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Sandra M. Barr, Chris E. White and Mike A. Hamilton

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See table of contents

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Article abstract

The Lower Coverdale intrusion near Moncton, New Brunswick, has been intersected in drill holes at depths of 100–200 m below unconformably overlying Carboniferous sandstone, conglomerate and, locally, limestone of the Windsor, Mabou, and Cumberland groups. A large positive aeromagnetic anomaly suggests that the intrusion has a subsurface area of at least 30–40 km^2. As revealed by drill core and cuttings, the intrusion consists of interlayered coarse-grained anorthosite and ferronorite, both intruded by gabbro, quartz monzonite, and minor felsic dykes. The ferronorite is high in Ti and P, and contains interstitial apatite and ilmenite/magnetite and layers of apatite-ilmenite rock (nelsonite) up to several metres thick. Much of the core shows pervasive effects of metamorphism and alteration but microprobe analyses of the freshest samples revealed that the plagioclase in both anorthosite and ferronorite has andesine composition. The anorthosite and ferronorite are chemically distinct, but their close spatial association suggests a genetic link. In contrast, the younger gabbroic rocks differ in mineralogy and chemistry from, and appear unrelated to, the anorthosite and ferronorite. They are altered but not metamorphosed, and preserve intergranular textures. They contain more calcic plagioclase and augite, and have low Ti and P. The deepest drill hole in the Lower Coverdale intrusion encountered highly altered coarse-grained quartz monzonite at a depth of 1095–1206 m. The quartz monzonite is mineralogically and chemically similar to quartz monzonite in quarries near Gaytons, 20 km to the east. Virtually identical Middle Devonian U-Pb zircon ages of 390.6 ± 1.0 Ma and 390.0 ± 0.5 Ma were obtained for samples from the Lower Coverdale and Gaytons quartz monzonite, respectively. However, the anorthosite-ferronoritegabbro is likely considerably older: perhaps ca. 540 Ma like gabbroic rocks elsewhere in the Brookville terrane; or possibly Mesoproterozoic, like intrusions with similar characteristics in Grenvillian parts of the Precambrian shield.

Lower Coverdale and Gaytons: Middle Devonian and possibly older anorthosite-ferronorite, gabbro, and quartz monzonite intrusions in southeastern New Brunswick

Sandra M. Barr,[1]* Chris E. White,[2] and Mike A. Hamilton[3]

1. Department of Earth and Environmental Science, Acadia University, Wolfville, Nova Scotia B4P 2R6, Canada
2. Department of Natural Resources, P.O. Box 698, Halifax, Nova Scotia B3J 2T9, Canada
3. Jack Satterly Geochronology Lab, University of Toronto, Toronto, Ontario M5S 3B1, Canada
*Corresponding author: <sandra.barr@acadiau.ca>

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ABSTRACT

The Lower Coverdale intrusion near Moncton, New Brunswick, has been intersected in drill holes at depths of 100–200 m below unconformably overlying Carboniferous sandstone, conglomerate and, locally, limestone of the Windsor, Mabou, and Cumberland groups. A large positive aeromagnetic anomaly suggests that the intrusion has a subsurface area of at least 30–40 km^2. As revealed by drill core and cuttings, the intrusion consists of interlayered coarse-grained anorthosite and ferronorite, both intruded by gabbro, quartz monzonite, and minor felsic dykes. The ferronorite is high in Ti and P, and contains interstitial apatite and ilmenite/magnetite and layers of apatite-ilmenite rock (nelsonite) up to several metres thick. Much of the core shows pervasive effects of metamorphism and alteration but microprobe analyses of the freshest samples revealed that the plagioclase in both anorthosite and ferronorite has andesine composition. The anorthosite and ferronorite are chemically distinct, but their close spatial association suggests a genetic link. In contrast, the younger gabbroic rocks differ in mineralogy and chemistry from, and appear unrelated to, the anorthosite and ferronorite. They are altered but not metamorphosed, and preserve intergranular textures. They contain more calcic plagioclase and augite, and have low Ti and P. The deepest drill hole in the Lower Coverdale intrusion encountered highly altered coarse-grained quartz monzonite at a depth of 1095–1206 m. The quartz monzonite is mineralogically and chemically similar to quartz monzonite in quarries near Gaytons, 20 km to the east. Virtually identical Middle Devonian U-Pb zircon ages of 390.6 ± 1.0 Ma and 390.0 ± 0.5 Ma were obtained for samples from the Lower Coverdale and Gaytons quartz monzonite, respectively. However, the anorthosite-ferronorite-gabbro is likely considerably older: perhaps ca. 540 Ma like gabbroic rocks elsewhere in the Brookville terrane; or possibly Mesoproterozoic, like intrusions with similar characteristics in Grenvillian parts of the Precambrian shield.

RÉSUMÉ

On a croisé l'intrusion de Lower Coverdale près de Moncton (Nouveau-Brunswick) dans des puits forés à des profondeurs de 100 à 200 m au-dessous de grès du Carbonifère sus-jacent non concordant, de conglomérat et, par endroits, de calcaire des groupes de Windsor, de Mabou et de Cumberland. Une anomalie aéromagnétique positive étendue permet de supposer que l'intrusion a une superficie souterraine d'au moins 30 à 40 kilomètres carrés. Les carottes de forage et les déblais révèlent que l'intrusion est constituée de ferronorite et d'anorthosite à grains grossiers interstratifiées, toutes deux pénétrées par du gabbro, de l'adamellite et des dykes felsiques secondaires. La ferronorite est riche en Ti et en P et renferme de l'ilménite/magnétite et de l'apatite interstitielles ainsi que des couches d'ilménite-apatite (nelsonite) pouvant avoir plusieurs mètres d'épaisseur. Une vaste part des carottes témoignent des effets intenses d'un métamorphisme et d'une altération, mais des analyses à la microsonde des échantillons les plus frais ont révélé que le plagioclase à l'intérieur de l'anorthosite et de la ferronorite est composé d'andésine. L'anorthosite et la ferronorite sont chimiquement distinctes, mais leur association spatiale étroite laisse supposer un lien génétique. Par contre, les roches gabbroïques plus récentes ont une composition minéralogique et chimique différant de celles de l'anorthosite et de la ferronorite et elles ne semblent pas y être apparentées. Elles sont altérées mais ne sont pas métamorphisées et elles conservent des textures intergranulaires. Elles renferment plus de plagioclase calcique et d'augite et ont une faible teneur en Ti et en P. Le puits de forage le plus profond dans l'intrusion de Lower Coverdale a recoupé de l'adamellite à grains grossiers fortement altérée à une profondeur de 1 095 à 1 206 m. L'adamellite est minéralogiquement et chimiquement similaire à l'adamellite des carrières situées près de Gaytons, à 20 kilomètres à l'est. On a obtenu des datations U-Pb sur zircon pratiquement identiques du Dévonien moyen de 390,6 ± 1,0 Ma et de 390,0 ± 0,5 Ma

Atlantic Geology 43, 163–179 (2007)
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d'échantillons d'adamellite de Lower Coverdale et de Gaytons, respectivement. Le gabbro d'anorthosite-ferronorite, toutefois, est probablement beaucoup plus âgé : il a peut-être 540 Ma, comme les roches gabbroïques d'ailleurs à l'intérieur du terrane de Brookville, ou il pourrait remonter au Mésoprotérozoïque, comme les intrusions présentant des caractéristiques analogues dans les parties grenvilliennes du bouclier précambrien.

[Traduit par la redaction]

INTRODUCTION

Plutonic igneous rocks lie buried beneath Carboniferous sedimentary rocks in the Lower Coverdale area south of Moncton, New Brunswick (Fig. 1). Although no surface outcrops have been found, the presence of these rocks was known as early as 1919, when gabbroic and anorthositic rocks were intersected at a depth of about 150 m in a hole drilled for oil and gas exploration (#52; Fig. 2). Assays revealed TiO_2 content up to 40% in ilmenite-bearing sections (New Brunswick Gas and Oilfields Limited 1919). Another hole drilled nearby in 1931 (#92; Fig. 2) yielded similar rocks (New Brunswick Gas and Oilfields Limited 1931). The large magnetic anomaly in the area (Nickerson 1994; Ascough 1997) suggests that the subsurface intrusion has an area of at least 30–40 km^2 (Fig. 2), and the complex shape of the anomaly indicates that the intrusion is composite and/or not uniformly magnetic. Four holes (T1 through T4; Fig. 2) were drilled by Killarney Oil and Gas in 1970 on the most southerly magnetic high, and encountered rocks described as gabbro, anorthosite, and anorthositic gabbro continuing to a depth of about 330 m in the deepest hole, T1. Subsequent holes drilled by Noranda Exploration Company Ltd. (LC94–1, LC95-1, LC95-2, LC95-3, and LC01-04; Fig. 2) yielded similar rocks (Woods 1995; Ascough 1997; Moreton 2001).

Despite its unusual characteristics, petrological studies of the Lower Coverdale intrusion have been few. Boyle and Stirling (1994) reported preliminary petrological descriptions in an abstract, but their data set was never published. Some of those data were provided to the present authors by J. Stirling (personal communication 2000) and are used in the present study. White (1996) described the petrography of a few samples from the 1919, 1931, and 1970 drill holes for comparison with other plutons of the Brookville terrane. McHattie (1998)

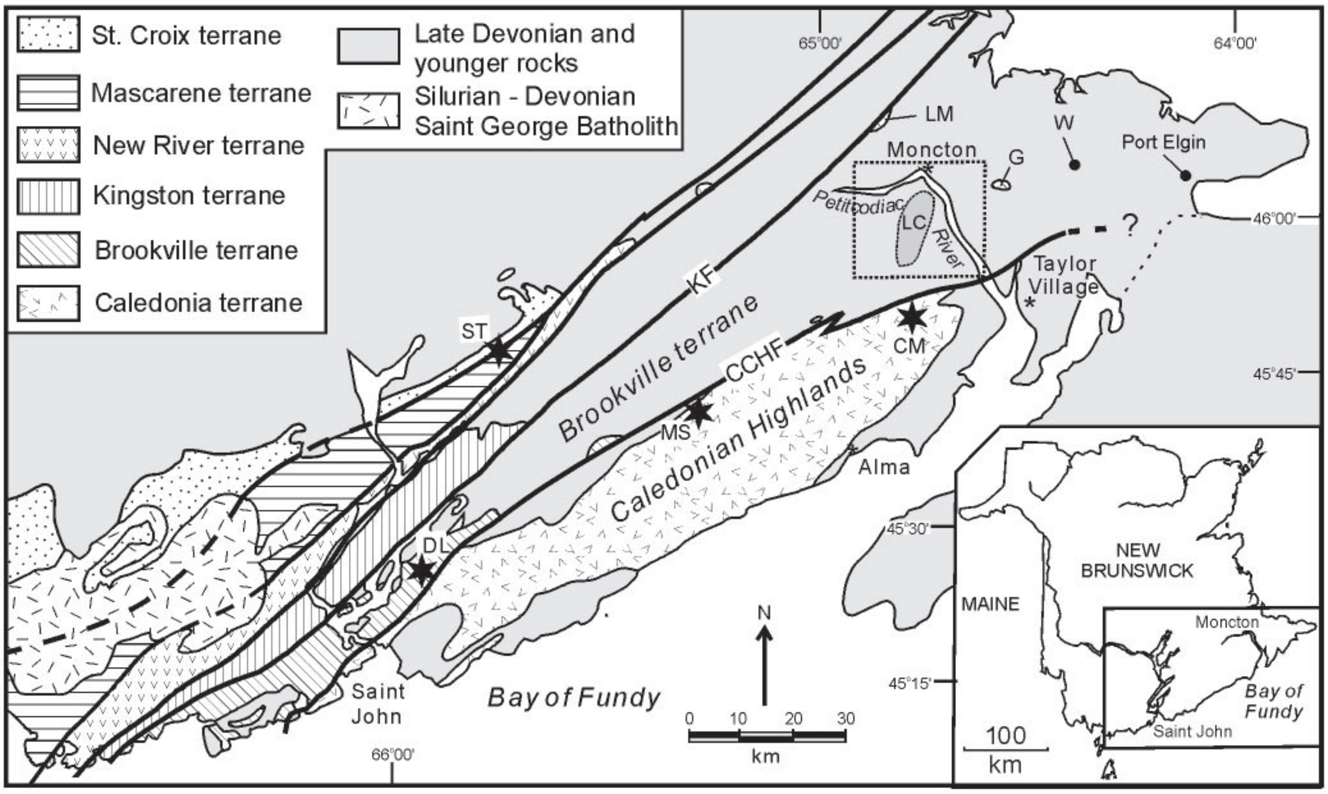

Fig. 1 **Terranes in southern New Brunswick (after White *et al.* 2002), showing locations of the Lower Coverdale area (LC), Gaytons quarries (G), and the Westmorland (W) and Port Elgin wells that are mentioned in this paper. Dotted box shows the area enlarged in Fig. 2. Inferred subsurface extent of the Lower Coverdale intrusion is shown as a darker grey area. Other abbreviations: CCHF, Caledonia-Clover Hill fault; CM, Caledonia Mountain Pluton; DL, Duck Lake Pluton; KF, Kennebecasis fault, LM, Lutes Mountain Diorite; MS, Mechanic Settlement Pluton; ST, Stewarton Gabbro.**

