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GEOLOGY OF THE HEADWATERS OF THE RIVER PHILIP, COBEQUID HIGHLANDS

by

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GEOLOGY OF THE HEADWATERS OF THE RIVER PHILIP, COBEQUID HIGHLANDS

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Abstract

The area mapped covers about 40 km^2 in the north central Cobequid Highlands (NTS 11E/12). It is characterized by E-W trending fault bounded horsts of Neoproterozoic plutonic, volcanic and metasedimentary rocks and grabens of late Devonian Fountain Lake Group volcanic rocks, all intruded by latest Devonian - earliest Carboniferous gabbros and granitoids.

The Neoproterozoic plutonic rocks are tonalites and granodiorites. They intrude a volcanic suite consisting of andesites, rhyolites and pyroclastics interbedded with argillites and fine grained turbidites that is correlated with the Jeffers Group of the western Cobequid Highlands. These rocks had not been previously recognised in this area.

The Fountain Lake Group is lithologically and structurally similar to the Byers Brook Formation of the eastern Cobequid Highlands, and shows similar mineralisation. It is cut by mafic intrusive rocks ranging from coarse gabbros to fine diabases. The felsic intrusive rocks consist of granites, tonalites, quartz monzodiorites, quartz diorites and aplites, similar to earliest Carboniferous plutonic rocks elsewhere in the Cobequid Highlands.

CONTENTS

TABLES

FIGURES

INTRODUCTION

Regional setting

The Cobequid Highlands consist principally of Neoproterozoic Avalonian igneous and low-grade metasedimentary rocks, minor Ordovician (?), Silurian and early Devonian sedimentary rocks, late Devonian and early Carboniferous volcanic rocks (Fountain Lake Group), and earliest Carboniferous diorite and granite plutons (Donohoe and Wallace, 1982, 1985) (Fig. 1).

In the northern and western Cobequid Highlands (Jeffers Block of Murphy et al., 1992), the latest Proterozoic volcanic rocks occur interbedded with turbidites in the Jeffers Group and correlative Warwick Mountain Formation (Pe-Piper and Piper, 1989). The Dalhousie Mountain volcanics of the southeastern Cobequid Highlands (Bass River block) may also be correlative (Murphy et al., 1988). There are three principal types of volcanic rocks: high-Ti tholeiite flows and hypabyssal intrusions; andesite to dacite flows of calc-alkaline affinity; and felsic tuffs. This suite is similar to that in Keppoch Formation of the Antigonish Highlands (Murphy et al., 1990), and is interpreted as having formed in an intra-arc or back-arc basin (Pe-Piper and Piper, 1989). South of the Rockland Brook Fault, in the Bass River Block, high-Ti tholeiite flows (and related dykes) of the Folly River Formation are interbedded with cherts and distal turbidites (Pe-Piper and Murphy, 1989). These rocks are similar to the Clydesdale Formation of the Antigonish Highlands (Murphy et al., 1992). Basin closure in the latest Proterozoic resulted in an inhomogeneous flat-lying cleavage and was followed by intrusion of a suite of broadly granodioritic plutons (including the Jeffers, Frog Lake, Debert River and McCallum Settlement plutons) (Pe-Piper, 1988; Hubley, 1987). $^{39}Ar/^{40}Ar$ hornblende and U/Pb zircon ages indicate a latest Proterozoic to early Cambrian age for these plutons (Keppie et al., 1990; Doig et al., 1991b). This volcanism and plutonism marks the trace of a more extensive latest Proterozoic arc-collision zone (Keppie and Dostal, 1991).

Evidence for Late Devonian - Carboniferous igneous activity comprises large diorite plutons, granite plutons, thick rhyolite and basalt sequences of the Fountain Lake Group and extensive mafic hypabyssal intrusions. This igneous activity all appears related (Piper et al., 1994).

The Fountain Lake Group in the eastern Cobequid Highlands (Byers Brook and Diamond Brook Formations) consists of felsic volcanics and basalt flows locally interbedded with sedimentary rocks. The Diamond Brook Formation contains Emsian-Eifelian and Tournaisian spores (Donohoe and Wallace, 1982). The volcanic rocks have yielded a whole-rock Rb/Sr isochron age of 387 ± 2 Ma (Pe Piper et al., 1989). These volcanic rocks occur in fault-bounded blocks, have steep dips, and young southward (Piper, 1994). The younger rocks in the eastern Cobequid Highlands are intruded by numerous gabbro bodies. The Murphy Brook Formation of the central Cobequid Highlands contains rhyolite-clast conglomerates and has yielded late Emsian- early Eifelian plant fossils (Donohoe and Wallace, 1985).

The diorites geochemically are olivine-normative continental tholeiites. Most granite plutons include minor diorite bodies; the margins of the larger diorite plutons show evidence for co-existence of mafic and felsic magmas. Granites are A-type granites, probably derived by partial melting of lower crust by the heat provided by the dioritic magma. The widespread mafic dykes record continuing igneous intrusion during Carboniferous deformation of the plutons and are associated with extensive hydrothermal alteration (Nearing, 1992). Dykes and mafic stringers in the granites are extensively altered, with the predominant development of secondary biotite and Fe-Ti oxides, and trace element signature suggesting circulation of both F and H_2O-rich fluids (Pe-Piper et al., 1991). Where a sequence of dyke emplacement can be recognised from cross-cutting relationships with deformed granites, the younger dykes have higher P_2O_5, TiO_2 and other high-field-strength elements (Pe-Piper, 1991). SiO_2, Th and TiO_2 content distinguish these Carboniferous dykes from Mesozoic tholeiites.

The widespread diorite/gabbro and smaller granite plutons of the Cobequid Highlands appear to be of latest Devonian to earliest Carboniferous age. Zircons, showing some inheritance, from three plutons (Cape Chignecto, Pleasant Hills, Hart Lake - Byers Lake) have yielded U/Pb ages of 361-363 ± 3 Ma (Doig et al., 1991a; J.B. Murphy pers. comm. 1992), corresponding to the Devonian-Carboniferous boundary. Rb/Sr isochrons on the major plutons are of early Carboniferous age, e.g. 342 ± 5 for the West Moose River pluton, 349 ± 12 Ma for the Cape Chignecto pluton (Pe-Piper et al., 1989) and 348 ± 9 Ma for the Hart Lake - Byers Lake pluton (Donohoe et al., 1986). Comparison with the U-Pb ages dates suggests considerable hydrothermal alteration in the rocks following intrusion. The Wyvern diorite has yielded a K/Ar hornblende date of 357 ± 12 Ma (Krueger Geochron Labs). The Cape Chignecto Pluton shows NW-vergent thrusting and the development of ductile fabrics that have yielded an age of 329±11 Ma

(K/Ar on biotite: Waldron et al. 1989), suggesting that thrusting and unroofing had occurred by the Namurian. Pe-Piper and Koukouvelas (1994) show that this thrusting was probably essentially synchronous with intrusion.

Physiography and access

Rivers are incised about 100 m below the regional Cobequid Highland surface, which dips gently northward in this area. Valleys are broad, with the present rivers appearing to be misfits: discharge was probably much greater during deglaciation. Till cover is thick, both on interfluves and in valleys, so that outcrop is sparse.

Much of the upland area is farmed for blueberries, so there is a good dirt-road network providing access to the area. River valleys are forested.

Previous work in the map area

The mapped area was previously mapped in a reconnaissance manner by Donohoe and Wallace (1982). Some revisions based on field work reported here were presented by Murphy et al. (1988). Aeromagnetic total field and vertical gradient maps were released by the Geological Survey of Canada in 1988 (maps 21350 and 41350, 11E/12 c,d) (see also Kiss et al., 1989).

Responsibility for mapping

Most Precambrian rocks in the map area were mapped by G. Pe-Piper and D. Turner in 1986 and 1987, using NSERC funding. Fountain Lake Group and the Precambrian of the Second River were mapped by D.J.W. Piper and K. Parlee in 1992 and 1993, using Geological Survey of Canada funding, including resources from the Canada - Nova Scotia Cooperation Agreement on Mineral Development in 1993. Geochemical analyses were carried out at the Regional Geochemical Centre at Saint Mary's University.

MAP UNITS AND FIELD GEOLOGY

Introduction

The map units recognised in the area are summarised in Table 1 and individual units are discussed in more detail below.

Carboniferous plutonic rocks

Carboniferous plutonic rocks include gabbro-diorite, pink granites and hybrid rocks of intermediate composition. These rocks outcrop only sparsely and in general their extent cannot be rigorously mapped. Age assignment is based on petrographic and geochemical similarity to dated latest Devonian - earliest Carboniferous plutons such as the Cape Chignecto, Pleasant Hills and Hart Lake plutons (Donohoe et al., 1986; Pe-Piper et al., 1989). In addition, a K/Ar age of 357 Ma has been obtained for diorite from Wyvern (Table 2).

