptifs des pôles de fractionnement du granite de Shoal Bay. Les roches appartenant au batholite de l'île Fogo sont interprétées comme étant directement équivalentes aux roches calco-alcalines bimodales du batholite de Mount Peyton, dans le nord-est de Terre-Neuve, mais la nature spécialisée de ce type-A des granites de Fogo suggère des conditions magmatiques différentes pour les deux suites.
[Traduit par la rédaction]

Introduction

Siluro-Devonian magmatism in the Appalachian–Caledonian orogen is characterized by composite mafic–felsic plutonic suites (e.g., Bevier and Whalen 1990; Dunning et al. 1990). In central Newfoundland, such composite bodies include the Mount Peyton, Hodges Hill, and Fogo Island batholiths, which make up a significant portion of exposed bedrock.

The Fogo Island granitic batholith underlies most of Fogo Island, northeast Newfoundland (Fig. 1), but a significant part of the southern and eastern portions of the island are made up of dioritic and gabbroic rocks. The mafic–ultramafic Tilting igneous complex contains the most mafic rocks to occur together with granitic rocks in all of Newfoundland, and has been described by Williams (1957), Baird (1958), Cawthorn (1978), and Aydin et al. (1994).

Little is published on the composition of the granitic rocks of Fogo Island. Hughes (1972) described granophyric and micrographic textured granitic rocks of the Fogo Peninsula and commented on their calc-alkaline affinities. Strong and Dickson (1978) briefly discussed the Fogo Island granites when contrasting plutonic complexes throughout east-central Newfoundland. They compared the Fogo Island batholith to the Mount Peyton batholith, a similar bimodal plutonic assemblage exposed within the Dunnage Zone of central Newfoundland. Using the Mount Peyton batholith as a lithodemic type, Williams et al. (1989) classified the rocks of the Fogo Island batholith as post-tectonic, "Mt. Peyton Types." They noted the restriction of similar bimodal intrusive suites to the northern part of the Exploits subzone of central Newfoundland and suggested a genetic control resulting from a common, lower crustal source. The enigmatic nature of these bimodal suites was further emphasized by Kerr et al. (1992).

A K–Ar determination of 380 ± 16 Ma presented by Wanless et al. (1964) and further discussed by Williams (1964) represented the first absolute geochronologic information for rocks of the Fogo Island batholith and corroborated the broadly Siluro-Devonian age suggested by Baird (1958). Little other geochronologic information is available, except a Rb–Sr isochron age of 412 Ma presented by Fryer et al. (1992) for a suite of granitic rocks from the Fogo Island batholith, indicating a Late Silurian age. This appears to be an increasingly common geochronologic result for granitic rocks of the Newfoundland Dunnage Zone (Kerr et al. 1992; Fryer et al. 1992).

The present article summarizes current ideas and conclusions from an ongoing study. Field, petrographic, and geochemical data obtained from rocks exposed on the western portions of Fogo Island indicate (*i*) a petrogenetic link through fractional crystallization for the various silicic igneous units exposed west of approximately 54°12′W longitude (Fig. 1); (*ii*) a transition from granites of dominantly I type to microgranites of A type; and (*iii*) that a temporal link between the mafic and silicic magmas appears likely, although no geochemical link is yet established.

Lithologies

Host rocks of the Fogo Island batholith comprise two sedimentary–volcanic packages dominating the northwestern and southwestern regions of the island. The northern package, belonging to the Brimstone Head and Fogo Harbour formations, consists of an interbedded sequence of ash-flow tuffs and volcanogenic sediments, and the volcanogenic sandstones and intercalated shaley sedimentary rocks of southwest Fogo Island have been correlated with the South End Formation of the nearby Change Islands (Eastler 1969).

