Petrology, tectonic setting, and $^{40}Ar/^{39}Ar$ (hornblende) dating of the Late Ordovician - Early Silurian Belle Côte Road orthogneiss, western Cape Breton Highlands, Nova Scotia

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The Belle Côte Road orthogneiss is a major component of the western Cape Breton Highlands, where it forms a belt approximately 60 km in length. Previous U-Pb dating has shown that the granodioritic to tonalitic protolith of the gneiss crystallized at 442 ± 3 Ma, providing a minimum age for the metavolcanic and metasedimentary units of the Aspy terrane intruded by the orthogneiss. The gneissic fabric in the orthogneiss is mainly conformable with the regional fabric, and generally trends north-south, except in the southern part of the unit where it is oriented east-west. Typical orthogneiss contains quartz, plagioclase, and biotite, with variable amounts of K-feldspar and muscovite and rarely epidote or garnet. A tonalitic variant contains amphibole. The orthogneiss is peraluminous, with A/CNK values of 1 to 1.2. Petrochemical characteristics are consistent with syntectonic emplacement in the roots of a volcanic arc built on continental crust. $^{40}Ar/^{39}Ar$ dating was done on hornblende from three samples of orthogneiss and seven samples of amphibolite from xenoliths in the orthogneiss and an adjacent amphibolite unit. Eight of these samples yielded cooling ages ranging between 384 and 370 Ma. Two younger ages (ca. 363 and 353 Ma) may reflect localized effects of younger plutonism and/or shearing. The $^{40}Ar/^{39}Ar$ data combined with previous U-Pb data from titanite indicate that the orthogneiss and associated units experienced rapid cooling from ca. 600 to 400°C between ca. 386 Ma and 370 Ma, perhaps related to uplift associated with ongoing terrane amalgamation in Cape Breton Island.

Les orthogneiss de Route de Belle Côte est un composant important des hautes terres du Cap Breton occidental, où il forme une ceinture approximative de 60 kilomètres de longueur. Des mesures connues d'U-Pb a prouvé que le granodioritique au protolite tonalitique du gneiss a cristallisé au ± 442 3 Ma, fournissant un âge minimum pour les unités métavolcaniques et métasédimentaires du terrane d'Aspy imposé par les orthogneiss. Le tissu gneissique dans les orthogneiss est principalement conforme au tissu régional, et a une tendance généralement nord-sud excepté dans la partie sud de l'unité où la tendance est est-ouest. Les orthogneiss typiques contient le quartz, le plagioclase, et la biotite, avec des quantités variables de K-feldspath et de muscovite et rarement d'épidote ou de grenat. Une variante tonalitique contient l'amphibole. Les orthogneiss sont peralumineux, avec des valeurs A/CNK de 1 à 1,2. Les caractéristiques pétrochimiques sont conformées à la mise en place syntectonique dans les racines d'un arc volcanique construit sur la croûte continentale. La datation d' $^{40}Ar/^{39}Ar$ a été faite sur la hornblende de trois échantillons d'orthogneiss et de sept échantillons d'amphibolite provenant de xénolites dans les orthogneiss et une unité adjacente d'amphibolite. Huit de ces échantillons ont rapporté des âges de refroidissement s'étendant entre 384 et 370 de Ma. Deux âges plus jeunes (ca. 363 et 353 Ma) peuvent refléter des effets localisés des plus jeunes plutonismes et/ou cisaillement. Les données $^{40}Ar/^{39}Ar$ combiné avec des données précédentes d'U-Pb de titanite indiquent que les orthogneiss et les unités associées ont éprouvé le refroidissement rapide ca. de 600 à 400°C entre ca. 386 Ma et 370 Ma, peut-être associé au soulèvement en plus d'amalgamation continue de terrane sur l'île du Cap Breton.

[Traduit par la rédaction]

INTRODUCTION

The Belle Côte Road orthogneiss is a major component of the western Cape Breton Highlands, and extends from near Pleasant Bay in the north to east of Margaree Centre in the south (Fig. 1). The orthogneiss was included in regional mapping and reconnaissance petrological studies of the area (Currie 1987; Jamieson *et al.* 1987, 1989; Marcotte 1987; Barr *et al.* 1992; Lynch *et al.* 1992; Lynch *et al.* 1993; Horne 1995), but this project is the first detailed field and petrological study to focus on the unit. Because of difficult access to the northern part of the orthogneiss, the project concentrated on the central and southern parts of the unit (Fig. 1). It included mapping and sample collection, structural observations, petrographic study to determine mineralogy and texture, mineral and whole-rock chemical analyses, and $^{40}Ar/^{39}Ar$ dating of amphibole in the orthogneiss and associated amphibolitic units. The data provide a basis for interpreting the nature of the protolith of the orthogneiss and the tectonic setting in which it was formed, as well as an enhanced understanding of the tectonothermal evolution of the western Cape Breton Highlands.

GEOLOGICAL SETTING

The Belle Côte Road orthogneiss is located in the Aspy terrane of Barr and Raeside (1989). The Aspy terrane is characterised by metasedimentary and meta-igneous rocks that

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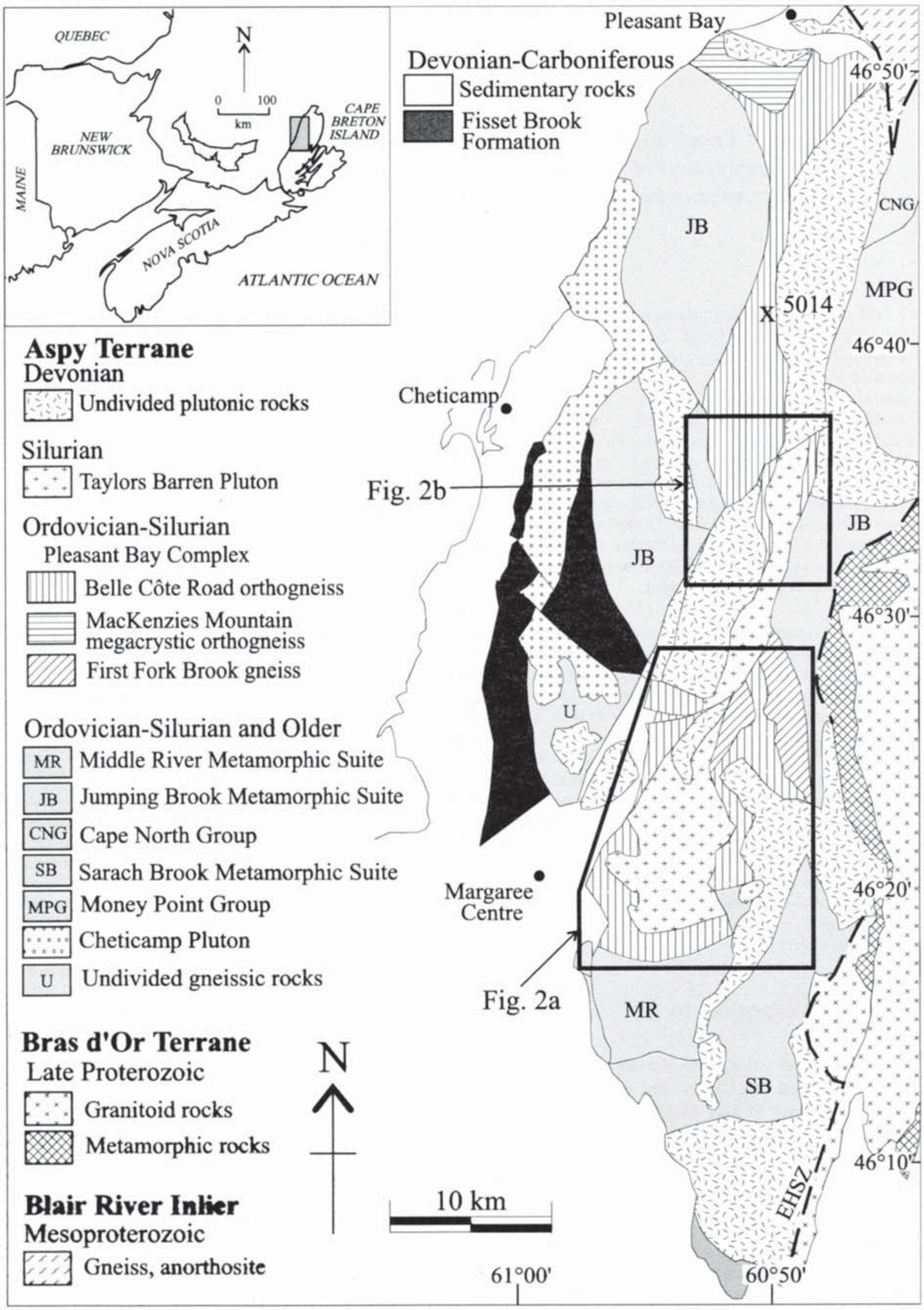


Fig. 1. Simplified geological map of the western Cape Breton Highlands (after Barr and Raeside 1989), showing the distribution of the Belle Côte Road orthogneiss and the location of the study areas show in Fig. 2a and b. The Eastern Highlands shear zone (EHSZ) separates the Aspy (to west) and Bras d'Or (to east) terranes of Barr and Raeside (1989). Location of analyzed sample CW86-5014 (Table 1) is indicated by "x".

vary widely in metamorphic grade from lower greenschist to amphibolite facies, intruded by extensive Silurian and Devonian plutons (Macdonald and Smith 1980; Barr and Raeside 1989; Plint and Jamieson 1989). The mainly lower grade metasedimentary and metavolcanic units, including the Jumping Brook and Sarach Brook metamorphic suites and the Money Point Group (Fig. 1), have been regionally correlated on the basis of lithology and field relationships (e.g., Barr and Jamieson 1991; Lynch 1996) and are interpreted to have been deposited or emplaced in the late Ordovician to early Silurian (Jamieson *et al.* 1987, 1989; Raeside and Barr 1992; Keppie *et al.* 1991; Horne 1995). The mainly higher grade units, including the Middle River Metamorphic Suite, Cape North Group, and Pleasant Bay Complex (which consists of the Belle Côte Road orthogneiss, MacKenzies Mountain meagacrystic orthogneiss, and First Fork Brook gneiss) (Fig. 1), are more controversial in terms of their age(s), regional correlations, and relationships to one another and to the mainly lower grade units mentioned above. Some interpretations have regarded them to be the higher grade equivalents of the lower grade units (e.g. Plint and Jamieson 1989; Barr *et al.* 1995), whereas others have considered them to be unrelated older "basement" units (e.g. Currie 1987; Keppie *et al.* 1991), or part of a complexly folded and dissected nappe of uncertain provenance, separated from the underlying lower grade units by a polydeformed thrust surface (Lynch 1996; Currie and Lynch 1997). In the latter model, the Belle Côte Road orthogneiss is included as part of the allochthonous nappe.