Carboniferous hypabyssal rocks

The rocks interpreted as hypabyssal diabase and rhyolite of probable earliest Carboniferous age include irregular bodies, tens of metres wide, of microgranite and granodiorite (commonly with hybrid textures: sample 4405[1]) that have fine grained rhyolitic margins, in some cases with aplitic veins cutting country rock. Diabase tends to occur in dykes, generally striking approximately N-S.

The gabbro in small hypabyssal bodies appears fresh and in places contains feldspar megacrysts (e.g., sample 4277). The gabbro weathers into large blocks. Margins of the bodies are rarely seen and as a result the shape of the bodies is uncertain.

Fountain Lake Group

The predominant lithology in the Fountain Lake Group is bedded air-fall tuff (locally fine agglomerate) and volcaniclastic sandstone, which achieve stratigraphic thicknesses of several hundred metres in upper Bulmer Brook, Arsenic Brook and lower Bulmer Brook. The rocks are steeply dipping, locally overturned, but are not cleaved. Minor rhyolites and basalts associated with the

[1] Samples referred to are described in Appendix. Some also appear in Tables 3 and 4

sequence may be either lavas or fine-grained hypabyssal rocks; rather rubbly weathering (e.g. samples 4401; 4427) and amygdules (e.g., sample 3521) probably indicates lava. Rarely, spherulitic rhyolite is found.

Similar steeply dipping pyroclastic rocks, lacking cleavage, and with rare interbedded flows, are found further east in the Cobequid Highlands, for example in the Byers Brook Formation south of Warwick Mountain (Piper, 1994). Assignment of the pyroclastic rocks in the map area to the Fountain Lake Group is based on this lithological and structural similarity.

Wilson Brook Formation

Fossiliferous shale and sandstone of the Silurian Wilson Brook Formation outcrop in lower Arsenic Brook (Donohoe and Wallace, 1982, 1985), but have not been found elsewhere in the map area.

Neoproterozoic plutonic rocks

An extensive area of Bulmer Brook exposes a greenish-grey somewhat inhomogeneous granodiorite or tonalite that in many places appears rather fractured. The granodiorite is locally cut by diabase dykes and reddish microgranite. No unequivocal contacts with other units have been seen. The petrology, geochemistry and degree of deformation of the granodiorite all suggest that it is correlative with the latest Proterozoic Jeffers Brook pluton.

Similar rocks have been found as abundant float in a small area of Second River; and on the Farmington road SW of Bulmer Brook.

A gabbroic body with large feldspar phenocrysts outcrops west of Second River. Its geochemical character (discussed below) indicates similarity to the Neoproterozoic plutonic rocks, but a Carboniferous age cannot be excluded.

Neoproterozoic Jeffers Group

In northern Bulmer Brook and McCormack Lake Road, outcrops of feldspar phyric andesites, in places with rubbly weathering textures, are interpreted as volcanic rocks. These rocks are locally amygdaloidal (e.g. sample 4355). No clear field relationships are seen with other units, but their geochemistry resembles that of the Jeffers Group of the Parrsboro area (see below).

In the Second River, cleaved intermediate pyroclastic rocks and laminated argillite are interbedded with andesite lavas (samples 5138, 5132). This association is characteristic of the Harrington River facies of the Gilbert Hills Formation (Pe-Piper and Turner, 1988; Pe-Piper and Piper, 1989). Further south on the Second River, thin bedded graded beds of volcaniclastic sandstone (with Bouma T_{ab} sequences) alternate with banded cherty argillite, characteristic of the Cranberry Lake Formation.

Distribution of map units

Because of the limited outcrop, critical relationships between map units are rarely seen. Aeromagnetic data suggest that there are important E-W linear features and perhaps a N-S lineament in the area south of Arsenic Brook. East-west faults appear to separate two horsts of Jeffers Group and associated Neoproterozoic intrusive rocks from linear basins of steeply dipping Fountain Lake Group. Fountain Lake Group also outcrops west of the main Jeffers Group horst, in the area of Arsenic Brook. Basin-margin faults appear to have acted as pathways for intrusion of gabbro, although gabbro is not restricted to these faults. The abundance of gabbro increases westward. In the northwest part of the study area, the Gilbert Mountain granite is very poorly exposed: its mapped boundaries are based largely on aeromagnetic data.

PETROGRAPHY

Introduction

Petrographic rock nomenclature is based on modal composition analysis. Representative modal analyses are given in Table 3.

Carboniferous plutonic rocks

The coarse-grained gabbros are blue-grey and white rocks, in some cases porphyritic. They contain many large feldspar crystals of euhedral outline, as well as numerous smaller feldspar laths randomly oriented. Some of the larger feldspars are zoned and the groundmass is quite fine and unidentifiable in hand specimen. There is also a group of medium grained gabbros which range from highly feldspathic (e.g. 3535) to minimally feldspathic (e.g. 2219) that may contain epidote veins. The feldspathic medium gabbros contain approximately equal amounts of randomly oriented feldspar laths and fine groundmass.

The diabases are massive and blue-grey to black in colour. In many cases small individual feldspar laths can be seen with a hand lens. Some samples appear altered with either a high amount of epidote or hematite coating. Some of the mafic rocks are spotted, with a reddish-grey to greenish-grey colour. The distinctive feature of these samples is that they contain numerous small (<1mm) circular black spots.

The quartz monzodiorites and quartz diorites are fine grained intermediate rocks ranging from black and white to red and black in colour. These rocks consist essentially of feldspars, quartz and amphibole/pyroxene. There is a marked variation in the mineralogy of these rocks, which ranges from a single feldspar (plagioclase) (e.g. 3458) to one containing predominantly K-feldspar (e.g. 2216). There also appear to be an intermediate representative (2215) containing two feldspars. However, sample 2216 may be an altered version of sample 2215. These rocks are fairly equigranular and massive.

The tonalites range from fine grained grey rocks to medium/coarse grained red rocks. They appear as "dirty" - looking granites. The fine grey rocks have a sugary texture and contain visible K-feldspar crystals (e.g., 3506). The fine portion of the grey samples cannot be identified in hand specimen, but appears to contain quartz and plagioclase/ amphibole/ pyroxene(?). The coarser red samples (e.g., 4260A) contain K-feldspar, quartz, amphibole and probably altered plagioclase (marked by green colour). These rocks also display a good granitic crystalline texture. There is one sample (4439) which is intermediate between the two above-mentioned descriptions. Sample 4412 appears to be porphyritic.

The pink granites (e.g., 4378) are medium to coarse grained felsic rocks that are equigranular in texture, with the exception of finer grained amphibole and biotite. These rocks consist essentially of quartz, plagioclase, and K-feldspar, with variable minor amounts of biotite and amphibole. The rocks are mostly pink with well defined crystal boundaries and numerous subhedral to euhedral crystals. Some alteration of the feldspars is noted by the chalky appearance.

There are some fine grained felsic rocks, quite equigranular and with a pink colour, which in hand specimen look like syenites (e.g., 4379). These rocks consist essentially of K-feldspar and quartz with a minor amount of an altered ferromagnesian mineral.

The aplites look like the syenites. They are fine grained, white and pink felsic rocks, and quite equigranular. They consist mainly of plagioclase, K-feldspar, quartz and a minor amount of an altered ferromagnesian mineral. In the case of sample 2213 there are mafic stringers, while in the case of sample 3425 the sample contains a large angular mafic xenolith.

The microgranites (e.g., 4364) are quite fine grained and sugary in texture. They are grey to purple and equigranular consisting mostly of quartz.

Neoproterozoic plutonic rocks

The Neoproterozoic granodiorites are medium grained felsic rocks with a good granitic (plutonic) texture, ranging in colour from white and black to red and black. The white and black samples (e.g. 3433) contain fine grained mafic xenoliths and consist essentially of plagioclase, quartz and hornblende and is fairly equigranular. The red and black samples (e.g. 4414) are fairly equigranular, and consist of plagioclase, quartz, hornblende and K-feldspar which appears albitized. These rocks also contain sparsely disseminated pyrite mineralization.

The Neoproterozoic tonalites are fine to medium grained felsic rocks which are grey-white-green and black. They are fairly equigranular and consist predominantly of quartz and plagioclase with lesser amounts of epidote/chlorite(?) and amphibole. In one case (sample 3527) there is a small xenolith which is igneous in nature and is essentially plagioclase and an altered ferromagnesian mineral. In another case (sample 3500) there is a weak fabric picked out by feldspars as well as large phenocrysts of quartz.

A second group of tonalites comprises medium to coarse grained rocks with a red-green and black colour. These rocks are inequigranular for the most part, marked by the coarser grained quartz. They consist essentially of green quartz, plagioclase, K-feldspar and an amphibole. They are noticeably coarser and more felsic than the first group of tonalites.

