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[See table of contents](#)

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Article abstract

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Earliest Silurian supra-subduction magmatism in central Cape Breton Island

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The Skye Mountain pluton intruded the Late Proterozoic Bras d'Or Gneiss in the Creignish Hills of central Cape Breton Island. It is composed of amphibole-bearing mafic rocks (gabbro and diorite) with quartz diorite occurring in the northern portion. U-Pb isotopic analyses of zircon give an age of 438 ± 2 Ma, i.e., earliest Silurian. The rocks are calc-alkaline with mantle-normalized patterns characterized by high LILE/HFSE (large-ion-lithophile elements/high-field-strength elements) ratio and pronounced negative Nb anomalies. The pluton is inferred to have intruded a supra-subduction zone setting. As such, it represents a southern extension of an Early Silurian arc that extends along the axis of the Cape Breton Highlands. These calc-alkaline rocks contrast with contemporaneous, tholeiitic rift-related volcanism that occurs in the Antigonish Highlands. A possible tectonic setting that explains both these suites suggests that oblique, sinistral south-dipping subduction began north of Cape Breton Island and changed westwards into a sinistral transform boundary, which induced rifting in mainland Nova Scotia.

Le pluton du mont Skye fait intrusion dans le gneiss du protérozoïque tardif de Bras D'Or des collines Creignish, dans le centre de l'île du Cap-Breton. Il est constitué de roches mafiques amphibolifères (gabbro et diorite) accompagnées de diorite quartzique dans la partie septentrionale. Des analyses isotopiques au U-Pb du zircon le situent à 438 ± 2 Ma, c.-à-d. à la fin du Silurien précoce. Les roches sont des roches calco-alcalines présentant des structures normalisées mantéliques caractérisées par un rapport élevé d'ELGI/EICE (éléments lithophiles à gros ions/éléments à intensité de champ élevée) et par des anomalies négatives de Nb prononcées. On suppose que le pluton fait intrusion dans le cadre d'une zone de supra-subduction. Il représente comme tel un prolongement méridional d'un arc du Silurien précoce qui s'étend le long de l'axe des hautes-terres du Cap-Breton. Ces roches calco-alcalines font contraste avec le volcanisme tholéiitique contemporain lié à une fracture qui est survenu dans les hautes-terres d'Antigonish. Une compaction tectonique possible expliquant ces deux cortèges laisse supposer que la subduction oblique sénestre inclinée vers le sud a commencé au nord de l'île du Cap-Breton et s'est transformée vers l'ouest en une marge de cisaillement sénestre qui a produit une distension continentale dans l'intérieur de la Nouvelle-Écosse.

[Traduit par la rédaction]

INTRODUCTION

The Late Ordovician and Early Silurian represent a critical time during the last stages of the closure of the Iapetus ocean. Magmatism forms an integral part of this geological record along the southeastern side of Iapetus in the Canadian Appalachians (Figs. 1, 2). Here, Early Silurian magmatism varies from calc-alkaline arc rocks in southern Newfoundland and the Cape Breton Highlands to tholeiitic rift-related rocks in the Antigonish and Cobequid Highlands (Keppie *et al.*, 1979, 1992; Dunning *et al.*, 1990a and b; Barr and Jamieson, 1991). This variation has been interpreted as an oblique subduction boundary in the northeast that became a sinistral transform boundary to the southwest (Keppie *et al.*, 1992), however, other interpretations are possible. For example, the calc-alkaline-tholeiitic transition could represent a change from an arc to a backarc environment with interfingering of magmatic types at the boundary. Unfortunately, a gap in Early Silurian rocks occurs between the Cape Breton Highlands and the Antigonish Highlands. The Skye Mountain pluton

lies in the middle of this gap thereby providing an important link between the two magmatic provinces.

GEOLOGICAL SETTING

The Canadian Appalachians have been subdivided into a number of zones or terranes which record the passing of Iapetus (Fig. 1) (Williams, 1978; Williams and Hatcher, 1982; Keppie, 1985; Keppie *et al.*, 1997): (1) Humber Zone marks the Laurentian margin of Iapetus; (2) Dunnage Zone (Notre Dame and Exploits terranes) preserves vestiges of Iapetus; (3) Gander Zone or Terrane is interpreted as the continental rise prism bordering the southeastern margin of Iapetus; (4) Avalon Zone or Composite Terrane represents a microcontinental block derived from the southeastern margin of Iapetus; and (5) the Meguma Zone or Terrane is inferred to be a continental rise prism deposited along the southeastern margin of the Avalon microcontinent.