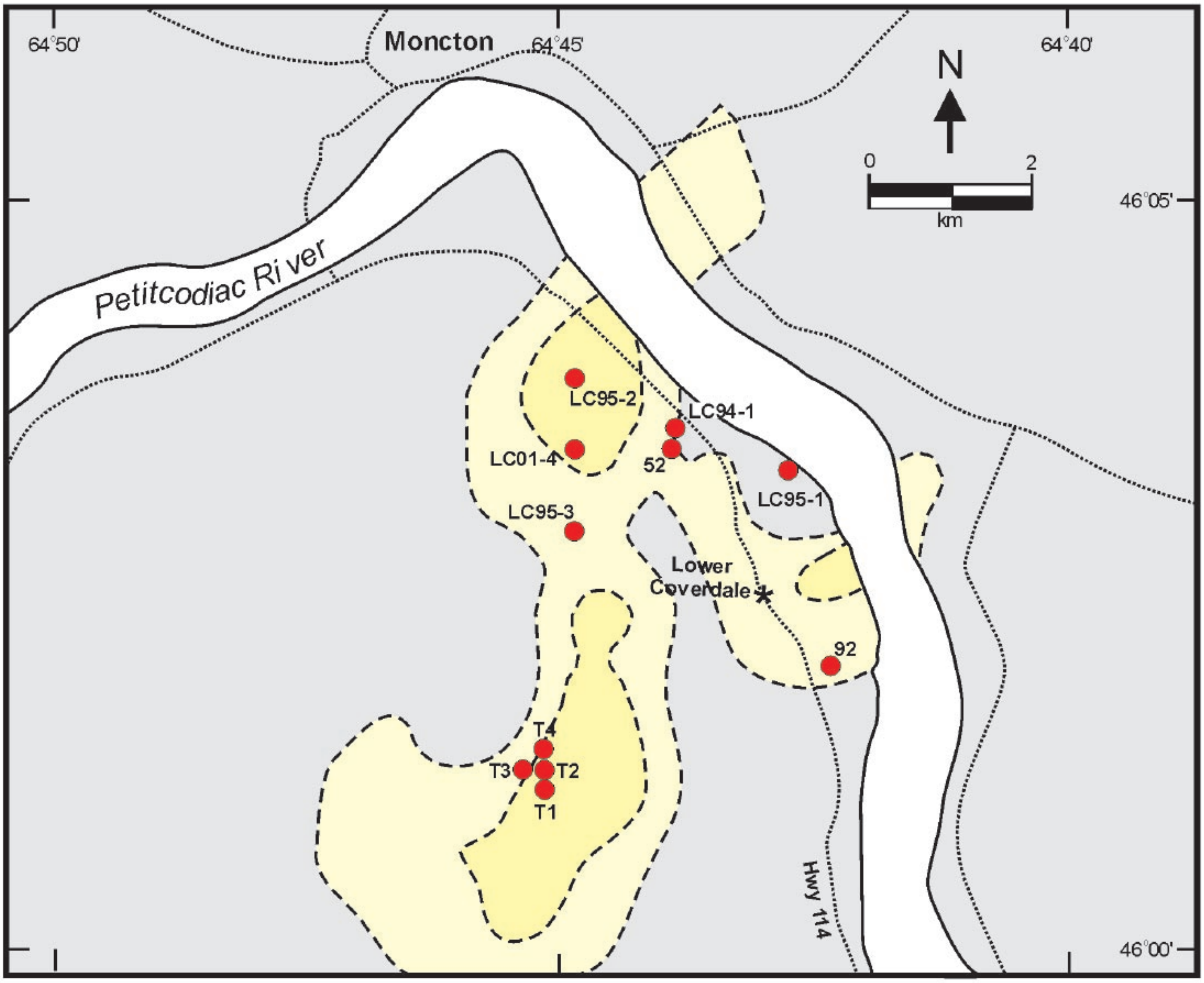

Fig. 2 Map of the Lower Coverdale area showing drill hole locations and magnetic contours at 53 750 (outer) and 55 000 (inner) nanotesla from the total field magnetic map of Ascough (2001).

compiled assay data and core logs from Noranda Exploration Company Ltd. assessment reports, and also reported about 65 additional major and trace element analyses, as well as petrographic descriptions, X-ray diffraction analyses, and Sr isotope data from apatite from holes LC94-1, LC95-1, LC95-2, and LC95-3 (Fig. 2). Barr *et al.* (2001, 2002) reported a preliminary U-Pb zircon age of 390 Ma from quartz monzonite, which forms the bottom 111 m of hole LC94-1, and a similar U-Pb age from quartz monzonite exposed in the quarries near Gaytons, about 20 km to the east of Lower Coverdale (Fig. 1). Although less prominent, the regional aeromagnetic anomaly associated with the Lower Coverdale area extends through the Gaytons area and east to Port Elgin (Nickerson 1994), suggesting an east-west zone of linked subsurface intrusions (Barr *et al.* 2001, 2002).

The purpose of this paper is to present a compilation of previous work on the Lower Coverdale intrusion, as well as additional petrographic and chemical data based on our examination and sampling of drill core and cuttings. In addition, we present U-Pb geochronological data for quartz monzonite from the Lower Coverdale drill core and the Gaytons quarry, which were cited in only preliminary form by Barr *et al.* (2001, 2002), and discuss possibilities for the age of the anorthositic and gabbroic rocks.

GEOLOGICAL SETTING

The Lower Coverdale intrusion and Gaytons quarries are located in the Brookville terrane, one of several narrow northeast-trending belts of pre-Carboniferous rocks of contrasting composition and age, separated by major faults, which make up southern New Brunswick (Fig. 1). The Brookville terrane is linked to Ganderia, a peri-Gondwanan terrane of the northern Appalachian orogen that is distinct from Avalonia (Hibbard *et al.* 2006). The Proterozoic to early Cambrian metamorphic and plutonic rocks that characterize the Brookville terrane are well exposed in the Saint John area, and can be traced on the basis of sparse outcrops and drill core data to the northeast through to the Moncton area (White 1996; White and Barr 1996; White *et al.* 2002). Boyle and Stirling (1994) inferred that the Lower Coverdale suite intruded metavolcanic and metasedimentary rocks of the Caledonian Highlands, but metavolcanic and metasedimentary rocks do not occur in the drill core logs, and the Lower Coverdale area is north of the projected boundary between the Avalonian Caledonia and Ganderian Brookville terranes (Fig. 1).

PREVIOUS STUDIES

The Lower Coverdale rocks were described as granitic in the 1919 core logs and as chloritic schist in the 1931 logs by New Brunswick Gas and Oilfields Limited. However, petrographic examination of cuttings from these holes by White (1996) and during the present study confirmed that they are gabbro and anorthosite. In the 1970 core logs by Killarney Oil and Gas Limited, the rocks were described more accurately as gabbro, anorthositic gabbro, and anorthosite, with dykes of "acidic", pegmatitic, and "dolerite" composition. Similar rock types were reported in the Noranda Exploration Company Ltd. core logs (Woods 1995; Ascough 1997), with the additional recognition of ferrogabbro, massive ilmenite layers, and in the bottom of LC94-1, at least 111 m of rock described as granodiorite. Based on examination of available core, Boyle and Stirling (1994) recognized four rock types: Ti-P ferrogabbro, nelsonite (apatite-ilmenite rock), anorthosite, and fine-grained diabase dykes. On the basis of his petrographic studies, McHattie (1998) better defined these rock types. He reported that the body is mainly a massif-type anorthosite, with locally antiperthitic plagioclase of labradorite composition. The ferrogabbro contains abundant titanium oxide minerals and apatite, structurally overlies and intrudes the anorthosite, and is associated with high magnetic areas on the aeromagnetic maps. Non-magnetic low-Ti gabbro is also present, especially in drill hole LC95-1. McHattie (1998) also noted that the suite is intruded by fine-grained diabase dykes that, based on chemical similarity, may be linked to the low-Ti gabbro. Much less abundant felsic dykes were interpreted to be related to the granodiorite intersected in the bottom of drill hole LC94-1 (McHattie 1998).

In drill holes, a saprolitic weathering profile separates the gabbro-anorthosite from overlying Carboniferous conglomerate of the Hopewell Cape Formation (basal Mabou Group) and Boss Point (Cumberland Group) formations (Woods 1995; C. St. Peter, written comm. 2006; Johnson 2006). A titanium paleoplacer containing locally transported, massive ilmenite pebbles has been reported to occur above the saprolite in LC94-1 (Woods 1995; Johnson 2006). A similar paleoplacer occurs near Taylor Village, 20 km to the southeast of Lower Coverdale (Fig. 1), in the Hopewell Cape Formation, and is assumed to have been derived from the Lower Coverdale intrusion (Hudgins 1999; Johnson 2006). The conglomerate at Taylor Village contains detrital clasts of ilmenite, 0.2 to 24 mm in size, variously altered to pseudo-rutile, rutile, and hematite (Bell 1984).

Geophysical models using aeromagnetic data as well as sparse gravity and seismic data suggested that the Lower Coverdale intrusion is lopolithic in shape with variable thicknesses between 800 and 1100 m (Burke 2000). Venugopal (2003) compared features of the Lower Coverdale suite to the Stewarton Complex, a gabbro-anorthosite body of inferred Early Devonian age located about 100 km southwest of Lower Coverdale (Fig. 1).

PETROGRAPHY

Introduction

Our petrographic work augments that of McHattie (1998) by including the subsequently drilled, deeper parts of holes LC95-2 and 3, and the additional hole LC01-4 (Moreton 2001). In addition, we examined and sampled core from holes T1 through T4, and made mounts for petrographic study from some of the cuttings from holes 52 and 92. No additional igneous rock types were detected in these studies, although a previously unnoted metamorphic unit was observed in drill hole LC95-3, as described below. As in previous studies, we recognize four main igneous units: anorthosite, ferronorite, gabbroic rocks, and quartz monzonite. In large sections of the core, the anorthosite and ferronorite are interlayered on a scale of several tens of metres down to less than 1 m and such sections are shown separately on the core logs (Fig. 3). However, contacts are sharp, and rocks intermediate between these end members types are not common. Mafic and much rarer felsic dykes were observed in all of the main rock types except the quartz monzonite, which occurs only in the deepest hole (LC94-1; Fig. 3). In addition, intervals of ilmenite-apatite rock (nelsonite) occur in LC95-2 and 3, LC94-1, T1 -T4, and in the cuttings of holes 52 and 92. Evidence of possible host rocks for the intrusion was observed only in drill hole LC95-3, as described below.

Correlation of specific units between drill holes is not obvious (Fig. 3), and the orientation of layering or of mafic and felsic dykes has not been investigated in detail. However, limited observation suggest that layering is approximately horizontal. All of the rocks in the core except the felsic dykes and quartz monzonite show evidence of pervasive upper greenschist-facies metamorphism, with mafic mineral assemblages dominated by chlorite, amphibole, and biotite.