Distribution and age of the Belle Côte Road Orthogneiss

Because varied terminology has been used in the past for gneissic rocks of the western Cape Breton Highlands, clarification of the unit names as used in this paper is required. Currie (1982 1983, 1987) used the term Pleasant Bay complex for mainly gneissic rocks in the area northeast of Cheticamp (Fig. 1). However, Jamieson *et al.* (1989) assigned parts of the Pleasant Bay complex of Currie (1987) to the Jumping Brook Metamorphic Suite, and used the modified term Pleasant Bay gneiss complex for the remaining areas of gneissic rocks, which were subdivided into the Belle Côte Road orthogneiss, McKenzies Mountain megacrystic orthogneiss, and undifferentiated quartzofeldspathic gneiss and amphibolite. Previously, Jamieson *et al.* (1986) had used the term Belle Côte Road gneiss for a mainly tonalitic orthogneissic unit in the area east and northeast of Margaree Centre (Fig. 1). Barr *et al.* (1992) used the term Belle Côte Road gneiss to include all of these gneissic areas in the western highlands, except the McKenzies Mountain megacrystic orthogneiss. Thus, their Belle Côte Road gneiss unit extends more or less continuously from the Pleasant Bay area in the north to the Middle River Metamorphic Suite in the south, although locally offset by faults and disrupted by younger plutons.

As a result of more detailed mapping, Horne (1995) subdivided the southern part of the Belle Côte Road gneiss unit of Barr *et al.* (1992) into the Belle Côte Road orthogneiss and the amphibolitic and paragneissic First Fork Brook gneiss, although he noted that in places the two lithologies occur together in outcrop. He used the term Pleasant Bay complex for the two units combined.

In this paper, the term Pleasant Bay complex is used in the sense of Horne (1995), and consists of the Belle Côte Road orthogneiss, the First Fork Brook gneiss, and the McKenzies Mountain megacrystic orthogneiss (Fig. 1). The First Fork Brook gneiss has been identified as a separate unit only in the area mapped by Horne (1995) (Fig. 2a), and may be equivalent to high-grade parts of the Jumping Brook Metamorphic Suite farther north.

Jamieson *et al.* (1986) reported an U-Pb age of 433+20/-10 Ma for zircon from a sample of orthogneiss from Belle Côte Road (Fig. 2b). G. Dunning (unpublished data, cited by Horne 1995) obtained a more precise U-Pb age of 442 ±3 Ma for zircon from another sample from the same location. These ages are the same within error, and 442 ±3 Ma is interpreted to represent the time of crystallization of the protolith of the orthogneiss (Horne 1995). Titanite from the same sample yielded a U-Pb age of 386 ±3 Ma (G. Dunning, unpublished data, cited by Barr and Jamieson 1991), interpreted to represent the approximate time of post-metamorphic cooling of titanite through its closure temperature (ca. 600°C; Heaman and Parrish 1991).

Contact Relations

On the south and east, the Belle Côte Road orthogneiss is in contact with metasedimentary and amphibolitic rocks of the Middle River Metamorphic Suite and the First Fork Brook gneiss (Fig. 2a). Although their original nature has been obscured by deformation, the contacts are generally parallel to the foliation in both the orthogneiss and the adjacent metamorphic units, suggesting that the units were deformed together after (or during) emplacement of the protolith of the orthogneiss. Toward the contact with the Middle River Metamorphic Suite, the orthogneiss exhibits an increasing abundance of muscovite and garnet over a distance of about 10 m, and the adjacent Middle River unit contains small discontinuous lenses of orthogneiss which appear to represent deformed dykes and stringers of the Belle Côte Road orthogneiss. At contacts with the First Fork Brook unit, amphibolite is interlayered with the Belle Côte Road orthogneiss, and quartz and feldspar-rich lenses are abundant. Discontinuous amphibolitic and paragneissic bands are scattered through the Belle Côte Road orthogneiss, and are interpreted to represent xenoliths of the First Fork Brook gneiss and Middle River Metamorphic Suite. Hence, it is inferred that the protolith of the Belle Côte Road orthogneiss intruded both the Middle River Metamorphic Suite and the First Fork Brook gneiss, but the relationship between the latter two units is unknown.

An isolated area of megacrystic orthogneiss with large (0.5 to 1.5 cm) K-feldspar and plagioclase augen occurs east of the First Fork Brook gneiss (Fig. 2a), and may be similar to the McKenzies Mountain megacrystic orthogneiss described by Jamieson *et al.* (1989). Its relationship to the typical Belle Côte Road orthogneiss is unknown, but farther north, the McKenzies Mountain megacrystic orthogneiss appears to have intruded the Belle Côte Road orthogneiss (Jamieson *et al.* 1989).

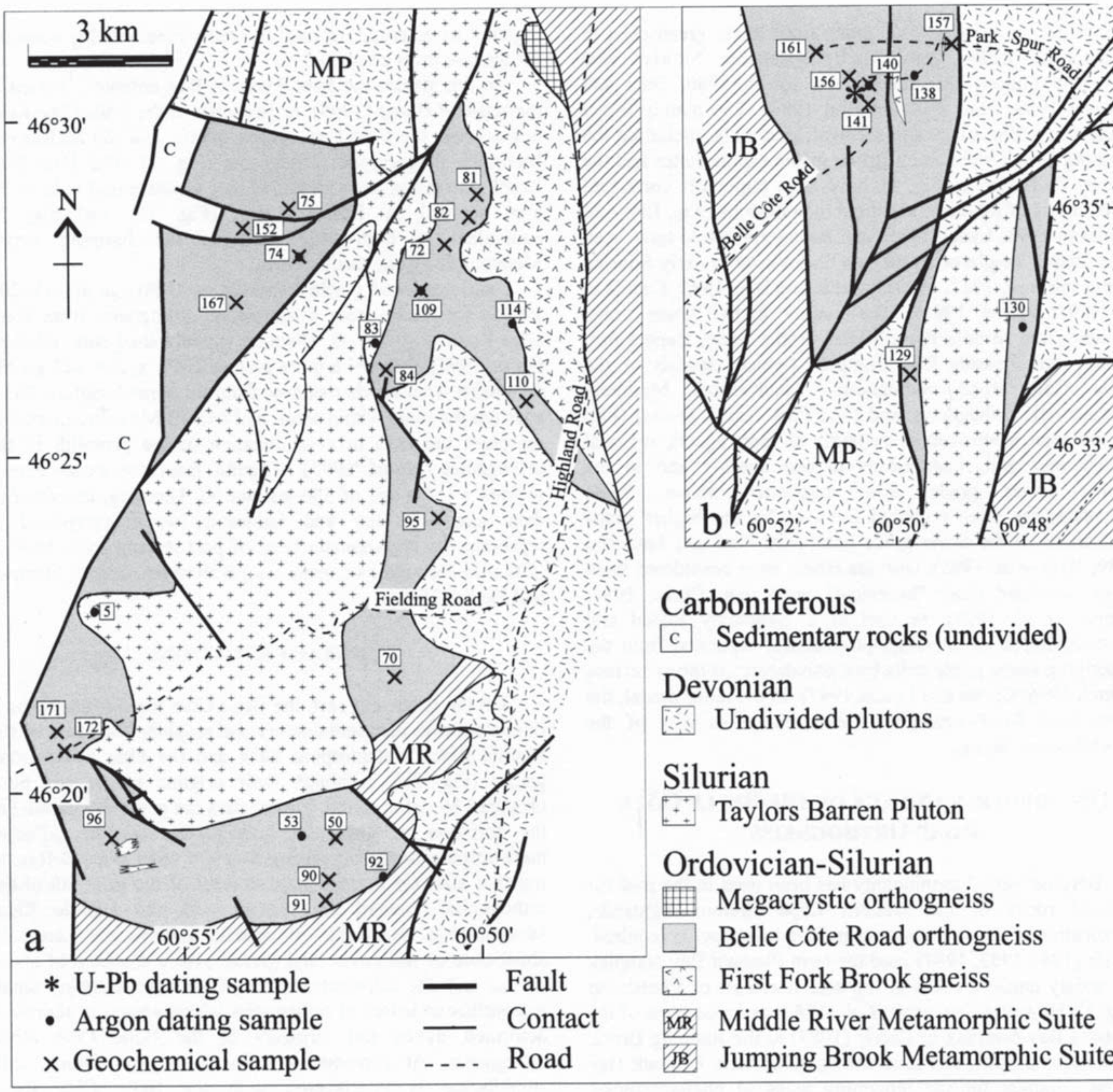


Fig. 2. Simplified geological maps of study areas a and b (after Price 1997), showing locations of samples for chemical analysis and U-Pb and $^{40}Ar/^{39}Ar$ dating. U-Pb dating was reported by Horne (1995). Sample designation JP96 is omitted from sample numbers. In (b), MP indicates the Margaree Pluton.

