

# New U-Pb (zircon) age and geochemistry of the Wedgeport pluton, Meguma terrane, Nova Scotia

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*Date received: March 22, 2004* ¶ *Date accepted: June 29, 2004*

## ABSTRACT

A new U-Pb (zircon) age of  $357 \pm 1$  Ma for the Wedgeport pluton in the Meguma terrane of southwestern Nova Scotia confirms that it is younger than other granitoid plutons of the Meguma terrane but not as young as the ca. 316 Ma age based on previous geochronological work. The pluton consists of mainly homogeneous biotite monzogranite characterized by abundant accessory phases including garnet, zircon, epidote, titanite, and ilmenite. Major minerals are quartz, plagioclase (albite-oligoclase), and perthitic microcline. The pluton has consistently high SiO<sub>2</sub> content (average ca. 75%) but shows some internal variation consistent with fractional crystallization of feldspar and biotite, together with accessory phases such as zircon. Tectonic setting during emplacement of the pluton was likely within plate, but classification is ambiguous because the pluton has characteristics of all three granite types. Peraluminous composition and presence of ilmenite and aluminous minerals such as Fe-rich biotite and garnet suggest S-type affinity, but other characteristics such as high-level emplacement, accessory fluorite, and some chemical characteristics (high Ga/Al ratio, elevated Nb and Y) indicate A-type affinity, whereas abundant titanite and overall chemical character is compatible with felsic I-type composition. The granite has specialized characteristics such as elevated Rb relative to Sr and Ba, and high U and Th compared to all of the average granite types. High  $\epsilon_{Nd}$  values (+2 to +3) indicate a relatively primitive source compared to other plutons of the Meguma terrane. The Wedgeport pluton appears to be unique in the Meguma terrane in both age and composition, although similar plutons may occur in inboard terranes of the Appalachian orogen.

## RÉSUMÉ

Une nouvelle datation au U-Pb (à partir de zircon) situant à environ 357 Ma le pluton de Wedgeport à l'intérieur du terrane de Meguma dans le Sud-Ouest de la Nouvelle-Écosse, confirme qu'il est plus récent que les autres plutons granitiques du terrane de Meguma, mais qu'il a plus des 316 Ma qu'on lui avait attribués dans le cadre de travaux géochronologiques antérieurs. Le pluton est constitué de monzogranite à biotite principalement homogène caractérisé par des phases accessoires abondantes, notamment du grenat, du zircon, de l'épidote, de la titanite et de l'ilménite. Les principaux minéraux présents sont le quartz, le feldspath plagioclase (albite-oligoclase) et la microcline perthitique. Le pluton a une teneur constamment élevée en SiO<sub>2</sub> (en moyenne environ 75 %), mais il présente une certaine variation interne correspondant à une cristallisation fractionnée des feldspaths et de la biotite, ainsi que des phases accessoires, dont du zircon. L'intrusion du pluton est probablement survenue dans un cadre tectonique intra-plaque, mais sa classification est ambiguë parce que le pluton possède des caractéristiques des trois types de granites. Sa composition hyperalumineuse et la présence d'ilménite et de minéraux alumineux, comme de la biotite riche en fer et du grenat, laissent supposer une affinité de type S, mais d'autres caractéristiques, comme l'intrusion de haut niveau, la fluorine accessoire et certaines caractéristiques chimiques (rapport Ga/Al élevé, teneur élevée en Nb et Y), témoignent d'une affinité de type A, tandis que l'abondance de titanite et son caractère chimique général sont compatibles avec une composition de type I felsique. Le granite présente des caractéristiques spécialisées, telles qu'une quantité élevée de Rb par rapport au Sr et au Ba, et des teneurs élevées en U et en Th comparativement à tous les types de granites moyens. Les valeurs  $\epsilon_{Nd}$  élevées (+2 à +3) signalent une source relativement primitive comparativement aux autres plutons du terrane de Meguma. Le pluton de Wedgeport semble unique à l'intérieur du terrane de Meguma tant du point de vue âge que composition, même si des plutons analogues peuvent être présents dans des terranes intérieurs.

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## INTRODUCTION

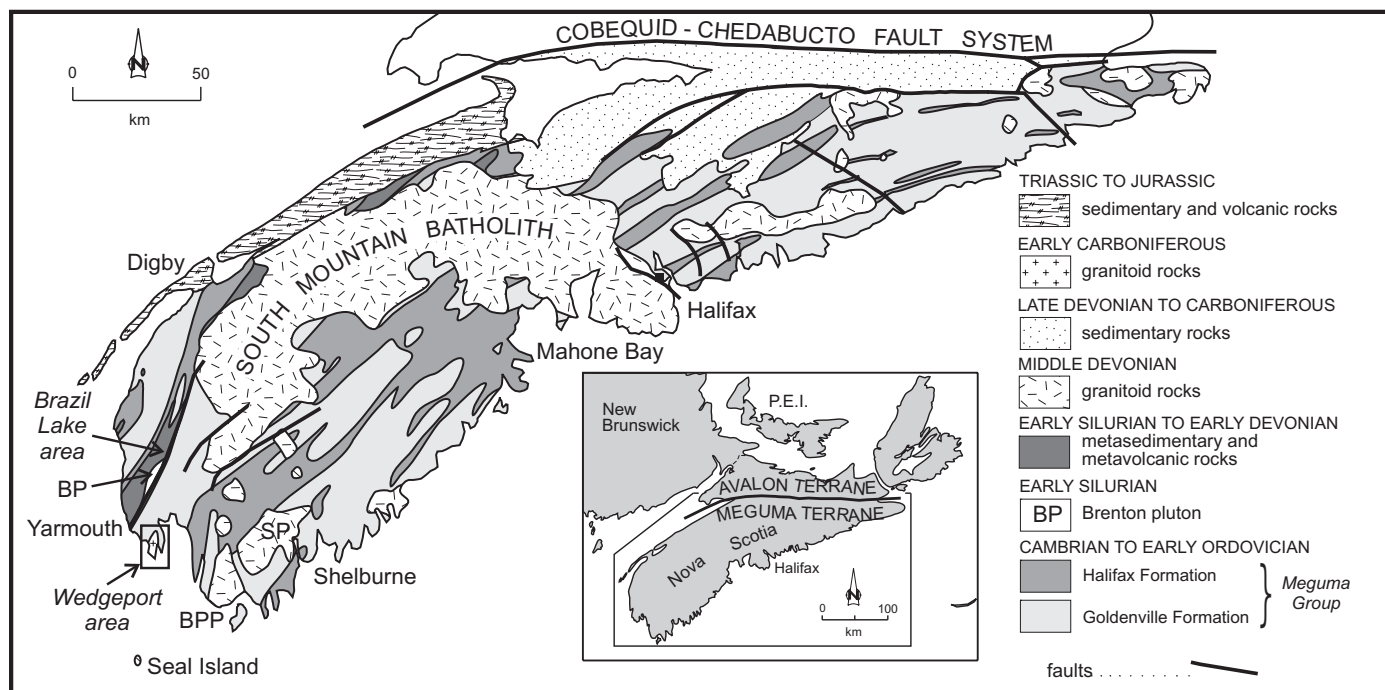
The Wedgeport pluton in southernmost Nova Scotia differs in both age and composition from the abundant Devonian plutons that characterize the Meguma terrane (Fig. 1). Its specialized characteristics were recognized in the Nova Scotia “granite boom” of the late 1970s and early 1980s, when the poorly exposed pluton was extensively explored and drilled for Sn, W, and U (Cant *et al.* 1978; Wolfson 1983). Subsequently, the pluton was reported to be significantly younger than the other plutons of the Meguma terrane, with a late Carboniferous U-Pb (zircon) and Rb-Sr whole rock age of  $316 \pm 5$  and  $323 \pm 12$  Ma, respectively (Cormier *et al.* 1988). This age is similar to some  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from mica in plutonic and metasedimentary units and shear zones in the area (e.g., Reynolds *et al.* 1981, 1987; Dallmeyer and Keppie 1987, 1988; Muecke *et al.* 1988; Keppie and Dallmeyer 1995; Culshaw and Reynolds 1997). The pluton also yielded younger  $^{40}\text{Ar}/^{39}\text{Ar}$  biotite and Rb-Sr mineral ages of ca. 257 Ma (Reynolds *et al.* 1981; Cormier *et al.* 1988), which, together with the inferred crystallization age, were used to suggest that Permian-Carboniferous plutonism was a significant factor for economic mineralization in the Meguma Terrane (Cormier *et al.* 1988). It was suggested more recently that emplacement of the Wedgeport pluton may have been linked to extension related to delamination (Keppie and Dallmeyer 1995) or transtension along shear zones as a result of relative motion of the Gondwanan and Laurentian plates (Pe-Piper and Jansa 1999).