GEOCHEMISTRY

Introduction

Whole rock geochemical analyses were made at the Saint Mary's University regional geochemical centre by X-ray fluorescence and instrumental neutron activation analysis. Samples were analysed for ten major and minor element oxides and fourteen trace elements on a Philips PW1400 sequential X-ray fluorescence spectrometer using a Rh-anode X-ray tube. Major oxide determinations were carried out on fused glass discs, whereas trace elements were determined on pressed powder pellets. International reference rocks were used for calibration. Analytical precision, as determined from replicate analyses, is generally better than 2%, except for MgO, Na_2O and Nb which are better than 5% and Th which is better than 10%. Loss on ignition (L.O.I.) was determined by treating the sample for 1.5 h at 105°C in an electric furnace. The rare-earth element concentrations were determined by neutron activation analysis with at least two standard reference materials which were chosen so as to roughly correspond to the composition of the unknowns. Concentration values for elements in the reference rocks are those reported by Govindaraju (1989). The precision of the results, as determined on replicate analyses, is generally better than 5% for La, Ce, Eu, Tb, Yb, Lu, Th, Sc, Co and better than 10% for Nd, Sm, Cs, Hf, Ta, U.

No detailed interpretation of geochemical data is presented here. Rather, geochemistry is used as a guide to rock classification in areas of limited outcrop. Rocks have been geochemically classified using the schemes of Winchester and Floyd (1977) (Fig. 3) and de la Roche et al. (1980) (Fig. 4).

Carboniferous igneous rocks

The chemical composition of the Carboniferous plutonic rocks compares well with the average analyses reported by Pe-Piper et al. (1991) for plutons of the southern Cobequid Highlands. In particular, the mafic rocks have TiO_2 > 1.2% and Y > 20 ppm, in contrast to lower abundances of both elements in Neoproterozoic rocks (Figs. 3, 5 and 6).

Granite and rhyolite have low TiO_2 (<0.3%), Pb > 10 ppm and Y > 30 ppm. This allows most samples to be distinguished from the Neoproterozoic rocks on the basis of their chemistry (Figs. 3, 5).

Neoproterozoic plutonic rocks

Analysed samples range from 66 to 71% SiO_2. TiO_2 content is characteristically low (<0.5%). The rocks show the trace element characteristics of "volcanic arc granites", including high LILE and low Nb, Y, Zr and Ga (Fig. 7). These rocks closely resemble the Jeffers Brook pluton (Pe-Piper, 1988) in their overall chemical composition. The feldspar-phyric gabbro from west of Second River has low Ti, Y, Zr and Nb characteristic of arc-related igneous rocks and is dissimilar to any analysed Carboniferous gabbros.

Neoproterozoic volcanic and sedimentary rocks

Analysed samples include basalt, andesite, dacite and rhyolite (Fig. 3). Compared with Carboniferous hypabyssal intrusions and Fountain Lake Group volcanic rocks from elsewhere in the Cobequid Highlands, these rocks have low abundances of Nb, Ti, Y, and Ga (Figs. 5, 6). Their trace element composition is typical of calc-alkali rocks and their overall geochemistry is similar to that of the Gilbert Hills Formation in the Parrsboro area (Pe-Piper and Piper, 1989). Dacites to rhyolites contain > 100 ppm Sr, in contrast to Carboniferous felsic rocks, which have < 70 ppm Sr.

DISCUSSION AND CONCLUSIONS

This remapping has extended the known distribution of the Neoproterozoic Jeffers Group. It has shown that plutonic rocks similar to the Jeffers Brook pluton are also present in the northern Cobequid Highlands. It has also extended westward the known distribution of the Byers Brook Formation of the Fountain Lake Group, which in the eastern Cobequid Highlands shows base metal mineralisation associated with rhyolitic domes and permeable sandstone horizons. The occurrence of minor Carboniferous mafic intrusions in the Byers Brook Formation is similar to that in the eastern Cobequid Highlands (Piper, 1994).

The overall structure of the mapped area is of E-W trending horsts of Neoproterozoic rocks, separated by graben in which steeply dipping Byers Brook formation rocks are preserved. Carboniferous intrusive rocks are concentrated along the faults bounding the horsts. Neither Neoproterozoic nor Fountain Lake Group rocks extend far to the east or west of the map area. To the west are the large Wyvern diorite and Gilbert Hills granite plutons, to the east the large Folly Lake diorite pluton.

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Table 1. Summary of map units

LATE DEVONIAN - EARLIEST CARBONIFEROUS INTRUSIONS

Diabase and microgranite dykes

Diorite - gabbro, and minor hybrid intermediate rocks

Pink granite

LATE DEVONIAN FOUNTAIN LAKE GROUP (Byers Brook Formation)

Tuff and fine agglomerate, volcaniclastic sandstone, rhyolite and basalt

SILURIAN WILSON BROOK FORMATION

Fossiliferous shales

NEOPROTEROZOIC INTRUSIONS

Tonalite - granodiorite

Feldspar-phyric gabbro [? might be Carboniferous]

NEOPROTEROZOIC JEFFERS GROUP

Gilbert Hills Formation:

Volcanic and pyroclastic rocks, minor argillites

Cranberry Lake Formation:

Turbidites

Table 2. Radiometric date

Sample 2214 diorite, biotite concentrate -80/+200 mesh

$^{40*}Ar$, ppm	$^{40*}Ar$/tot.Ar	ave $^{40*}Ar$, ppm
0.1946	0.841	0.1933
0.1920	0.937	

% K	Ave % K	^{40}K, ppm
7.083	7.066	8.429
7.043		

$^{40*}Ar/^{40}K$ = 0.02293   Age = 357±12 Ma

determination by Krueger Geochron Laboratories, 1987.

Table 3: Representative modal compositions of rocks in the study area

	Neoproterozoic				Devonian-Carboniferous				
Sample No	3385	3395	3500	3387	2214	2216	3427	4405	4378
Quartz	18.3	15.5	30.8	35.4	11	10.3	21.4	16.1	35.4
K-Feldspar	22.0	12	-	3.4	3	17	1.7	-	33.7
Plagioclase	45.4	47.5	59.9	56.5	42	44.9	46.1	56.8	26
Hornblende	-	2	-	-	26	17.4	0.3[+]	1.2	3.4[+]
Biotite	5.4[*]	17	0.3	0.9	11	1.1	2.7[*]	-	0.6
Opaques	1.5	5	0.2	1.3	5	-	4.4	4.6	0.4
Apatite	0.1	-	-	-	1	-	-	-	-
Chlorite	2.1	0.4	0.5	2.3	1	7.5	0.1	11	0.1
Epidote	4.4	-	7.3	0.2	1	1.8	22.9	6	-
Sphene	0.8	-	0.1		-	-	-	-	-
Calcite	-	0.6	0.9	-	-	-	-	2.7	-
Others	-	-	-	-	-	-	0.4	1.6	0.4
Name	GRD	GRD	TO	TO	QD	QMD	TO	TO	GR

[+] Includes actinolite; [*] Includes secondary biotite

GR = Granite

GRD = Granodiorite

TO = Tonalite

QD = Quartz Diorite

QMD = Quartz Monzodiorite

Modes are based on counting 1000 to 1500 points in one or two thin sections (depending on grain size of rock) stained using a modification of the method of Bailey and Stevens (1960) (M. Zentilli, personal communication, 1972).

Table 4. Whole rock geochemical analyses

Neoproterozoic plutonic rocks

sample	5142	3464*	4262A*	3500*	3385*	3395*	3527*	3387*
SiO_2	48.42	66.64	65.02	65.47	66.48	66.53	67.79	71.23
TiO_2	0.43	0.45	0.50	0.48	0.45	0.47	0.39	0.32
Al_2O_3	18.44	16.08	15.13	15.16	15.16	15.40	15.27	15.73
Fe_2O_3	9.46	3.89	4.06	3.93	3.41	3.86	2.99	1.98
MnO	0.17	0.08	0.10	0.07	0.07	0.06	0.06	0.03
MgO	5.10	2.30	2.65	2.66	2.30	2.54	2.10	1.38
CaO	11.81	1.39	3.32	3.77	2.38	1.41	2.90	2.58
Na_2O	1.92	3.60	3.20	3.47	4.36	4.77	4.09	5.07
K_2O	0.23	3.24	3.31	2.05	3.54	2.79	2.59	1.04
P_2O_5	0.02	0.14	0.15	0.15	0.14	0.15	0.13	0.09
L.O.I	3.20	1.60	2.70	3.70	1.90	1.50	1.90	0.90
Total	99.20	99.41	100.14	100.91	100.19	99.48	100.21	100.35
Ba	216	933	1110	394	1098	916	838	413
Rb	7	118	153	67	124	98	72	51
Sr	284	494	359	200	482	370	404	291
Y	7	11	14	10	9	12	12	8
Zr	28	130	105	110	104	109	133	96
Nb	<5	7	6	7	7	8	8	9
Th	<4	4	<4	4	11	8	12	18
Pb	11	<5	<5	7	11	<5	8	14
Ga	14	14	18	19	13	15	18	17
Zn	56	53	75	65	60	54	48	46
Cu	113	62	<5	21	20	356	29	10
Ni	25	20	22	16	14	13	11	8
V	220	88	91	94	82	84	62	57
Cr	39	57	73	51	42	49	39	32
La	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	31.9	n.d.
Ce	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	56	n.d.
Nd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	16	n.d.
Sm	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3.02	n.d.
Eu	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.73	n.d.
Tb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.50	n.d.
Yb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.75	n.d.
Lu	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.15	n.d.
Cs	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.7	n.d.
Hf	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3.9	n.d.
Sb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.6	n.d.
Sc	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	6.15	n.d.
Ta	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.6	n.d.
Th	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	12.0	n.d.
U	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.8	n.d.