The Belle Côte Road orthogneiss partially envelops the Taylors Barren Pluton (Fig. 1, 2a, b), which consists of variably foliated megacrystic granite (Horne 1995; MacDonald 1996). Contacts between the two units are characterised by alternating, foliation-parallel bands of orthogneiss and granite. However, in places, granitic apophyses have intruded along the foliation in the orthogneiss and dykes of granite are folded with the foliation in the orthogneiss (Horne 1995). Such relationships, well documented by Horne (1995) and also observed during the present study, show that the Taylors Barren Pluton intruded the orthogneiss, consistent with U-Pb ages of 442±3 Ma for the orthogneiss and 430±2 Ma for the Taylors Barren granite (Horne 1995). Mainly undeformed Devonian plutons later intruded the Belle Côte Road orthogneiss and surrounding units (Fig. 2a; Horne 1995). On its western margin, the orthogneiss is in faulted contact with Carboniferous sedimentary rocks, as inferred from the steep topography and lack of preserved unconformities (Fig. 2a).

To the north, in the vicinity of Belle Côte Road, the orthogneiss is in faulted contact with rocks of the Jumping Brook Metamorphic Suite and the Margaree Pluton (Fig. 2b). Farther north, contact relationships with adjacent units are not well known because of limited mapping and poor exposure, but the orthogneiss appears to continue to the Pleasant Bay area (Fig. 1), where it has been intruded by younger plutons (including the McKenzies Mountain megacrystic orthogneiss) and covered by Carboniferous sedimentary units (Currie 1987;

Barr *et al.* 1992).

STRUCTURAL FEATURES

The gneissic fabric in the Belle Côte Road orthogneiss varies in orientation but tends to parallel the shape of the unit in map view. In the northern area along Belle Côte Road (Fig. 2b), trends are mainly north-south, with steep dips dominantly to the east (Fig. 3a). In the area west of the Taylors Barren Pluton, trends are more scattered, perhaps related to faulting in this area, but are mainly northwesterly, with moderate to steep dips to the northeast (Fig. 3b). Around the southern margin of the Taylors Barren Pluton, foliations trend mainly east-west, with steep dips mainly to the north (Fig. 3c), and on the eastern side of the Taylors Barren Pluton, trends are again more north-south, with dips steep to both east and west (Fig. 3d). These trends are parallel to the main foliations in adjacent metamorphic units, and outline a regional U-shaped pattern apparent on aeromagnetic maps (Dehler and Verheuf 1996).

A lineation marked by elongate biotite flakes is commonly visible on foliation planes. The lineations generally trend north or south but plunge varies markedly from steep to shallow (Fig. 3a - d). No pattern emerges from one area to another.

Metre-scale, similar-style folds occur locally in the Belle Côte Road orthogneiss, and display redistribution of leucocratic material toward the hinge regions. Fold axes plunge moderately toward the north-northeast or south-southeast and axial planes are parallel or subparallel to the foliation. The folds resemble those in the Middle River and Jumping Brook metamorphic suites (Plint 1987; Doucet 1983), and probably formed during the same deformational event(s).

Textural features seen in thin section, such as curved albite twin lamellae in plagioclase and bent cleavage in biotite, are consistent with regional deformation having been at least partially synchronous with emplacement of the Belle Côte Road orthogneiss. Veinlets of Taylors Barren granite locally cross-cut gneissic layering in the Belle Côte Road orthogneiss, but overall the foliation in the Taylors Barren Pluton parallels that in the surrounding orthogneiss (MacDonald 1996). However, in contrast to the homogeneously developed foliation throughout the Belle Côte Road orthogneiss, foliation in the Taylors Barren Pluton varies in intensity, with moderately to weakly deformed zones bordering a narrower northeasterly trending central zone of strong deformation and mylonitisation (MacDonald 1996). Widespread shear fabrics in the Taylors Barren Pluton reflect a component of dextral shear in the plane of the principal foliation during deformation (Horne 1995; MacDonald 1996), and based on structural and petrochemical charcateristics, the Taylors Barren pluton has been interpreted to have been emplaced in a transcurrent tectonic regime (MacDonald 1996). Hence the tectonic regime appears to have evolved from compressional during emplacement of the Belle Côte Road pluton at ca. 442 Ma to transcurrent during emplacement of the Taylors Barren Pluton at ca. 430 Ma.

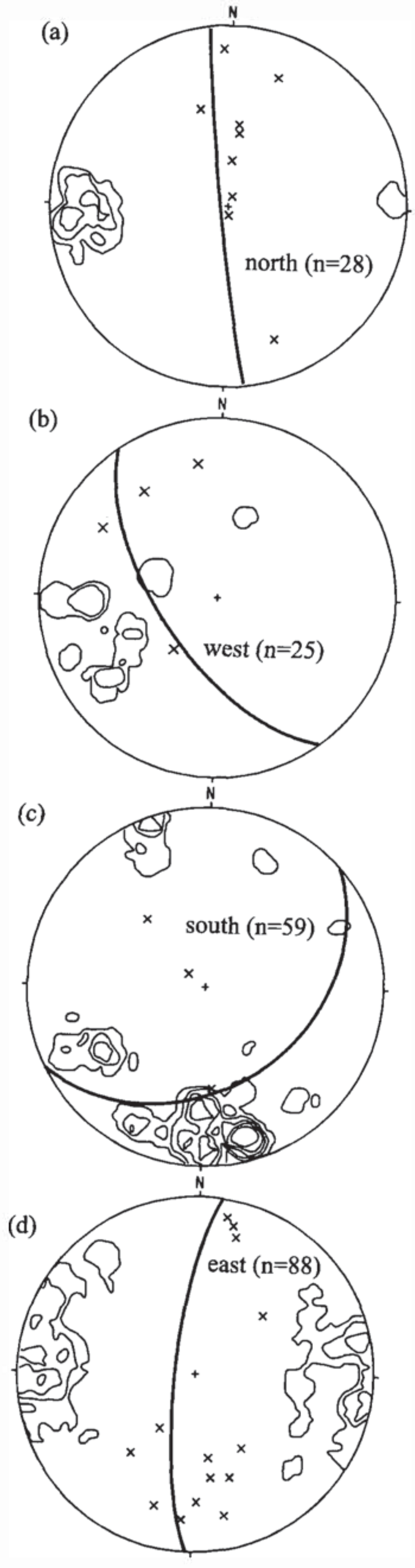


Fig. 3. Equal area stereonets showing contoured poles to gneissic layering and mineral lineations (x) from the (a) northern, (b) western, (c) southern, and (d) eastern parts of the Belle Côte Road orthogneiss. The average foliation plane is drawn for each area. Contours are (a) 5, 10, and 15% per unit area, (b) 4 and 8% per unit area, (c) 2, 4, 6, and 8% per unit area, and (d) 2, 4, 6, and 8% per unit area.

PETROGRAPHY

In outcrop and hand specimen, the Belle Côte Road orthogneiss is typically grey, with granular quartzofeldspathic layers, 1 mm to 3 cm in width, alternating with thinner, more schistose biotite-rich layers. Major minerals are quartz, plagioclase, and biotite, with variable amounts of K-feldspar and muscovite. Epidote and/or garnet are present in some samples, and most samples contain accessory zircon, apatite, opaque minerals, and rarely rutile and titanite. Based on modal mineralogy and the classification of Streckeisen (1976), compositions are mainly granodiorite gradational to tonalite. Some tonalite samples, mainly from the eastern part of the unit, contain little or no K-feldspar, tend to have a higher quartz content than other samples, and in some cases contain amphibole, as described below.

Plagioclase is the most abundant mineral in the orthogneiss, forming subhedral grains with albite twinning. Microprobe analyses indicate that composition shows little variation within individual samples, but wide variation between samples, and ranges from oligoclase (An_{16}) to andesine (An_{44}) (Price 1997). Quartz occurs typically as small (0.5 to 6 mm), slightly elongate to ribbon-like grains with undulose extinction. Irregular grain boundaries, subgrain development at grain boundaries, and increase in grain size toward the centre of quartzofeldspathic layers indicate that the quartz has been recrystallised. Anhedral microcline grains with cross-hatched twinning are typically small (0.2 to 0.6 mm), associated with recrystallised quartz, and characterized by irregular grain boundaries. Myrmekitic textures are common.

Biotite occurs as single grains and as patches and bands of interlocking grains, oriented parallel to the gneissic layering. It is typically strongly pleochroic (yellow-brown to brown-green), and contains randomly oriented inclusions of rutile, opaque minerals, zircon, apatite, titanite, and epidote. Cleavage planes commonly exhibit microfractures and bending, indicative of translation gliding during syntectonic crystallisation or recrystallisation (Kretz 1994). Microprobe analyses (Price 1997) indicate that the biotite is high in Fe (Fe/(Fe+Mg) about 0.6) and Al, and hence plots mainly in the field for peraluminous granites on the $FeO\text{-}MgO\text{-}Al_2O_3$ diagram of Abdel-Rahman (1994). Minor muscovite is associated with biotite in most samples, and is most abundant in samples from the southern part of the area adjacent to the contact with the Middle River Metamorphic Suite. It is not clear from textural relations whether any of the muscovite is of igneous origin.

Crystals of epidote, 0.8 to 3 mm in size, are euhedral against biotite, plagioclase, and hornblende (where present), and commonly exhibit concentric compositional zoning. Allanite cores, some of which are metamict, are common in euhedral epidote. These features are consistent with magmatic origin (Zen and Hammarstrom 1984), although the degree of metamorphism and deformation of the orthogneiss make this interpretation speculative. Smaller, mainly anheral epidote grains are also present, completely enclosed in biotite, garnet, and/or plagioclase. They consistently exhibit bright, second order, maximum birefringence colours, and lack zoning. The latter variety of epidote is similar in appearance to epidote in amphibolite of the First Fork Brook gneiss and is probably of metamorphic origin, whereas the former more euhedral zoned variety is not present in the amphibolite, further evidence for its possible igneous origin in the orthogneiss.

Euhedral to subhedral garnet is present in some samples from the eastern and northern parts of the study area. Garnet crystals range in diameter from 0.2 mm to 10 mm and are generally associated with biotite. The larger garnet crystals have abundant epidote inclusions in their cores. Microprobe analyses indicate that the garnet is Fe-rich (Price 1997). Garnet-biotite geothermometry of the Belle Côte Road orthogneiss suggests a metamorphic equilibration temperature of approximately 600°C (Price 1997).