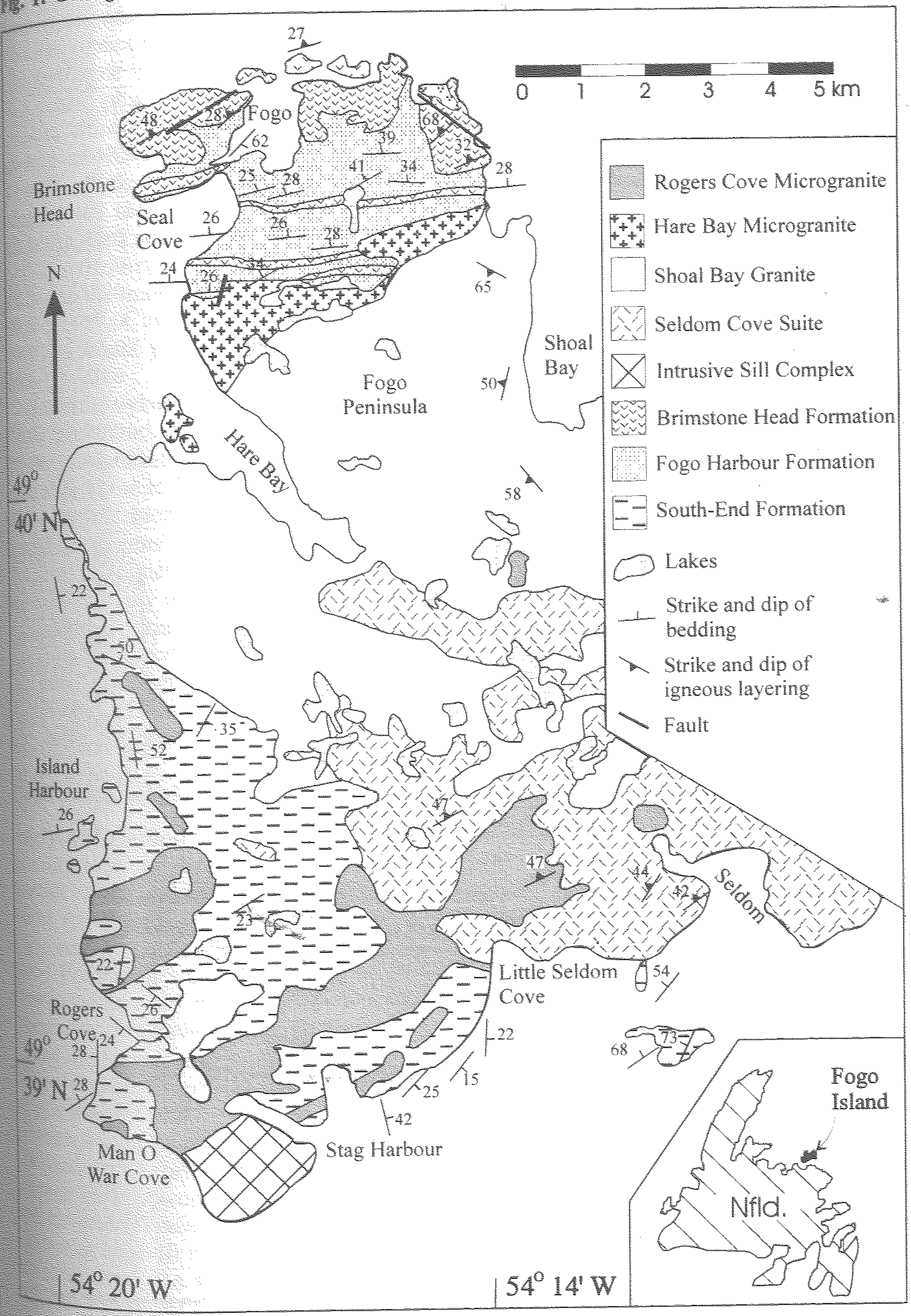
Volcanic units

Volcanic rocks include thin horizons (≤20 m) of strongly welded ash-flow tuff in massive volcanogenic sandstone comprising the Fogo Harbour Formation. Directly overlying them, in a conformable relationship, is a resistant unit (≤100 m) of welded ash-flow tuffs named the Brimstone Head Formation (Baird 1958). Both formations typically dip approximately 25–40° northwards, away from intrusive rocks of the Fogo Island batholith. Volcaniclastic rocks of the Brimstone Head Formation consist of three distinct facies of ash-flow tuff: a moderately welded, devitrified basal and lower–middle facies, a strongly welded upper–middle facies containing abundant lithophysae, and an unwelded upper facies dominated by pyroclastic breccia. These three facies are considered to form a single thick cooling unit. The Brimstone Head Formation typically consists of rare, broken phenocrysts (<0.2 mm) of quartz and alkali feldspar in a cryptocrystalline, devitrified groundmass of strongly silicic composition. Fiamme are rare and are replaced by irregular lensoid patches of intergrown quartz, alkali feldspar, and rare amphibole. Thin layers of ash-flow tuff, interbedded with volcanogenic sedimentary rocks of the Fogo Harbour Formation, are similar in petrography, mineralogy, and chemistry to the ash flows of the Brimstone Head Formation, and together record the earliest volcanic activity on Fogo Island.

Plutonic units

We divide the granitic rocks of the Fogo Island batholith into three distinct units on the basis of their petrology, each showing a variety of textures indicative of epizonal crystallization. The preponderant unit, the Shoal Bay granite (new term), consists of variably textured, generally medium-grained biotite–hornblende granodiorite–syenogranite, which dominates the north and north-central portions of the island. This granite contains euhedral, prismatic plagioclase, commonly

Fig. 1. Geological map of western Fogo Island.



mantled by granophyric intergrowths, and anhedral, perthitic feldspar intergrown with anhedral quartz having undulatory extinction. Biotite and blue-green amphibole are rare, and modal biotite decreases, whereas amphibole increases towards the northern and western contacts with the volcanic–sedimentary packages. Other minerals present include apatite, zircon, and magnetite.

To the north and west, the Shoal Bay granite grades into the Hare Bay microgranite (new term). This unit appears to be a chilled variety of the Shoal Bay granite and, at the contact with the Fogo Harbour Formation, is characterized by an orange–pink colour, is commonly traversed by thin veinlets (<5 mm in thickness) of amphibole, magnetite, and plagioclase, and contains abundant mafic clots of comparable mineralogy. In thin section, drusy cavities and spherulites are common in a fine-grained groundmass consisting of anhedral blue–green amphibole, quartz, plagioclase, magnetite, zircon, and titanite. The microgranite passes transitionally southward into alkali-feldspar-phyric, amphibole granite and finally into Shoal Bay granite.

The Shoal Bay granite is intruded by the Rogers Cove microgranite (new term), as a series of sills on the southwest

Table 1. Major and trace element geochemistry for the Fogo Island granites and associated ash-flow tuffs of the Fogo Group.