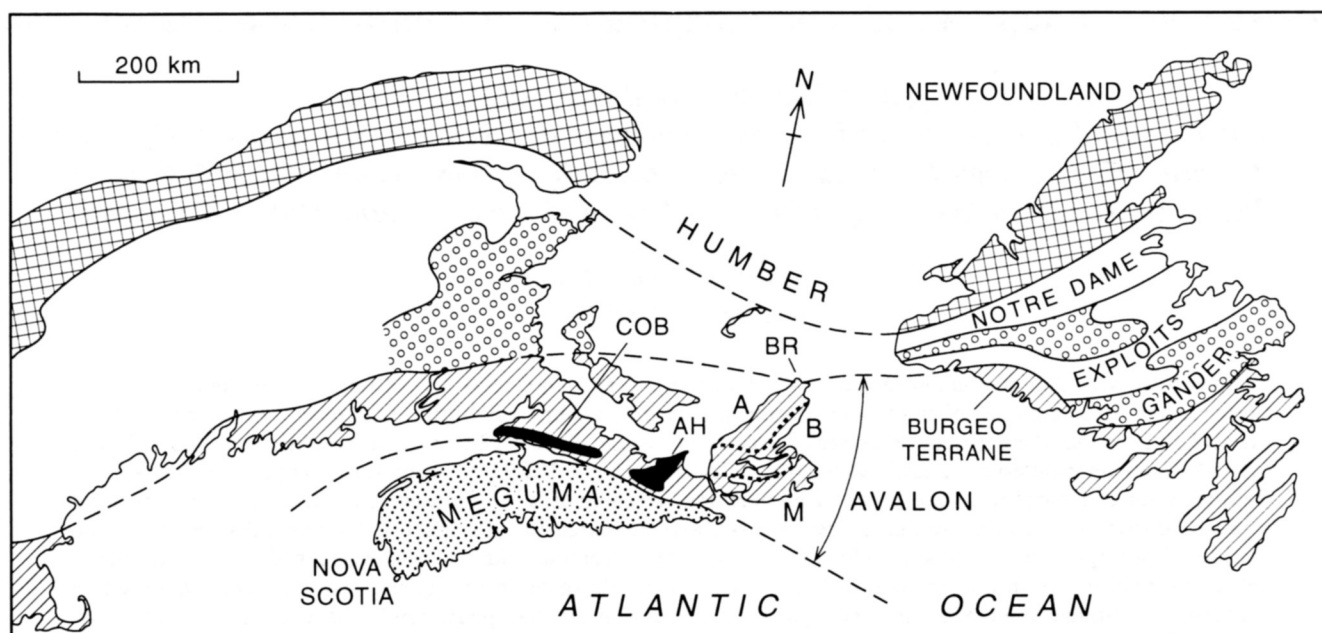


Fig. 1. Terrane map of the northern Appalachians modified from Keppie *et al.* (1998). Humber: cross hatched; Notre Dame and Exploits: blank; Gander: circles; Avalon: diagonal lines; Meguma: dotted. (M = Mira Terrane; B = Bras d'Or Terrane; A = Aspy Terrane; BR = Blair River Terrane; AH = Antigonish Highlands; COB = Cobequid Highlands.)