A few tonalitic samples contain small (ca. 0.5 mm), euhedral to subhedral grains of green hornblende in association with biotite. Amphibole is most abundant in sample JP96-109 from the area east of the Taylors Barren Pluton (Fig. 2a) and sample JP96-140 from the Belle Côte Road area (Fig. 2b). Sample JP96-109 contains about 20% modal amphibole, whereas sample JP96-140 contains much less amphibole (ca. 7%). Amphibole in both samples is calcic, and classified as pargasitic hornblende (classification of Leake 1978). However, amphibole in sample 109 is less varied in composition than that in sample 140, and has lower Mg/(Mg+Fe) ratio (ca. 0.4 vs. ca. 0.65; Price 1997). In both samples, high Al contents (Al_2O_3 contents ca. 10 - 14%; Price 1997) are consistent with pressures of crystallization in the range of 3 - 6 kbar using the Al-in-hornblende geobarometer (Schmidt 1992). Such estimates may not be significant in these rocks because the geobarometer was calibrated for igneous rocks and only one of the samples (JP96-109) contains the specified mineral assemblage. Nevertheless, even in metamorpic rocks, elevated aluminum (and Na) contents in calcic amphiboles are indicative of high pressure and temperature metamorphism (Laird and Albee 1981).

GEOCHEMISTRY

Twenty-five samples from the Belle Côte Road orthogneiss were analyzed for major and trace elements (Table 1). They include 18 samples from the area of Figure 2a, 6 samples from the Belle Côte Road area (Fig. 2b), and 1 sample (CW87-5014) from north of the Belle Côte Road area (Fig. 1). Most of the samples represent typical granodioritic to tonalitic orthogneiss; however, one sample (#109) contains abundant hornblende, and 5 samples (#72, 74, 81, 84, and 140) are of tonalite which lacks K-feldspar and has higher modal quartz contents compared to the other samples; three of the latter samples (#74, 84, and 140) contain minor modal hornblende (up to 7%).

The typical granodioritic to tonalitic samples range in silica content from 64.7 to 71.2 %, and within this group the oxides TiO_2, Al_2O_3, $Fe_2O_3^t$, MnO, MgO, CaO, and P_2O_5 generally show reasonable negative correlation with SiO_2, K_2O shows positive correlation, and Na_2O shows no correlation with SiO_2 (Fig. 4). In general, the negative correlation trends on the SiO_2 variation diagrams are consistent with decreasing amounts of modal biotite present in the samples. The 5 tonalitic samples have higher SiO_2 contents (73 to 77%) but generally fall on the trends defined by the

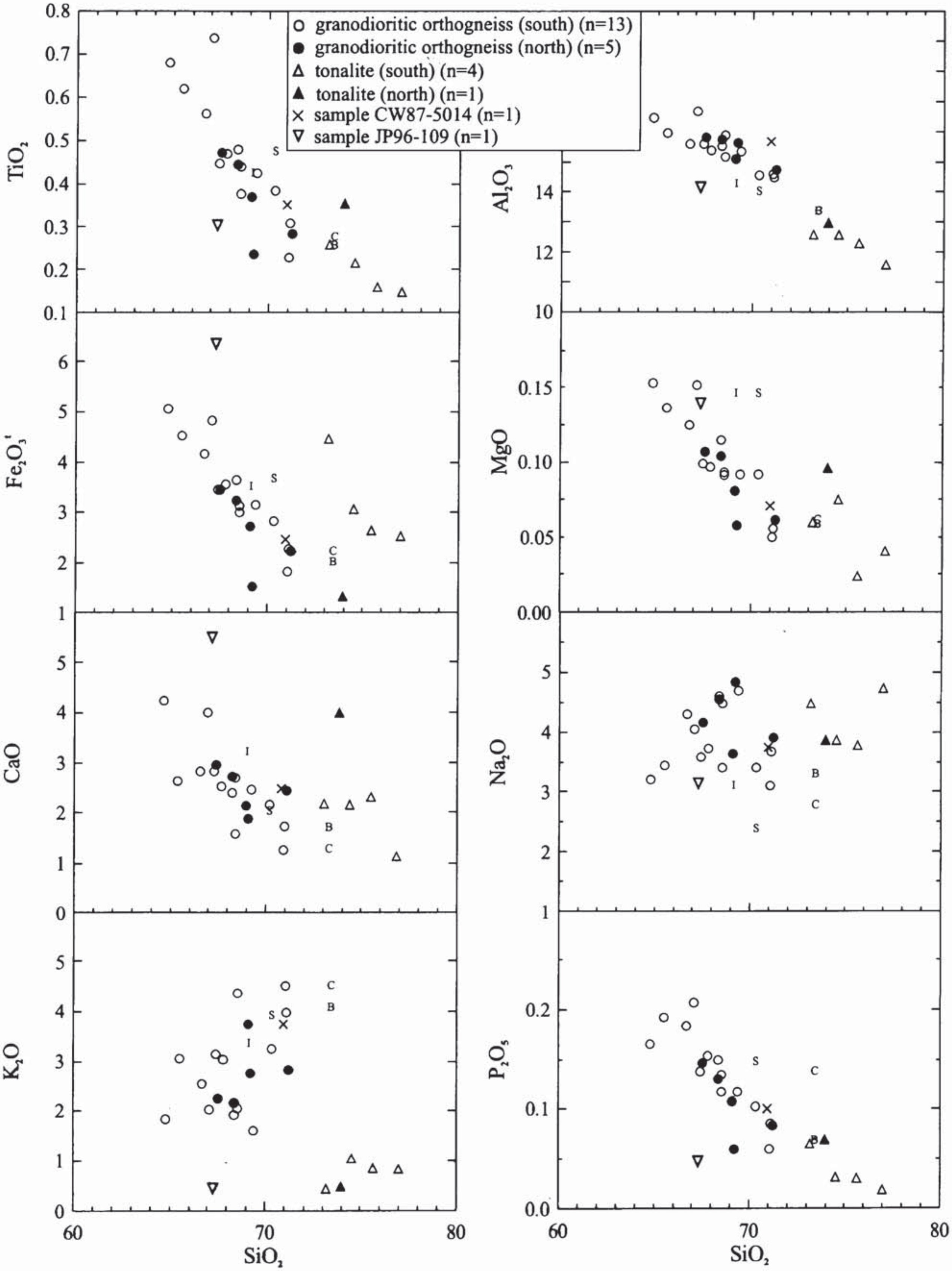


Fig. 4. Plots of major element oxides against SiO_2 for samples from the Belle Côte Road orthogneiss. Data are from Table 1. Symbols I, B, S, and C indicate the average I-, felsic I-, S-, and felsic S-type granites from Whalen *et al.* (1987)

Table 1. Geochemical[1] data for samples from the Belle Côte Road orthogneiss

Sample wt%	50	70	72 (t)	74 (t)	75	81 (t)	82	84 (t)	90	91	95	96	109 (t)
SiO_2	67.79	67.07	76.98	73.16	65.52	74.53	71.07	75.64	67.43	69.39	64.79	68.54	67.34
TiO_2	0.47	0.74	0.15	0.26	0.62	0.22	0.23	0.16	0.45	0.42	0.68	0.38	0.31
Al_2O_3	15.38	16.68	11.60	12.58	15.96	12.59	14.59	12.28	15.61	15.34	16.44	15.17	14.25
$Fe_2O_3^t$	3.57	4.83	2.54	4.47	4.52	3.06	1.81	2.65	3.45	3.16	5.07	3.01	6.43
MnO	0.06	0.06	0.05	0.04	0.11	0.07	0.04	0.07	0.07	0.06	0.08	0.06	0.12
MgO	0.92	1.46	0.36	0.55	1.31	0.70	0.45	0.22	0.94	0.87	1.48	0.89	1.33
CaO	2.47	3.95	1.08	2.14	2.59	2.12	1.20	2.28	2.78	2.40	4.20	1.52	5.47
Na_2O	3.73	4.05	4.73	4.48	3.44	3.87	3.10	3.78	3.58	4.69	3.20	3.41	3.16
K_2O	3.03	2.02	0.83	0.44	3.05	1.04	4.52	0.84	3.15	1.59	1.84	4.37	0.46
P_2O_5	0.15	0.21	0.02	0.07	0.19	0.03	0.06	0.03	0.14	0.12	0.17	0.12	0.05
LOI	1.10	0.80	0.60	0.90	1.70	0.70	1.30	0.80	1.20	0.90	1.10	1.10	0.90
Total	98.67	101.86	98.94	99.08	99.01	98.92	98.37	98.75	98.78	98.94	99.05	98.56	99.81
A/CNK	1.11	1.04	1.09	1.07	1.17	1.11	1.20	1.09	1.09	1.11	1.10	1.16	0.91
ppm													
V	46	76	3	18	63	19	18	9	42	44	61	39	94
Y	24	22	64	30	38	32	11	26	22	31	19	11	29
Zr	239	237	150	101	254	77	124	85	203	167	218	196	46
Nb	15	13	3	2	14	3	10	2	10	10	16	13	1
Ba	913	606	43	44	1267	92	855	178	925	481	609	1285	86
La	37	62	11	4	47	4	6	*	8	89	27	9	7
Ce	105	83	48	27	72	8	19	30	67	73	70	67	28
Cr	8	7	9	8	10	5	10	5	8	7	24	6	5
Co	65	71	86	90	77	89	70	106	69	70	64	85	88
Ni	2	2	2	*	2	*	*	*	*	*	7	*	*
Zn	75	78	41	17	109	390	370	350	73	630	65	79	45
Rb	125	68	36	13	119	21	148	15	98	68	99	138	4
Sr	401	732	60	161	455	86	287	148	453	348	258	342	134
Nd	42	35	22	12	31	1	6	13	28	43	29	21	11
Pb	*	*	*	*	*	*	7	*	*	*	1	*	*
Th	16	10	1	*	14	*	13	1	9	13	6	21	*
U	4	2	4	20	2	10	4	1	1	4	1	2	*
Ga	16	20	16	14	20	12	18	13	19	18	21	19	14

[1] Analysis by X-Ray Fluorescence at the Univeristy of Ottawa Geochemical Centre. All samples are JP96 series except CW87-5014. Tonalite samples are indicated by (t). Abbreviations: LOI, loss-on-ignition; *, not detected; A/CNK, molar $Al_2O_3/CaO+Na_2O+K_2O$; $Fe_2O_3^t$, total Fe as Fe_2O_3.