The Southwest Nova Mapping Project (White 2003) provided an opportunity to revisit the Wedgeport pluton with detailed mapping and sampling, which was used as the

basis for a BSc honours thesis project by the senior author. Furthermore, the previously reported U-Pb (zircon) age was based on a single bulk zircon fraction and thus is not reliable by current standards; hence, the opportunity was also taken to re-date the pluton. The purpose of this paper is to report the results of these studies, together with a compilation of some earlier work on the pluton. The results show that the pluton is older than was indicated by previous dating, but still younger than other granitoid rocks of the Meguma terrane.

## GEOLOGICAL SETTING

The Wedgeport pluton (Taylor 1967) intrudes thickly bedded metasediment, metasilstone, and slate of the New Harbour Member, the lower part of the Goldenville Formation (White and King 2002; White 2003) (Figs. 1, 2). The Goldenville Formation is overlain by the mainly pelitic Halifax Formation. In the Yarmouth area west of the Wedgeport pluton (Fig. 1), metavolcanic and metasedimentary rocks of the late Ordovician to Silurian White Rock Formation disconformably overlie or are in faulted contact with the Halifax Formation (MacDonald *et al.* 2002; White *et al.* 2001). These units were deformed and metamorphosed during the Acadian orogeny at ca. 395–380 Ma (Hicks *et al.* 1999), prior to emplacement of the South Mountain Batholith and related plutons at ca. 378–372 Ma (see Clarke *et al.* 1997 for a summary). The Meguma terrane was juxtaposed with the Avalon terrane to the north by Devonian-Carboniferous dextral transcurrent motion along the Cobequid-Chedabucto fault system (e.g., Keppie 2000). Mantle-derived mafic igneous activity in the Middle Devonian



**Fig. 1** Geological map of southern Nova Scotia, showing the location of the Wedgeport pluton. Abbreviations: BPP = Barrington Passage Pluton; BP = Brenton Pluton; SP = Shelburne Pluton.

to Carboniferous may have provided the heat source to generate these granitoid magmas by crustal melting (Tate and Clarke 1995). Ongoing localized deformation occurred along shear zones during the Carboniferous (Culshaw and Liesa 1997; Culshaw and Reynolds 1997).

### FIELD RELATIONS

Although the Wedgeport pluton is poorly exposed and outcrop is sporadic, second derivative aeromagnetic data (King 1997a, b, and unpublished data) combined with several drill holes (Cant *et al.* 1978) clarify the position of the contact in areas of limited or no outcrop. The pluton intruded along the western limb of a north-south-trending, north-plunging anticline (Fig. 2). It produced a narrow (approximately 400 m wide) contact metamorphic aureole of spotted hornfels containing andalusite and cordierite superimposed on biotite zone assemblages (Cullen 1983). Abundant garnet also was noted during the present study in the more pelitic beds in the metasediment. The contact metamorphic mineral assemblage is indicative of the albite-epidote to hornblende-hornfels facies, and indicates that the pluton was emplaced at relatively shallow crustal depth, about 3–4 km below surface. The contact zone is well exposed on the western shore of Pinkneys Point (Fig. 2), where the metasedimentary rocks are intruded by granitic dykes from the pluton.

The mainly granitic pluton contains scattered fine- to medium-grained, biotite-rich, round granodioritic enclaves that range in size from a few 10s of cm to 1–2 m in longest dimension. None of the enclaves were included in the present study. Narrow (2–5 cm wide, rarely > 1 m), pale grey veins and pods of aplite and pegmatite intrude the pluton. Near the margins of the pluton the granite is heterogeneous with textures that range from fine-grained to porphyritic. In addition, igneous layering is present, defined by alternating biotite-rich and feldspar-quartz-rich bands that are broadly parallel to the contact with the adjacent country rocks. Mirolitic cavities are present locally but are generally uncommon (Wolfson 1983). These textural variations suggest that a significant amount of fluid was present during crystallization of the pluton, especially near the margins.

The pluton and adjacent country rock are cut by several thin (1–2 mm to several cm) quartz, quartz-tourmaline, quartz-carbonate, and greisen veins. Typically, the quartz-carbonate and greisen veins contain various sulphide minerals, fluorite, scheelite, white mica, and cassiterite (Wolfson 1983). Northeast- to east-trending shear zones, reported to contain cassiterite, wolframite, molybdenite, and scheelite, cut the pluton, and appear rusty as the result of weathering of associated sulphide minerals, mainly pyrite and arsenopyrite (e.g., Wolfson, 1983). Mylonitic fabrics are common in the shear zones which display well-developed asymmetric quartz augen and C–S fabrics indicating dextral sense of motion (White 2003).

The pluton is cut by lamprophyre and alkaline olivine diabase dykes of early Jurassic age (Cant *et al.* 1978; Chatterjee

and Keppie 1981; Wolfson 1983; Pe-Piper and Reynolds 2000; White and King 2002; White 2003).

### PETROGRAPHY

The Wedgeport pluton is composed mainly of medium- to coarse-grained biotite monzogranite which grades in composition to syenogranite (Fig. 3). Texture is typically hypidiomorphic equigranular and, locally, inequigranular to porphyritic, especially near the margins as described above. Microcline is the dominant feldspar, and simple Carlsbad twins are visible in some grains suggesting that orthoclase was the original form. Perthitic texture is typically present, and albitic lamellae have compositions similar to those of separate plagioclase grains in the rock. Granophyric texture occurs only in samples from the northwestern part of the intrusion; that area may represent the shallowest part at the time of emplacement. Subhedral plagioclase is slightly to extensively altered to saussurite and sericite. Microprobe analyses of plagioclase in 6 samples showed a range in composition from An<sub>1</sub> to An<sub>17</sub>; zoned plagioclase grains do not greatly vary in composition from the core to the rim (MacLean 2003). Anhedral quartz grains commonly show undulatory extinction.

Biotite forms about 15% of the rock, and typically is partially or wholly altered to chlorite and muscovite. Microprobe analyses (MacLean 2003) revealed that the biotite has a high iron content (Fe/Fe+Mg = 0.73 to 0.83) and tetrahedral Al contents of 2 to 2.2, close to the annite end member. Common inclusions in biotite are titanite, zircon, apatite, ilmenite, epidote, and probably monazite (not easily identified because of small grain size). Titanite is the most abundant accessory mineral in the samples and mainly occurs in association with biotite and ilmenite; the latter mineral is partially or in some cases entirely altered to titanite. Many samples also contain minor amounts of garnet and fluorite. Electron microprobe analyses revealed that the garnet is of almandine-grossular composition with high manganese content (MacLean 2003).

Chatterjee and Keppie (1981) and Chatterjee *et al.* (1985) divided the Wedgeport pluton into the Goose Bay and Pinkneys Point units, forming the eastern and western parts of the pluton, respectively, with the mutual contact not exposed. They described the Goose Bay granite as garnetiferous, and similar to parts of the South Mountain Batholith. In contrast, the Pinkneys Point granite was described as a more variable unit, containing topaz granite, greisenized granite, albitite, and greisen, and associated with mineralization, including cassiterite, wolframite, scheelite, and a variety of similar lithophile-element minerals (Chatterjee *et al.* 1985). Chatterjee and Keppie (1981) suggested that the Pinkneys Point pluton may have been the source of fluids that resulted in alteration and mineralized veins in the Wedgeport pluton and adjacent rocks. Observations made during the present study do not provide any evidence to support this subdivision; garnet was observed in samples distributed throughout the pluton, and features ascribed to the Pinkneys Point unit are more likely a reflection