Mica schist and calc-silicate rocks

Mica schist and calc-silicate rocks were sampled in drill hole LC95-3 at a depth from about 700 m to 780 m, with interlayered anorthosite and ferronorite above and below (Fig. 3). These metamorphic rocks are strongly foliated and consist of plagioclase, quartz, white mica, biotite, chlorite, titanite, magnetite, apatite, and carbonate minerals in varying proportions. Based on mineralogy, they appear to have sedimentary protoliths, and may represent the original host rocks for the plutonic suite, although contact relations are uncertain. Amphibolite

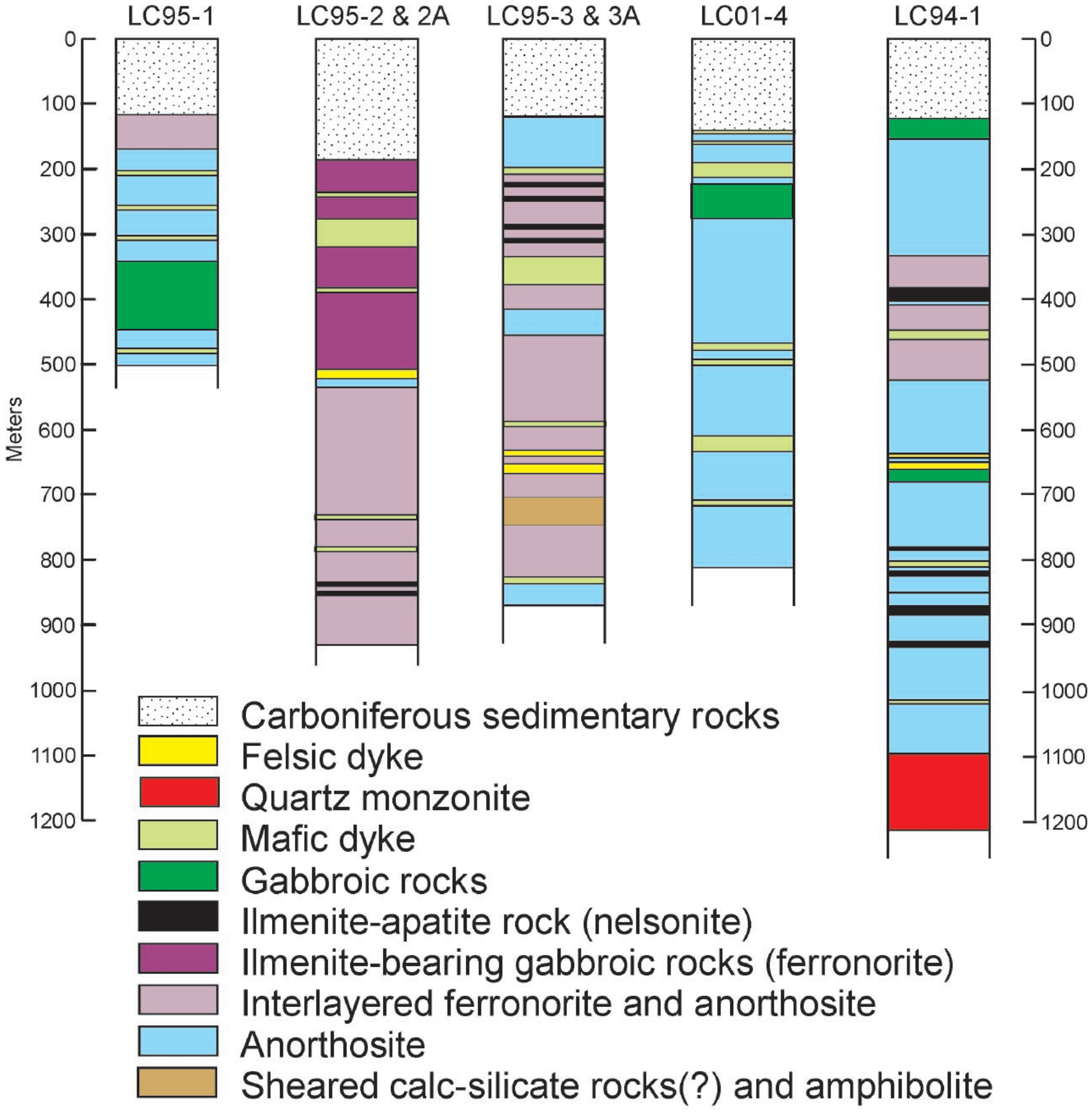

Fig. 3 **Generalized stratigraphic logs of drill core from the Lower Coverdale area, compiled from information in Woods (1995), Ascough (1997), McHattie (1998), Moreton (2001), and the present study.**

Table 1. Feldspar compositions* in selected samples from the Lower Coverdale anorthosite-ferronorite suite.

	weight %											cations calculated on the basis of 32 oxygen											end member components		
Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	BaO	CaO	Na_2O	K_2O	Total	Si	Al	Fe^3	Ti	Fe^2	Mn	Mg	Ba	Ca	Na	K	Ab	An	Or
ferronorite																									
LC95-2-286	59.68	0.09	27.10	0.18	0.08	0.19		8.28	7.38	0.13	103.11	10.38	5.55	0.00	0.01	0.03	0.01	0.05	0.00	1.54	2.49	0.03	61.30	38.00	0.70
LC95-2-286	59.03	0.01	25.78	0.05			0.14	7.55	7.30	0.23	100.09	10.55	5.43	0.00	0.00	0.01	0.00	0.00	0.01	1.45	2.53	0.05	62.80	35.90	1.30
LC95-2-286	64.69	0.11	19.18		0.05		1.48	0.04	1.40	14.95	101.90	11.83	4.13	0.00	0.02	0.00	0.01	0.00	0.11	0.01	0.50	3.49	12.40	0.20	87.40
LC95-2-286	58.90	0.04	26.57	0.04	0.02	0.04	0.01	8.20	7.16	0.19	101.17	10.42	5.54	0.00	0.01	0.01	0.00	0.01	0.00	1.56	2.46	0.04	60.60	38.30	1.10
LC95-2-286	59.21		26.41	0.12		0.12	0.08	8.01	7.51	0.10	101.56	10.45	5.49	0.00	0.00	0.02	0.00	0.03	0.01	1.51	2.57	0.02	62.60	36.90	0.60
LC95-2-286	58.94		26.38		0.06	0.03		8.16	7.18	0.11	100.86	10.46	5.51	0.00	0.00	0.00	0.01	0.01	0.00	1.55	2.47	0.03	61.00	38.30	0.60
LC95-2-286	60.71	0.10	25.95	0.16	0.09	0.09		4.25	6.53	1.53	99.41	10.81	5.44	0.00	0.01	0.02	0.01	0.02	0.00	0.81	2.26	0.35	66.10	23.80	10.20
ferronorite																									
LC95-2-357	55.24		25.82	2.83		0.76	0.07	8.15	6.26	0.14	99.27	10.13	5.57	0.00	0.00	0.43	0.00	0.21	0.01	1.60	2.23	0.03	57.70	41.50	0.90
LC95-2-357	59.18		26.08		0.02		0.10	8.02	7.22	0.04	100.66	10.51	5.46	0.00	0.00	0.00	0.00	0.00	0.01	1.53	2.49	0.01	61.80	37.90	0.20
LC95-2-357	59.40		26.38	0.09	0.04	0.19		8.10	7.46	0.04	101.70	10.46	5.47	0.00	0.00	0.01	0.01	0.05	0.00	1.53	2.55	0.01	62.40	37.40	0.20
LC95-2-357	58.89	0.06	26.02					8.03	7.36	0.07	100.43	10.49	5.46	0.00	0.01	0.00	0.00	0.00	0.00	1.53	2.54	0.02	62.20	37.50	0.40
LC95-2-357	58.83		25.40	0.15		0.03	0.15	7.34	7.47	0.10	99.47	10.58	5.38	0.00	0.00	0.02	0.00	0.01	0.01	1.41	2.60	0.02	64.40	35.00	0.60
ferronorite																									
LC95-2-431	59.35	0.14	26.24	0.09		0.02		7.77	7.39	0.01	101.01	10.50	5.47	0.00	0.02	0.01	0.00	0.01	0.00	1.47	2.54	0.00	63.20	36.70	0.00
LC95-2-431	59.56	0.04	26.15	0.04		0.10		7.81	7.51	0.02	101.23	10.52	5.44	0.00	0.01	0.01	0.00	0.03	0.00	1.48	2.57	0.01	63.40	36.40	0.10
LC95-2-431	59.54		25.98				0.03	7.43	7.80	0.06	100.84	10.55	5.42	0.00	0.00	0.00	0.00	0.00	0.00	1.41	2.68	0.01	65.30	34.40	0.30
anorthosite																									
LC95-2-555	58.73		26.65	0.03				8.54	6.87		100.82	10.42	5.57	0.00	0.00	0.00	0.00	0.00	0.00	1.62	2.36	0.00	59.30	40.70	0.00
LC95-2-555	58.55	0.02	26.43	0.02			0.02	8.71	6.61	0.06	100.42	10.43	5.54	0.00	0.00	0.00	0.00	0.00	0.00	1.66	2.28	0.01	57.70	42.00	0.40
LC95-2-555	57.66		26.81			0.04		8.81	6.68	0.05	100.05	10.32	5.65	0.00	0.00	0.00	0.00	0.01	0.00	1.69	2.32	0.01	57.70	42.00	0.30
LC95-2-555	57.56		26.46					8.62	6.81	0.14	99.59	10.36	5.61	0.00	0.00	0.00	0.00	0.00	0.00	1.66	2.38	0.03	58.40	40.80	0.80
LC95-2-555	57.68		26.47	0.08	0.01			8.82	6.74	0.25	100.05	10.35	5.59	0.00	0.00	0.01	0.00	0.00	0.00	1.70	2.34	0.06	57.20	41.40	1.40
LC95-2-555	58.01		26.73	0.10		0.05		8.69	6.70	0.08	100.36	10.35	5.62	0.00	0.00	0.02	0.00	0.01	0.00	1.66	2.32	0.02	58.00	41.60	0.50
LC95-2-555	57.58		26.62	0.12		0.02	0.04	8.76	6.64	0.31	100.09	10.33	5.62	0.00	0.00	0.02	0.00	0.01	0.00	1.68	2.31	0.07	56.80	41.40	1.70
LC95-2-555	56.97	0.05	26.55		0.05	0.04	0.01	8.53	6.69	0.05	98.94	10.32	5.66	0.00	0.01	0.00	0.01	0.01	0.00	1.66	2.35	0.01	58.50	41.20	0.30
LC95-2-555	57.33	0.05	27.09		0.10	0.05		8.68	7.01	0.08	100.39	10.25	5.71	0.00	0.01	0.00	0.02	0.01	0.00	1.66	2.43	0.02	59.10	40.40	0.40
mafic dyke																									
LC95-2-305	52.31		30.41	0.05		0.10	0.18	13.57	4.46		101.08	9.43	6.46	0.00	0.00	0.01	0.00	0.03	0.01	2.62	1.56	0.00	37.30	62.70	0.00
LC95-2-305	52.99		29.58	0.18			0.28	12.28	5.06	0.13	100.50	9.60	6.31	0.00	0.00	0.03	0.00	0.00	0.02	2.38	1.78	0.03	42.40	56.90	0.70
LC95-2-305	54.80		28.55	0.36		0.07		11.32	5.62	0.10	100.82	9.84	6.04	0.00	0.00	0.05	0.00	0.02	0.00	2.18	1.96	0.02	47.10	52.40	0.60
LC95-2-305	52.32		30.79	0.06	0.07		0.10	13.60	4.22		101.16	9.41	6.52	0.00	0.00	0.01	0.01	0.00	0.01	2.62	1.47	0.00	36.00	64.00	0.00

*Analyses by JEOL 8200 electron microprobe in the Dalhousie University Regional Electron Microprobe Laboratory.

layers composed mainly of amphibole and plagioclase may represent metamorphosed mafic dykes.