Table 1. Continued

Sample wt%	110	129	140 (t)	141	152	156	157	161	167	171	172	5014
SiO_2	70.35	69.22	73.97	71.24	66.71	67.53	69.09	68.36	71.11	68.55	68.37	70.95
TiO_2	0.38	0.24	0.35	0.28	0.56	0.47	0.37	0.45	0.31	0.44	0.48	0.35
Al_2O_3	14.55	15.64	12.99	14.74	15.61	15.81	15.10	15.75	14.49	15.89	15.52	15.67
$Fe_2O_3^t$	2.82	1.52	1.32	2.23	4.16	3.45	2.73	3.23	2.28	3.14	3.64	2.47
MnO	0.06	0.04	0.02	0.07	0.08	0.08	0.07	0.05	0.08	0.06	0.07	0.06
MgO	0.87	0.53	0.91	0.57	1.20	1.02	0.76	0.99	0.51	0.88	1.10	0.66
CaO	2.12	1.82	3.96	2.39	2.78	2.90	2.09	2.66	1.67	2.65	2.34	2.44
Na_2O	3.41	4.83	3.86	3.90	4.30	4.15	3.63	4.54	3.67	4.48	4.61	3.74
K_2O	3.24	2.76	0.47	2.83	2.55	2.23	3.74	2.16	3.98	2.05	1.92	3.74
P_2O_5	0.10	0.06	0.07	0.08	0.18	0.15	0.11	0.13	0.09	0.13	0.15	0.10
LOI	1.10	0.90	0.70	0.70	0.90	1.40	1.20	0.80	0.80	1.10	1.00	0.35
Total	99.00	97.56	98.62	99.03	99.04	99.19	98.89	99.11	98.98	99.37	99.19	100.53
A/CNK	1.12	1.10	0.92	1.07	1.05	1.09	1.09	1.08	1.08	1.10	1.12	1.07
ppm												
V	37	15	25	24	52	47	40	44	29	29	44	20
Y	25	18	44	22	48	22	22	12	13	16	16	14
Zr	181	117	133	148	265	189	155	173	188	195	208	161
Nb	13	1	3	14	19	13	12	11	12	13	13	8
Ba	510	1094	84	595	620	544	943	629	1017	744	860	840
La	33	47	0.8	14	82	40	48	25	43	7	30	27
Ce	54	53	15	57	141	57	60	50	77	66	64	38
Cr	14	11	4	7	10	6	8	10	10	9	9	1
Co	75	83	90	80	74	78	87	80	80	70	70	22
Ni	2	*	*	*	*	*	*	*	*	*	*	9
Zn	54	43	120	50	81	73	57	52	52	61	78	64
Rb	99	69	7	86	113	77	115	122	122	83	79	95
Sr	185	1404	232	322	357	447	368	361	360	419	413	329
Nd	21	22	9	20	66	24	23	20	32	24	26	12
Pb	6	16	*	6	*	*	*	*	7	*	*	25
Th	15	2	*	11	20	11	9	10	27	12	10	9
U	4	9	5	8	6	5	4	3	3	3	3	3
Ga	19	20	12	18	21	21	18	19	17	19	20	23

typical granodioritic to tonalitic samples, except in the case of K_2O which is anomalously low (<1%) in all five of these samples, consistent with their lack of modal K-feldspar. They also tend to have higher $Fe_2O_3^t$ and MgO contents. The two groups of samples show clearly on the normative quartz - orthoclase - plagioclase diagram (Fig. 5), on which the first group form a coherent trend from granodiorite to monzogranite, and the second a trend toward increased quartz content in the tonalite and granodiorite fields. Sample #109, although lower in SiO_2 and normative quartz contents, also appears to be part of the tonalitic group. The lower SiO_2 content is consistent with the abundance of modal hornblende in this sample, as described above.

Both groups of samples are dominantly peraluminous, with molar $Al_2O_3/CaO+Na_2O+K_2O$ (A/CNK) ratios of 1.05 to 1.2, except for samples #109 and 140 which are slightly metaluminous (Table 1). The orthogneiss contains characteristic minerals of peraluminous granitoids including Al-rich biotite, muscovite, and garnet (Clarke 1981), although the magmatic origin of these phases is not certain. The general lack of amphibole is also consistent with peraluminous compositions (e.g., Chappell and White 1974).

Selected plots against SiO_2 (Fig. 6) illustrate trace element variations in the samples. In the granodioritic to tonalitic group of samples, Sr shows a weak negative correlation with SiO_2, whereas Ba and Rb are scattered with no significant correlation with SiO_2 (Fig. 6). The other group of tonalitic samples have reasonable Sr values for their silica contents but are depleted in Ba and Rb, consistent with their low K_2O contents. These samples are also very low in Nb compared to the other group (Fig. 6). Both V and Zr show negative correlation with SiO_2, with the tonalitic group of samples lying on the trend of the other sample group. La is generally lower and Y higher in the tonalitic group compared to the granodioritic to tonalitic group (Fig. 6).

Although the differences between the two groups of samples are supported by mineralogical differences, a plot of alkali element oxides suggests that the chemical differences may be a result of post-magmatic processes because the tonalitic samples plot outside the field of normal igneous compositions (Fig. 7, after Hughes 1973). In contrast, the other group of samples displays a more typically igneous trend (Fig. 7). Chemical variations in the latter group of samples are consistent with crystal fractionation of plagioclase and biotite.

On the Rb vs Y+Nb tectonic setting discrimination diagram, the majority of samples plot in the volcanic arc field (Fig. 8). The tonalitic samples also plot mainly in the volcanic arc field but due to their lower Rb and Nb values (perhaps related to alteration), they plot well away from the other group. In general, the granodioritic to tonalitic samples show chemical characteristics typical of intermediate to felsic igneous rocks, as demonstrated by comparison with the average I-, S-, felsic I-, and felsic S-type granites from Whalen *et al.* (1987), which are shown on figures 4, 6, 7, and 8. The trends displayed in the suite are similar to those between both average I- and S-type granites and their evolved (felsic) equivalents. The MgO contents are lower than those of both the average I- and S-types, and the Na_2O contents are higher and P_2O_5 contents lower than in the average S-type granite. Due to the probable overprinting effect of metamorphism on

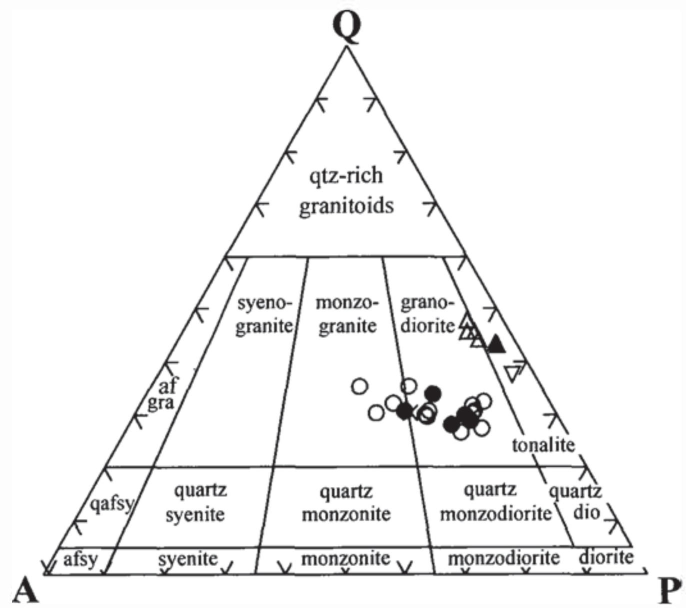


Fig. 5. Normative Q(quartz) - A(orthoclase) - P(albite+anorthite) diagram, showing fields from Streckeisen (1976). Normative mineralogy was calculated using $Fe^{2+}/Fe^{total}= 0.5$.

the original igneous mineralogical and chemical characteristics, it is difficult to assess the I-type or S-type affinity of the suite, using the commonly accepted criteria (e.g. White and Chappell 1983). However, Figure 8 demonstrates that, in either case, a volcanic arc setting seems most likely. The epsilon Nd value of -4 reported by Barr *et al.* (1998) for sample JP96-90 indicates some involvement of continental crust in its petrogenesis.

$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY

Hornblende separates from 3 samples (#74, 109, and 140) of the Belle Côte Road orthogneiss, 6 samples (#5, 53, 92, 114, 130, and 138) from amphibolitic bands (xenoliths?) in the orthogneiss, and 1 sample (#83) from amphibolite in the First Fork Brook gneiss adjacent to the orthogneiss (Fig. 2a) were dated by the $^{40}Ar/^{39}Ar$ method. For irradiation, the separated mineral concentrates were individually wrapped in Al foil. Interspersed among the samples were 5 to 8 aliquots of the flux monitor, the hornblende standard, MMhb-1 (assumed age = 520 ± 2 Ma; Samson and Alexander 1987). The entire package was shielded with Cd and irradiated in the McMaster University nuclear reactor. An internal resistance furnace of the double-vacuum type was used to carry out the step-heating. All isotopic analyses were made on a VG 3600 mass spectrometer using both Faraday and electron multiplier collectors. The detailed data are tabulated in Appendix D of Price (1997).