	Shoal Bay granite				Hare Bay microgranite		Rogers Cove microgranite			Ash-flow tuffs		
	F-244	F-469	F-199	F-484	F-531	F-438	F-176	F-88B	F-91	F-9	F-15	F-37
SiO_2 (wt.%)	76.20	76.80	77.20	73.40	77.00	76.50	76.50	76.70	76.90	76.80	77.10	76.80
TiO_2	0.16	0.24	0.12	0.40	0.16	0.24	0.12	0.16	0.16	0.20	0.16	0.24
Al_2O_3	12.40	12.20	11.20	13.20	11.20	11.10	11.10	11.10	11.40	11.80	11.80	11.20
FeO*	1.33	1.94	1.71	2.99	1.53	2.89	2.67	2.53	2.40	1.79	0.95	2.33
MnO	0.03	0.03	0.02	0.05	0.02	0.04	0.04	0.04	0.04	0.03	0.04	—
MgO	0.23	0.28	0.04	0.90	0.07	0.05	0.04	0.06	0.05	0.17	0.20	0.19
CaO	0.92	0.88	0.24	2.06	0.44	0.98	0.56	0.86	0.72	1.12	0.72	0.94
Na_2O	3.88	3.61	3.72	3.84	3.75	4.18	3.71	2.49	3.37	3.56	2.57	3.66
K_2O	4.26	4.18	4.10	3.29	4.27	2.81	3.85	5.03	4.29	3.24	6.02	4.03
P_2O_5	0.02	0.02	0.01	0.02	0.02	0.02	—	—	—	—	—	—
LOI	0.89	0.58	0.72	0.45	0.44	0.39	0.87	1.52	1.04	0.59	0.58	0.52
Total	100.32	100.76	99.08	100.60	98.89	99.20	99.46	100.49	100.37	99.30	100.14	99.91
V (ppm)	—	—	—	25.00	—	—	—	—	—	—	—	—
Cu	—	—	—	—	—	—	—	—	—	34.00	—	—
Pb	44.00	27.00	18.00	22.00	27.00	28.00	19.00	23.00	29.00	35.00	29.00	80.00
Zn	13.00	20.00	17.00	25.00	—	21.00	10.00	—	10.00	82.00	362.00	75.00
Rb	143.00	166.00	130.00	125.00	101.00	63.00	115.00	151.00	112.00	114.00	177.00	117.00
Ba	426.00	441.00	503.00	475.00	602.00	411.00	575.00	653.00	587.00	573.00	1131.00	555.00
Sr	67.00	56.00	57.00	118.00	60.00	105.00	64.00	71.00	102.00	146.00	110.00	80.00
Ga	23.00	22.00	21.00	22.00	—	37.00	21.00	20.00	20.00	22.00	17.00	24.00
Nb	14.00	17.00	18.00	14.00	19.00	18.00	20.00	18.00	21.00	23.00	23.00	18.00
Zr	130.00	184.00	195.00	186.00	278.00	413.00	336.00	315.00	332.00	350.00	289.00	272.00
Y	85.00	84.00	98.00	71.00	61.00	68.00	92.00	92.00	89.00	99.00	90.00	92.00
Th	32.00	28.00	19.00	17.00	34.00	14.00	23.00	28.00	26.00	20.00	24.00	26.00
U	2.00	4.00	5.00	—	4.00	3.00	4.00	—	2.00	7.00	7.00	—
La	36.80	61.40	59.50	50.00	31.60	25.30	57.60	54.80	50.80	—	—	—
Ce	92.50	126.60	126.10	96.50	88.70	68.50	129.10	127.60	117.90	—	—	—
Pr	11.60	13.10	13.90	12.30	10.40	9.10	13.80	13.40	12.00	—	—	—
Nd	45.30	60.30	68.70	53.20	39.50	39.30	66.90	65.80	58.60	—	—	—
Sm	10.00	12.70	16.80	10.80	9.30	9.90	16.20	13.00	13.60	—	—	—
Eu	1.10	0.50	0.60	0.70	1.10	3.00	1.70	1.50	1.50	—	—	—
Gd	9.10	11.50	15.60	11.60	8.80	11.70	13.80	13.90	12.60	—	—	—
Tb	1.80	2.00	2.10	1.80	1.40	2.00	2.30	1.90	2.00	—	—	—
Dy	11.00	13.40	15.50	11.50	9.80	12.40	14.50	14.10	14.10	—	—	—
Ho	2.40	2.30	2.50	2.00	2.20	2.50	2.80	2.70	3.00	—	—	—
Er	7.20	7.60	8.50	6.80	6.40	7.40	9.00	8.30	8.50	—	—	—
Yb	6.90	6.20	6.30	5.60	5.30	5.20	7.60	6.20	6.90	—	—	—
Lu	1.10	1.40	1.40	1.30	0.60	0.90	1.32	1.50	1.60	—	—	—
Total REE	237.00	319.00	337.00	264.00	215.00	197.00	337.00	325.00	303.00	—	—	—
Eu/Eu*	0.35	0.12	0.11	0.19	0.38	0.85	0.34	0.34	0.36	—	—	—
Ce_N/Yb_N	3.41	5.19	5.09	4.38	4.26	3.35	4.32	5.23	4.35	—	—	—

Notes: REE not determined for ash-flow tuffs. —, not detected.

coast of the island. This is an orange–pink, fine-grained hornblende microgranite typified by flow-banding and spherulitic textures. The spherulites consist of acicular intergrowths of quartz, alkali feldspar, and rarely amphibole, are commonly nucleated on phenocrysts of quartz or alkali feldspar, and are enclosed in a micrograhitic groundmass of similar composition. Amphibole typically occurs as anhedral, medium-grained masses closely associated with abundant hematite–ilmenite intergrowths and rare titanite and zircon, but also in veinlets (< 1 mm) with associated magnetite and plagioclase. These mineral clots and veinlets appear to be late-stage crystallization products that fill drusy cavities and crosscut all other features, and are considered products of deuteric crystallization. The Rogers Cove microgranite is therefore interpreted as a fluid-rich, high-level, late-stage magmatic pulse.

The granitic rocks of the Fogo Island batholith clearly intrude a series of mafic rocks, in which they also form small bosses and plugs. These mafic rocks consist of undivided monzodiorites and gabbros belonging to the Seldom Cove suite (new term). They commonly display compositional layering and contain abundant hornfelsed sedimentary xenoliths derived from the local country rocks. Where characterized by cumulate layering, rocks of the Seldom Cove suite contain subhedral plagioclase chadacrysts in ortho- and clinopyroxene oikocrysts. Clinopyroxene is the most abundant mafic phase, but is invariably rimmed by secondary uralite. More evolved examples of the Seldom Cove suite contain amphibole as the dominant mafic phase and up to 5–10% sphene. Micrographic textures indicative of rapidly supercooled rocks become progressively more common to the northwest, suggesting a north- and westward-shallowing of the mafic intrusive complex. Although these rocks may be related to the mafic–ultramafic rocks of eastern Fogo Island (Baird 1958; Cawthorn 1978; Saunders 1990; Aydin et al. 1994), a direct petrochemical link has not yet been established.