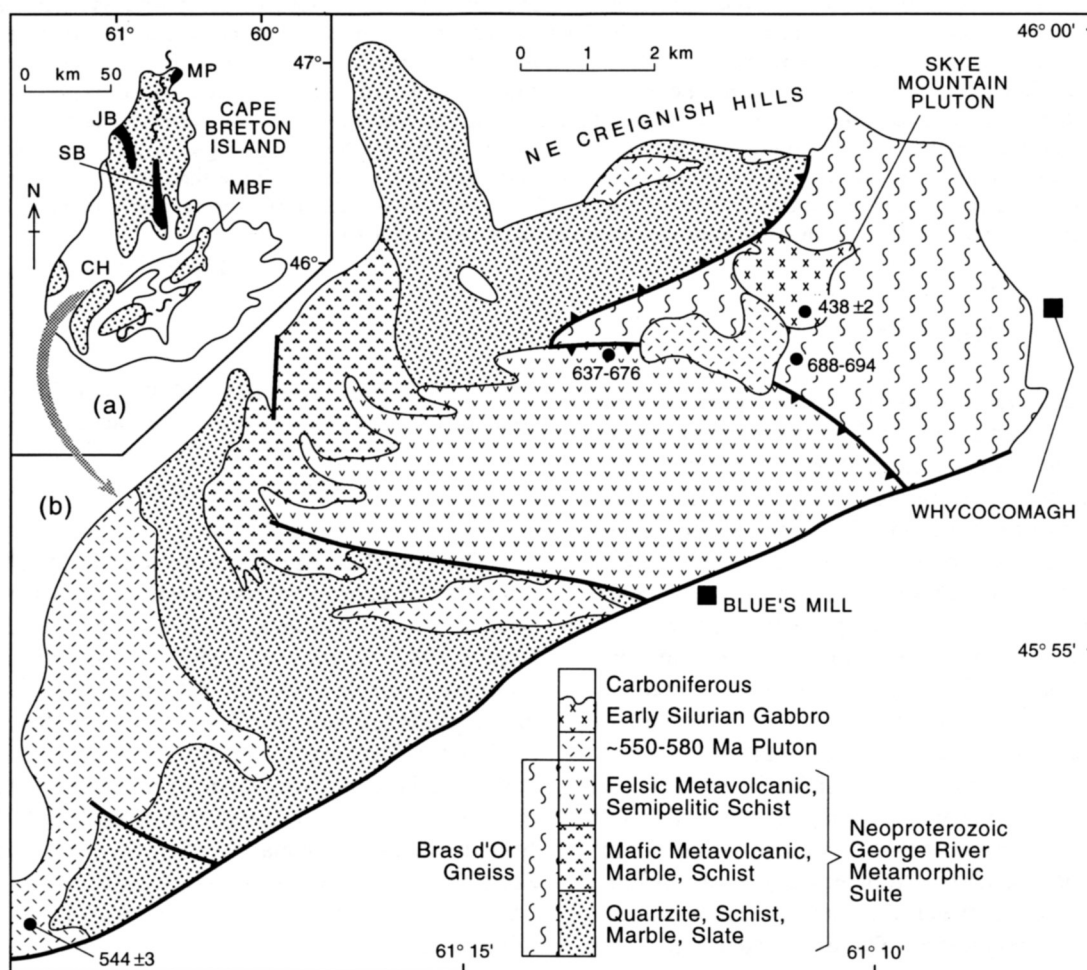


Fig. 2. (a) Map of Cape Breton Island showing highland areas (dotted) and Early Silurian volcanic rocks (black: MP = Money Point Group; JB = Jumping Brook Metamorphic Suite; SB = Sarach Brook Metamorphic Suite; CH = Creignish Hills; MBF = McMillan Brook Fault) (b) Geological map of the Creignish Hills showing selected age dates (after Keppie *et al.*, 1998).

The Skye Mountain pluton is roughly circular about 1.5 km in diameter (Fig. 2b), and intruded the high-grade Late Proterozoic Bras d'Or Gneiss at the northeastern end of the Creignish Hills. Exposure is limited to a north-south river section and a few isolated outcrops. The pluton is undeformed and cuts across the structural fabrics in the gneisses. In southern Cape Breton Island, the Bras d'Or Gneiss is unconformably overlain by Cambrian–Ordovician rocks typical of the Avalon overstep sequence (Keppie, 1989; White *et al.*, 1994). Volcanogenic gneiss just south of the pluton has yielded nearly concordant U–Pb zircon ages between 688 ± 3 and 694 ± 1 Ma (Keppie *et al.*, 1998), whereas from the same location $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite from gneiss gave a plateau age of 449 ± 7 Ma, and from a pegmatite yielded a discordant spectrum that decreases from ~485 to 450 Ma (Dallmeyer and Keppie, 1993).

PETROGRAPHY

The Skye Mountain pluton is composed of mafic rocks which pass locally into quartz diorite along its northern part. The mafic rocks have colour indices typically ranging between 45 and 30, whereas the quartz diorites have indices between 30 and 20. The mafic rocks are medium- to coarse-grained, hypidiomorphic but commonly non-equigranular. The gabbro-diorite is composed of plagioclase, amphibole and minor biotite with accessory zircon, sphene, apatite, ilmenite, magnetite, pyrite and hematite; epidote and calcite generally occur as fine veinlets. The quartz diorites differ in having a higher content of plagioclase, a minor amount of quartz and a higher proportion of biotite relative to amphibole. The rocks were affected by low-grade metamorphism which saussuritized the plagioclase and converted amphibole and biotite to chlorite (Horton, 1994).

Plagioclase, the most abundant phase in both lithologies, forms crystals typically about 1 mm in size, although locally it reaches up to 5 mm. Although plagioclase is generally altered, the complex oscillatory zoning is still discernable.

The composition of the unaltered grains ranges between An_{32} and An_{58} . Amphibole is the dominant ferromagnesian phase occurring as stumpy prismatic subhedral crystals. All are calcic amphiboles and according to the classification of Leake (1978) correspond to magnesio-hornblende. Biotite (<10%) is Ti-rich (typically 3.5–4% TiO_2) with X_{Mg} ranging from 0.45 to 0.55 (Horton, 1994). Quartz is generally anhedral in shape and exhibits undulose extinction. Apatite, zircon, magnetite, and ilmenite represent the magmatic accessory phase assemblage in the pluton. Apatite and zircon are typically enclosed or in contact with ferromagnesian minerals. Opaque phases include magnetite, ilmenite and pyrite which generally occur adjacent to hornblende and biotite. Although most epidote is secondary, some epidote might be a primary phase as it is commonly enclosed within hornblende and biotite and is generally subhedral.