* sample with detailed petrographic description. 5142 - feldspar phyric gabbro, Neoproterozoic age uncertain.

Neoproterozoic volcanic rocks

sample	3521	3534	5138	4443	4356	4355	3506	5132	4405	4415
SiO_2	49.39	48.88	45.00	51.85	52.24	51.69	55.66	56.00	58.38	62.93
TiO_2	0.83	0.82	1.06	0.88	1.26	1.26	0.80	0.86	0.94	0.63
Al_2O_3	16.84	20.95	15.50	17.18	15.71	15.96	16.91	16.10	16.04	15.63
Fe_2O_3	11.82	10.19	12.10	10.79	8.37	9.36	7.64	9.59	9.38	5.04
MnO	0.18	0.16	0.18	0.17	0.18	0.15	0.12	0.18	0.10	0.08
MgO	5.78	4.43	6.23	6.56	6.91	7.27	4.35	3.98	2.89	2.80
CaO	8.76	6.58	7.41	4.82	3.77	3.89	3.55	7.12	2.34	3.88
Na_2O	2.49	2.84	2.13	3.34	5.23	5.54	4.21	2.95	2.84	4.36
K_2O	0.24	1.30	1.65	1.15	0.94	0.12	1.52	0.24	2.98	2.23
P_2O_5	0.15	0.17	0.23	0.12	0.24	0.19	0.19	0.15	0.33	0.19
L.O.I	2.90	3.00	7.90	3.20	4.00	4.40	4.10	2.90	4.00	2.00
Total	99.38	99.32	99.39	100.06	98.85	99.83	99.05	100.07	100.22	99.77
Ba	143	942	1037	604	6343	134	510	93	417	860
Rb	9	50	59	33	12	3	64	9	186	56
Sr	700	539	201	239	794	237	511	286	114	594
Y	15	20	23	18	15	16	14	29	30	12
Zr	88	82	69	65	179	160	99	97	111	121
Nb	4	6	7	4	11	8	8	5	5	7
Th	<5	<5	<5	<5	<5	5	5	<5	<5	<5
Pb	<5	<5	<5	<5	<5	<5	<5	12	<5	<5
Ga	15	19	15	19	20	16	17	18	18	19
Zn	110	132	92	104	116	116	79	95	65	63
Cu	24	65	124	<5	37	14	162	29	10	4
Ni	44	26	41	52	88	92	22	19	11	28
V	391	323	312	280	244	214	232	194	176	141
Cr	53	39	70	74	238	263	36	25	9	75

no REE determinations

3521, 3534, 4443, 4355 - vesicular basalt. 5138 - medium-grained basalt. 4356 - porphyritic mafic rock. 3506 - fine-grained andesite. 5132 - andesite. 4405 - medium-grained porphyritic andesite. 4415 - crystal tuff.

Neoproterozoic volcanic rocks (cont.)

sample	4432	4357	4287	4289	3514
SiO_2	59.65	66.70	69.65	71.27	71.05
TiO_2	0.64	0.88	0.43	0.44	0.36
Al_2O_3	18.03	15.51	14.90	13.74	14.09
Fe_2O_3	6.45	4.13	2.12	3.16	2.45
MnO	0.12	0.05	0.05	0.04	0.06
MgO	1.94	1.35	1.57	1.45	1.30
CaO	3.85	2.33	2.71	1.24	1.84
Na_2O	3.89	3.77	1.74	4.44	3.64
K_2O	2.30	2.68	4.16	2.69	2.00
P_2O_5	0.21	0.19	0.07	0.09	0.08
L.O.I	2.50	2.90	3.50	1.80	2.40
Total	99.58	100.49	100.90	100.36	99.27
Ba	1169	378	842	717	487
Rb	82	99	184	84	91
Sr	418	119	100	160	232
Y	27	29	28	23	37
Zr	133	333	294	143	268
Nb	5	19	13	9	13
Th	<5	<5	26	6	14
Pb	<5	<5	<5	<5	17
Ga	24	18	17	13	18
Zn	93	53	30	27	59
Cu	<5	<5	<5	<5	7
Ni	5	9	5	8	5
V	64	67	7	43	18
Cr	7	14	11	22	14

no REE determinations

4432, 4357, 4287, 4289, 3514 - dacite to rhyolite

Carboniferous igneous rocks

sample	3388	4359	4277	4429	4410	4382	4361	2218	2219	3535
SiO_2	47.41	45.55	45.90	47.06	48.58	50.23	50.86	43.46	45.91	45.47
TiO_2	1.51	1.52	2.29	1.51	1.54	1.79	1.80	3.03	1.99	2.46
Al_2O_3	15.72	16.32	16.15	15.63	15.88	14.71	14.76	14.83	15.16	14.89
Fe_2O_3	10.93	10.73	11.79	10.96	10.66	10.68	10.80	13.30	12.65	14.05
MnO	0.30	0.28	0.22	0.18	0.23	0.27	0.25	0.17	0.23	0.21
MgO	8.22	7.30	5.79	7.95	7.32	6.01	5.81	5.59	7.07	7.60
CaO	8.82	9.85	8.26	10.65	8.31	6.96	6.71	9.68	9.68	9.42
Na_2O	2.04	3.00	2.52	2.54	2.42	2.53	3.26	1.91	2.58	2.59
K_2O	1.53	1.47	1.26	0.21	1.20	2.70	2.28	0.74	0.51	0.56
P_2O_5	0.19	0.25	0.48	0.20	0.21	0.35	0.36	0.62	0.22	0.29
L.O.I	2.50	3.30	4.80	2.10	3.10	2.50	2.10	7.50	3.30	1.70
Total	99.17	99.57	99.46	98.99	99.45	98.73	98.99	100.83	99.30	99.24
Ba	751	2670	385	186	430	1094	612	453	311	309
Rb	84	73	51	3	45	147	98	24	27	9
Sr	374	506	537	302	335	339	369	311	290	338
Y	26	23	28	21	27	33	32	26	24	33
Zr	104	135	184	109	132	195	203	211	130	165
Nb	6	8	16	7	7	10	11	24	8	12
Th	<5	<5	<5	<5	<5	<5	<5	4	<5	<5
Pb	8	<5	<5	<5	<5	<5	<5	21	<5	<5
Ga	23	21	23	21	20	23	21	19	17	19
Zn	121	113	124	60	112	121	116	113	79	80
Cu	79	61	34	60	54	56	58	31	64	51
Ni	119	117	78	117	109	75	68	64	97	90
V	256	226	249	224	232	250	266	356	306	307
Cr	220	234	78	160	151	142	155	52	106	92

no REE determinations

3388 - diabase. 4359, 4277, 4429, 4410, 4382, 4361, 2219 - medium grained gabbro. 2218 - fine grained gabbro. 3535 - medium grained feldspathic gabbro.

Carboniferous igneous rocks (cont.)