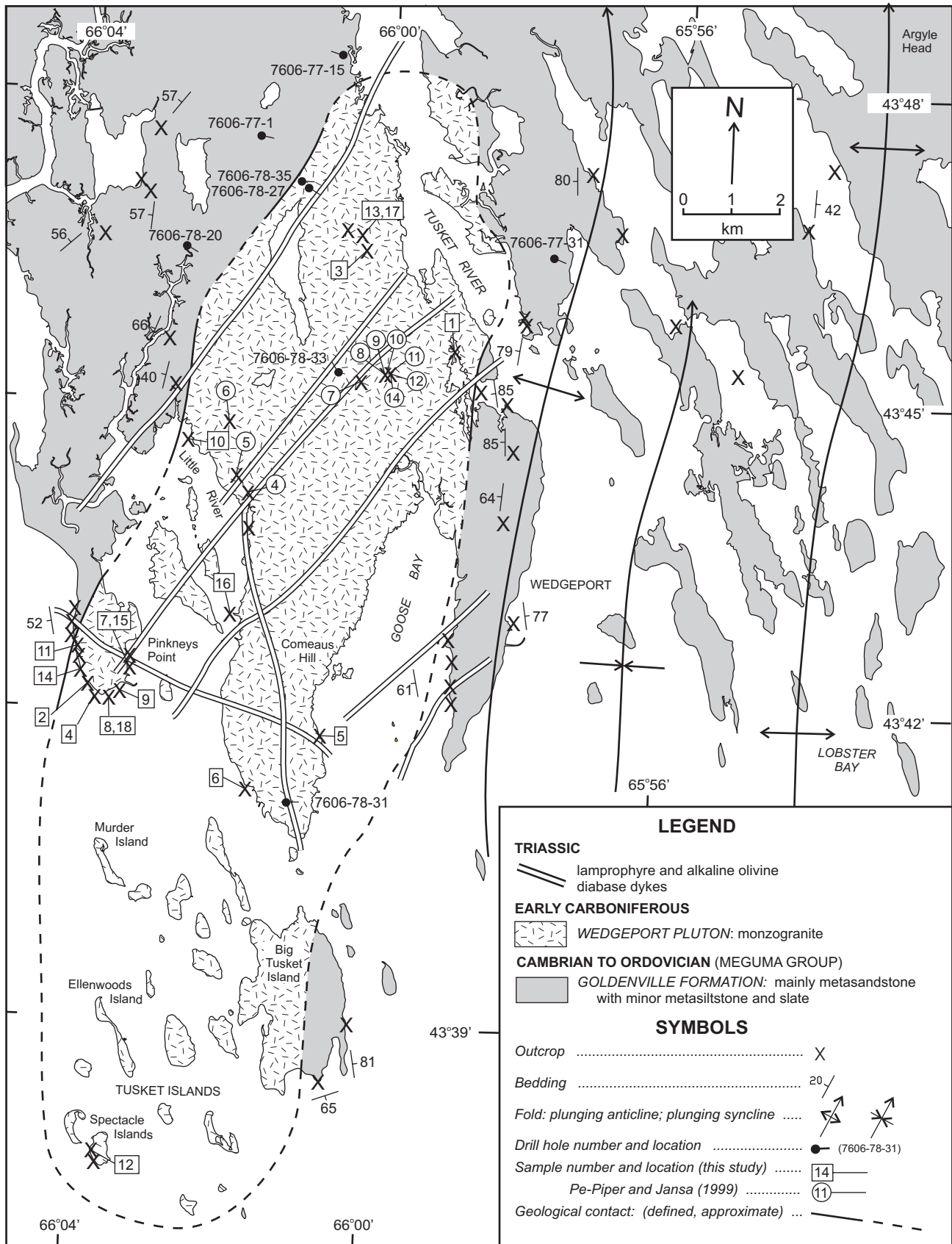
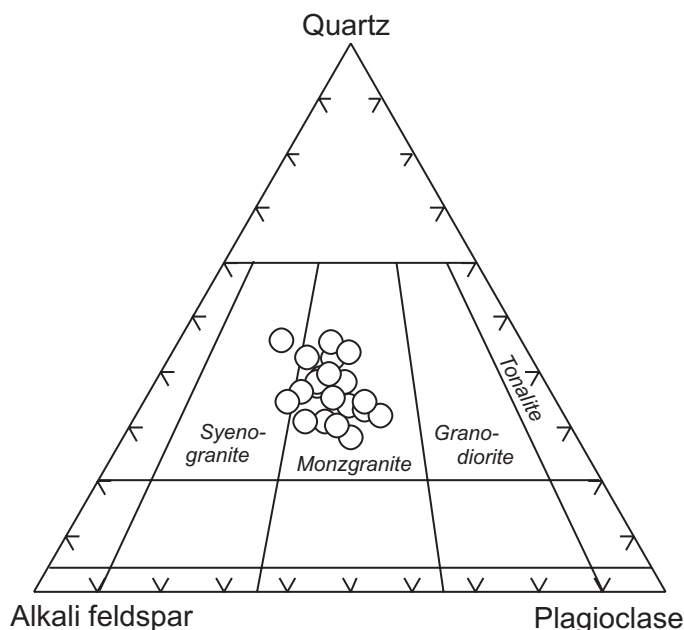


Fig. 2 Geological map of the Wedgeport pluton showing sample locations of the present study and those from Pe-Piper and Jansa (1999). Map is based on White (2003) and the present study.



**Fig. 3** Modal mineralogy of samples from the Wedgeport pluton plotted on a Q-A-P ternary diagram with fields from Streckeisen (1976).

of the excellent exposure in the Pinkneys Point section and its position near the margin of the pluton.

## GEOCHRONOLOGY

### Previous Work

U-Pb and Rb-Sr data presented by Cormier *et al.* (1988) indicated that the Wedgeport pluton crystallized at  $316 \pm 5$  Ma, but was reheated at  $257 \pm 8$  Ma during a thermal event. However, the U-Pb data of Cormier *et al.* (1988) are difficult to re-assess as no U isotopic information was provided and some aspects of the data are inconsistent between data table and text. Additionally, only one zircon fraction was analyzed, and presumably that fraction was large and multigrain. The zircon was reported to be of poor quality, and it is unlikely that it was air-abraded prior to analysis because at the time of the work, the abrasion technique (Krogh 1982) was not widely used.

An  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age on biotite at  $258 \pm 8$  Ma has also been reported from the Wedgeport pluton (Reynolds *et al.* 1981); however, this sample showed appreciable alteration of biotite to chlorite (Reynolds *et al.* 1981). The similarity between the Rb-Sr mineral isochron ages (Cormier *et al.* 1988) and the  $^{40}\text{Ar}/^{39}\text{Ar}$  age from chloritized biotite suggests that both the Rb-Sr and  $^{40}\text{Ar}/^{39}\text{Ar}$  systems may record the timing of pervasive alteration in the Wedgeport pluton as opposed to a re-heating event.

Even younger hornblende and biotite  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau ages (ca. 231 to 222 Ma and ca. 209 to 203 Ma) were reported for the lamprophyre and alkaline olivine diabase dykes that

occur in the area (Reynolds *et al.* 1987; Pe-Piper and Reynolds 2000).

### Analytical Methods

A 20 kg monzogranite sample was processed at the Royal Ontario Museum in Toronto using standard techniques, including heavy liquids and a Frantz magnetic separator for isolation of heavy mineral fractions. Zircon was selected from the least paramagnetic fraction by hand picking grains under a binocular microscope. All picked zircons were given an air abrasion treatment to eliminate cracked grains and remove exterior surfaces (Krogh 1982). Final selection of grains for analysis was then made. The weight of each fraction (consisting of one to four grains) was determined using an unpublished spreadsheet calculation that estimates fraction weights from photomicrograph measurements of individual zircons. Uncertainties on the estimated weights have not been calculated but are likely to be <30% in most cases. This uncertainty only affects the calculation of Pb and U concentrations and has no influence on age data.

The selected grains were washed in 4N and 7N  $\text{HNO}_3$  and then loaded into Teflon bombs with HF and a measured amount of  $^{205}\text{Pb}$  -  $^{235}\text{U}$  isotopic tracer solution (Krogh 1973). Dissolution occurred over four to five days at  $195^\circ\text{C}$ . No chemical isolation of U and Pb was carried out on the dissolved grains. Fractions were dried down with phosphoric acid and then loaded with silica gel onto out-gassed rhenium filaments. The isotopic compositions of Pb and U were measured using a single Daly collector with a pulse counting detector in a solid source VG354 mass spectrometer. A detector mass discrimination of 0.14% per atomic mass unit (AMU) and a dead time of 22.5 nsec were employed for Daly detector measurements. A thermal source mass discrimination correction of 0.1% per atomic mass unit for both Pb and U was also used.

Assigned laboratory blank for U is 0.2 pg. Total measured common Pb in each fraction was below 1 pg in all cases and was assigned the isotopic composition of lab blank (see footnotes to Table 1). Error estimates were calculated by propagating known sources of analytical uncertainty for each analysis including ratio variability (within run), uncertainty in the fractionation correction, and uncertainties in the isotopic composition of laboratory blank. Decay constants used are those of Jaffey *et al.* (1971). Uncertainties are given at the 95% confidence level. Discordia lines and concordia intercept ages were calculated by the method of Davis (1982) using the in-house program ROMAGE. The average  $^{206}\text{Pb}/^{238}\text{U}$  age reported below was also calculated using ROMAGE.