Gabbroic dykes and sills of intermediate to mafic composition are found in the vicinity of Stag Harbour (Fig. 1). These are intimately associated with the sheeted micrographic sills of the Rogers Cove microgranite, and the two rock types form a thick, shallow-dipping intrusive complex with abundant screens of hornfelsed sedimentary country rock. Textural relationships, such as globular inclusions of basaltic material in many of the microgranitic sills, and back-veining of basaltic material into microgranite, suggest that magmatic mingling occurred between two coexisting but contrasting magmas. Although similar features have been described by Aydin et al. (1994) from an area on the east coast of Fogo, they have not been documented on a regional scale.

Petrochemistry

Analytical methods

In order to ascertain petrogenetic relationships between the granitic units and their country rocks, samples from the Shoal Bay granite, the Hare Bay microgranite, the Rogers Cove microgranite, and ash-flow tuffs from the Brimstone Head Formation were analysed at Memorial University of Newfoundland for major, trace, and rare earth elements. These analyses have been supplemented by some data presented in Strong and Dickson (1978) where appropriate. Major elements were determined on a Perkin Elmer 2380 atomic absorption spectrophotometer after dissolution of the powdered samples in hydrofluoric acid. Trace elements were obtained by X-ray fluorescence (XRF) spectrometry of pressed rock powder discs on a Phillips P.W. 1450 XRF spectrometer. Trace element determinations were calibrated against at least 10 standard reference materials. Rare earth elements were also analysed by XRF spectrometry using the thin film method of Fryer (1977). Representative whole-rock geochemical analyses are presented in Table 1. Total iron in the samples has been recalculated as ferrous oxide and is given as FeO*.

Mineral compositions were determined at Memorial University using a Jeol JX-5A electron probe microanalyser equipped with three computer-controlled wavelength dispersive spectrometers. Kakanui augite was used as a primary mineral standard for all analyses, and analytical data were checked against appropriate standard reference minerals.

Major and trace elements

The samples range in SiO_2 content from 68 to 78.5 wt.% (hydrous) and vary in composition from tonalite to monzogranite. The volcaniclastic rocks are rhyolitic grading to alkali rhyolitic. Ash-flow tuffs are highly silicic and because of their recrystallized nature and scattered geochemical trends (see below) are inferred to have undergone deuteric alteration during cooling. We present Harker variation diagrams for both the granitic and volcanic rocks of western Fogo Island (Fig. 2). Most elements have somewhat scattered curvilinear trends and there is extreme enrichment of FeO*, Zr, and Nb in the most silicic end members. There is some scatter of the data but the general trends, mineralogic and compositional similarities of the various rock units, and the geochemical coherency of each rock type suggest that all could be petrogenetically linked through crystal–liquid fractionation mechanisms. The extreme enrichment of FeO* and the high field strength elements (HFSE) Nb, Zr, and Y and the rare earth elements in the most silicic rocks, as emphasized in Fig. 3, may in part be attributed to deuteric processes involving separation of an alkali-rich fluid from the crystal-rich melt at the terminal stage of crystallization. The "early" magmatic trends exhibited by the Shoal Bay granites are not significantly changed by the introduction of the fluid, but we acknowledge that redistribution of many elements may have occurred, resulting in scattering of the geochemical data and poorly defined fractionation trends. Strong FeO*-enrichment trends observed in the granitic rocks are supported by the amphibole and biotite compositions. Amphiboles are generally hastingsitic hornblendes but span the range from ferrohornblende through ferro-edenitic hornblende to hastingsite (s.st.) (Leake 1978). Amphiboles are chlorine-rich, particularly those in the microgranitic rocks, which contain up to 1.75 wt.% Cl, suggesting that they have crystallized from a Cl-rich fluid. Biotites are annitic (FeO*/ FeO* + MgO = 0.64–0.79) and enriched in FeO and impoverished in Al^{iv} compared with biotites from typical calc-alkaline intrusive rocks.

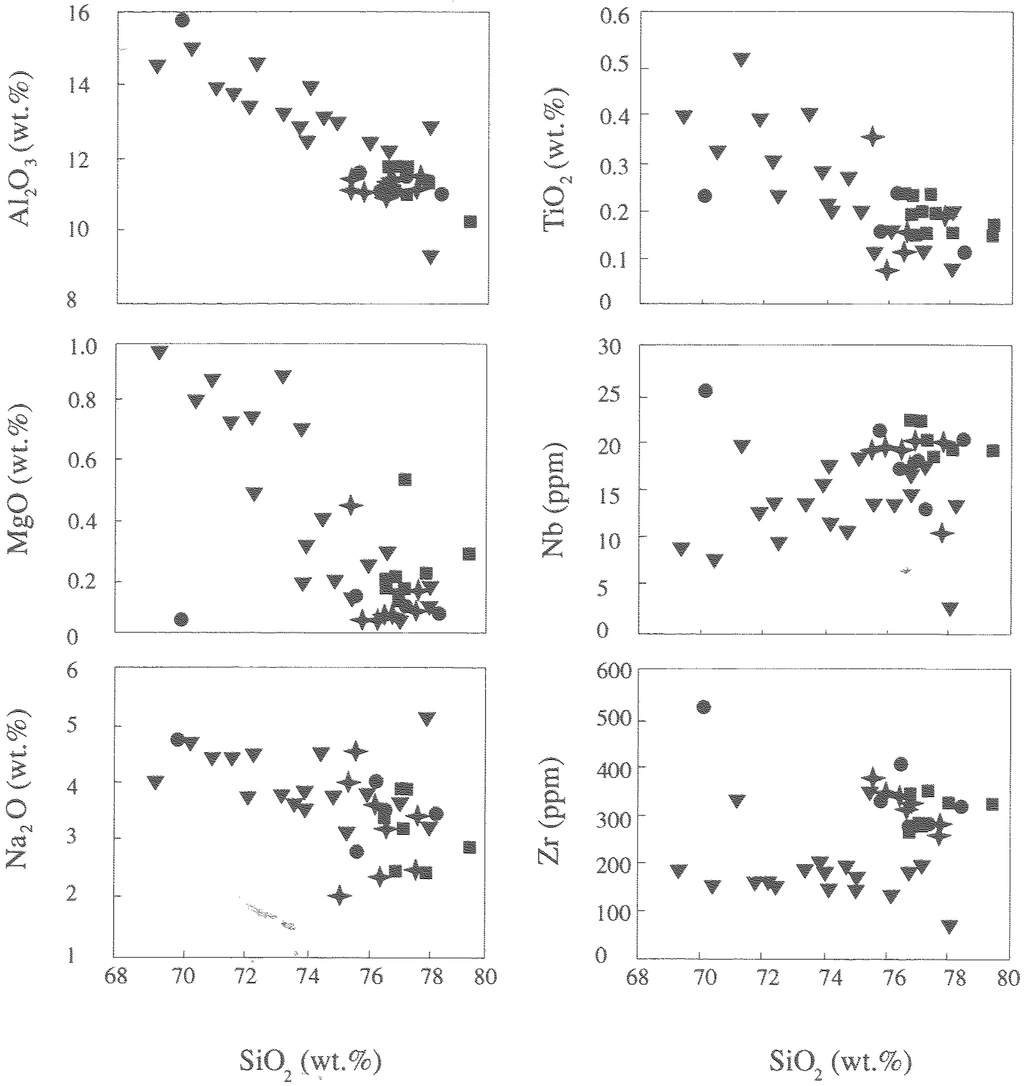
The data suggest that the volcaniclastic rocks in general might be chemically equivalent to the most silicic examples of Shoal Bay granite, or, conversely, the least felsic examples of the two microgranite suites, although this is not conclusive. The volcaniclastic rocks are somewhat more potassium enriched than most of the granitic rocks.