ANALYTICAL TECHNIQUES

Zircon was separated from a 20 kg crushed sample and analyzed using standard procedures at the Royal Ontario Museum (Krogh and Keppie, 1990). Results are given in Table 1 and plotted on Figure 3. Errors in Table 1 are given at 1 sigma, whereas error ellipses in the figure are plotted at 2 sigma. Regressions are calculated using the program of Davis (1982) and the age errors are quoted at 95% confidence levels.

The major and several trace element (Rb, Ba, Sr, Y, Zr, Nb, Ga, Pb, Zn, Cr and Ni) analyses of twenty samples (detailed locations available from the authors) were determined by X-ray fluorescence at the Regional Geochemical Centre, Saint Mary's University, using a Philips PW1400 spectrometer. Reproducibility of the trace elements is about 1 to 5% (Dostal *et al.*, 1986). In addition, eight samples were analyzed for rare-earth elements (REE), Th and Hf by ICP-MS at the Department of Earth Sciences of Memorial University of Newfoundland. Reproducibility is estimated to be better than 5%.

Table 1. U–Pb isotopic data on abraded zircon fractions from the Skye Mountain pluton.

No.	Fraction	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	1 sig	$^{207}\text{Pb}/^{235}\text{U}$	1 sig	$^{207}\text{Pb}/^{206}\text{Pb}$ Age (Ma)	1 sig	% Disc.
CN243Z Skye Mountain gabbro													
1	17 eq & elong zr	0.060	247.0	0.67	4.2	865.2	0.06973	0.00019	0.5353	0.0014	439.5	2.6	1.2
2	3 largest zr	0.040	196.2	0.71	3.5	556.3	0.06913	0.00017	0.5318	0.0009	444.1	4.8	3.1
3	23 best zr	0.050	147.7	0.66	1.4	1367.5	0.06993	0.00010	0.5365	0.0009	438.3	1.4	0.6
4	15 zr, cracks	0.050	118.7	0.68	0.8	1899.2	0.06956	0.00015	0.5337	0.0012	438.3	1.6	1.1

Errors are given at 1 sigma.

zr - zircon grain; eq - equant; elong - elongate.

Pbcom - Common Pb, assuming all has blank isotopic composition.

Th/U calculated from radiogenic $^{208}\text{Pb}/^{206}\text{Pb}$ ratio and $^{207}\text{Pb}/^{206}\text{Pb}$ age assuming concordance.

% Disc. - percent discordance for the given $^{207}\text{Pb}/^{206}\text{Pb}$ age.

Decay constants are from Jaffey *et al.* (1971).