Age spectra and $^{37}Ar/^{39}Ar$ plots are shown in Figure 9a for the seven samples from the southern area (Fig. 2a) and Figure 9b for the three samples from the northern area (Fig. 2b). For all samples, low and variable apparent ages were obtained over the first ~30% of argon released. Relatively low $^{37}Ar/^{39}Ar$ ratios over this release interval suggest that these ages may be due to minor biotite contamination. Over the

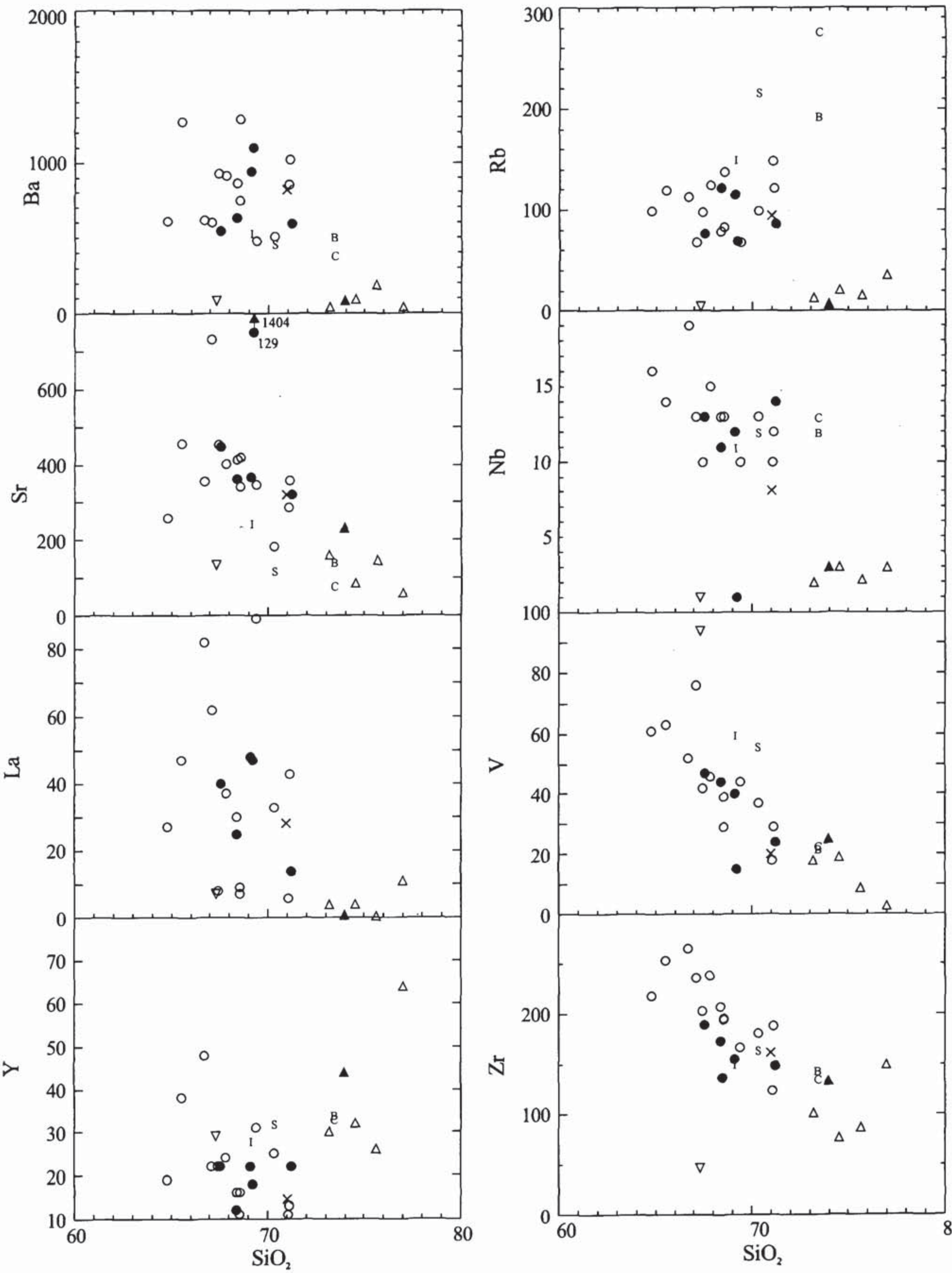


Fig. 6. Plots of selected trace elements against SiO_2 for samples from the Belle Côte Road orthogneiss. Symbols as in Fig. 4.

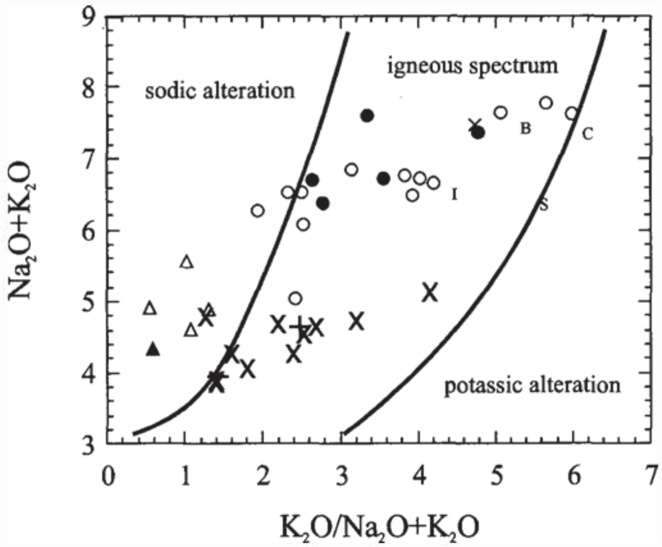


Fig. 7. Plot of Na_2O+K_2O against K_2O/Na_2O+K_2O, with fields after Hughes (1973). Symbols as in Fig. 4.

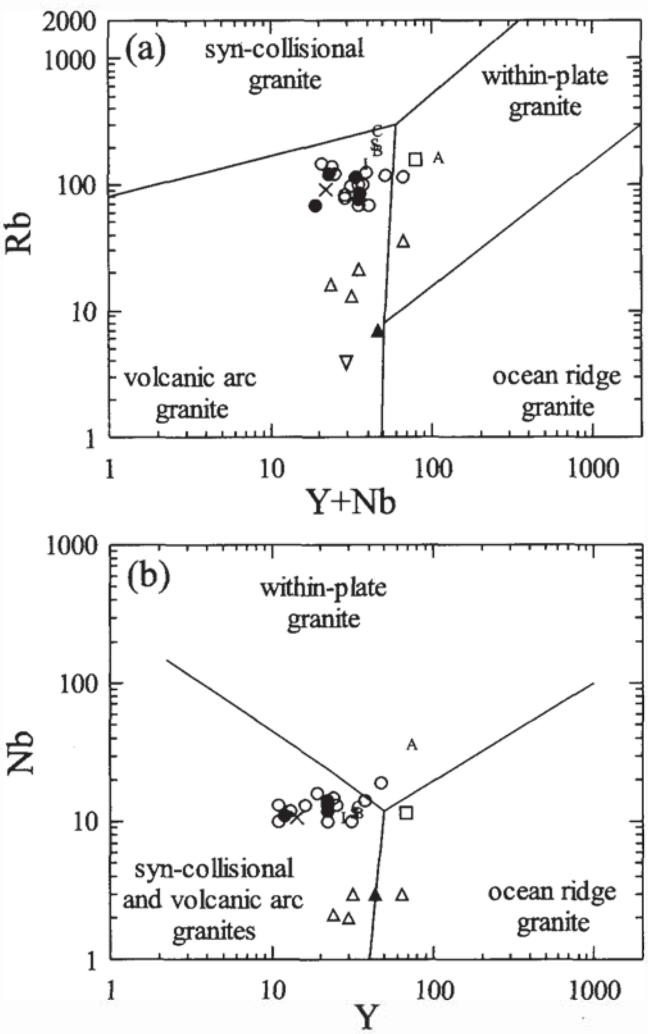


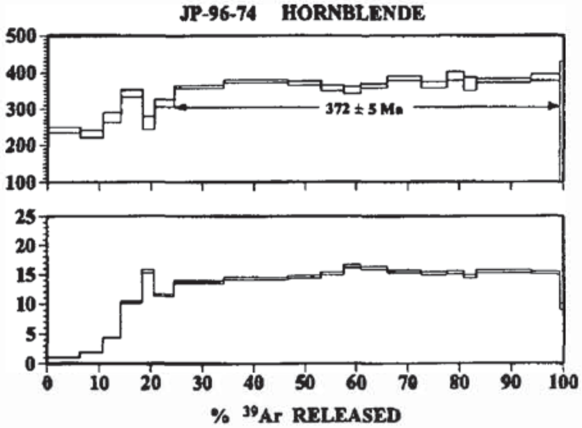
Fig. 8. Plots of (a) Rb vs. Y+Nb and (b) Y vs. Nb for samples from the Belle Côte Road orthogneiss. Symbols as in Fig. 4. Fields are from Pearce *et al.* (1984).