Anorthosite

Assuming that the drill cores are representative, anorthosite is the most abundant plutonic rock in the Lower Coverdale intrusion. It also appears to be the oldest, intruded by all of the other rock types. Anorthosite is especially abundant in holes LC95-1, LC01-4, and LC94-1, which are located in areas of low magnetic field (Fig. 2). Susceptibility measurements of anorthosite samples with a hand-held susceptibility meter (KT-9 Kappameter manufactured by Geoexploranium Ltd.) yielded uniformly low results (less than 0.1×10^{-3} SI units). Much of the anorthosite is coarse-grained, with crystals more than 5 mm across in many samples. Larger grains are anhedral and in some samples contain antiperthitic exsolution blebs. They appear to be relict igneous grains, and are typically surrounded by masses of finer grained plagioclase. Electron microprobe analyses of plagioclase in one anorthosite sample (Table 2) indicated andesine composition (An_{40-43}), but compositions determined by traditional petrographic methods are typically somewhat lower (An_{30-40}). The plagioclase shows little zoning and may originally have had adcumulate texture; however, most samples are recrystallized and intensely altered, with interstitial flakes of chlorite. Scattered opaque minerals (ilmenite) occur in some samples. In hand sample, many core sections are salmon pink, attributed by Woods (1995) and earlier workers to the presence of the zeolite mineral laumontite, although that suggestion was not investigated in the present study.

Ferronorite

Ferronorite is almost as abundant as anorthosite in the drill core. It forms thick sections of holes LC92-2 and 2A, and is interlayered with anorthosite in sections of the other holes, especially LC95-3 and 3A. Although termed ferrogabbro in earlier studies, these rocks contain mainly orthopyroxene in addition to plagioclase, ilmenite, and apatite, and hence ferronorite is more accurate following Streckeisen (1976). Orthopyroxene is characteristically the most abundant mineral, with subordinate plagioclase (Fig. 4a, b). Ilmenite and apatite are interstitial to the silicate minerals. Orthopyroxene analyses were difficult to obtain because of pervasive alteration to anthophyllite, as also identified by McHattie (1998) by X-ray diffraction and confirmed in the present study by electron microprobe analyses. Microprobe analyses in two least altered samples indicated orthopyroxene compositions of about En_{60-70}, with up to 7% wollastonite component (Table 2). Plagioclase compositions in three samples showed little variation in the range of An_{34-42}, similar to the compositions in anorthosite samples, and on the basis of plagioclase composition the rock could be termed ferrodiorite. Antiperthitic exsolution blebs are common in the plagioclase (Fig. 4c), as in the anorthosite samples, and electron microprobe analyses indicated that they consist of alkali feldspar of composition Or_{87} and about 1.5% BaO (Table 2).

Table 2. Pyroxene compositions* in selected samples from the Lower Coverdale anorthosite-ferronorite suite.

	weight %												numbers of cations calculated on the basis of 6 oxygen														end members		
Sample	SiO_2	TiO_2	Al_2O_3	FeO	Cr_2O_3	MnO	NiO	MgO	CaO	Na_2O	K_2O	Total	TSi	TAl	M1Al	M1Ti	M1Fe^3	M1Fe^2	M1Cr	M1Mg	M1Ni	M2Mg	M2Fe^2	M2Mn	M2Ca	M2Na	Wo	En	Fs
ferronorite																													
LC95-286	54.95	0.07	3.74	7.71	0.02	0.04	0.00	21.38	11.68	0.46	0.03	100.08	1.98	0.02	0.14	0.00	0.00	0.00	0.00	0.86	0.00	0.28	0.23	0.00	0.45	0.03	24.60	62.66	12.74
LC95-286	66.11	0.00	0.55	13.26	0.00	0.35	0.00	17.85	0.33	0.24	0.00	98.69	2.51	0.00	0.03	0.00	0.00	0.00	0.00	0.98	0.00	0.03	0.42	0.01	0.01	0.02	0.92	69.39	29.69
LC95-286	55.94	0.00	1.34	16.68	0.00	0.39	0.13	24.27	0.48	0.38	0.00	99.61	2.05	0.00	0.06	0.00	0.00	0.00	0.00	0.94	0.00	0.39	0.51	0.01	0.02	0.03	1.01	70.98	28.01
ferronorite																													
LC95-431	54.98	0.05	1.82	19.22	0.01	0.44	0.05	20.98	1.42	0.45	0.06	99.48	2.05	0.00	0.08	0.00	0.00	0.00	0.00	0.92	0.00	0.25	0.60	0.01	0.06	0.03	3.09	63.51	33.40
LC95-431	54.99	0.06	1.36	20.19	0.00	0.52	0.00	21.59	0.48	0.39	0.00	99.58	2.05	0.00	0.06	0.00	0.00	0.00	0.00	0.94	0.00	0.26	0.63	0.02	0.02	0.03	1.03	64.34	34.63
LC95-431	60.05	0.02	0.90	19.04	0.08	0.42	0.14	19.58	0.50	0.10	0.01	100.84	2.23	0.00	0.04	0.00	0.00	0.00	0.00	0.95	0.00	0.13	0.59	0.01	0.02	0.01	1.16	63.45	35.39
LC95-431	55.78	0.10	1.02	20.42	0.01	0.50	0.00	20.97	0.45	0.32	0.06	99.63	2.09	0.00	0.05	0.00	0.00	0.00	0.00	0.95	0.00	0.22	0.64	0.02	0.02	0.02	0.98	63.48	35.54
LC95-431	54.25	0.10	1.49	20.90	0.01	0.53	0.00	20.77	0.43	0.14	0.01	98.63	2.05	0.00	0.07	0.00	0.00	0.00	0.00	0.93	0.00	0.24	0.66	0.02	0.02	0.01	0.93	62.74	36.33
LC95-431	54.52	0.09	1.53	20.55	0.00	0.63	0.15	21.19	0.56	0.23	0.00	99.45	2.04	0.00	0.07	0.00	0.00	0.00	0.00	0.93	0.01	0.26	0.64	0.02	0.02	0.02	1.20	63.29	35.50
LC95-431	53.00	0.12	3.45	18.89	0.02	0.36	0.00	19.21	3.47	0.61	0.05	99.18	1.98	0.02	0.14	0.00	0.00	0.00	0.00	0.86	0.00	0.21	0.59	0.01	0.14	0.04	7.67	59.10	33.23
mafic dyke																													
LC95-305	53.43	0.34	2.02	6.08	0.56	0.16	0.18	18.63	20.77	0.21	0.01	102.39	1.90	0.09	0.00	0.01	0.00	0.00	0.02	0.97	0.01	0.02	0.18	0.01	0.79	0.02	40.28	50.27	9.45
LC95-305	52.36	0.45	2.66	6.03	0.78	0.18	0.00	17.92	21.03	0.36	0.00	101.77	1.88	0.11	0.00	0.01	0.00	0.01	0.02	0.96	0.00	0.00	0.17	0.01	0.81	0.03	41.39	49.07	9.54
LC95-305	50.13	1.03	4.06	11.40	0.06	0.31	0.00	13.30	20.74	0.46	0.00	101.49	1.85	0.15	0.03	0.03	0.00	0.21	0.00	0.73	0.00	0.00	0.14	0.01	0.82	0.03	42.86	38.24	18.90
LC95-305	53.07	0.26	1.97	7.47	0.26	0.30	0.00	18.05	19.82	0.34	0.00	101.54	1.91	0.08	0.00	0.01	0.00	0.02	0.01	0.97	0.00	0.00	0.21	0.01	0.77	0.02	38.86	49.24	11.90
LC95-305	52.66	0.30	2.83	7.09	0.39	0.15	0.06	18.02	20.34	0.34	0.00	102.18	1.88	0.12	0.00	0.01	0.00	0.02	0.01	0.96	0.00	0.00	0.19	0.01	0.78	0.02	39.83	49.10	11.07
LC95-305	49.42	0.53	5.16	8.30	0.15	0.11	0.00	16.44	18.63	0.47	0.03	99.24	1.82	0.18	0.05	0.02	0.00	0.03	0.00	0.90	0.00	0.00	0.23	0.00	0.74	0.03	38.76	47.59	13.66
LC95-305	51.12	0.35	3.00	7.10	0.39	0.22	0.10	16.90	20.50	0.28	0.00	99.96	1.87	0.13	0.00	0.01	0.00	0.05	0.01	0.92	0.00	0.00	0.17	0.01	0.81	0.02	41.22	47.28	11.49

*Analyses by JEOL 8200 electron microprobe in the Dalhousie University Regional Electron Microprobe Laboratory. T, M1, and M2 are sites in the pyroxene crystal structure. End members are wollastonite (Wo), enstatite (En), and ferrosilite (Fs).

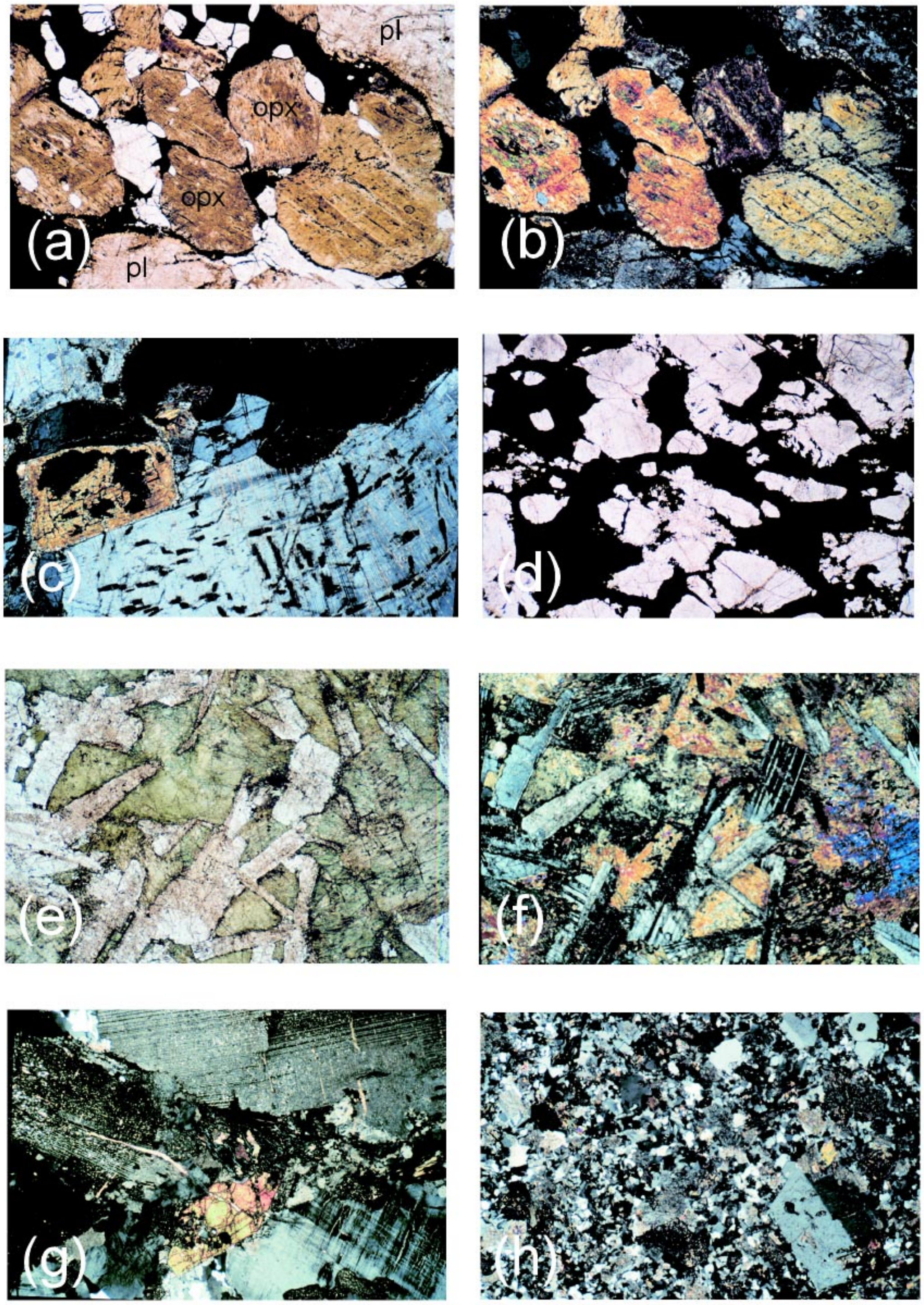

Fig. 4 Photomicrographs of samples from the Lower Coverdale intrusion and Gaytons quarries. Long dimension of all photos is approximately 4 mm. (a) Ferronorite sample LC95-2-241 showing altered orthopyroxene (opx) and plagioclase (pl), with interstitial apatite (white) and ilmenite (black). (b) Same view as (a) in crossed polars. (c) Ferronorite sample LC95-2-286 showing plagioclase with exsolution blebs of Ba-rich alkali feldspar, under crossed polars. (d) Nelsonite sample LC 95-3-346 showing apatite (white) and ilmenite (black) in plane polarized light. (e) Gabbro sample LC95-1-356, showing plagioclase, chlorite, and actinolite in intergranular texture in plane polarized light. (f) Same view as (e) in crossed polars. (g) Quartz monzonite from the Gaytons quarries showing microcline, plagioclase, interstitial quartz, and a large titanite grain in crossed polars. (g) Felsic dyke sample LC95-2-242 showing plagioclase, K-feldspar, and quartz microphenocrysts in a finer grained groundmass of quartz, feldspar, and chlorite (after biotite) in crossed polars.