Log–log plots of Sr–Ba–Rb (Fig. 4) demonstrate that combined fractionation of plagioclase and alkali feldspar with less significant separation of amphibole best account for the trends exhibited by the Shoal Bay granites. The trends of the micrographic suites are difficult to interpret, and consistent element–element variations are not observed, indicating that mobilization and redistribution of these elements has occurred. Preferential removal of amphibole in the latter stages of differentiation would essentially counteract the element–element trends resulting from removal of the feldspars. This may explain in part the scattered trends shown by the microgranitic suites.

Rare earth elements

In Fig. 5, we have plotted rare earth element (REE) data for representative samples of the three varieties of granite. REE patterns for two samples of each rock unit define tight groupings, thereby discriminating the granite types. Also shown are the patterns for one specimen of Mount Peyton granite (CD-66; Strong and Dupuy 1982) and one sample of amphibole granite from the Topsails intrusive suite (TB83; Whalen

Fig. 2. Selected major and trace element Harker variation diagrams for the Fogo Island granites and associated volcanic rocks. Triangles, Shoal Bay; stars, Rogers Cove; circles, Hare Bay; squares, ash-flow tuffs.



and Currie 1990). Note the depleted abundances of the REE in the Mount Peyton granite and the slightly enriched REE contents of the specimen of amphibole granite from the Topsails suite relative to the Fogo Island granites.

The Shoal Bay granites are characterized by intermediate REE contents where light rare earth elements (LREE) values are 100× chondrite, and heavy rare earth element (HREE) contents are 30–40× chondrite. These rocks are typified by $Ce_N/Yb_N = 3.4-5.2$ and have large Eu anomalies as indicated by $Eu/Eu^* = 0.11-0.35$, where Eu* represents the value for Eu interpolated from Sm and Gd concentrations.

The REE data are more supportive of the conclusion that the granitic units are related through fractional crystallization. Specimens of Rogers Cove microgranite are enriched in all REE (Σ REE = 303–380 ppm) relative to Shoal Bay granites (Σ REE = 237–337 ppm). They are characterized by $Ce_N/Yb_N = 4.3-5.2$, values that are comparable to those for the Shoal Bay granites, and by $Eu/Eu^* = 0.25-0.36$. These observations are in agreement with field evidence that indicates that the Rogers Cove microgranite represents a late pulse of silicic magma within which feldspar fractionation may have slowed and (or) amphibole fractionation increased, giving rise to Eu/Eu* typically greater than those for the Shoal Bay granites.

Samples of Hare Bay microgranite typically have lower combined REE contents (Σ REE = 197–215 ppm) with lower $Ce_N/Yb_N = 3.4-4.3$. Eu/Eu* values are highly variable for individual intrusive bodies, suggesting variable degrees of feldspar fractionation in localized zones of crystallization and (or) a more significant effect of amphibole fractionation.

Tectonic setting and petrogenesis

In the geochemical classification of granitoids, two major schemes are utilized: Barbarin (1990) classifies granitoid rocks on the basis of their source region and defines three main groups corresponding to a crustal (C type), a mantle (T type), or a mixed source (H type). Chappell and White's (1974) classification considers granitoid rocks to be dominantly of crustal origin and defines I- and S-type granites,

Fig. 3. SiO_2 and Zr plotted against FeO*/MgO. Note the extreme enrichment of FeO* in the Rogers Cove microgranite and the Hare Bay microgranite and less so in the volcanic rocks. Symbols as in Fig. 2.