sample	6040	2214*	2217*	4371*	4377*	4378*	4379*
SiO_2	49.50	52.08	50.65	71.22	72.64	75.32	76.15
TiO_2	1.23	2.09	1.91	0.38	0.25	0.19	0.05
Al_2O_3	18.70	14.99	15.88	13.87	13.26	12.64	13.22
Fe_2O_3	12.70	11.23	10.60	2.75	2.59	1.92	1.21
MnO	0.17	0.19	0.23	0.09	0.07	0.04	0.04
MgO	4.19	5.05	5.87	0.99	0.93	0.75	0.59
CaO	2.98	6.52	6.51	0.62	0.40	0.33	0.20
Na_2O	4.53	3.60	3.30	4.38	3.74	3.80	3.82
K_2O	2.80	2.45	2.18	4.71	4.34	3.67	5.15
P_2O_5	0.33	0.31	0.40	0.09	0.05	0.03	0.01
L.O.I	2.65	0.90	1.50	0.30	0.70	0.50	0.40
Total	99.78	99.41	99.03	99.40	98.97	99.19	100.84
Ba	1681	713	912	523	234	248	316
Rb	113	84	83	154	163	176	398
Sr	308	443	450	67	50	54	19
Y	37	28	28	45	32	41	78
Zr	140	154	169	311	378	261	119
Nb	6	16	16	24	33	36	43
Th	<5	<5	<5	18	30	68	50
Pb	15	17	94	30	17	21	11
Ga	23	27	22	19	24	20	24
Zn	144	138	300	69	76	55	52
Cu	20	53	50	<5	<5	<5	<5
Ni	21	36	50	6	6	5	5
V	294	304	233	6	6	4	<5
Cr	26	62	105	33	43	24	25
La	n.d.	25.2	n.d.	n.d.	n.d.	n.d.	n.d.
Ce	n.d.	54	n.d.	n.d.	n.d.	n.d.	n.d.
Nd	n.d.	25	n.d.	n.d.	n.d.	n.d.	n.d.
Sm	n.d.	6.1	n.d.	n.d.	n.d.	n.d.	n.d.
Eu	n.d.	1.5	n.d.	n.d.	n.d.	n.d.	n.d.
Tb	n.d.	0.9	n.d.	n.d.	n.d.	n.d.	n.d.
Yb	n.d.	2.9	n.d.	n.d.	n.d.	n.d.	n.d.
Lu	n.d.	0.48	n.d.	n.d.	n.d.	n.d.	n.d.
Cs	n.d.	3.1	n.d.	n.d.	n.d.	n.d.	n.d.
Hf	n.d.	4.7	n.d.	n.d.	n.d.	n.d.	n.d.
Sb	n.d.	0.5	n.d.	n.d.	n.d.	n.d.	n.d.
Sc	n.d.	32	n.d.	n.d.	n.d.	n.d.	n.d.
Ta	n.d.	1.0	n.d.	n.d.	n.d.	n.d.	n.d.
Th	n.d.	4.3	n.d.	n.d.	n.d.	n.d.	n.d.
U	n.d.	1.2	n.d.	n.d.	n.d.	n.d.	n.d.

* sample with detailed petrographic description. 6040 - medium grained diabase.

APPENDIX: DETAILED PETROGRAPHIC DESCRIPTIONS OF REPRESENTATIVE SAMPLES

NEOPROTEROZOIC PLUTONIC ROCKS

Tonalite

Sample 3387

This rock is characterized by an equigranular texture whose mineral constituents are generally anhedral, with the presence of some subhedral feldspar crystals. The crystals generally range from 0.5 mm to 1.5 mm with the exception of very fine quartz and epidote crystals.

The mineralogy of this rock consists mainly of quartz and plagioclase with minor biotite, chlorite, sericite, opaque oxides and epidote.

Alteration and deformation are extensive to moderate respectively. The feldspars are almost completely altered to sericite and only traces of the twinning lamellae remain. In regards to the deformation, the rock contains many fractures and the quartz shows initial stages of subgrain boundary development. Also some of the larger fractures are now filled in with epidote and quartz. There are also traces of biotite still present, but for the most part the biotite is almost completely altered to chlorite. A rough plagioclase determination gives An_{10} (i.e. albite)

Sample 3500

This sample is characterized by an equigranular texture with mineral crystals between 0.1 mm and 1.5 mm in size. There are however some crystals which are less than 0.1 mm in size and these are epidote, sericite and some quartz. The mineral constituents of this rock are all generally anhedral, but there are however some subhedral sphene, epidote and plagioclase crystals.

The mineralogy of this sample is somewhat different from that of sample 3387. In this rock the main minerals are quartz, plagioclase and calcite, with lesser amounts of biotite, chlorite, epidote, sphene opaques and sericite. Although this rock is texturally similar to 3387, it is mineralogically quite different. This difference is noted by the presence of calcite (fair amount) and sphene which are absent in sample 3387.

This rock has pseudomorphs of biotite outline which are almost totally altered to Mg-rich and Fe-rich chlorite and only traces of the biotite remain.

The alteration of this sample is quite extensive and is illustrated by the overall general dusty appearance of the thin section and by the great amount of alteration of the feldspar crystals, which contain numerous sericite microlites. The alteration of the feldspars is so great that only traces of the twinning lamellae remain in many cases. The deformation on the other hand is only moderate and is noted by numerous fractures and the development of subgrain boundaries in many of the quartz crystals.

Sample 3527

This sample, unlike samples 3387 and 3500, is characterized by a porphyritic texture. The phenocrysts are large (1 mm to 2 mm) and consist of quartz, plagioclase and pseudomorphs of biotite and hornblende (although the majority are of biotite outlines). Calcite crystals are also present. The groundmass consists mainly of quartz, feldspar, epidote calcite and opaques. This groundmass portion is generally <0.1mm. Many of the phenocrysts are subhedral to euhedral in outline, while the groundmass consists essentially of anhedral crystals. The texture of this rock suggests that it may be a hypabyssal rather than plutonic rock. The large biotite/hornblende pseudomorph phenocrysts are now entirely converted to an aggregate of Fe-rich and Mg-rich chlorite, epidote and opaques and no traces of the original mineral remain as previously observed.

This rock is moderately altered and deformed. The alteration is again, as in sample 3500, marked by the dusty appearance of the thin section as well as the alteration of the feldspar crystals (numerous sericite microlites). The deformation is marked by the numerous fractures some of which are filled in with calcite. The quartz and plagioclase in this sample are the least deformed of the Neoproterozoic tonalites examined, with subgrain boundaries observed in only a few crystals.

Sample 4262A

This sample is characterized by an inequigranular texture with the mineral constituents ranging from 0.5 mm to 2.5 mm in size. The mineral crystals are generally anhedral in outline with some observed euhedral sphene and subhedral epidote.

The mineralogy of this sample consists of quartz, plagioclase, pseudomorphs of biotite outline, sphene, Mg-rich chlorite, epidote, opaques, sericite/muscovite, secondary biotite, actinolite and calcite.

The pseudomorphs contain traces of primary biotite, but for the most part have now been totally converted to an aggregate of epidote, fibrous Mg-rich chlorite and actinolite, platy secondary biotite and opaques. These aggregate minerals are generally less than 0.1 mm in size.

This sample shows a very dusty appearance and the feldspars are almost totally sericitized, although the twin lamellae are still distinct in many crystals. The deformation is observed by numerous fractures as well as subgrain development in the quartz. The sphene is also strongly associated with the pseudomorphs.

<u>Granodiorite</u> (e.g., samples 3433, 4414, 3385, 3395, 3464)

Sample 3395

This sample is slightly pinkish and is characterized by an inequigranular texture whose mineral constituents are generally between 0.3 mm to 1.5 mm in size. The mineral crystals of this rock are generally anhedral (quartz) to subhedral in outline (plagioclase).

The mineralogy of this rock is mainly quartz, K-feldspar and plagioclase with lesser amounts of epidote, sphene, biotite, Mg and Fe-rich chlorite and opaques. This sample also contains pseudomorphs of biotite outline which in most cases have been completely converted to a crystal aggregate of epidote, chlorites and opaques. These crystal aggregates are generally less than 0.1 mm in size and in cases subhedral in outline. It is also observed that in other cases traces of the original biotite can still be seen. Sphene is associated with these crystal aggregates in several occasions.

Alteration is noted by sericitization and saussuritization of the feldspars, which in cases obliterates the plagioclase twin lamellae. The deformation as in all cases is illustrated by fractures and subgrain boundary development.

Samples 3385, 3433, 3464 and 4414

These samples show inequigranular texture with anhedral to subhedral mineral crystals. In some samples e.g. 3464 and 4414 there are however numerous euhedral hornblende crystals.

The mineralogy of these rocks consist mainly of quartz, plagioclase and K-feldspar with lesser amounts of biotite, secondary biotite, epidote, sphene, chlorite, apatite, zircon and opaques. The primary biotite occurs as large plates, whereas the hornblende occurs generally as well twinned prismatic crystals to euhedral crystals with hexagonal outline.

There are some mineralogical differences among individual samples. Thus in samples 3385 and 3433 there are only traces of primary biotite remaining. The biotite has mostly been converted to chlorite, opaques, epidote and secondary biotite. These new minerals occur as small crystal aggregates within the crystal boundaries of the biotite pseudomorphs. The other difference deals with samples 3464 and 4414. These two samples also contain fresh hornblende. Also these two samples do not contain any secondary biotite. In sample 4414 there are rare epidote crystals rimmed with chlorite which represent original hornblende crystals with biotite overgrowths.

All these samples show great sericitization of the feldspars as well as chloritization of biotite. The deformation is only moderate, marked by fractures and subgrain boundary development, but many quartz crystals show good even extinction.

CARBONIFEROUS PLUTONIC ROCKS

Quartz Diorite and Quartz Monzodiorite (e.g. samples 2214, 2216, 2217)

These rocks show an inequigranular to equigranular texture, whose mineral constituents are generally anhedral to subhedral (prismatic, platy) in crystal outline.

The mineralogy of these rocks consists essentially of plagioclase, quartz and K-feldspar with lesser amounts of biotite, hornblende, chlorite, apatite, actinolite, epidote and opaques. Many of the hornblende prisms show good twinning planes. The biotite in these rocks show a variable degree of alteration to chlorite.