With decreasing amounts of orthopyroxene and plagioclase, the ferronorite grades to ilmenite-apatite rock or nelsonite (Fig. 4d) that forms layers up to 5 m in thickness. Both the ferronorite and nelsonite are characterized by high magnetic susceptibility, up to 60 × 10^{-3} SI units. Apatite analyses in two ferronorite samples and one nelsonite sample showed that they are fluoro-apaite with up to 3% F (Venugopal 2003).

Gabbro

Gabbro forms thick sections in holes LC95-1 and LC94-1 (Fig. 3). It is medium-grained with plagioclase and pyroxene in relict intergranular texture. However, in most samples the pyroxene has been completely altered to actinolitic amphibole and chlorite (Fig. 5e, f). Opaque minerals and apatite are minor components. No mineral analyses were obtained from gabbro samples, but optical methods indicate that plagioclase is of labradorite composition, and hence more calcic than in the ferronorite and anorthosite. Magnetic susceptibility measured in gabbro samples is low, less than 1 × 10^{-3} SI units, in contrast to the higher values measured in the ferronorite.

Mafic dykes

Mafic dykes occur in the anorthosite and ferronorite units, but were not observed in the quartz monzonite unit, suggesting that the dykes are older than the quartz monzonite but younger than the other units. They typically have well developed chilled margins. Some of the dykes are foliated amphibolite with metamorphic textures, but most are gabbro, and consist of plagioclase and variably altered pyroxene with intergranular texture. The similarity of the gabbroic dykes to the larger gabbro units described above suggests that they are related, as also supported by their chemical similarities

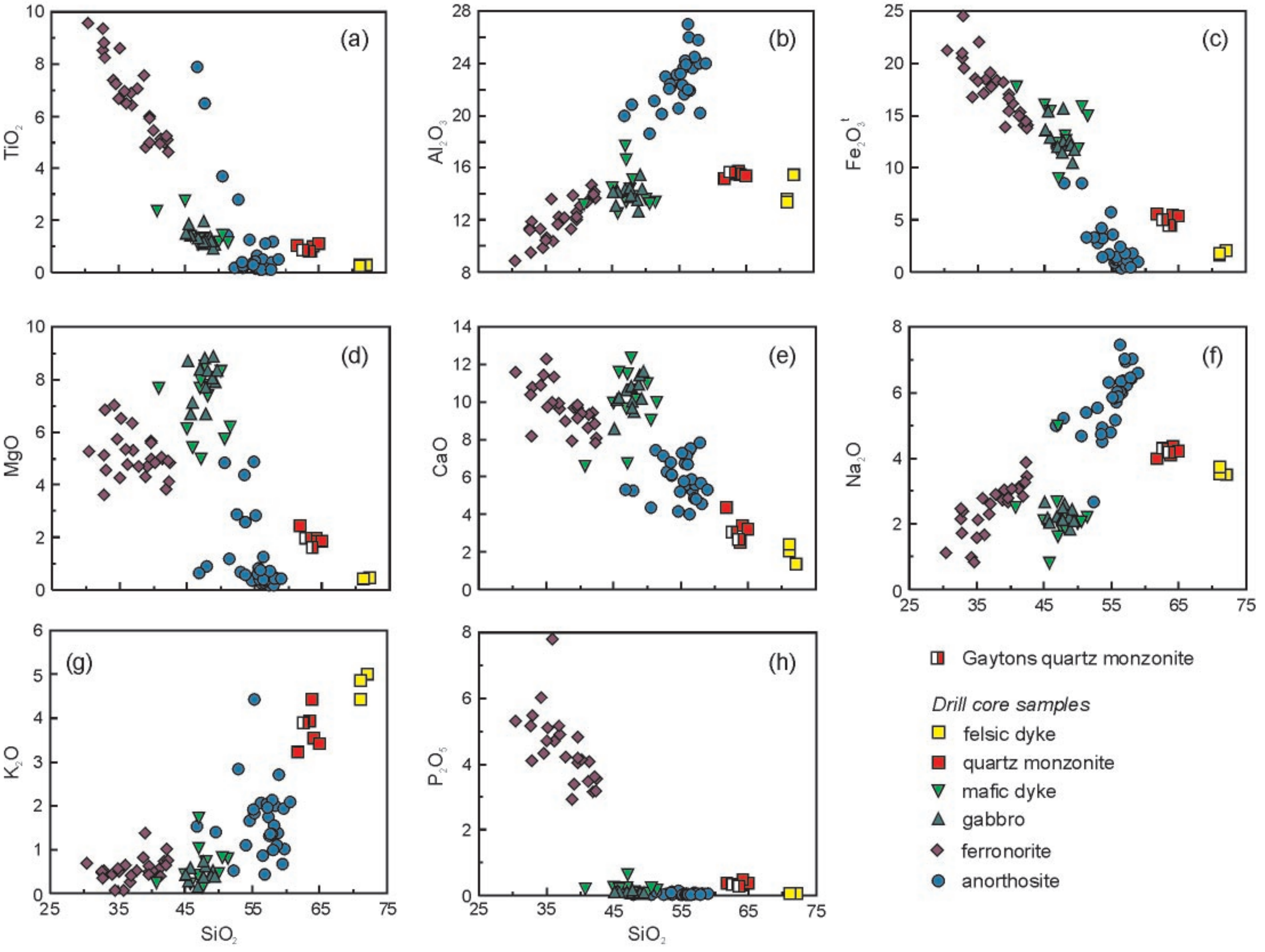

Fig. 5 **Plots of (a) TiO_2, (b) Al_2O_3, (c) $Fe_2O_3^t$, (d) MgO, (e) CaO, (f) Na_2O, (g) K_2O, and (h) P_2O_5 against SiO_2 to illustrate the chemical characteristics of the Lower Coverdale and Gaytons quarry samples. Data are from Table 3 and other sources cited in text.**

described below. Electron microprobe analyses in one dyke sample indicated that the plagioclase is labradorite (Table 1), consistent with optical determinations in other dyke samples, and the clinopyroxene is of augite composition (Table 2). The opaque phase in the dyke is present in minor amounts and electron microprobe analyses indicate that it is magnetite, not ilmenite as in the ferronorite. Low measured magnetic susceptibilities, less than 1×10^{-3} SI units, reflect the low abundance of magnetite.

Quartz Monzonite

Quartz monzonite occurs only in drill hole LC94-1 from a depth of about 1095 m to the bottom of the hole (1206 m). Both the overlying anorthosite and the quartz monzonite are highly sheared and altered near the contact, and hence the nature of the contact is uncertain. The quartz monzonite is very coarse grained, and relatively homogeneous. It is brecciated and sheared, with abundant veins of carbonate and epidote. The most abundant minerals are plagioclase and K-feldspar (microcline), with less abundant granular quartz. Because of the amount of alteration, accurate modal analysis is not possible, but estimates suggest that the rock is quartz monzonite like that in the Gaytons quarries (described below). Original mafic minerals have been replaced by chlorite, but big grains of titanite and apatite are a distinctive feature.

Gaytons Quartz Monzonite

The Gaytons Quartz Monzonite is exposed in aggregate quarries near the village of Gaytons, east of Moncton (Fig. 1). It is the most abundant rock type in the quarries, and consists of large phenocrysts of both K-feldspar (microcline) and plagioclase in a coarse-grained groundmass of plagioclase, quartz, biotite, and amphibole. Accessory titanite, apatite, and opaque minerals are abundant (Fig. 4g). To the east of the Gaytons quarries, the Westmorland and Port Elgin wells (Fig. 1) reached granitic rocks at depths of 314 m and 927 m, respectively (St. Peter 1987). Thin sections made from chips from the cuttings from both of these wells show mineral assemblages consistent with a quartz monzonite source, in that they contain abundant K-feldspar (microcline) and plagioclase, and less abundant quartz, as well as minor biotite and chlorite. The correlation is most convincing in the Port Elgin sample because it contains large grains of titanite, a feature characteristic of the quartz monzonite in both the Gaytons quarries and the Lower Coverdale core.

Felsic dykes

Felsic dykes were observed in holes LC95-2 and 3 and LC94-1. They consist of plagioclase, quartz, and minor K-feldspar microphenocrysts in a fine-grained granular groundmass of quartz and feldspar (Fig. 4h). Biotite (altered to chlorite) is a minor component. Overall, they appear to preserve igneous texture, and are late in the intrusive sequence. They were assumed previously to be related to the quartz monzonite (McHattie 1998; Barr *et al.* 2001), but are more felsic in composition (see chemistry below) and a genetic link with the quartz monzonite is equivocal.

CHEMISTRY

Chemical data with petrographic control on rock type were presented by McHattie (1998). Those data are combined with new data obtained during the present study (Table 1) to provide a total of 89 major and trace element analyses with petrographic control. These data are displayed on a variety of diagrams to illustrate chemical variation in the suite (Figs. 5, 6, 7). In addition, these data are displayed on selected diagrams together with the full set of assay data from other sources (Fig. 8). The latter data are mainly from sections of core without regard to rock type, and hence may not represent end member rock type compositions in every case, but they provide an indication of the overall chemical variation in the suite.

Three chemically distinct groups of samples are apparent in the data, representing anorthosite, ferronorite, and gabbro plus mafic dykes (Figs. 5, 6). The majority of anorthosite samples have SiO_2 contents between 50 and 60%, whereas the ferronorite samples have lower SiO_2 (30–45%) and the gabbro and mafic dyke samples are intermediate with 40–50% SiO_2. The anorthosite samples have high Al_2O_3 (more than 18%), with higher values in samples with higher SiO_2 (Fig. 5b), and consistently low P_2O_5 (Fig. 5h). Some more gabbroic (pyroxene-bearing) anorthosite samples have higher MgO (Fig. 5d), and other samples have elevated concentrations of opaque phases leading to elevated TiO_2, $Fe_2O_3^t$, and V (Figs. 5a, c, 6h). The anorthosite samples show spread in CaO, Na_2O, and K_2O, and correspondingly in Ba, Rb, and Sr (Fig. 6a-c), probably related to variation in both plagioclase abundance and composition, as well as to the effects of alteration. Low P_2O_5 is consistent with lack of apatite observed in anorthosite thin sections. The elements Y, Nb, and Zr are all low, but Cr and Ni show a spread of higher values in some anorthosite samples, reflecting variations in pyroxene and/or opaque mineral abundance.