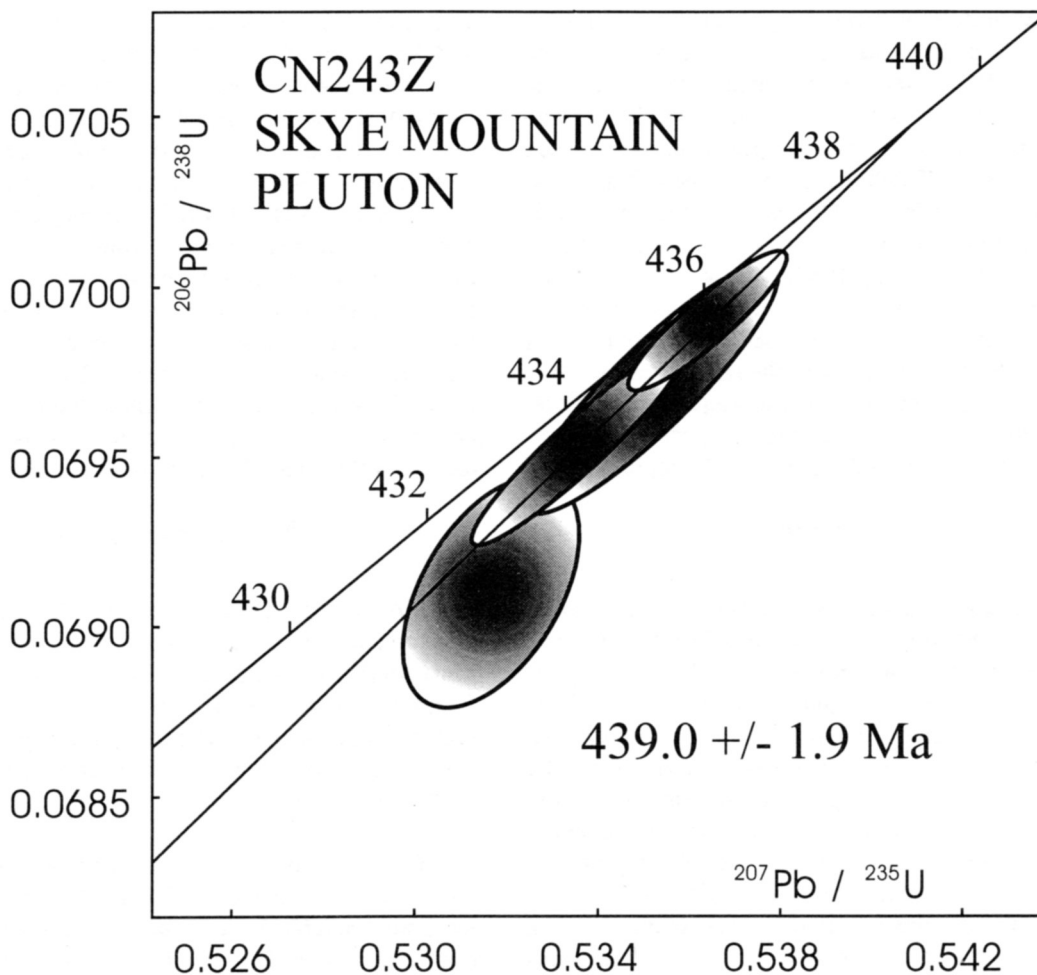


Fig. 3. Concordia plot of the U-Pb isotopic data from the Skye Mountain pluton.

AGE

Four zircon fractions were analyzed from the Skye Mountain pluton (Fig. 3, Table 1), three of which are nearly concordant and define an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 439.0 ± 1.9 Ma (91% probability of fit). The oldest $^{206}\text{Pb}/^{238}\text{U}$ age is 436 ± 1 Ma, which provides a younger limit on the time of crystallization. Thus, the crystallization age is 438 ± 2 Ma. Using the Time Scale of Okulitch (1995), this age falls in the Llandoveryan Epoch near the Silurian–Ordovician boundary at 441 ± 2 Ma. The southern edge of the Skye Mountain pluton is ~1 km from the dated muscovite samples (Dallmeyer and Keppie, 1993), which may explain their anomalously young ages.

GEOCHEMISTRY

Although the rocks were affected by secondary processes including low-grade metamorphism, it appears that the abundances of most major and trace elements were not significantly modified and retain their magmatic distribution. The rocks have a range of silica contents from 49 to 59% (Table 2, Fig. 4), with most samples falling within a narrow interval of 50 to 56% (LOI-free).

The mafic rocks of the pluton display subalkaline characteristics (Fig. 4) and are calc-alkaline (Fig. 5). Their chondrite-normalized REE concentrations (Fig. 6) have similar, moderately fractionated patterns [$(\text{La}/\text{Yb})_n = 3\text{--}6$; mostly 3–5] and small but variable Eu anomalies. The samples with lower absolute concentrations of REE display small positive Eu anomalies, whereas the sample with the highest REE contents has a small negative Eu anomaly. These variations are consistent with crystallization and accumulation of the major mineral phases present in the rocks: hornblende and plagioclase. Several rocks, such as sample 249, were affected by an accumulation of hornblende as reflected by their REE patterns (Fig. 6).

The mantle-normalized profiles are also similar (Fig. 7) displaying pronounced negative Nb and other high-field-strength elements (HFSE, including Ti, Zr and Hf) anomalies and an enrichment in large-ion-lithophile elements (LILE, e.g., Rb, Th, light REE) that results in high LILE/HFSE ratios. These trace element characteristics are typical of arc magmatism. Several studies have shown plutonic and volcanic rocks of the same magmatic arc to be identical in composition (Saunders *et al.*, 1980; McCulloch and Perfit, 1981). The mantle-normalized patterns of the Skye Mountain rocks are closely comparable to the range of the calc-alkaline andesites from the central volcanic zone of the Andes, South America (Thorpe *et al.*,

Table 2. Major and trace element compositions of samples from the Skye Mountain pluton.