### New Results

Zircon grains in the Wedgeport granite sample are dominated by euhedral, 4-sided, well-formed igneous prisms ranging from small to large (Fig. 4a, b). Most grains are cracked and/or contain inclusions but the selected grains are free of these



Table 1. U-Pb isotopic data for Wedgeport pluton sample 016-WO2-004A

Reference	Fraction <sup>(a)</sup>	Weight (mg)	U (ppm)	Th <sup>(b)</sup> U	total Pb (pg)	com. <sup>(c)</sup> Pb (pg)	Ratios				Ages (Ma)				disc. <sup>(d)</sup> (%)	
							$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	2 $\sigma$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	2 $\sigma$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	2 $\sigma$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$		2 $\sigma$
jk10p16	Z1 euh clr 2:1 pr (1)	0.0028	265	0.53	44.8	0.2	15796	0.0575	0.0002	0.428	0.002	360.4	1.1	373.3	4.6	3.6
jk10p17	Z2 euh clr 3:1 pr incl (3)	0.0032	314	0.53	59.6	0.3	13947	0.0566	0.0002	0.421	0.001	355.0	1.1	368.1	4.9	3.7
jk10p18	Z3 euh clr 3:1 pr incl (3)	0.0030	415	0.47	72.7	0.3	15268	0.0565	0.0002	0.419	0.002	354.4	1.4	363.0	4.4	2.4
jk10p22	Z4 eq clr ball (1)	0.0050	308	0.42	89.3	0.5	10838	0.0570	0.0003	0.422	0.002	357.4	1.6	356.0	4.9	-0.4
jk10p23	Z5 euh 2:1 pr (4)	0.0028	345	0.39	54.9	0.4	8044	0.0561	0.0002	0.415	0.001	351.6	1.0	358.3	4.8	1.9
jk10p75	Z6 clr ball (1)	0.0045	226	0.62	62.2	0.4	8911	0.0570	0.0003	0.422	0.002	357.1	1.7	362.4	5.0	1.5

Data are from abraded zircons (Krogh 1982). Decay constants used are those of Jaffey *et al.* (1971).

Notes: (a) Abbreviations: Z - zircon; euh - euhedral; eq - equant; pr - prism; clr - colourless; incl - inclusions; 2:1, 3:1, etc. - length:breadth ratio; Number in brackets indicates number of grains analysed. (b) Th/U - based on radiogenic  $^{208}\text{Pb}/^{206}\text{Pb}$  ratio and  $^{207}\text{Pb}/^{206}\text{Pb}$  age. (c) Com. Pb = total common Pb; blank isotopic composition:  $^{206}\text{Pb}/^{204}\text{Pb} = 18.221$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.612$ ,  $^{208}\text{Pb}/^{204}\text{Pb} = 39.36$ . (d) Disc. = percent discordance for the given  $^{207}\text{Pb}/^{206}\text{Pb}$  age

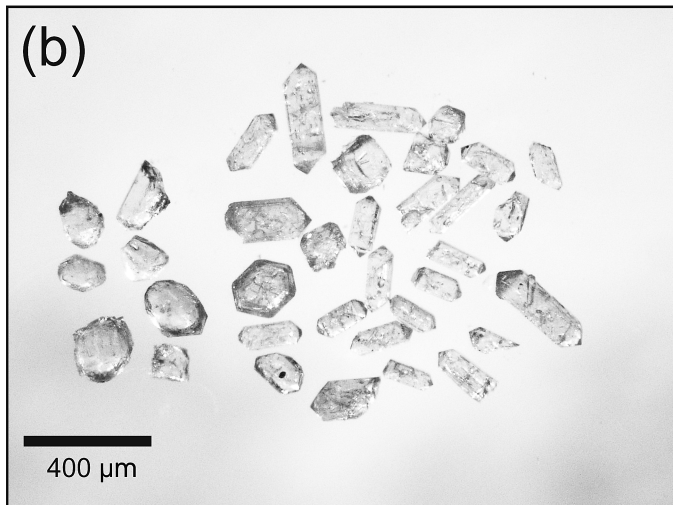
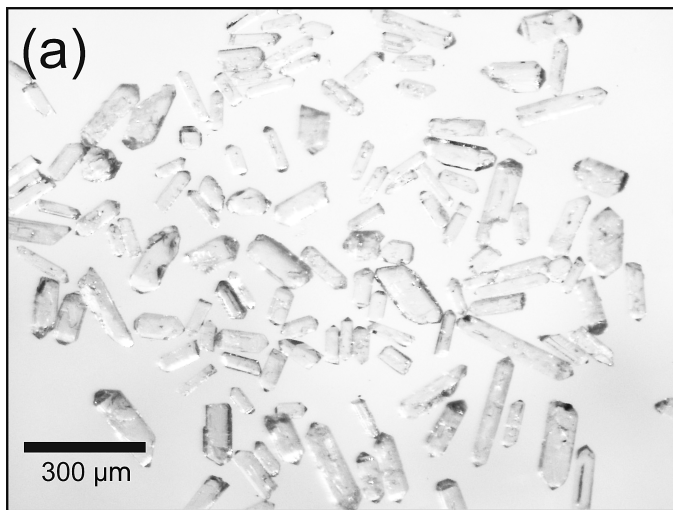


Fig. 4 Photomicrographs of zircon grains from monzogranite sample 016-WO2-004A. (a) small prismatic grains. (b) large prismatic grains.

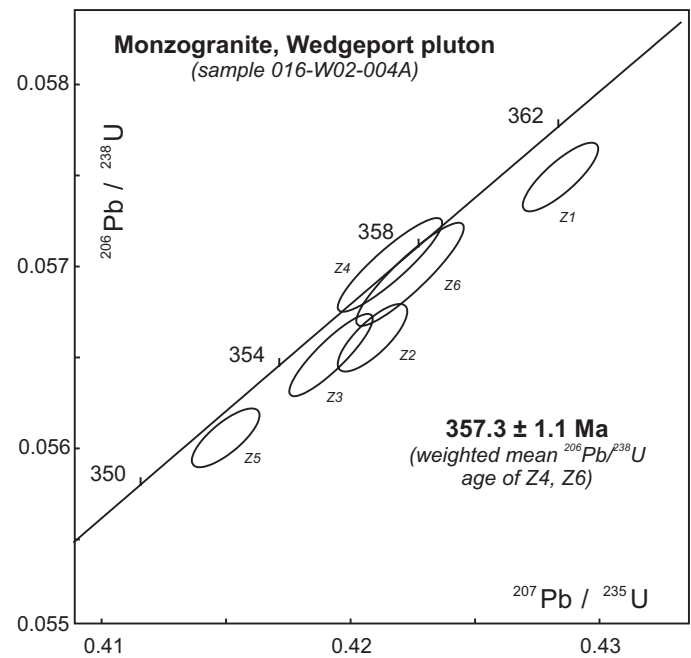


Fig. 5 Concordia diagrams for sample 016-WO2-004A, based on data presented in Table 1.

features. Six fractions of small and large grains were abraded and analysed separately (Table 1). Fractions Z2, Z3, and Z5 are multigrain fractions of small prisms with inclusions. On the concordia diagram (Fig. 5), these analyses plot distinctly below and to the left of two concordant analyses (Z4, Z6) of larger single prisms. Fraction Z1, also a single large grain, is older than all other fractions. Although interpretation of these data is not straightforward, we consider the following scenario to be the most likely. Concordant fractions Z4 and Z6, with identical  $^{206}\text{Pb}/^{238}\text{U}$  ages of 357 Ma, are interpreted to give the igneous crystallization age of the granite. The weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of these fractions is  $357.3 \pm 1.1$  Ma. Fraction Z5 is interpreted to consist of ca. 357 Ma zircons that experienced some modern-day Pb loss, and fraction Z1 appears to contain an inherited component. The age of this component is modelled as  $1340 +830/-500$  Ma, the upper intercept age of a discordia line through fractions Z1, Z4, and Z6. The remaining fractions (Z2, Z3) have  $^{207}\text{Pb}/^{206}\text{Pb}$  ages significantly older than 357 Ma and therefore modern-day Pb loss alone cannot account for their discordance. We suggest that Pb loss combined with the presence of a minor inherited component best explains the discordance of these analyses.

We consider the weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $357.3 \pm 1.1$  Ma to be the best estimate for the crystallization age of the Wedgeport pluton. The previously reported age of  $316 \pm 5$  Ma (Cormier *et al.* 1988), which was based on a single analysis of highly fractured and metamict grains, may be erroneously young due to significant Pb loss from these zircons.

## GEOCHEMISTRY

### Introduction

We acquired major and trace element data (Table 2) for 18 samples from surface outcrops of the Wedgeport pluton (Fig. 2). Rare-earth element data were obtained for 5 of these samples (Table 3), and Sm-Nd isotopic data for the dated sample (Table 4). Wolfson (1983) had reported whole-rock analyses of 8 samples from drill core in the Wedgeport pluton, but her data included only a limited suite of trace elements. Pe-Piper and Jansa (1999) also obtained chemical data from 7 samples from the pluton, in order to compare to offshore plutons sampled in drill core. Those data include a suite of trace elements and in two samples, also rare-earth elements, comparable to the present data set, although no petrographic descriptions were provided. Locations for these samples (G. Pe-Piper, written communication, 2004) are shown on Fig. 2. In addition, Chatterjee *et al.* (1985) presented a large amount of chemical data from the Wedgeport pluton in the form of variation diagrams; however, their focus was on mineralization processes, not petrogenesis and tectonic setting, and the actual chemical data for those samples were not published.