The ferronorite samples display negative correlation of TiO_2, Fe_2O_3, CaO, and P_2O_5 with SiO_2, and positive correlation of Al_2O_3 and Na_2O with SiO_2, reflecting variations in the proportions of ilmenite and apatite relative to silicate minerals. MgO is more scattered, and linked to the proportion of orthopyroxene. K_2O is less than 1%, and likely resides mainly in antiperthitic plagioclase. Among the trace elements (Fig. 6), Ba shows wide variation, apparently reflecting its presence in K-feldspar exsolution lamellae in plagioclase. Ni and Cr contents are both low. The chemical gap between anorthosite and ferronorite samples evident on all of the diagrams in Figures 5 and 6 is consistent with the petrographic observation that lithologies gradational between these two interlayered rock types are not common. Although some analytical discrepancies clearly exist in the assay datasets, a gradation from ferronorite through to nelsonite with TiO_2 up to nearly 35%, P_2O_5 up to

15%, and V up to 1500 ppm is apparent (Fig. 8a, c, d). The trend to high V apparent mainly in low-Ti gabbroic samples in the data set with petrographic control (Fig. 6h) appears to be present also in some ferronorite samples, although the assay data set for V is smaller. Analyses of the opaque phases are required in order to understand the relationship between ilmenite and magnetite in these rocks, and the distribution of Ti and V in those minerals.

Gabbro and mafic dyke samples are chemically similar. They have low TiO_2 and P_2O_5 (relative to the ferronorite), and wide variation in Ni, V, and Cr suggesting pyroxene and magnetite fractionation (Fig. 6g, h, i). Although the gabbroic and mafic dyke samples show compositions that overlap with both the anorthosite and ferronorite samples, suggesting chemical trends, they show some significant differences which preclude that relationship (Figs. 5, 6). For example, the gabbroic and mafic dyke samples have higher CaO and lower Na_2O and Al_2O_3 than anorthosite samples with similar SiO_2 contents, consistent with the more calcic plagioclase compositions in the gabbroic rocks. Compared to the ferronorite samples, the gabbro and mafic dyke samples have distinctly lower TiO_2 and P_2O_5, and higher MgO (Fig. 5) and trends in Ni, V, and Cr are very different (Figs. 6g, h, i, 8e). The textures in the gabbro and mafic dyke samples indicate that they are not cumulate rocks, and their compositions are appropriate for plotting on commonly used tectonic setting discrimination diagrams (e.g., Figs. 7a, b). Although the data are scattered, variations in V and Ti suggest that they formed in an ocean-floor to volcanic-arc tectonic setting (Fig. 7a), as do relatively high contents of Zr and Y relative to Nb (Fig. 7b).

The quartz monzonite in the lower part of drill hole LC94-1 is chemically similar to quartz monzonite from the Gaytons quarries (Figs. 5, 6). The quartz monzonite samples contain 61–65% SiO_2, and compared to the anorthosite samples, have low Al_2O_3, CaO, and Na_2O_3, and generally higher TiO_2, Fe_2O_{3t}, MgO, K_2O, and P_2O_5 (Fig. 5). A notable feature of samples

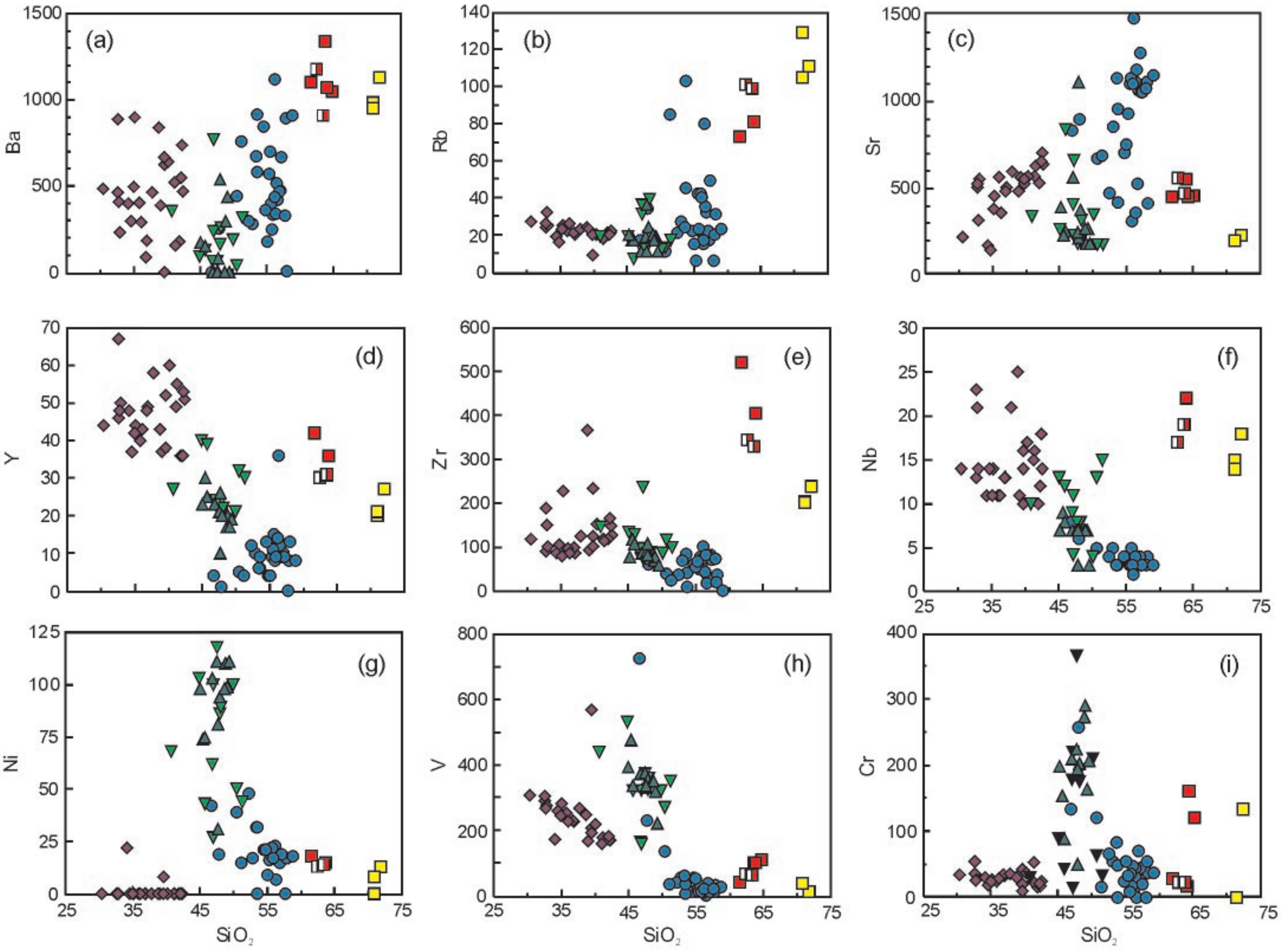

Fig. 6 Plots of (a) Ba, (b) Rb, (c) Sr, (d) Y, (e) Zr, (f) Nb, (g) Ni, (h) V, and (i) Cr against SiO_2 to illustrate the chemical characteristics the Lower Coverdale and Gaytons quarries samples. Symbols are as in Fig. 5. Data are from Table 3 and other sources cited in text. The number of data points varies because not all trace elements were analyzed in all samples.

from both the Gaytons quarries and core LC94-1 is high Ba content, a trend also noted in the anorthosite samples (Fig. 6a). The quartz monzonite is high in Y, Zr, and Nb compared to the anorthosite (Fig. 6d, e, f). It shows affinity with A-type granite (e.g., Fig. 7c), and plots at the boundary between volcanic arc and within-plate granite fields on the tectonic setting discrimination diagram (Fig. 7c). Their petrological and age similarities leave no doubt that the quartz monzonite in drill hole LC94-1 and exposed in the Gaytons quarries are correlative. The high Ba content and abundance of modal titanite and apatite also suggest the possibility of some relationship to the Lower Coverdale anorthosite and ferronorite (see further discussion below).

Three felsic dyke samples contain higher SiO_2 than the quartz monzonite (~ 72% compared to 61–65%), but share some chemical similarities such as high Ba and relatively high Y, Zr, and Nb (Fig. 6a, d, e, f). They also appear to have affinities with A-type granite (Fig. 7c), but appear to have formed in a volcanic-arc tectonic setting (Fig. 7d). As described above, their petrographic features are unlike those of the quartz monzonite, but they are similarly late in the intrusive sequence, and hence a genetic linkage cannot be ruled out.

U-PB (ZIRCON) AGES

Quartz monzonite samples for U-Pb (zircon) dating were collected from drill hole LC94-1 (by D.R. Boyle) and the eastern part of the Gaytons quarries (by S. Barr and C. White). Three fractions of water-clear colourless to very pale pinkish-brown and yellow-brown elongate zircon prisms (length:width = 2:1 to 4:1) were analyzed from drill core sample LC94-1. Most grains contained small numbers of rounded, irregular fluid inclusions. All of the fractions cluster on or near Concordia, and yield a weighted mean $^{206}Pb/^{238}U$ age of 390.6 ± 1.0 Ma (Fig. 9a), interpreted to be the age of crystallization of the Lower Coverdale quartz monzonite. A sample from the eastern part of the Gaytons quarries yielded similar-looking zircon grains (also rich in fluid inclusions) as well as a population of stubby, flat, sharply terminated prisms. Three fractions were analyzed and show nearly identical Pb/U ages, with error ellipses overlapping each other and Concordia (Fig. 9b). A weighted mean $^{206}Pb/^{238}U$ age of two fractions is 390.0 ± 0.5 Ma because of the possibility of a small amount of Pb-loss in fraction c. These ages are interpreted to represent the time of crystallization of the Lower Coverdale and Gaytons quartz monzonite units.

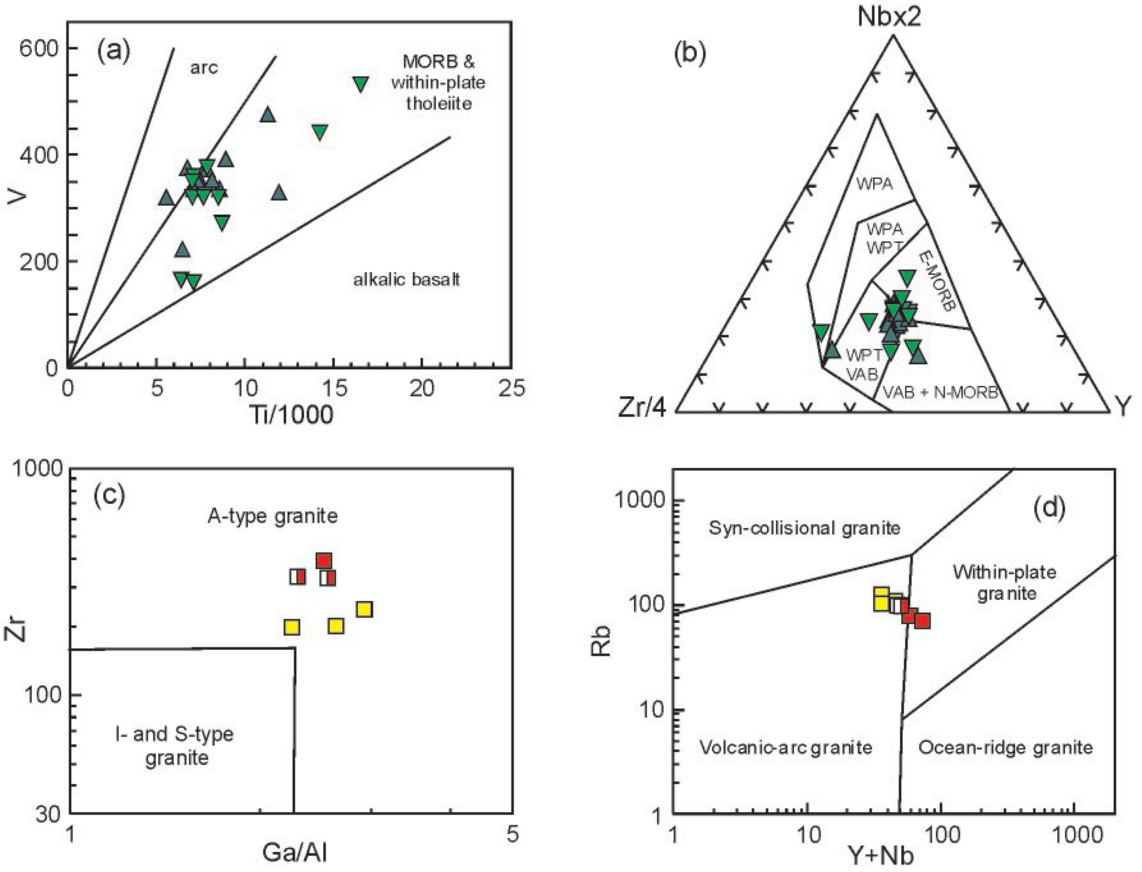

Fig. 7 Discrimination diagrams to illustrate the chemical affinity and tectonic setting of gabbroic (a, b) and quartz monzonite (c, d) samples. Fields are from: (a) Meschede (1986), (b) Shervais (1982), (c) Whalen *et al.* (1987), and (d) Pearce *et al.* (1984). Data are from Table 3 and other sources cited in text.