Sample	243	247	248	249	250	253	253A	273	335
SiO ₂ (%)	53.02	48.43	53.85	49.80	53.96	52.17	53.73	56.30	49.53
TiO ₂	0.95	1.09	0.73	1.16	0.70	0.88	0.92	0.66	0.93
Al ₂ O ₃	18.40	20.23	16.95	18.40	16.36	19.11	17.04	15.61	20.42
Fe ₂ O ₃ *	8.63	9.44	6.98	9.37	7.96	9.19	8.70	7.70	8.35
MnO	0.17	0.20	0.26	0.14	0.14	0.12	0.16	0.13	0.27
MgO	4.99	5.11	6.70	5.61	6.34	4.09	5.64	7.13	4.89
CaO	6.31	7.61	4.30	6.82	6.52	7.74	6.96	6.64	5.71
Na ₂ O	3.32	3.27	3.62	3.44	3.07	3.19	3.14	2.69	4.78
K ₂ O	1.56	1.59	2.88	2.38	1.96	1.75	1.60	1.43	1.27
P ₂ O ₅	0.33	0.20	0.14	0.30	0.09	0.27	0.16	0.10	0.20
LOI	1.90	2.10	2.80	2.70	2.10	1.70	1.80	1.90	3.80
Σ	99.58	99.27	99.21	99.21	99.20	100.21	99.85	100.29	100.15
Mg#	0.53	0.52	0.66	0.54	0.61	0.47	0.56	0.65	0.54
Cr (ppm)	69	44	281	82	261	16	81	318	93
Ni	49	44	114	63	78	21	56	119	55
V	241	318	147	267	248	246	252	195	234
Cu	41	95		77	40	29	54	49	9
Pb	44	49	80			13	34		12
Zn	122	186	262	88	93	74	85	77	405
Rb	69	69	107	107	88	69	63	54	73
Ba	241	229	306	371	316	225	271	272	187
Sr	464	514	418	467	396	472	379	325	563
Ga	21	23	16	21	19	19	20	16	20
Nb	5.0	3.5	4.3	7.7	3.5	4.9	5.5	4.8	3.3
Hf	2.70	1.54	2.58	3.31	2.81	2.18	2.28	2.92	1.27
Zr	94	56	98	111	105	78	68	114	43
Y	18	14	17	36	18	20	22	23	13
Th	4.06	2.25	4.72	2.94	4.85	3.34	4.24	4.23	1.75
La	16.42	10.54	13.32	18.75	13.08	15.76	13.40	14.24	10.02
Ce	37.93	24.37	29.74	51.24	29.03	34.98	31.82	28.52	22.28
Pr	4.84	3.11	3.74	7.45	3.67	4.39	4.23	3.88	2.83
Nd	20.04	13.91	15.88	34.23	15.40	17.85	18.08	16.32	12.34
Sm	4.29	2.97	3.63	8.04	3.74	4.22	4.50	4.15	2.77
Eu	1.31	1.10	1.05	1.74	1.05	1.25	1.16	1.06	1.13
Gd	4.17	3.00	3.78	7.84	3.55	4.20	4.54	4.06	2.69
Tb	0.61	0.43	0.55	1.21	0.56	0.66	0.70	0.68	0.42
Dy	3.53	2.61	3.25	7.04	3.37	3.99	4.38	4.12	2.49
Ho	0.72	0.54	0.67	1.40	0.69	0.80	0.89	0.86	0.50
Er	2.01	1.45	1.99	3.94	1.97	2.22	2.54	2.51	1.52
Tm	0.27	0.21	0.27	0.56	0.29	0.30	0.35	0.36	0.22
Yb	1.82	1.33	1.89	3.46	1.87	2.01	2.38	2.40	1.37
Lu	0.27	0.21	0.27	0.51	0.29	0.30	0.34	0.36	0.22

Mg# = Mg/(Mg + Fe_{tot}).

1984) and Hercynian quartz diorites from the French Massif Central (Shaw *et al.*, 1993). The strong enrichment of LILE in mafic rocks is indicative of emplacement into a continental crust. Compared to oceanic equivalents, a distinct enrichment of LILE in continental calc-alkaline magmas is usually

considered to result from either the presence of enriched mantle source beneath continental margins (Saunders *et al.*, 1980) or to "MASH" (melting, assimilation, storage, homogenization) processes (Hildreth and Moorbath, 1988).

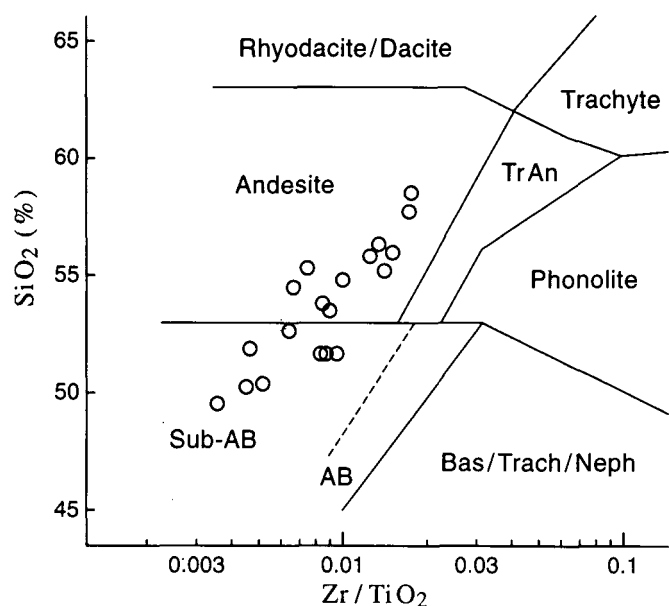


Fig. 4. Zr/TiO_2 versus SiO_2 (%) diagram of Winchester and Floyd (1977) for the rocks of the Skye Mountain pluton. AB = alkali basalts; Sub-AB = subalkaline basalts; TrAn = trachyandesites; Bas/Trach/Neph = basalt/trachyte/nephelinite.