### Major and trace elements

All analyzed samples from the Wedgeport pluton have high silica content (Table 2) that averages about 75%. Although scattered, most major element oxides show a negative correlation with  $\text{SiO}_2$  (Fig. 6). Exceptions are  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  (Fig. 6f, g) which show little or no correlation with  $\text{SiO}_2$ . These variations mainly reflect variations in the amount of modal biotite and plagioclase in the analyzed samples. No consistent differences are apparent between samples that contain garnet compared to those that do not, or between the porphyritic sample and the other samples. The two aplite samples do not differ significantly in major element composition from their host rocks. In terms of major element composition, the Wedgeport pluton does not show a clear affinity with any of the average A-type and felsic I- and S-type granites of Whalen *et al.* (1987). For example,  $\text{Na}_2\text{O}$  contents are similar to that in the average I-type but lower than in the average A-type and higher than in the average S-type (Fig. 6f), whereas MgO and CaO contents are most similar to the average A-type (Fig. 6d, e) and  $\text{P}_2\text{O}_5$  content to the average S-type (Fig. 6h).

Trace elements show more diagnostic features (Fig. 7). Both Ba and Sr show negative correlation with  $\text{SiO}_2$ , and concentrations below those typical of average felsic I- and S-type granite and most similar to average A-type (Figs. 7a, b). On the other hand, Rb values show no correlation with  $\text{SiO}_2$  and are elevated compared to all three granite types (Fig. 7c). This feature is also shown on the Ba-Rb-Sr ternary diagram (Fig. 8a), in which the samples plot in the area of enriched granite according to El Bouseily and El Sokkary (1975).

The trace elements Y, Nb, and Ga show scatter and no consistent correlation with  $\text{SiO}_2$  (Figs. 7d, e, f), whereas Zr shows a weak negative correlation (Fig. 7g). The abundances of all of these elements are below those of the average A-type granite, although they tend to be higher than those in the average felsic I- and S-type granites. V show strong negative correlation with  $\text{SiO}_2$ , and higher values than I-, S-, and especially A-type granites (Fig. 7h). Values in the Pe-Piper and Jansa (1999) samples are uniformly lower than those obtained during the present study, most likely due to a systematic analytical problem in one of the data sets. Both Pb and Zn show negative correlation with  $\text{SiO}_2$  (Fig. 7i, j). Pb tends to be higher in samples that contain garnet, and Zn values are low compared to the average A-type granite. Concentrations of Ni, Cu, and Cr are low and commonly below the detection limit of the analytical method (Table 2), and hence are not displayed graphically.

Th and U values are scattered, but overall higher than those in the average felsic I-, S-, or A-type granites (Fig. 9a, b). A plot of Th against U shows a positive correlation (Fig. 9c), and two trends are suggested that correspond to the "unaltered" (lower U) and "altered" (higher U) sample trends identified by Chatterjee *et al.* (1985). The majority of samples analyzed during the present study, as well as those of Pe-Piper and Jansa (1999), follow the "unaltered" trend.

The Wedgeport pluton is not easily assigned to I-, S-, or A-type on the basis of major or trace element compositions

Table 2. Chemical data for samples from the Wedgeport pluton

Map #	Sample	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> <sup>†</sup>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	LOI	Total	Ba	Rb	Sr	Y	Zr	Nb	Th	Pb	Ga	Zn	Cu	Ni	V	Cr	Co	U	
Biotite monzogranite																														
1	P13-W02-023	72.81	0.30	13.45	2.34	0.03	0.29	0.70	3.80	4.43	0.08	0.74	98.97	302	220	71	37	196	16	32	19	19	29	29	<4	6	36	<4	71	7
2	09-W01-222	73.22	0.33	13.99	2.52	0.05	0.51	0.74	3.34	5.38	0.14	0.70	100.92	314	342	73	46	203	28	20	29	20	40	4	12	42	14	61	7	
3	016-W02-003(g)	73.26	0.29	13.25	2.52	0.05	0.36	0.85	3.52	4.72	0.09	0.64	99.55	269	348	54	56	186	25	41	18	20	32	<4	5	37	<4	85	8	
4	09-W01-223(g)	74.45	0.26	13.50	2.34	0.06	0.40	0.87	3.63	4.77	0.09	0.60	100.97	277	292	61	40	176	20	34	33	19	45	<4	5	34	7	71	7	
5	09-W02-019	74.56	0.35	13.74	2.77	0.04	0.50	0.48	3.70	4.05	0.11	1.12	101.42	167	208	87	67	228	25	46	13	21	38	<4	9	42	6	73	8	
6	09-W02-017	74.57	0.23	13.31	2.03	0.04	0.31	0.92	3.74	4.47	0.08	0.51	100.21	389	261	64	41	150	20	23	22	19	27	<4	4	29	5	72	7	
7	09-W02-010B(g)	74.58	0.17	12.62	1.71	0.04	0.22	0.45	3.30	4.96	0.06	0.61	98.72	261	343	30	48	121	25	30	45	18	28	14	5	23	<4	82	8	
8	09-W02-033A(g)	74.76	0.13	12.47	1.55	0.03	0.16	0.48	3.64	4.94	0.05	0.50	98.71	141	335	27	46	107	23	39	24	16	22	<4	6	18	<4	73	8	
9	09-W02-009(g)	75.10	0.18	12.39	1.65	0.03	0.22	0.51	3.24	4.79	0.06	0.88	99.05	152	315	29	53	130	25	38	22	18	23	5	5	24	<4	73	10	
10	09-W02-014(g)	75.79	0.15	12.77	1.55	0.04	0.17	0.46	3.51	4.72	0.05	0.69	99.89	75	343	25	48	120	25	31	45	20	21	13	5	21	<4	83	8	
11	09-W01-221C	75.98	0.18	13.41	1.51	0.02	0.25	0.68	3.47	5.25	0.06	0.41	101.23	174	352	35	49	137	23	37	17	21	16	<4	6	27	21	74	7	
12	09-W02-082	76.09	0.19	13.02	1.77	0.05	0.24	0.79	3.59	4.51	0.06	0.20	100.51	279	263	64	48	139	28	19	25	20	27	<4	6	26	<4	83	9	
13	016-W02-004a(g)	76.45	0.15	12.01	1.59	0.03	0.15	0.34	3.27	4.67	0.04	0.28	98.98	58	344	18	52	124	23	48	22	17	22	7	5	20	6	84	10	
14	09-W02-034A(p)	76.58	0.12	12.46	1.07	0.02	0.10	0.37	3.43	4.91	0.03	0.40	99.49	82	281	20	81	125	23	51	16	19	14	<4	7	16	11	89	15	
15	09-W02-010A(g)	77.28	0.17	12.79	1.88	0.04	0.20	0.44	3.44	4.16	0.06	0.39	100.85	109	348	17	72	131	24	32	51	17	32	4	5	23	6	69	13	
16	09-W02-015(g)	77.51	0.13	12.43	1.37	0.04	0.17	0.44	3.51	4.76	0.04	0.66	101.05	136	301	25	26	111	22	39	17	19	27	<4	6	19	<4	82	7	
Aplite dykes																														
17	016-W02-004b	75.55	0.10	12.56	1.18	0.02	0.09	0.42	3.82	4.23	0.03	0.61	98.61	29	320	20	63	110	20	52	20	21	13	6	12	17	0	81	12	
18	09-W02-033C	76.04	0.08	12.37	1.18	0.03	0.10	0.47	3.61	4.50	0.03	0.49	98.90	171	291	15	32	96	22	37	21	21	15	<4	6	13	<4	82	12	