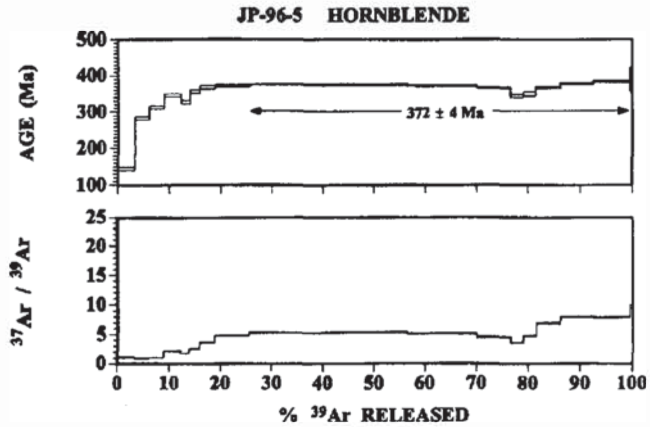
remaining gas release (~70-95% of the total), the data are characterized by relatively uniform age and $^{37}Ar/^{39}Ar$ values. The most uniform data were obtained from samples 92, 138 and 130; for these samples, the preferred ages (with their 2 sigma uncertainties) are respectively 384±3, 381±2 and 371±3 Ma. Samples 140, 114, 5, 53 and 74 yielded moderately discordant data; the preferred ages of these range from 370±4 to 376±3 Ma. The most discordant data were obtained from tonalitic orthogneissic sample 109 and from nearby amphibolite sample 83 from the First Fork Brook gneiss. Also, these two samples yielded the youngest preferred ages: 363±3 Ma for sample 109 and 353±2 Ma for sample 83. Apart from the fact that the two youngest ages occur together near the middle of the study area, no correlation is obvious between apparent age and either rock type or geographic location. These younger ages and associated relatively discordant age spectra suggest the possibility that a localized thermal disturbance occurred in this area, perhaps related to movement on nearby faults or to younger intrusions. The age range (370 to 384 Ma) defined by the remaining samples, although narow, also could be a reflection of temperature variations over the study area. Alternatively, or in addition, it could reflect variation in the closure temperature of hornblende (ca. 450±50°C; Harrison 1981). Titanite from the sample used for U-Pb zircon dating (located near $^{40}Ar/^{39}Ar$ dating sample 140) yielded a U-Pb age of 386±3 Ma (G. Dunning, unpublished data, cited by Barr and Jamieson 1991). Given that the closure temperature of titanite is ~600°C (Heaman and Parrish 1991), the data suggest that these rocks experienced very rapid cooling from ca. 600 to 500°C at about 385 Ma. From ca. 385 to 370 Ma, cooling was less rapid, perhaps ~5-10°C/m.y.

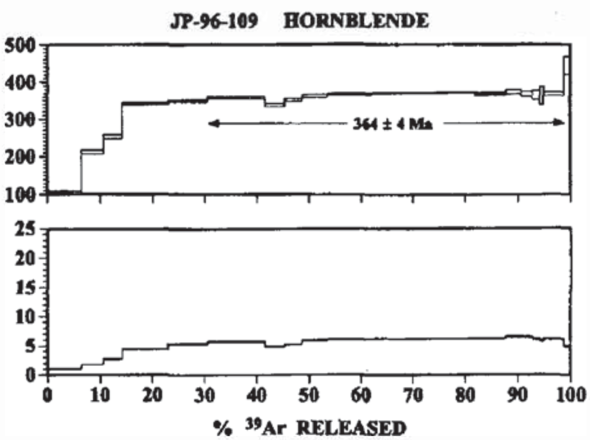
DISCUSSION

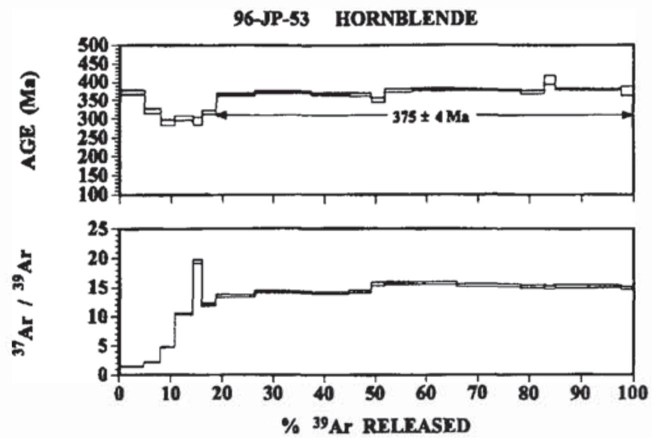
The Belle Côte Road orthogneiss is the only pluton in the Aspy terrane known to have a crystallization age of approximately 442 Ma (Late Ordovician to Early Silurian, using ca. 441 Ma as the Ordovician - Silurian boundary; Okulitch 1995). It intruded units (First Fork Brook gneiss, Middle River Metamorphic Suite, Jumping Brook Metamorphic Suite) that appear to have been deformed and metamorphosed during its emplacement. Thus the Belle Côte Road orthogneiss provides evidence that these metavolcanic and metasedimentary units are Ordovician (or older), and hence older than metavolcanic-metasedimentary units such as the Sarach Brook Metamorphic Suite and Money Point Group which have yielded Silurian (ca. 430 Ma) crystallization ages (Dunning *et al.* 1990; Keppie *et al.* 1991).

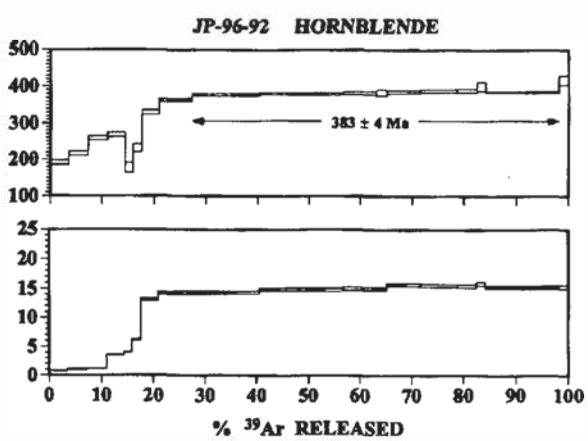
The petrochemical characteristics of the Belle Côte Road orthogneiss are unusual but apparently not unique. Similar characteristics were reported by Saavedra *et al.* (1987) in Ordovician granitoid suites in northwestern Argentina. Like the Belle Côte Road orthogneiss, the Argentinian suite consists of peraluminous two-mica granodiorite and tonalite, some of which contain epidote of inferred magmatic origin, as well as garnet and amphibole (Saavedra *et al.* 1987). The Argentinian suite was interpreted by Saavedra *et al.* (1987) to have formed in a back-arc setting under tectonic stress, but we suggest that the Belle Côte Road orthogneiss may have formed

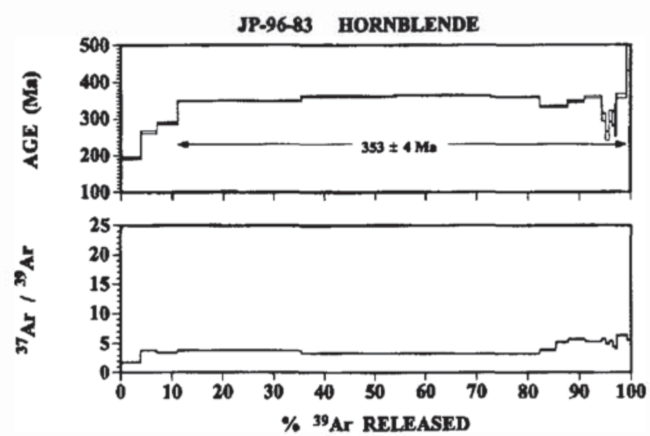












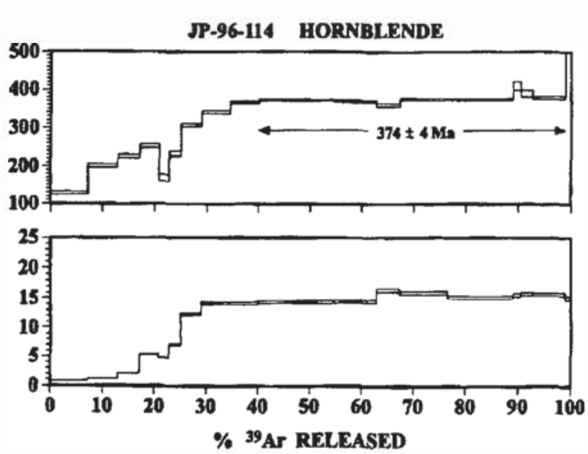


Fig. 9a. Age and isotopic data for hornblende separates from the southern part of the study area (sample locations showin in Fig. 2a). In the plots, the half-heights of open rectangles indicate the 1 sigma relative (between-step) uncertainties. Numerical uncertainties are given at the 2 sigma level. Detailed argon data for each sample are tabulated in Appendix D of Price (1997).

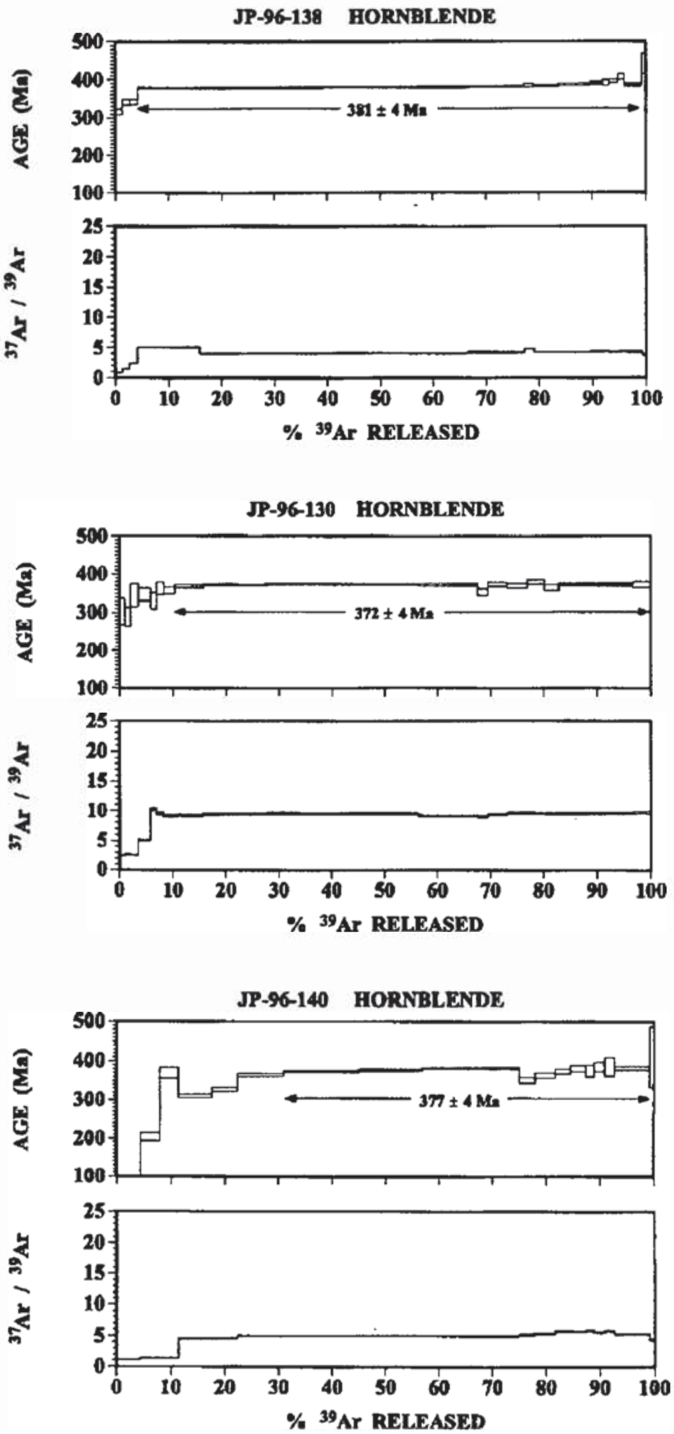


Fig. 9b. Age and isotopic data for hornblende separates from the northern part of the study area (sample locations shown in Fig. 2b). In the plots, the half-heights of open rectangles indicate the 1 sigma relative (between-step) uncertainties. Numerical uncertainties are given at the 2 sigma level. Detailed argon data for each sample are tabulated in Appendix D of Price (1997).