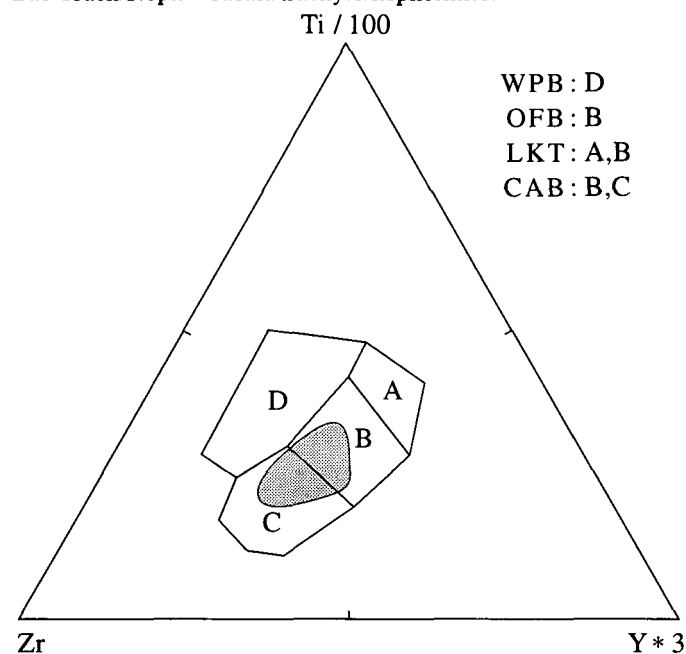


Fig. 5. Zr-Y-Ti discrimination diagram of Pearce and Cann (1973) for the mafic rocks of the Skye Mountain pluton. Cumulate rocks were not plotted. Fields: A = island arc tholeiites and ocean floor basalts; B = ocean floor basalts and calc-alkaline basalts; C = calc-alkaline basalts; D = within-plate basalts.

TECTONIC IMPLICATIONS

The geochemistry of the Skye Mountain pluton compares most closely with the following similar calc-alkaline volcanic rocks in the Cape Breton Highlands (Macdonald and Smith, 1980; Barr and Jamieson, 1991) and southern Newfoundland: (1) Sarah Brook metamorphic suite in the southern Cape Breton Highlands includes rhyolites which have been dated at $434 \pm 7/-4$ Ma (U-Pb zircon age: Dunning *et al.*, 1990a); (2) Jump-

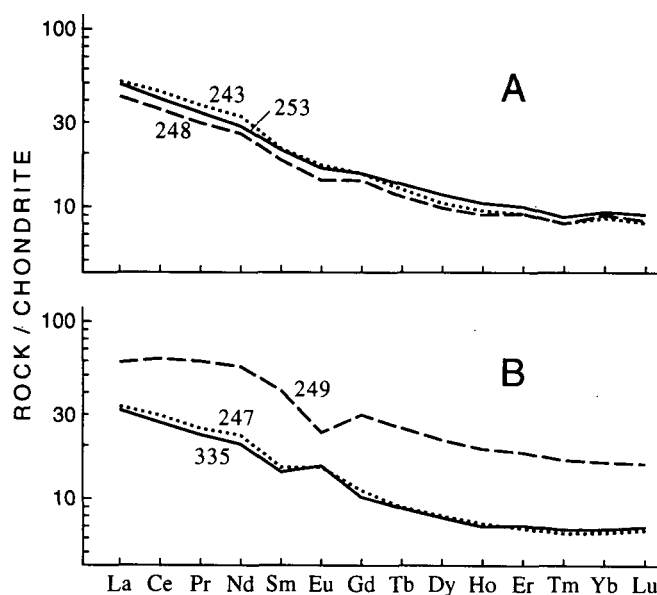


Fig. 6. Chondrite-normalized rare-earth element abundances of the rocks from the Skye Mountain pluton. A = non-cumulate plutonic rocks; B = cumulate plutonic rocks (249 - hornblende cumulate; 247 and 335 - plagioclase cumulate). Normalizing values after Sun (1982).