Table 3. New chemical data* from the Lower Coverdale drill core and Gaytons quarry.

Sample	Rock type	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Ba	Rb	Sr	Y	Zr	Nb	Th	Pb	Ga	Zn	Cu	Ni	V	Cr	Co	U	La	Nd
LC94-1-218.5**	mafic dyke	50.00	1.18	13.60	11.90	0.24	8.33	11.00	2.00	0.46	0.09	4.20	103.00	190	12	350	21	87	4		12		54	120	100	320	210	41		4.6	8.7
LC94-1-453.8**	mafic dyke	51.40	1.17	13.40	15.00	0.22	6.21	10.00	2.20	0.79	0.18	2.50	103.07	320	17	180	30	100	15		4		86	57	44	350	33	42		13	16
LC94-1-592.4**	mafic dyke	47.10	1.28	13.40	12.40	0.17	7.96	11.50	1.60	1.04	0.11	6.15	102.71	240	36	230	23	75	4.2		< 2		55	93	100	320	220	40		5.8	11
LC94-1-751	ferronorite	46.81	7.87	19.97	12.04	0.07	0.65	5.34	5.00	1.52	0.08	0.99	100.33	< 5	17	834	4	89	8	2	< 3	20	60	45	42	725	133	62	< 1	< 5	6
LC94-1-809**	mafic dyke	45.80	1.42	12.50	15.40	0.16	5.42	11.60	0.80	0.22	0.21	9.50	103.03	130	6.9	840	39	130	12				81	88	43	320	43	40		21	22
LC94-1-810	mafic dyke	50.52	1.45	13.24	15.85	0.21	5.75	9.04	2.08	0.83	0.24	1.50	100.71	38	13	180	32	117	13	5	4	17	121	72	50	270	63	72	< 1	15	16
LC94-1-1005	mafic dyke	47.09	1.19	16.62	8.98	0.15	5.00	6.73	4.99	1.73	0.64	6.89	100.00	770	31	660	24	236	11	10	3	22	102	48	27	158	15	46	2	66	60
LC94-1-1070**	anorthosite	51.20	1.44	21.10	1.30	0.06	1.20	7.44	5.40	2.85	0.12	6.37	100.40	760	85	690	4	25	1.4		2		< 5	< 10	15	35	16	6		5.3	4.6
LC94-1-1092	anorthosite	53.58	0.25	22.44	1.44	0.04	0.57	6.13	4.50	4.42	0.11	7.02	100.50	912	103	421	6	41	< 1	< 2	3	21	10	< 4	< 3	36	< 4	13	3	7	15
LC94-1-1145	quartz monzonite	63.84	0.82	15.76	4.51	0.06	1.88	2.50	4.10	4.44	0.32	1.80	100.03	1340	81	554	36	405	22	10	14	21	55	12	15	100	18	54	4	55	42
LC94-1-1200**	quartz monzonite	61.70	1.06	15.20	2.00	0.08	2.45	4.37	4.00	3.23	0.37	2.97	100.90	1100	73	450	42	520	29		13		40	12	18	41	29	10		100	80
LC95-1-437	gabbro	47.77	1.99	13.90	15.68	0.24	6.72	9.69	2.49	0.37	0.17	1.53	100.55	< 5	11	218	26	108	7	4	3	21	95	519	81	329	51	83	< 1	5	14
LC95-1-449	gabbro	49.42	1.08	14.37	11.75	0.19	8.34	11.65	2.11	0.39	0.10	1.36	100.76	< 5	11	184	19	59	3	2	< 3	17	82	52	111	221	206	63	2	< 5	6
LC95-2-431.5	ferronorite	39.68	5.92	12.22	16.70	0.17	5.58	9.85	2.77	0.44	4.81	1.40	99.53	< 5	9	556	38	235	10	3	4	17	108	26	8	568	10	56	< 1	38	62
LC95-2-542	felsic dyke	71.06	0.28	13.59	1.67	0.02	0.42	2.06	3.53	4.85	0.07	2.03	99.59	984	129	202	20	204	15	22	18	19	24	< 4	< 3	39	< 4	54	7	53	40
LC95-2-555	anorthosite	56.42	0.12	26.01	0.37	0.00	0.28	7.55	6.33	0.99	0.04	1.50	99.61	340	80	1181	36	82	< 1	12	12	15	13	11	7	22	< 4	53	4	64	50
LC95-2A-811.3	anorthosite	57.79	0.11	25.77	0.46	0.00	0.18	7.83	6.45	0.67	0.04	0.66	99.96	329	6	1073	< 3	74	1	< 2	< 3	15	9	4	< 3	20	< 4	55	< 1	< 5	7
LC95-3A-673	felsic dyke	71.14	0.27	13.40	1.78	0.03	0.42	2.43	3.74	4.43	0.07	1.36	99.06	951	105	201	21	203	14	21	27	16	38	< 4	8	39	< 4	67	7	51	34
LC95-3A-789	anorthosite	54.83	0.33	20.52	5.77	0.05	4.87	5.22	4.79	0.86	0.05	2.59	99.88	361	15	751	4	55	< 1	< 2	4	16	90	< 4	21	55	55	46	< 1	< 5	<5
LC95-3A-862.6	anorthosite	53.51	0.39	22.06	4.26	0.05	4.37	6.78	4.73	1.91	0.09	2.42	100.57	671	24	1133	6	84	3	< 2	9	15	66	< 4	32	61	83	38	< 1	13	16
LC95-3A-871	anorthosite	55.19	0.30	23.16	3.60	0.04	2.83	7.30	5.85	0.44	0.05	0.90	99.65	180	6	932	4	67	1	< 2	7	19	53	< 4	9	51	33	40	< 1	< 5	10
NB91-8108A	Gaytons QM	62.61	0.85	15.71	5.00	0.07	1.96	3.08	4.30	3.92	0.34	2.90	100.74	1178	101	562	30	344	17	10	12	19	59	6	13	66	23				
NB94-9500D	Gaytons QM	63.50	0.84	15.53	4.50	0.06	1.63	2.65	4.18	3.93	0.28	2.40	99.50	909	99	476	31	329	19	11	14	21	54	5	14	63	23				

*Analyses were done by X-ray Fluorescence at the Regional Geochemical Centre, Saint Mary's University, Halifax, Nova Scotia. **Data from D.R. Boyle, provided by J. Stirling. Analystical details are unavailable. Blanks indicate no analyses for that element.

DISCUSSION

The close physical association between anorthosite, ferronorite, and nelsonite in the Lower Coverdale drill core strongly suggests that these rocks are of similar age. However, the cross-cutting relationship of the gabbro bodies and dykes, with their well-defined chilled margins, suggests that these gabbroic rocks may be significantly younger, emplaced after the other rocks had cooled. Furthermore, the occurrence of mafic dykes of at least two ages is suggested by the presence of both foliated amphibolite dykes and unfoliated dykes showing lower grade metamorphic effects. Younger still are the petrologically distinct felsic dykes and quartz monzonite in drill hole LC94-1. The quartz monzonite appears to lack cross-cutting gabbroic dykes and retains primary igneous textures. Hence, whether all or part of the Lower Coverdale anorthosite-ferronorite-gabbro suite is middle Devonian in age like the quartz monzonite is not clear because they are seen in contact only in drill core LC94-1 and that contact is sheared. Evidence for a co-genetic relationship includes their close spatial association and some petrological features of the quartz monzonite such as abundant titanite and apatite and high Ba (Fig. 6a). However, other petrochemical features are distinctly different and show few overlapping trends (e.g., Fig. 5, 6) to suggest that the quartz monzonite is a more evolved part of the same suite. The epsilon Nd value for the anorthosite is much lower than that of the quartz monzonite (–7.20 vs. +0.30 at 390 Ma; Samson *et al.* 2000), which is also evidence against a petrogenetic link. Although the lack of petrological similarity between the quartz monzonite and the anorthosite-ferronorite-gabbro suite does not preclude them from being of similar age, it makes it less likely.

Venugopal (2003) compared the Lower Coverdale suite to the undated but post-Middle Silurian Stewarton Gabbro, located 100 km to the west at the boundary between the more inboard Mascarene and St. Croix terranes (Fig. 1). He suggested that they have enough similarities to indicate that they are coeval, although in the absence of a definite age for either intrusion, this interpretation is speculative. Gabbroic intrusions also occur in the Caledonia terrane in the Mechanic Settlement and Caledonia Mountain areas (Fig. 1), but those plutons do not appear to have any petrological features in common with the Lower Coverdale suite (e.g., Grammatikopoulos *et al.* 2007; Barr *et al.* 2000).

Other possibilities for the age of the Lower Coverdale suite include Grenvillian, as suggested by Boyle and Stirling (1994), and Late Neoproterozoic-Cambrian, like other plutons in the Brookville terrane. Considering first the Grenvillian option, many characteristics of the Lower Coverdale anorthosite and ferronorite, in particular, are typical of Grenvillian massif-type anorthosite-ferrodiorite suites (e.g., Herz and Force 1987; Force 1991). They include the presence of antiperthitic plagioclase of andesine composition, orthopyroxene in the compositional range of En_{70}, and the occurrence of nelsonite layers. A discussion of the origin of such unusual rocks is well beyond the scope of this paper, but a variety of origins including immiscible liquid separation, crystal accumulation, subsolidus recrystallization, and late-stage differentiation have been proposed (e.g., Duchesne 1999; Kärkkäinen and Appelqvist 1999 and references therein). Textural features in the Lower Coverdale ferronorite are similar to those in equivalent units in the Allard Lake (Lac Tio) district in Quebec, as described and illustrated by Force (1991, p. 27), and in the Roseland District of central Virginia (Herz and Force 1987). Another similarity is the evidence that the Lower Coverdale suite was emplaced before or during regional metamorphism (Force 1991). Massif-type anorthosite suites are Mesoproterozoic in age (> 900 Ma) and typically located in Grenvillian crust (Force 1991; Ashwal 1993). Hence, if it is of Grenvillian age, the Lower Coverdale suite has significant implications for the nature of the crust in southern New Brunswick.