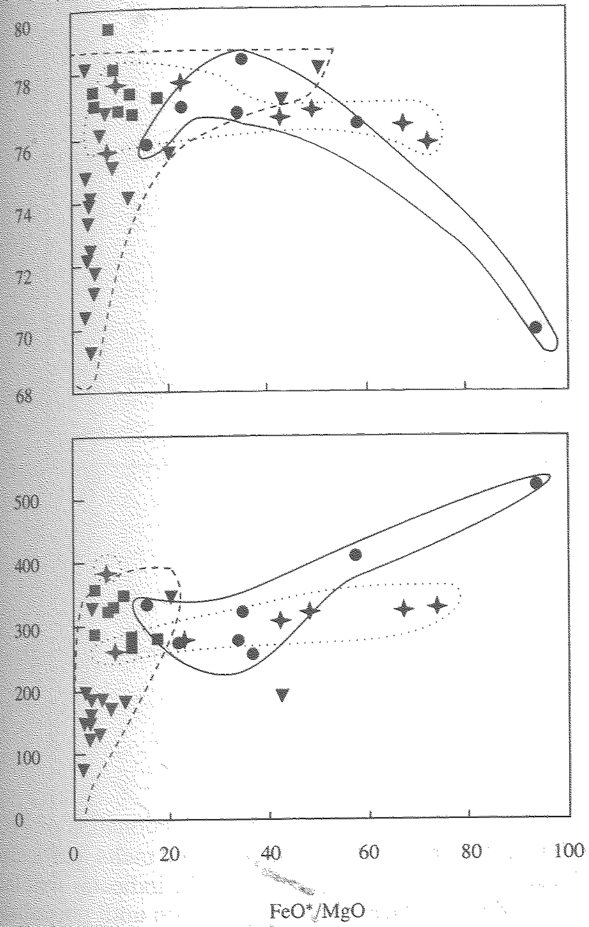
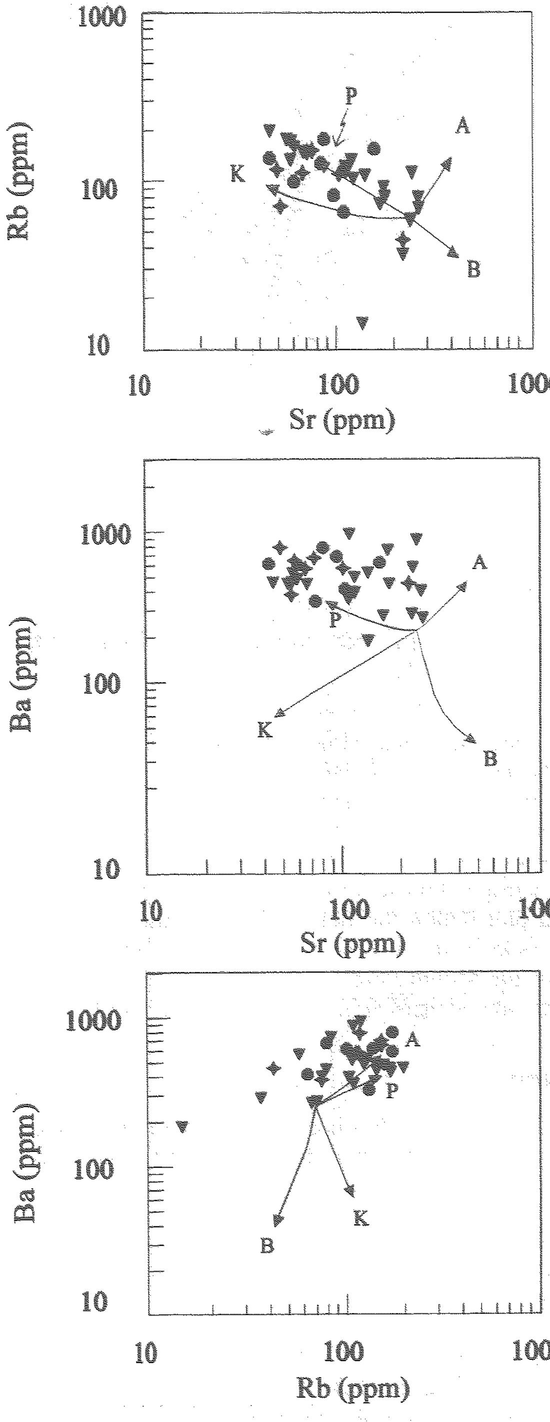


Fig. 4. Log–log plots of Rb vs. Sr, Ba vs. Sr, and Ba vs. Rb for granitic rocks of the Fogo Island batholith. Arrows represent 50% total-equilibrium fractional crystallization of the respective minerals from a parental magma having a composition corresponding to specimen 155 from Strong and Dickson (1978). The initial elemental concentrations were as follows: Rb = 66 ppm, Sr = 265 ppm, Ba = 258 ppm. Symbols as in Fig. 2.

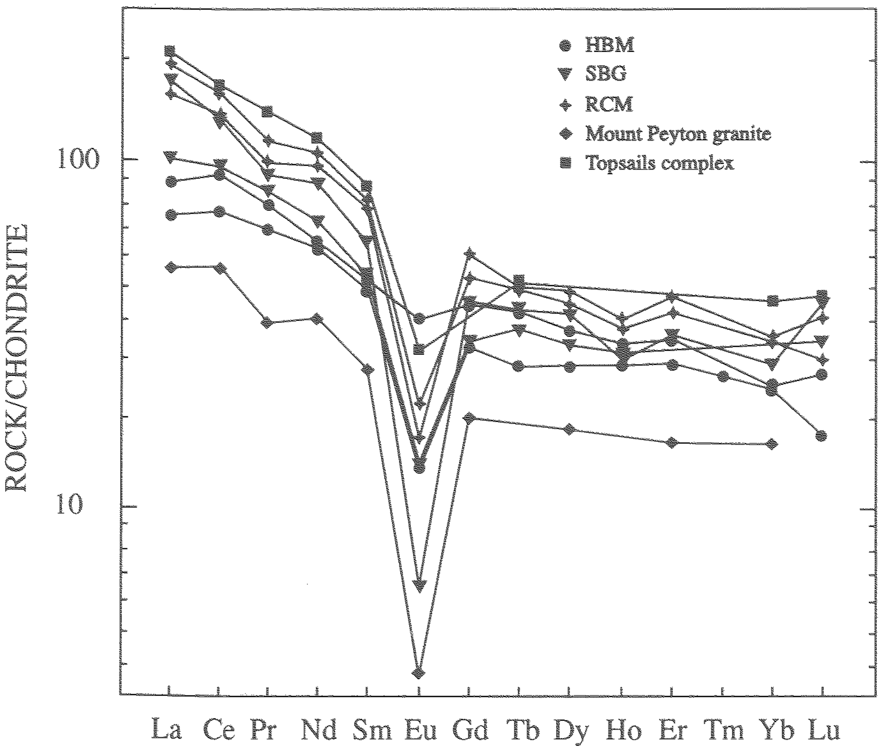


which were extracted from igneous and sedimentary protoliths, respectively. This classification has been extended by adding an M type for the most calc-alkaline plagiogranites and an A type for anorogenic granites thought to result from partial melting of granulitic residue after extraction of an orogenic granite (e.g., Whalen et al. 1987).