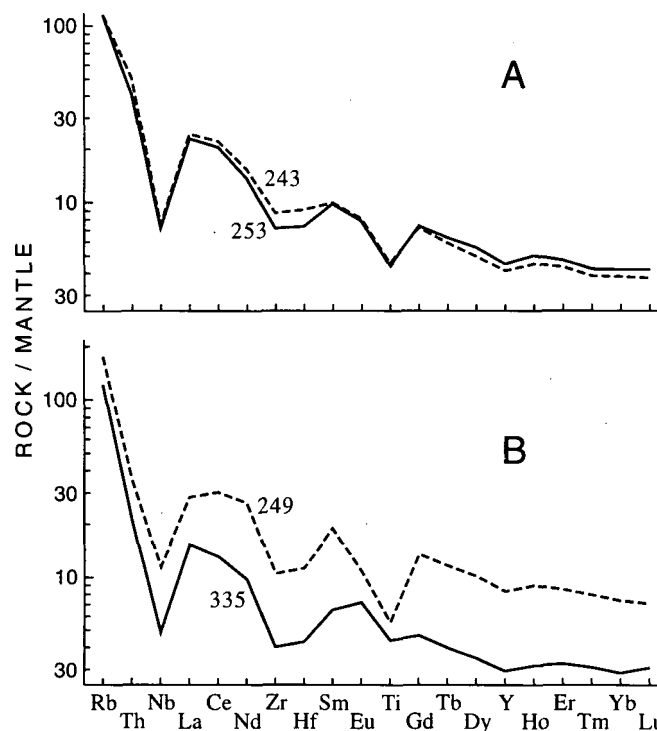


Fig. 7. Primitive mantle-normalized abundances of trace elements in the rocks from the Skye Mountain pluton. A = non-cumulate plutonic rocks; B = cumulate plutonic rocks (249 - hornblende cumulate; 335 - plagioclase cumulate). Normalizing values after Sun and McDonough (1989).

ing Brook metamorphic suite in the western Cape Breton Highlands for which a feeder dyke yielded an age of 439 ± 7 Ma (U-Pb zircon age: Currie *et al.*, 1982); (3) Money Point Group in northern Cape Breton Island gave an age of 428 ± 4 Ma

(U-Pb zircon age: Keppie *et al.*, 1992); and (4) La Poile Group in the Burgeo Terrane of southern Newfoundland yielded ages ranging from 428 ± 6 Ma to $420 \pm 8/2$ Ma (Dunning *et al.*, 1990b). The calc-alkaline nature of these volcanic rocks is interpreted as a supra-subduction zone magmatic arc, which extended as far south as central Cape Breton Island. The rapid burial of these rocks to 25 km by ca. 415 Ma (Keppie *et al.*, 1992) has been interpreted in terms of an intra-arc rifting above an oblique subduction zone, similar to that in the present-day arc of Central America (Burkart and Self, 1985). Associated rifting may also explain the earliest Silurian tholeiitic magmatism in the Antigonish Highlands (Fig. 7; Keppie *et al.*, 1997).

Chandler *et al.* (1987) have suggested that Lower Silurian rocks represent an overstep sequence between Laurentia and the Avalon, a proposition supported by the first appearance of Laurentian Nd signatures in the Avalon during the earliest Silurian (Murphy *et al.*, 1996). However, the occurrence of calc-alkaline magmatism through the Llandoverly and Wenlock in the Cape Breton Highlands and southern Newfoundland suggests that Iapetus was not completely closed until the Late Silurian. These observations may be reconciled if only small ocean basins remained in the Early Silurian and convergence was mainly orogen-parallel (Fig. 8).

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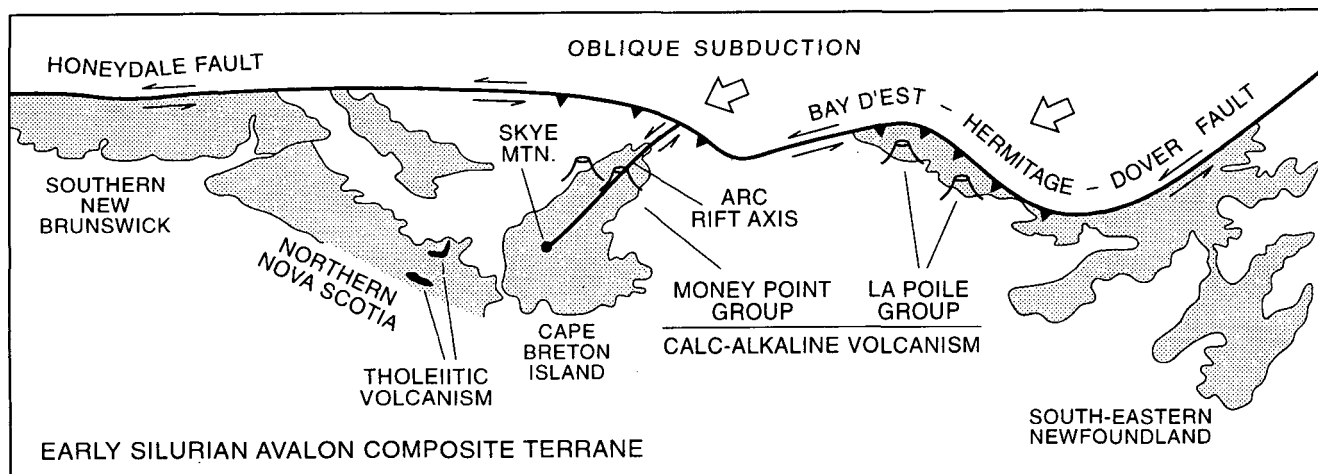


Fig. 8. Early Silurian tectonic model for the Avalon Composite Terrane (modified from Keppie *et al.*, 1992; Whalen *et al.*, 1996: see text for other references).

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