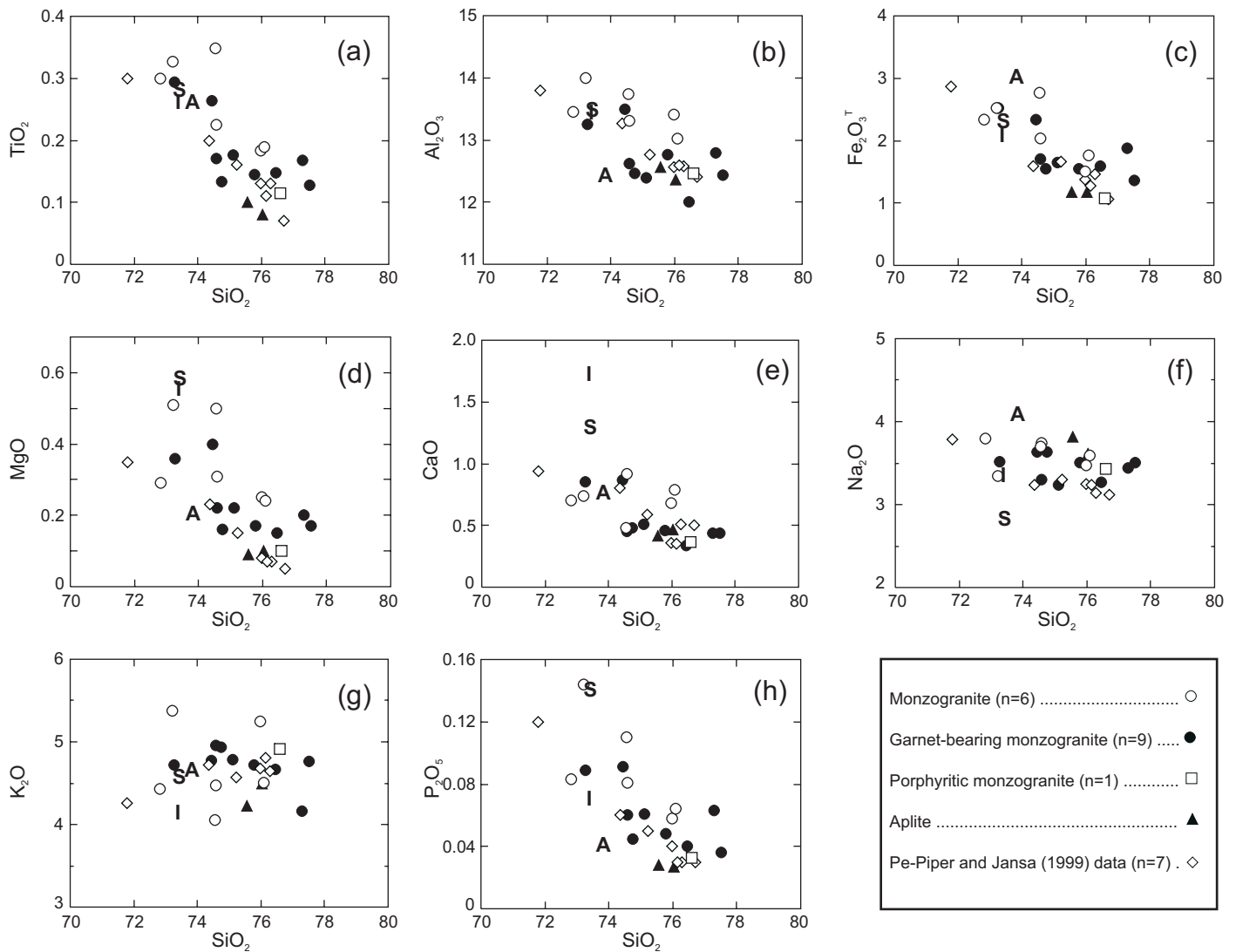
Notes: (g) = has garnet; (p) = porphyritic. Analyses were done by X-ray Fluorescence at the Regional Geochemical Centre, Saint Mary's University, Halifax, Nova Scotia. Major elements and some trace elements were determined on fused glass disks and other trace elements were measured in pressed powder pellets (see <http://www.stmarys.ca/academic/science/geology/rcg/home.htm> for description of the methodology, and accuracy/precision information). Analytical error is generally less than 5% for major elements and 2-10% for trace elements. Fe<sub>2</sub>O<sub>3</sub><sup>†</sup> is total Fe as Fe<sub>2</sub>O<sub>3</sub>. LOI is loss on ignition at 1000 °C.

Table 3. Rare-earth element, Hf, and Ta data\* for samples from the Wedgeport pluton

Map #	Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta
3	016-W02-003	33.85	65.86	7.42	26.81	5.92	0.47	6.06	1.05	6.63	1.30	3.98	0.65	4.40	0.65	6.04	5.00
4	009-W01-223	22.65	50.99	4.92	17.68	3.92	0.28	3.96	0.70	4.53	0.90	2.87	0.45	3.18	0.49	4.01	4.53
14	009-W02-033C	3.14	8.94	1.00	4.05	1.48	0.08	1.84	0.39	2.96	0.62	2.23	0.42	3.38	0.53	3.21	5.25
16	016-W02-004a	31.48	63.21	7.28	25.82	5.59	0.17	5.19	0.93	5.96	1.18	3.67	0.60	4.26	0.62	4.33	5.52
17	009-W02-034A	25.19	53.73	6.28	23.05	6.04	0.14	6.53	1.24	8.31	1.69	5.55	0.94	6.80	1.04	3.98	7.72

\*Analyses at Memorial University of Newfoundland and by ICP-MS, using the Na<sub>2</sub>O<sub>2</sub> sinter method (Longerich *et al.* 1990).



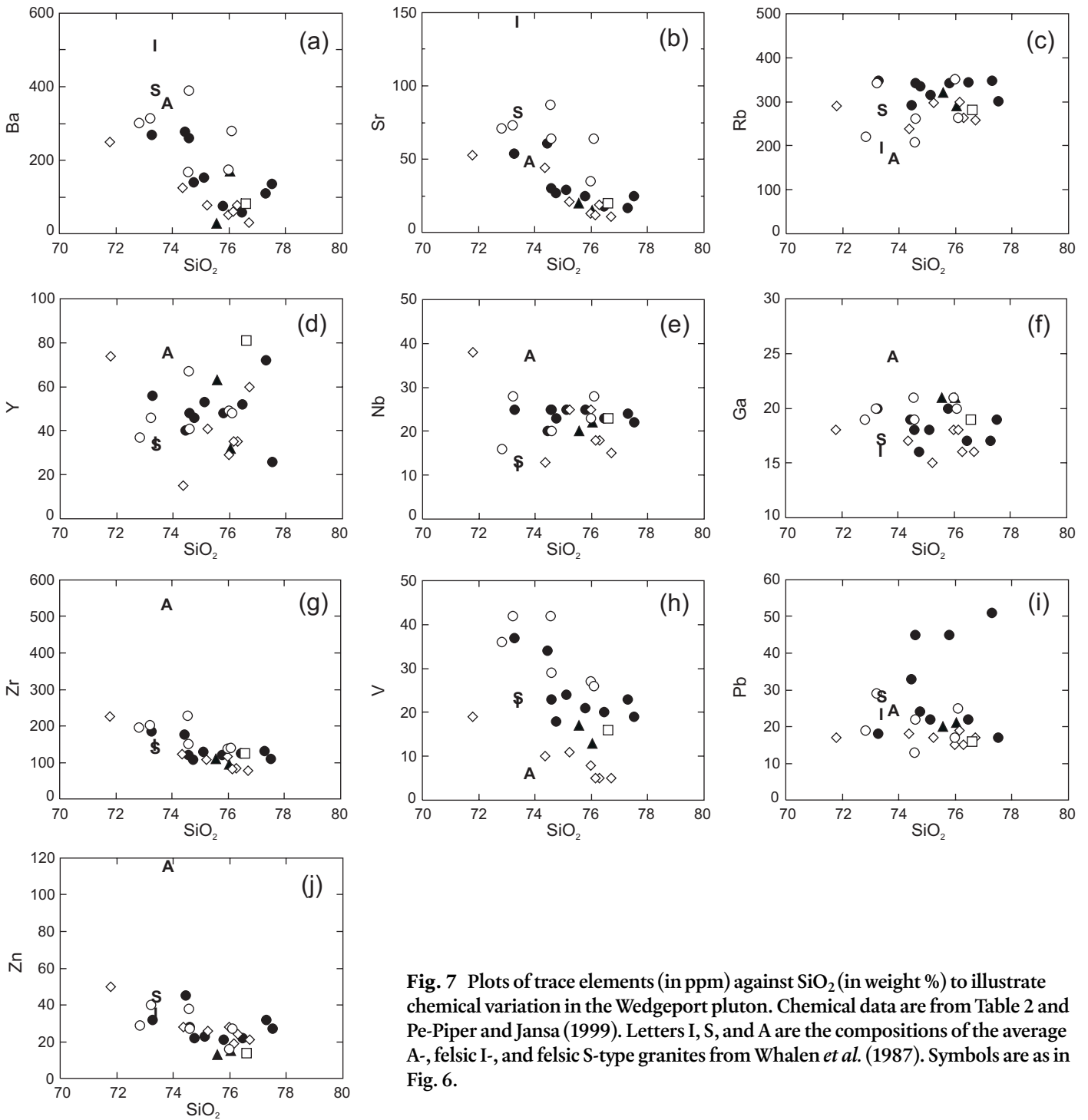


**Fig. 6** Plots of major element oxides against  $\text{SiO}_2$  (all in weight %) to illustrate chemical variation in the Wedgeport pluton. Chemical data are from Table 2 and Pe-Piper and Jansa (1999). Letters I, S, and A are the compositions of the average A-, felsic I-, and felsic S-type granites from Whalen *et al.* (1987).