In Fig. 6, analyses of granitic rocks of the Fogo Island batholith are plotted in the tectonic discrimination diagrams of Pearce et al. (1984). Analyses of Shoal Bay granites plot as volcanic-arc granites (VAG) or within-plate granites (WPG), but samples of the Hare Bay and the Rogers Cove microgranites plot as WPG. When plotted in the tectonic discrimination diagrams of Maniar and Piccoli (1989), the granites of the Fogo Island batholith plot as postorogenic granites (POG), and continental epeirogenic granites (CEUG), essentially corroborating the conclusions drawn from the plots of Pearce et al. (1984). The Fogo Island granites are clearly not fully developed, rift-related granites, but are distinct from calc-alkaline I-type granitoids.

These conclusions are further corroborated using the discriminant criteria of Whalen et al. (1987) (Fig. 7). It is evident that the Fogo Island granites, and in partiçular the Hare Bay and Rogers Cove micrograntes, are enriched in Ga relative to Al and have elemental abundances typical of A-type anorogenic granitoids. Fields for the alkaline rocks of the Topsails igneous complex (Whalen 1989; Whalen and Currie 1990) and for the Mount Peyton granites (Strong and Dupuy 1982) are also indicated. Of the three units making up the

Fig. 5. Chondrite-normalized (values from Sun 1982) rare earth element diagram for six granitic specimens from western Fogo Island. These are compared to one sample of Mount Peyton granite (Strong and Dupuy 1982) and one sample of amphibole granite of the Topsails igneous complex (Whalen and Currie 1990). HBM, Hare Bay microgranite; SBG, Shoal Bay granite; RCM, Rogers Cove microgranite.



Fogo Island batholith, the Shoal Bay granites have the lowest Ga/Al ratios and are most similar to typical I- or S-type granites. The ash-flow tuffs of the Fogo Group are again comparable to the most fractionated examples of the Shoal Bay granites.

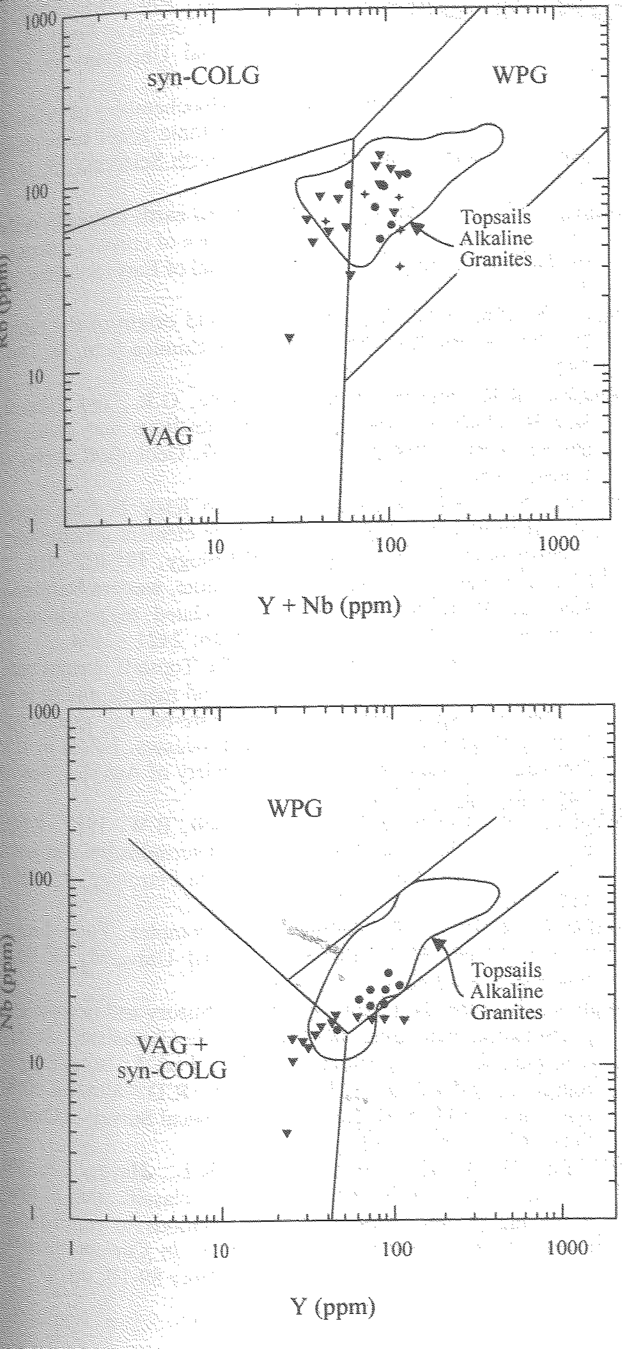
The Rogers Cove and Hare Bay microgranites have Ga/Al ratios that correspond most closely to those of typical A-type granites and plot within the field defined by the alkaline–peralkaline rocks of the Topsails complex. In contrast, granitic rocks of the Mount Peyton batholith have Ga/Al ratios and elemental abundances typical of I-type granitoids.