These rocks show both alteration and deformation. It is however observed, that these samples appear more altered than tectonized. The alteration is observed by the sericitization and saussuritization of the feldspars, the chloritization of the biotite and the formation of actinolite from hornblende. The deformation is marked by fractures and only slight subgrain boundary development. However a lot of the quartz shows good even extinction.

Hybrids (e.g samples 3427, 3421, 4405, 4412)

These rocks illustrate a porphyritic texture, which in some cases may be only slight. Individual samples show differences in phenocrysts. Thus, in samples 3421 and 3427 the phenocrysts are subhedral plagioclase crystals and pseudomorphs of hornblende outline now converted to an aggregate of tiny secondary biotite, actinolite, epidote, chlorite and opaques. In sample 3421 there are rare large crystals of epidote rimmed by secondary biotite and actinolite which may represent original clinopyroxene crystals with hornblende coronas. The phenocrysts of 4405 and 4412 are subhedral plagioclase and quartz crystals with some calcite. In 4412 there are phenocrysts that are now completely altered to chlorite with only faint traces of biotite.

In all cases the finer portion of these rocks consists of fine feldspar, quartz, epidote, actinolite, secondary epidote as well as calcite in 4405 and 4412. These rocks are extensively altered and only moderately deformed. The alteration is noted by the great amount of epidote and sericitization/saussuritization of the feldspars and dusty opaques. The deformation on the other hand is illustrated by fractures and subgrain boundary development.

Pink granite (e.g. samples 4377, 4378, 4371)

These rocks illustrate an inequigranular texture, where mineral constituents range in size from 0.3 to 3 mm in size. The majority of the crystals are anhedral, but there are however some subhedral to euhedral plagioclase crystals and euhedral zircon crystals.

Mineralogically, these rocks consist predominantly of perthite, plagioclase and quartz with minor amounts of hornblende, actinolite, biotite, zircon, epidote, opaques, chlorite and allanite. The biotite in these rocks is green to brown and is somewhat altered to chlorite. There are also large hornblende crystals which are altering and are now seen to be composed mostly of fibrous actinolite, also prismatic actinolite, epidote and opaques. Zircon is mostly seen as small euhedral crystals near or within these altering hornblende crystals.

Alteration is observed by sericitization of the feldspars, while deformation is observed by bent lamellae in the plagioclase, subgrain boundary development and fractures.

Syenite (e.g. sample 4379)

This sample illustrates an inequigranular to a granophyric texture containing numerous spherulitic crystals. The mineral crystals are all essentially anhedral, with the exception of some subhedral to euhedral feldspar crystals.

The mineralogy of this rock consists essentially of K-feldspar and quartz with lesser amounts of plagioclase, calcite, opaques, hornblende, sphene, minor epidote and muscovite. In general, the minerals are all less than 0.4 mm in size. The muscovite in these samples in many cases is found as small rosettes. This is also observed in some of the K-feldspar.

This rock is relatively undeformed and only slightly altered. This alteration is noted by the slight dusty appearance of the thin section. Most of the quartz in this range shows good uniform extinction.

Aplite (e.g. sample 2213)

This rock illustrates an inequigranular to granophyric texture, where mineral constituents are essentially anhedral in outline. A few subhedral plagioclase crystals are also observed.

The mineralogy of this rock consists mainly of quartz and K-feldspar (perthite) with minor amounts of plagioclase, opaques, chlorite, muscovite/sericite and epidote. The mineral crystals are on average between 0.3 mm and 2 mm in size, however some minerals are less than 0.1 mm. These finer crystals are found filling in fractures. These rocks also contain many quartz and feldspar intergrowths.

The effects of alteration and deformation have affected this sample. The alteration is noted by the dusty appearance of the feldspars and numerous muscovite/sericite microlites. The deformation on the other hand is noted by subgrain boundary development in the quartz as well as large fractures. These fractures penetrate the entire sample and are generally filled in with epidote, quartz and feldspar. Large fractures have been found offset along smaller fractures.

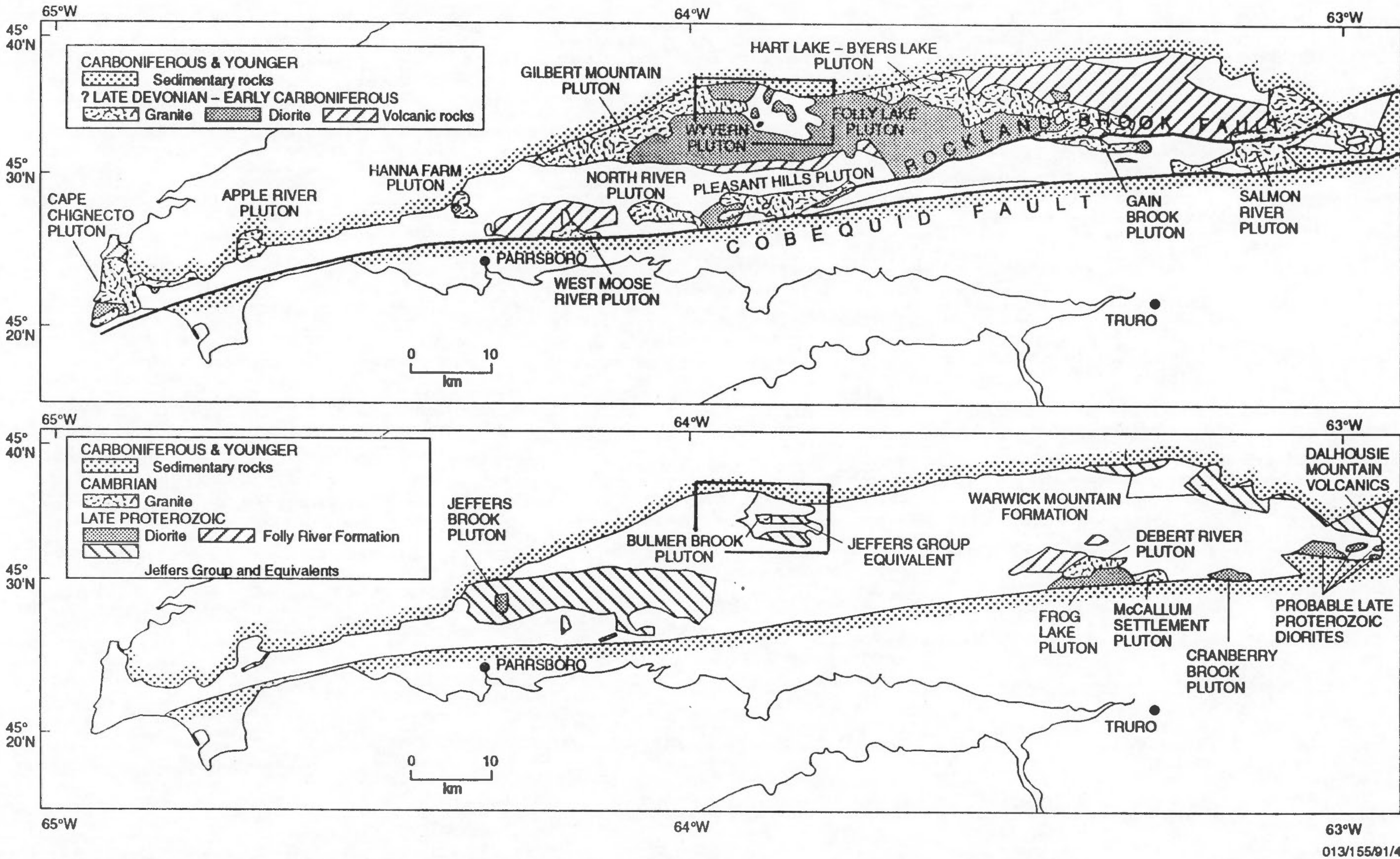

Fig. 1. Map showing regional location of detailed map area.