in a volcanic arc. Tectonic models for Cape Breton Island have suggested that Ordovician-Silurian volcanic suites in the Aspy terrane formed as a result of subduction at the continental margin of the Bras d'Or terrane (Lin 1993, 1995; Barr *et al.* 1995, 1998), and the protolith of the Belle Côte Road orthogneiss may have been emplaced in the roots of this arc (Fig. 10a). The magma may have been derived from melting of lower crustal rocks of the Bras d'Or terrane.

By the Early to mid-Silurian, a back-arc region may have formed, thus separating the future Aspy terrane (with underlying Bras d'Or terrane crust) from the remainder of the Bras d'Or terrane (Fig. 10b). Silurian volcanic-sedimentary suites such as the Sarach Brook Metamorphic Suite (Lister 1998) and Money Point Group (Lin 1995), and the ca. 430 Ma Taylors Barren Pluton (MacDonald 1996) have petrochemical features suggesting that they formed in this back-arc region. Evidence for transcurrent faulting during emplacement of the Taylors Barren Pluton (MacDonald 1996) indicates that oblique collision may have begun, perhaps marking the start of the juxtaposition of the Bras d'Or and Aspy terranes. Peak metamorphism apparently occurred in the early Devonian, presumably as a result of thrusting of the Bras d'Or terrane over the Aspy terrane (Fig. 10c). The minimum age of the metamorphism may be reflected in the First Fork Brook amphibolite by the U-Pb (monazite) date of 411±2 Ma (Barr and Jamieson 1991). The differences in thermal history between the Aspy and Bras d'Or terranes (Reynolds *et al.* 1989; Barr and Raeside 1994; Barr *et al.* 1995) may be explained by the fact that Bras d'Or terrane formed the hanging wall during juxtaposition.

Continued compression, possibly related to collision with Laurentia (as represented by the Blair River Inlier in Fig. 10c and d), caused continued crustal thickening and further granitoid magmatism (Fig. 10d). Dextral strike-slip motion on the Eastern Highlands shear zone between the Aspy and Bras d'Or terranes has been dated at between 415 and 410 Ma (Lin 1992). Folding of the steeply dipping gneissic foliation in the southern part of the Belle Côte Road orthogneiss into its "U-shape" may have been related to this motion.

By mid-Devonian, the Mira terrane was also being juxtaposed against the Bras d'Or terrane (White and Barr 1998) to complete terrane amalgamation in Cape Breton Island, although transcurrent motion may have continued into the Carboniferous. This collision may have initiated the rapid uplift recorded in the U-Pb (titanite) and $^{40}Ar/^{39}Ar$ data of the Aspy terrane at ca. 385 Ma.

The $^{40}Ar/^{39}Ar$ hornblende ages obtained in this study are somewhat younger than previously reported $^{40}Ar/^{39}Ar$ hornblende ages (Reynolds *et al.* 1989) from the McKenzies Mountain megacrystic orthogneiss (ca. 383 Ma), Jumping Brook Metamorphic Suite (384 Ma to 390 Ma), and Middle River Metamorphic Suite (388 and 390 Ma). The difference may reflect the presence of mid-Devonian (ca. 375 Ma; Horne 1995) plutons in the present study area, and thus the persistence of elevated temperatures for a longer period of time. Alternatively, the age differences could reflect variations in the chemistry and/or texture of hornblende that in turn control its closure temperature.

In Newfoundland, syn-tectonic S-type granites with ages of ca. 430 to 417 Ma have been reported in the Gander Zone (Kerr 1997). The Burgeo Suite (429+5/-3, U-Pb zircon) located on the southern coast of Newfoundland (Kerr 1997) appears to be somewhat similar to the Belle Côte Road orthogneiss, except that it is younger. It is characterised by foliated biotite and muscovite granite, is closely associated with K-feldspar megacrystic granite and contains migmatitic

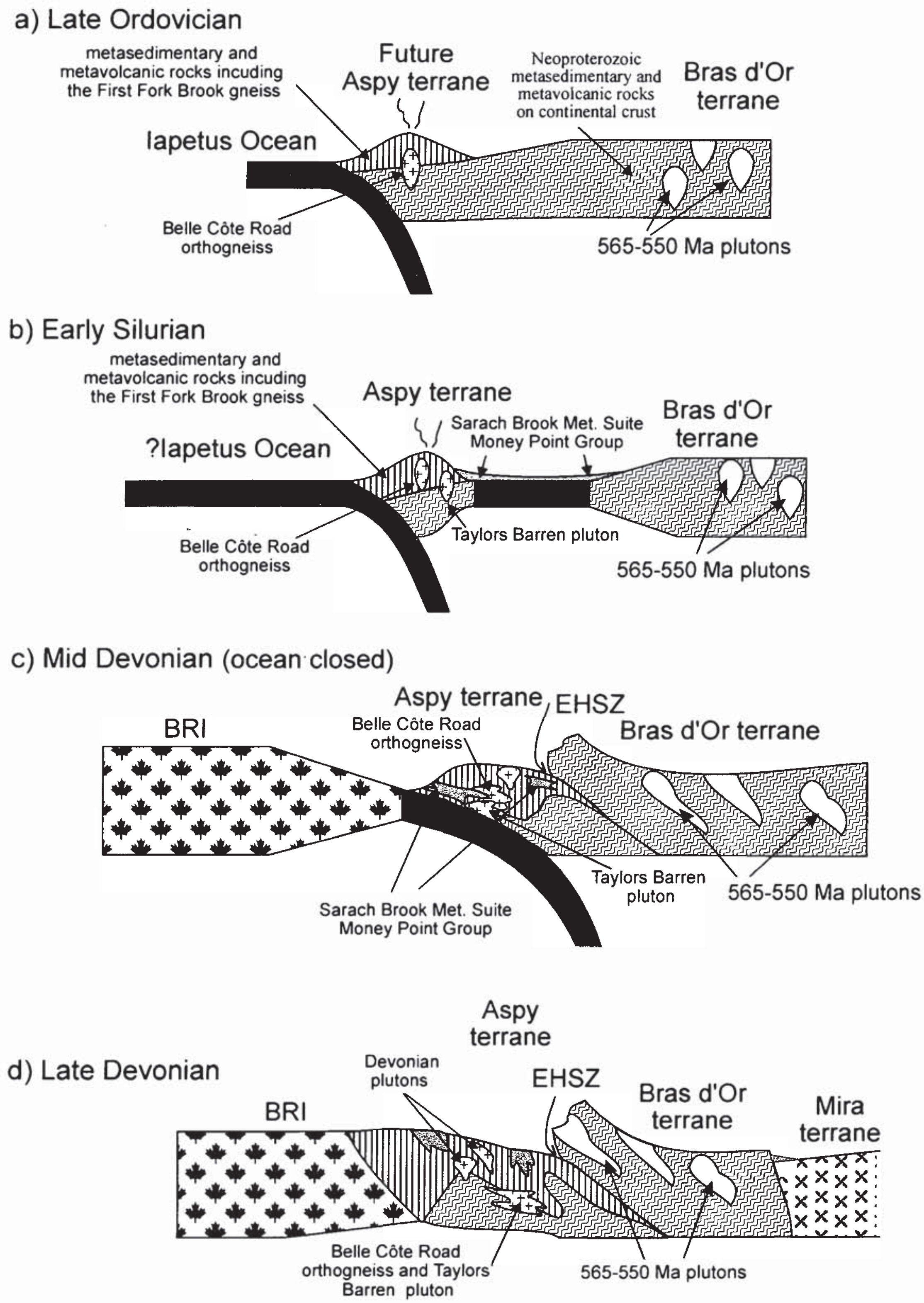


Fig. 10. A speculative tectonic model for development of the Aspy terrrane (modified from Barr *et al.* 1995, 1998), as discussed in the text. Abbreviations: BRI, Blair River Inlier; EHSZ, Eastern Highlands shear zone; met., metamorphic.

gneiss, mafic and metasedimentary enclaves, and melanocratic inclusions (Kerr 1997), features similar to those of the Belle Côte Road orthogneiss. The chemical characteristics of plutonic suites in the Gander Zone of Newfoundland are also similar to those of the Belle Côte Road orthogneiss. Both the Gander Zone plutonic suites and the Belle Côte Road orthogneiss are dominated by samples with >60% SiO_2 and high A/CNK ratios. All the samples also plot in a similar position in the volcanic-arc field of the Rb-(Y+Nb) tectonic setting discrimination diagram (Kerr 1997). The apparently older ages of metaplutonic and metavolcanic rocks in the Aspy terrane compared with southwestern Newfoundland may suggest that collision in Newfoundland occurred slightly later than in Cape Breton Island. Because of the geological complexity in both of these areas, apparently related at least in part to promontory - promontory collision (Lin *et al.* 1994), more detailed petrological and geochronological studies are needed in both areas before more specific correlations can be made.

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