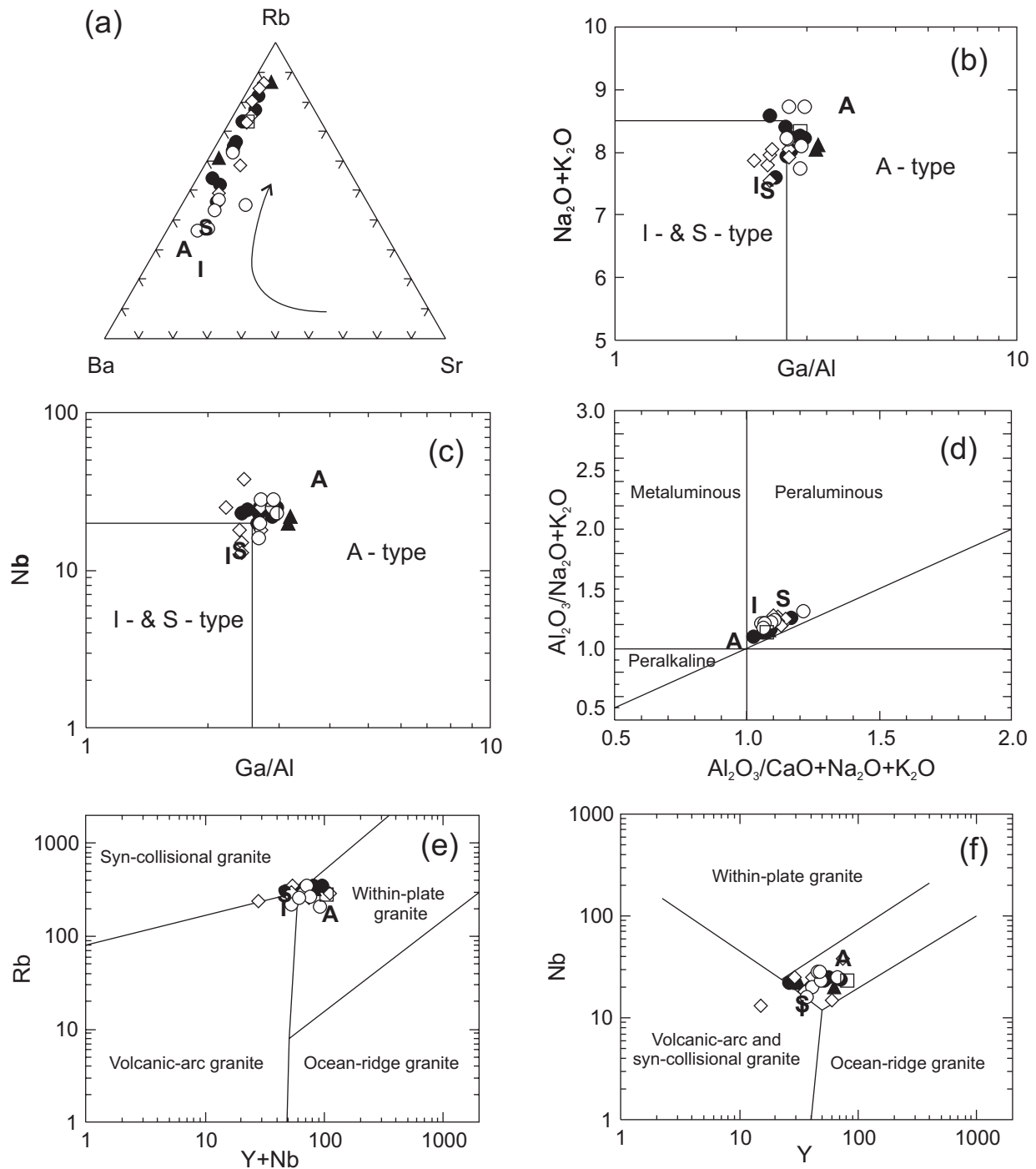
**Table 4.** New Sm-Nd isotopic data for sample 016-WO2-04A from the Wedgeport pluton

Nd (ppm)	Sm (ppm)	$\frac{^{147}\text{Sm}}{^{144}\text{Nd}}$	$\frac{^{143}\text{Nd}}{^{144}\text{Nd}}$	$2\sigma$	$\epsilon_{\text{Nd}(0)}$	$\epsilon_{\text{Nd}(t)}$	$T_{(\text{DM})}$
26.52	5.964	0.1360	0.512602	0.000030	-0.7	2.1	873 Ma

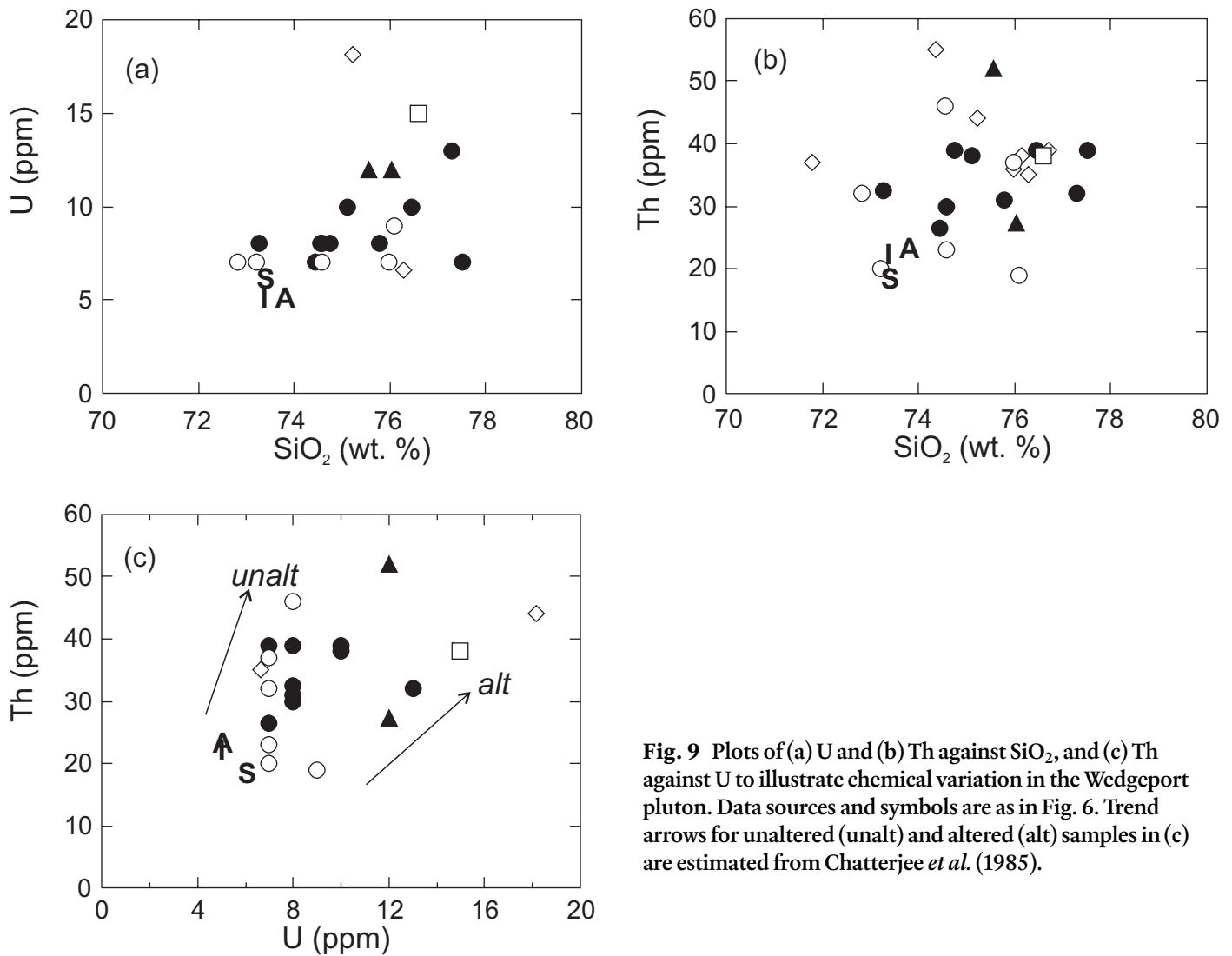
Notes: Analyses by Alain Potrel, Memorial University of Newfoundland. Sm and Nd contents and Nd isotopic composition were analyzed using a multicollector Finnigan Mat 262 mass spectrometer in static mode. Nd isotopic ratios are normalized to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ . The reported values were adjusted to La Jolla Nd standard ( $^{143}\text{Nd}/^{144}\text{Nd} = 0.511860$ ). During the course of data acquisition replicates of the standard gave a mean value of  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511886 \pm 26$  ( $2\sigma$ ,  $n=18$ ). The in-run precisions on Nd isotopic ratio are given at 95% confidence level. Error on Nd isotopic compositions are  $<0.002\%$  and errors on the  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio are estimated to be less than 0.1%. The  $\epsilon_{\text{Nd}}$  values are calculated using a  $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$  and  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$  values for the present day chondrite uniform reservoir (CHUR).  $^{147}\text{Sm}$  decay constant is  $6.54 \cdot 10^{-12} \text{ y}^{-1}$  (Steiger and Jäger 1977). The depleted mantle model age,  $T_{(\text{DM})}$ , was calculated both with respect to depleted mantle with  $\epsilon_{\text{Nd}(0)}$  value of +10 isolated from the CHUR since 4.55 Ga and following a linear evolution with respect to the De Paolo (1988) mantle model.