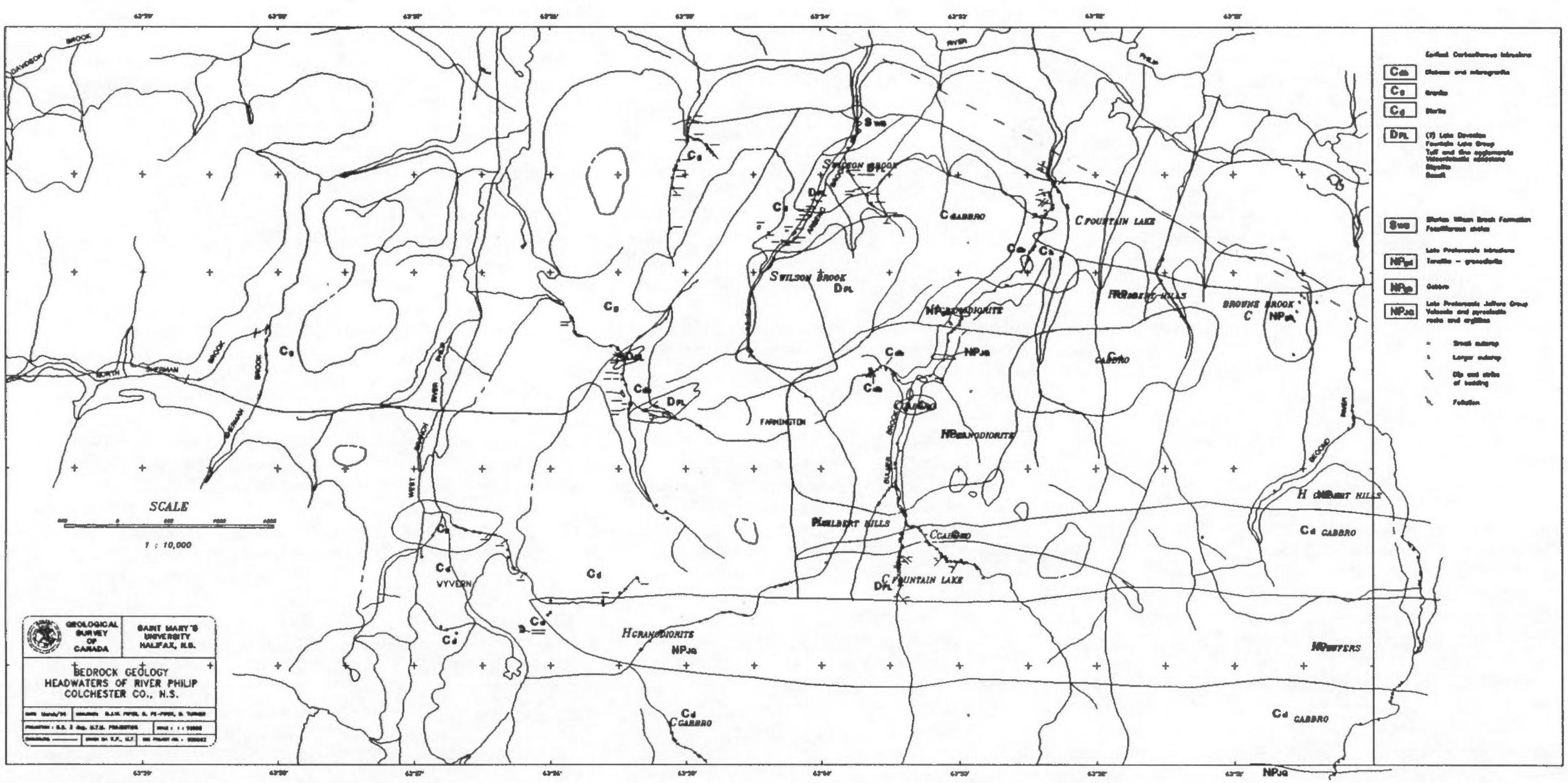

Fig. 2. Page-size version of 1:10 000 map.

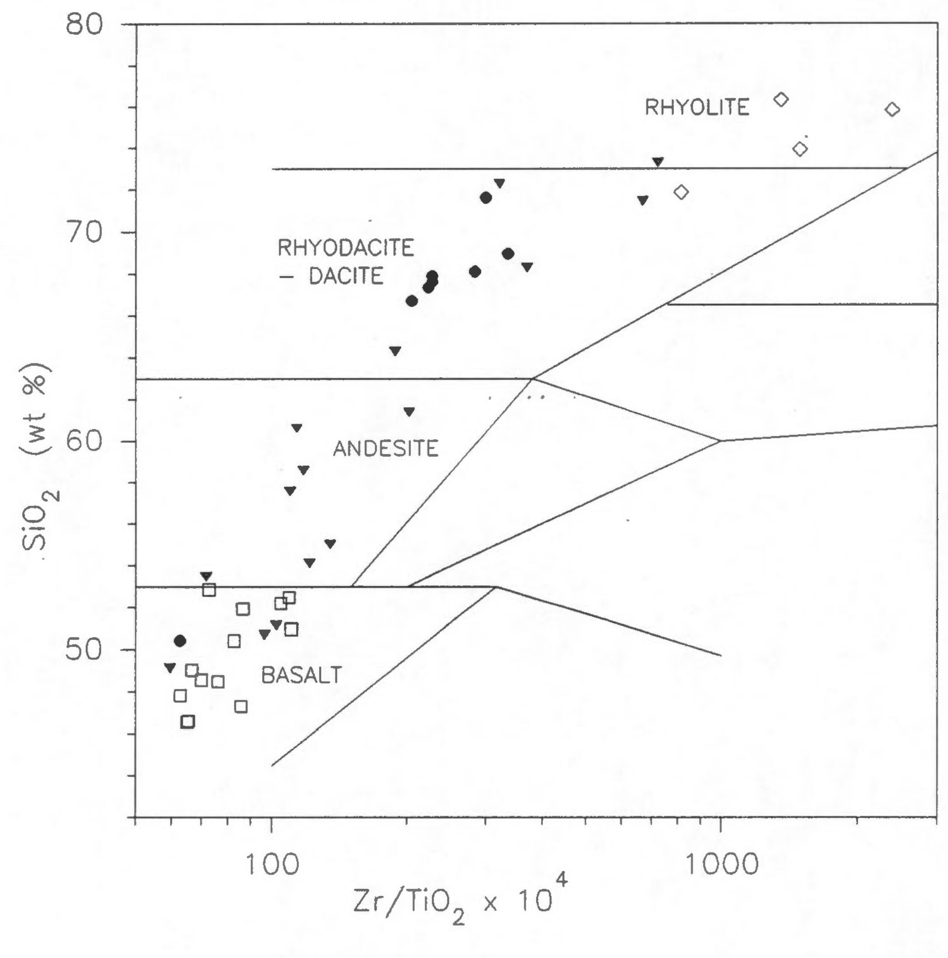

Fig. 3. SiO_2 *v.* Zr/TiO_2 plot (after Winchester and Floyd, 1977) showing distribution of analysed rock samples. Open symbols: Carboniferous igneous rocks (squares = mafic, circles = felsic). Solid symbols: Neoproterozoic igneous rocks (circles = intrusive, triangles = extrusive).

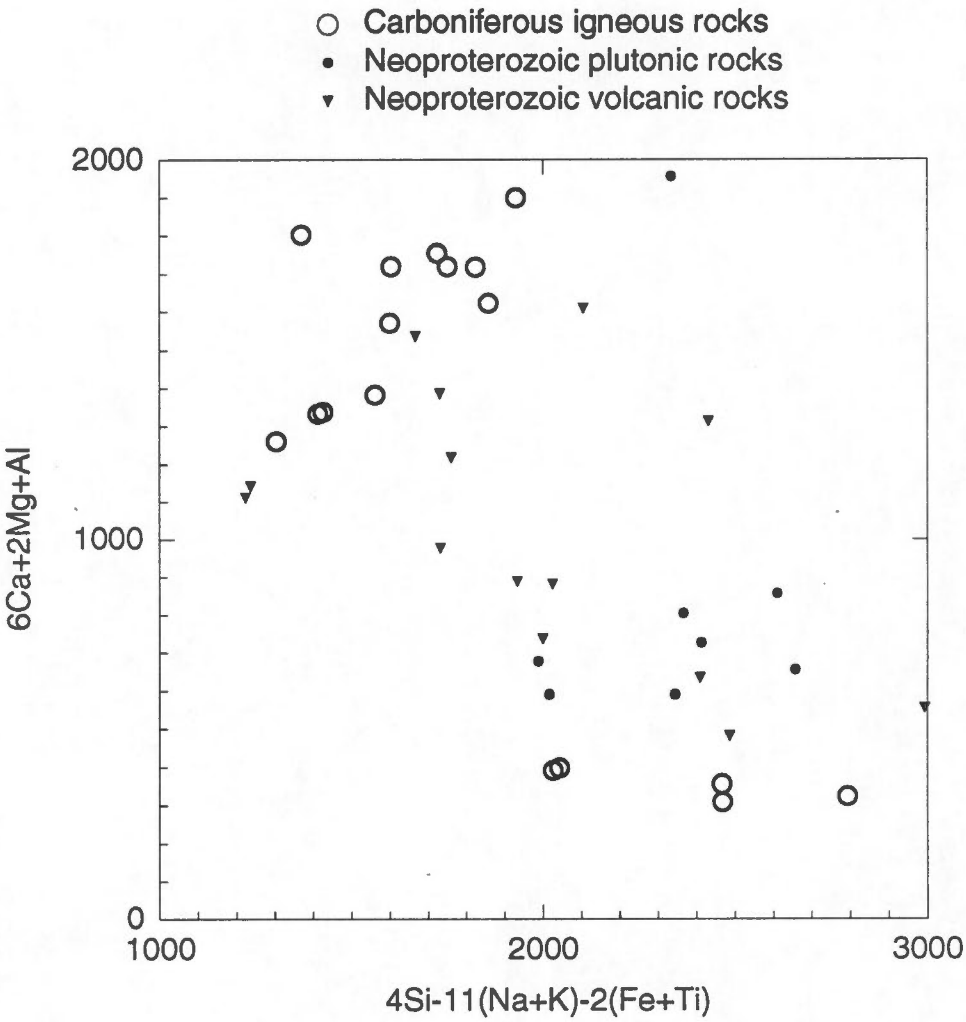

Fig. 4. Major element variation of plutonic rocks using the scheme of de la Roche (1981).