Discussion

The Fogo Island batholith has been quoted as an example of the widespread Siluro-Devonian plutonism prevalent in the Appalachian–Caledonian Orogen. However, the field, petrographic, and geochemical data presented here demonstrate the anorogenic, alkaline nature of the granites of Fogo Island, and distinguish them from typical I-type, calc-alkaline granites of the Mount Peyton batholith, with which the Fogo Island granites have been previously directly compared (Strong and Dickson 1978; Williams et al. 1989). This distinction is supported by major, trace, and REE data that demonstrate the geochemical evolution of the Fogo Island granites as a function of dominantly plagioclase and then alkali-feldspar (perthite) fractionation with a significant contribution from amphibole, most critically at times during crystallization when the residual melt reached the period of major deuteric activity. The extreme fractionation of FeO*, Zr, Nb, and Y into the late-stage, evolved melts, particularly in localized regions of "trapped" melt, indicates that these elements did not reach effective saturation until immediately prior to final quenching of the magma. Stabilization of Zr and comparable HFSE in magmas has been discussed by Watson (1979) with reference to highly peralkaline melts, and it may be that similar conditions commonly arise in the A-type granite suite. Whether A-type granites exist as a distinct class is not clear from this investigation, but it is certain that some granites having A-type characteristics may be formed through progressive fractionation of less specialized, I-type, calc-alkaline parents. In rocks of the Fogo Island batholith, an increase in alkalinity during fractionation is most strongly associated with development of fine-grained micrograntic rocks having textures indicative of deuteric or autometasomatic processes.

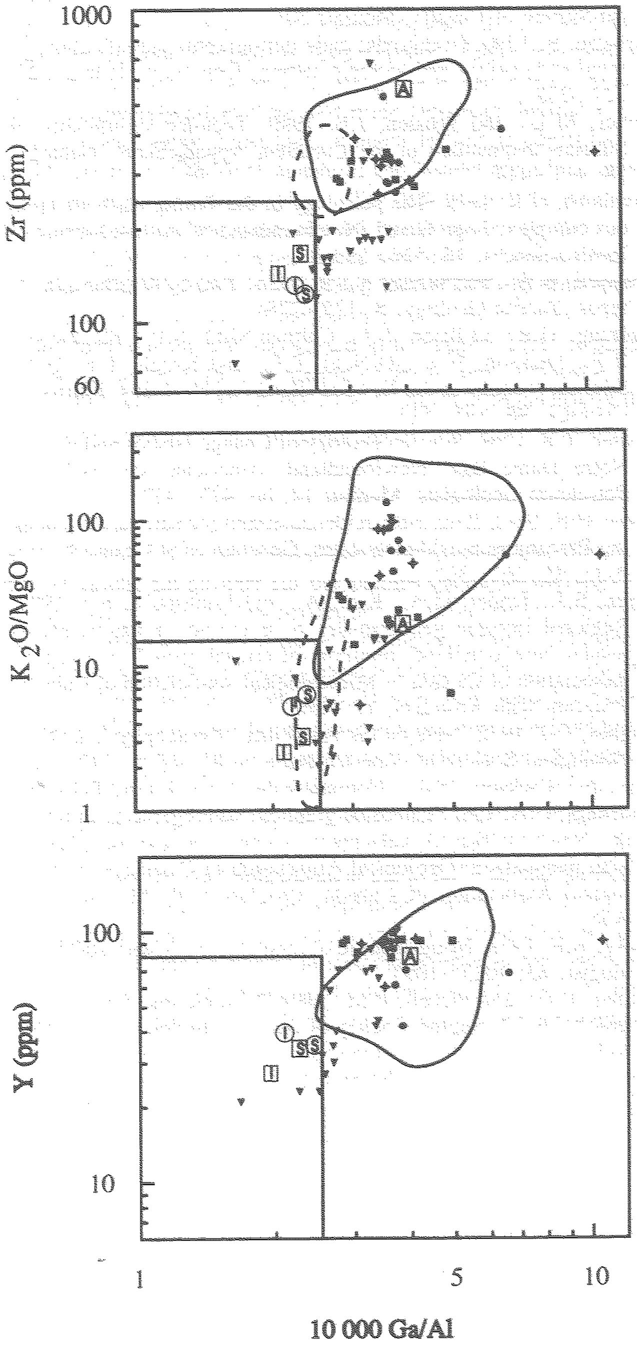
The geographic separation and inherent difficulties in correlating lithostratigraphic and tectonic elements between Fogo Island and mainland Newfoundland adds significantly to problems of interpreting the tectonic setting of the Fogo Island batholith. These rocks are located in the Botwood belt of the Dunnage Zone (Exploits subzone), within the northeasternmost extremity of the North American Appalachians, a region described by Williams et al. (1989), Fryer et al. (1992), and Kerr et al. (1992) as characterized by a complex suite of Siluro-Devonian magmatic rocks, probably derived from ensialic (no direct input from subduction of oceanic crust) melting during tectonic thickening of the Central

Fig. 6. Tectonic discrimination diagrams of Rb vs. Y + Nb and Nb vs. Y after Pearce et al. (1984). Symbols as in Fig. 2.



Mobile Belt (CMB). This is considered to have occurred well after final closure of Iapetus at ca. 470 Ma. The bimodal gabbro–granite complexes can be considered the result of delamination of the lithosphere during crustal thickening, subsequent material and thermal input from mantle-derived melts, and concomitant crustal melting. On the basis of geochemical and isotopic data, it has been argued that the strong geographic zonations of Devonian intrusive suites reflect the preclosure structure of the CMB, and that the igneous suites owe their contrasting geochemical signatures to characteristic lower crustal blocks from which they were derived.

Fig. 7. Discriminant plots after Whalen et al. (1987) comparing the Fogo Island granites with fields for the Topsails alkaline granites (solid lines) and the Mount Peyton granites (broken lines). Also plotted are average compositions for A-, S-, and I-type granites (within squares) and average compositions for fractionated S- and I-type granites (within circles). Data for the Mount Peyton granites are from Strong and Dupuy (1982), and data for the Topsails granites are from Whalen et al. (1987), Whalen (1989), and Whalen and Currie (1990). Symbols as in Fig. 2.



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