Turning to the other option, the Brookville terrane is dominated by Late Neoproterozoic to Cambrian (ca. 555–525 Ma) plutonic rocks (White *et al.* 2002), and typical Brookville terrane dioritic rocks of Early Cambrian age are exposed near Moncton at Lutes Mountain (Fig. 1). Although most Brookville terrane plutons are dioritic to granitic in composition, anorthosite and gabbro occur in Duck Lake, French Village, Indiantown, and other small plutons in the city of Saint John (White 1996;

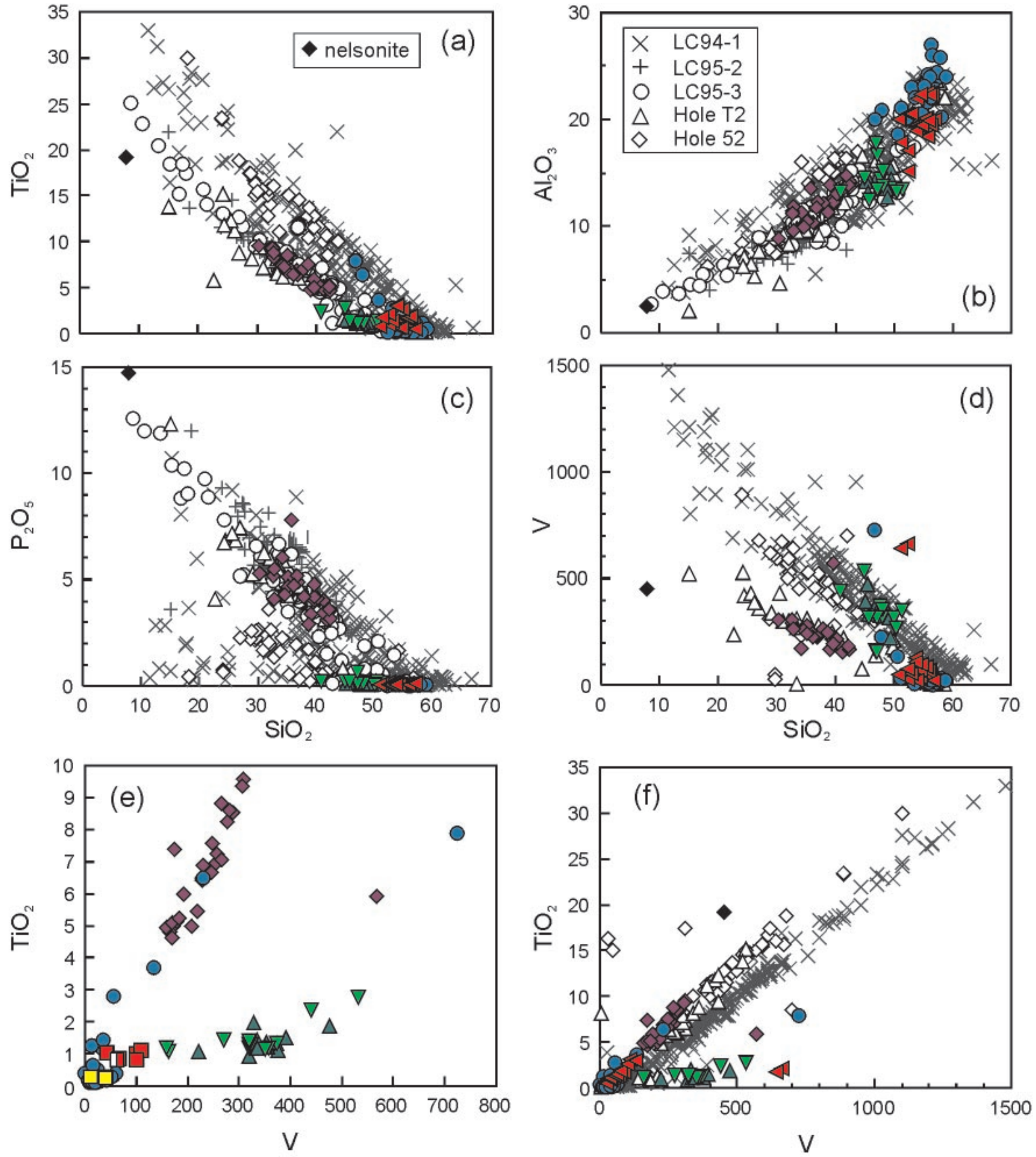

Fig. 8 Selected diagrams to illustrate the full range of chemical compositions in drill core samples. Symbols are as in Fig. 5, with additional data as shown in the legends on (a) and (b) from assessment reports (LC94-1, LC95-2, and LC95-3) and unpublished data of D.R. Boyle (T2 and 52). Nelsonite analysis (black diamond) is from McHattie (1998).

White *et al.* 2002). However, the anorthosite in these plutons lacks massif-type features like those of the Lower Coverdale intrusion, and no ferrodiorite, ferronorite, or nelsonite has been reported. On the other hand, the possible volcanic-arc tectonic setting suggested by the gabbroic rocks in the Lower Coverdale core (Fig. 7a, b) is consistent with the arc setting interpreted for the Brookville terrane plutons (White *et al.* 2002). In addition, the mica schist and calc-silicate rocks interlayered with anorthosite and ferronorite are similar in lithology and metamorphic grade to units in the Brookville terrane (e.g., Green Head Group; White 1996). Also, the epsilon Nd value of –5.11 for the Lower Coverdale anorthosite (calculated at 540 Ma) is compatible with values as low as –4.25 reported for ca. 540 Ma plutons in the Brookville terrane in the Saint John area (Samson *et al.* 2000).

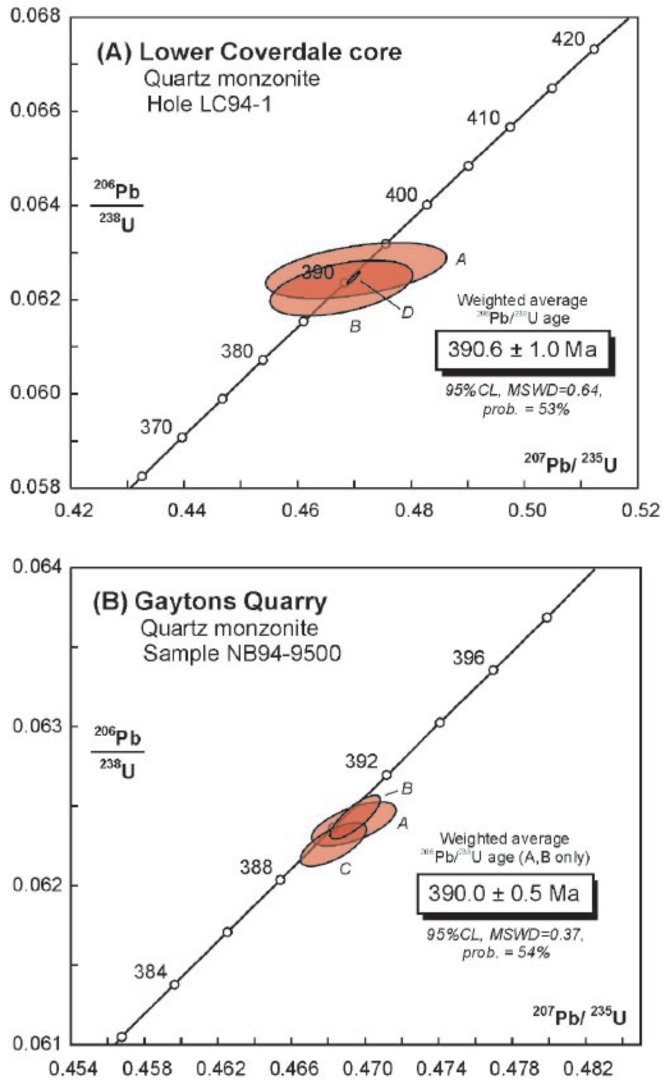

Fig. 9 U-Pb concordia diagram for (a) quartz monzonite from drill hole LC94-1 and (b) quartz monzonite sample NB94-9500 from the eastern part of Gaytons quarries. Data are from Table 4.

Table 4. Zircon U-Pb isotopic data for Lower Coverdale and Gaytons Quarry quartz monzonite samples.

Fraction	Weight (mg)	U (ppm)	Pb^* (ppm)	Pb_C (pg)	Th/U	Atomic ratios							Age (Ma)						
						$^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	± 2σ	$^{207}Pb/^{235}U$	± 2σ	$^{207}Pb/^{206}Pb$	± 2σ	$^{206}Pb/^{238}U$	± 2σ	$^{207}Pb/^{235}U$	± 2σ	$^{207}Pb/^{206}Pb$	± 2σ	Disc. (%)
LC94-1 Lower Coverdale core (quartz monzonite)																			
A - 3 clr, pbr-ppk, 2-3:1 euh prisms; incl	5	110	8	8	0.77	300	0.062628	0.000487	0.470155	0.013089	0.054447	0.001372	391.6	3.0	391.3	9.0	389.6	42.2	-0.5
B - 7 clr, pybr, elongate euh prisms; incl	4	159	11	8	0.87	306	0.062257	0.000484	0.467576	0.010298	0.054471	0.000975	389.3	2.9	389.5	6.5	390.6	40.2	0.3
D - 33 clr, cls-pbr, 2-3:1 euh prisms; incl	132	276	19	18	0.72	8020	0.062474	0.000105	0.469696	0.000939	0.054528	0.000040	390.7	0.6	391.0	0.6	392.9	1.6	0.6
NB94-9500 Gaytons Quarry (quartz monzonite)																			
A - 33 clr, cls-pbr, 3-5:1 euh cyl prisms; incl	32	241	17	11	0.83	2801	0.062390	0.000112	0.469380	0.001887	0.054564	0.000176	390.1	0.7	390.8	1.3	394.4	7.2	1.1
B - 20 clr, cls-pbr, 2-3:1 euh sl flat prisms; incl	51	299	21	8	0.78	7292	0.062433	0.000114	0.469449	0.001127	0.054535	0.000080	390.4	0.7	390.8	0.8	393.2	3.3	0.7
C - 16 clr, cls-pbr, equant flat prisms; incl	37	291	20	11	0.78	3946	0.062261	0.000112	0.468248	0.001480	0.054546	0.000127	389.4	0.7	390.0	1.0	393.7	5.2	1.1

Notes: All analyzed fractions represent least magnetic, air-abraded single zircon grains, free of visible cores or cracks. Abbreviations: clr - clear; cls - colourless; pbr - pale brown; ppk - pale pink; pybr - pale yellow-brown; euh - euhedral; cyl - cyl incl - fluid inclusions present. Pb^* is total amount (in ppm) of radiogenic Pb. Pb_C is total measured common Pb (in picograms) assuming the isotopic composition of laboratory blank. Pb/U atomic ratios are corrected for spike, fractionation, blank, and, where necessary, initial common Pb; $^{206}Pb/^{204}Pb$ is corrected for spike and fractionation. Th/U is model value calculated from radiogenic $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{206}Pb$ age, assuming concordance. Disc. (%) - per cent discordance for the given $^{207}Pb/^{206}Pb$ age. Uranium decay constants are from Jaffey *et al.* (1971).

In the absence of direct dating of the anorthosite-ferronorite-gabbro suite, the uncertainty about its age cannot be resolved unequivocally. However, it is important to note that, although most Fe-Ti-P-rich rocks are associated with Proterozoic massif-type anorthosite, not all have that association. A better analogy for the Lower Coverdale intrusion may be the Qareaghaj mafic-ultramafic intrusion in Iran, which is similar in size and petrological features to the Lower Coverdale intrusion, similarly includes Fe-Ti-P rocks, and appears to be of Late Precambrian or Paleozoic age (Mirmohammadi *et al.* 2007). Clearly more detailed study of the Lower Coverdale anorthosite-ferronorite and associated ilmenite-apatite rocks is needed to more fully understand their origin.

The similarity in petrological features and identical-within-error 390 Ma U-Pb ages demonstrate that quartz monzonite in the Lower Coverdale drill core LC94-1 is correlative with the quartz monzonite exposed in the Gaytons quarries. Chips of similar rock also form the "basement" encountered at a depth of about 314 m in the nearby Westmorland well and 910 m in the Port Elgin well, more than 35 km to the east (Fig. 1). This belt of rocks is associated with a series of magnetic anomalies (Nickerson 1994), and quartz monzonite samples from both drill core and the Gaytons quarries yielded relatively high susceptibility, averaging 17.61×10^{-3} SI. Hence the magnetic anomalies do not require that magnetic ferronorite-nelsonite bodies be associated with those granitic rocks, although they could be. The A-type chemical characteristics of the quartz monzonite is consistent with emplacement in a late-orogenic or post-orogenic tectonic setting, perhaps associated with transtension along the faulted boundary between the Brookville terrane and Avalonia.

CONCLUSIONS

The Lower Coverdale intrusion consists of anorthosite and ferronorite with massif-type characteristics, younger gabbroic rocks, and younger quartz monzonite and felsic dykes. The quartz monzonite is correlative with quartz monzonite in the nearby Gaytons quarries, and both have identical U-Pb (zircon) ages of about 390 Ma. This age provides a minimum for the age of the gabbroic rocks and anorthosite-ferronorite, but in the absence of direct dating, it is uncertain whether they are similar in age to the quartz monzonite, similar in age to other plutons of the Brookville terrane (555–525 Ma), Grenvillian (as suggested by the massif-type petrological features of the anorthosite- ferronorite suite), or of some other age. Hence, the regional tectonic significance of this unusual assemblage of rocks remains unresolved.

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