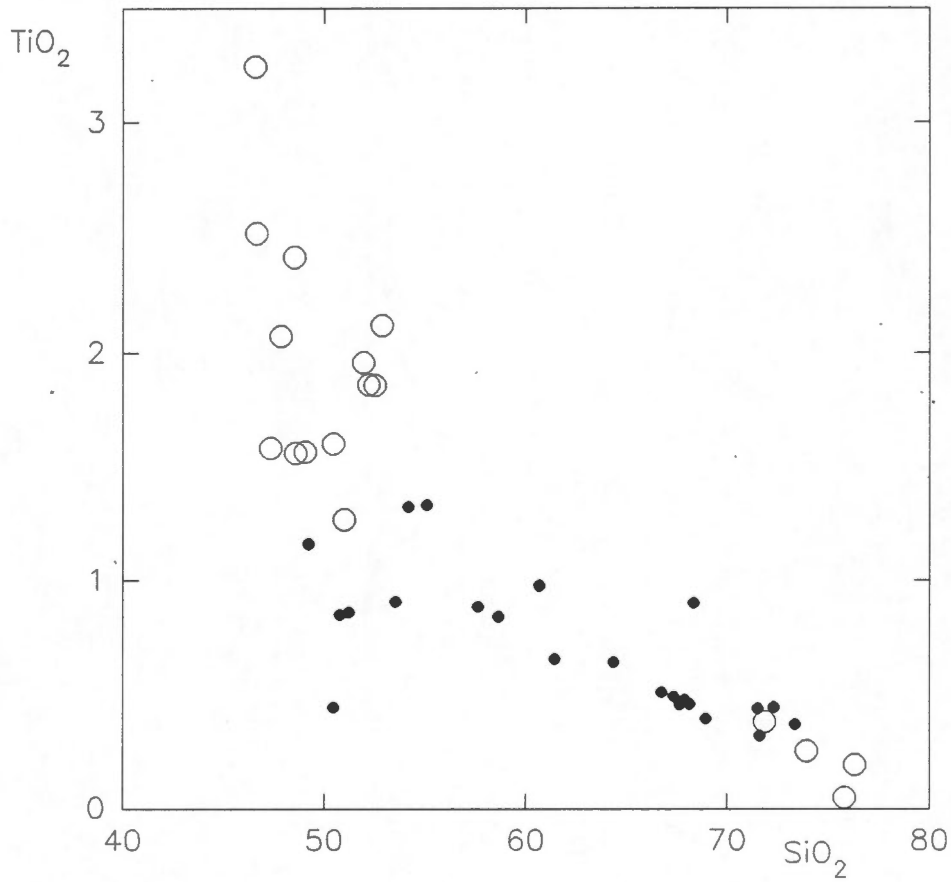

Fig. 5. Plot showing variation of wt % TiO_2 with SiO_2 for Neoproterozoic and Carboniferous igneous rocks. Symbols as in Fig. 4.

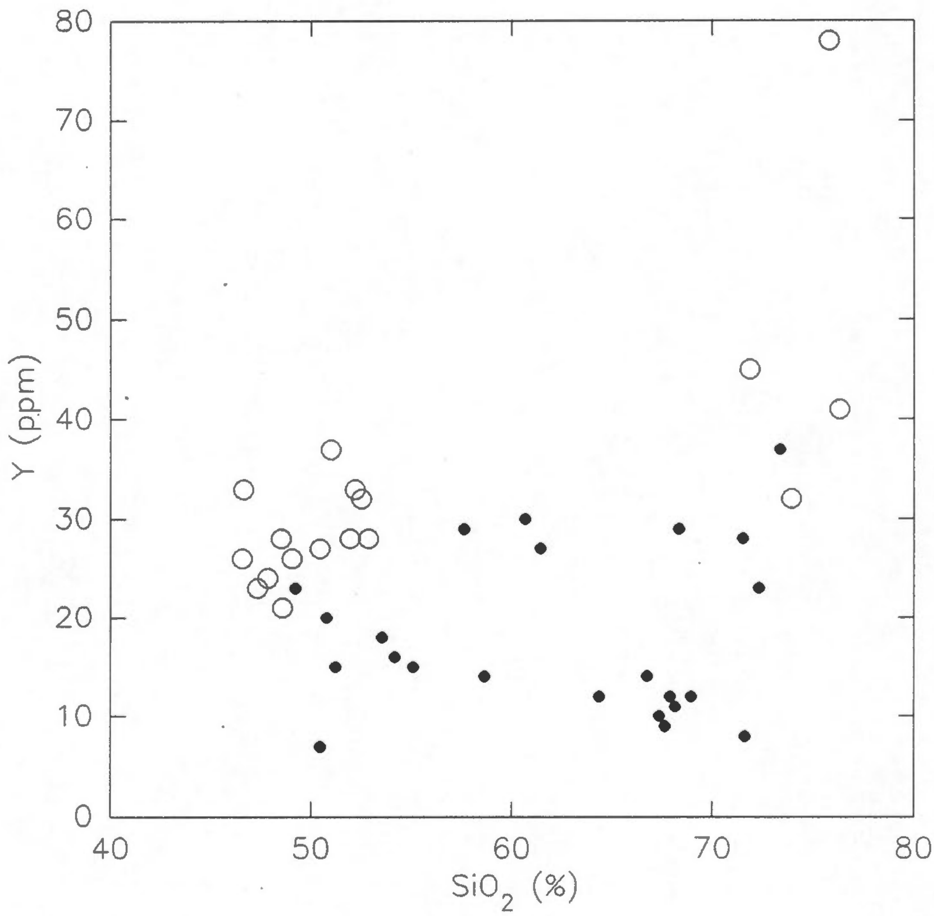

Fig. 6. Plot showing variation of Y with SiO_2 for Neoproterozoic and Carboniferous igneous rocks. Symbols as in Fig. 4.

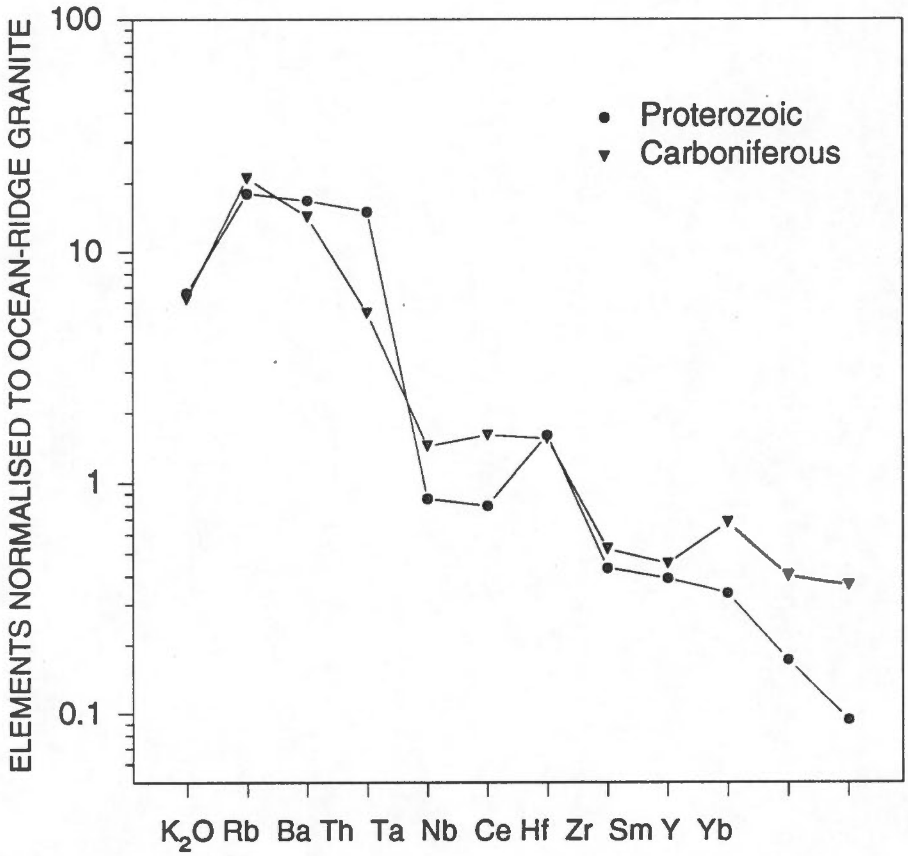

Fig. 7. Abundance of elements relative to ocean-ridge granite (after Pearce et al., 1984) for representative Neoproterozoic granodiorite (sample 3527) and Carboniferous diorite.