**Fig. 7** Plots of trace elements (in ppm) against  $\text{SiO}_2$  (in weight %) to illustrate chemical variation in the Wedgeport pluton. Chemical data are from Table 2 and Pe-Piper and Jansa (1999). Letters I, S, and A are the compositions of the average A-, felsic I-, and felsic S-type granites from Whalen *et al.* (1987). Symbols are as in Fig. 6.



**Fig. 8** Plots of (a) Ba-Rb-Sr, (b)  $\text{Na}_2\text{O}+\text{K}_2\text{O}$  against  $\text{Ga}/\text{Al}$ , (c) Nb against  $\text{Ga}/\text{Al}$ , (d)  $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})$  against  $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ , (e) Rb against  $\text{Y}+\text{Nb}$ , and (f) Nb against Y. Arrow in (a) shows trend toward enriched granite after El Bouseily and El Sokkary (1975). Fields in (b) are from Maniar and Piccoli (1989), in (c) and (d) from Whalen *et al.* (1987), and in (e) and (f) from Pearce *et al.* (1984). Data sources and symbols are as in Fig. 6.



**Fig. 9** Plots of (a) U and (b) Th against SiO<sub>2</sub>, and (c) Th against U to illustrate chemical variation in the Wedgeport pluton. Data sources and symbols are as in Fig. 6. Trend arrows for unaltered (unalt) and altered (alt) samples in (c) are estimated from Chatterjee *et al.* (1985).

compared to the averages from Whalen *et al.* (1987). Whalen *et al.* (1987) used the Ga/Al ratio as a distinguishing feature of these granite types, and plots of Na<sub>2</sub>O+K<sub>2</sub>O and Nb against Ga/Al suggest a composition intermediate between A-type and felsic I- and S-type granites (Fig. 8b, c). However, the presence of iron-rich biotite and abundant titanite and fluorite are more consistent with A-type character. A plot of Al<sub>2</sub>O<sub>3</sub> / Na<sub>2</sub>O + K<sub>2</sub>O against Al<sub>2</sub>O<sub>3</sub> / CaO + Na<sub>2</sub>O + K<sub>2</sub>O shows that the Wedgeport pluton is peraluminous (Fig. 8d). Other peraluminous characteristics of the Wedgeport pluton include the presence of garnet in many samples.

The samples plot at the junction of the within-plate, syn-collisional, and volcanic-arc granitoid fields on the Rb against Y+Nb discrimination diagram (Fig. 8e) but more definitively in the A-type field on the Nb-Y diagram (Fig. 8f).

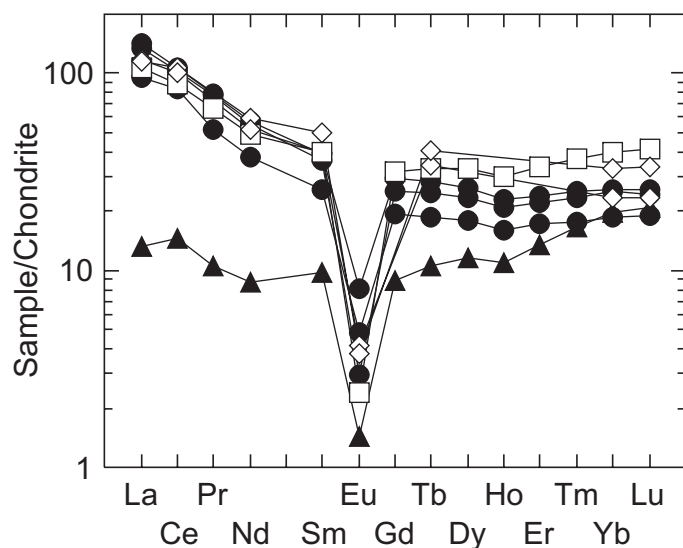
#### Rare-Earth Element Data

Rare-earth element (REE) data were obtained for 5 samples (four granite and one aplite) during the present study (Table

3), and an additional two samples are available from Pe-Piper and Jansa (1999). The patterns for all of the granite samples are similar, and show moderate enrichment in the light REE, a large negative Eu anomaly, and a flat heavy REE at 20 to 40 times chondritic values (Fig. 10). The aplite sample shows a strongly contrasting pattern, with no enrichment in the light REE and increasing enrichment in the heavy REE. No obvious mineralogical differences such as high garnet content are evident in the aplite to explain the REE pattern.

#### Isotopic Data

The Sm-Nd data for the dated sample 016-WO2-004A (Table 4) are similar to those reported for two samples by Pe-Piper and Jansa (1999). The  $\epsilon_{Nd}$  value at 357 Ma is 2.1, whereas the two samples from Pe-Piper and Jansa (1999) have values (at 357 Ma) of 2.1 and 3.1. These relatively high positive values contrast markedly with reported  $\epsilon_{Nd}$  values for other granitic plutons in the Meguma terrane, which have negative values ranging from -1.4 to -5.2 at 372 Ma (Clarke *et al.* 1988).



**Fig. 10** Chondrite-normalized REE plot, using data from Table 3 and Pe-Piper and Jansa (1999). Chondrite-normalizing values are from Sun and McDonough (1989). Symbols are as in Fig. 6.

The positive values in the Wedgeport pluton samples suggest a relatively primitive source and allow for little contamination from the metasedimentary host rocks of the Meguma Group, which have very negative  $\epsilon_{Nd}$  values of ca. -10 (Clarke *et al.* 1988). Instead, they are similar to values from minor mafic plutons of the Meguma terrane, for which mainly positive values have been reported (Tate and Clarke 1995). They are also similar to values reported by MacDonald *et al.* (2002) for ca. 440 Ma rhyolite in the White Rock Formation in the Yarmouth area ( $\epsilon_{Nd} = 1.37$ ), although the ca. 440 Ma Brenton pluton has a lower value ( $\epsilon_{Nd} = -0.42$ ).

## DISCUSSION AND CONCLUSIONS

The revised age reported here for the Wedgeport pluton shows that it is 40 million years older than previously assumed, that is earliest Carboniferous (Okulitch 2002) as opposed to late Carboniferous. Hence the pluton cannot be associated with the late thermal events at ca. 320–315 Ma in the Meguma terrane, nor with the shear zones of late Carboniferous age, as suggested by previous workers (Dallmeyer and Keppie 1987; Keppie and Dallmeyer 1995; Culshaw and Reynolds 1997; see compilation in White 2003).

The  $357 \pm 1$  Ma age is significantly younger than the ages from the South Mountain Batholith and its satellite plutons, Shelburne and Barrington Passage (Fig. 1), all of which have yielded ca. 372 Ma ages. It is also much younger than the nearby Brenton Pluton (Fig. 1), which is Silurian (MacDonald *et al.* 2002). No other igneous activity of ca. 357 Ma is known in the Meguma terrane, although abundant plutons of similar age occur north of the Cobequid - Chedabucto fault system in northern mainland Nova Scotia (Dunning *et al.* 2002).

However, the latter plutons differ from the Wedgeport pluton in that they are part of bimodal gabbro-granite suites with clear A-type features, and occur in association with voluminous bimodal volcanic rocks. Pe-Piper and Jansa (1999) compared offshore plutons with onshore plutons, including the Wedgeport pluton, and showed that none of the offshore plutons has petrochemical characteristics that match those of the Wedgeport pluton.

A possible link may exist between the Wedgeport pluton and mineralization in spodumene-bearing pegmatite bodies in the Brazil Lake area north of the Wedgeport pluton (Fig. 1). Pegmatite in this area occurs as elongate lenses in deformed metavolcanic and metasedimentary rocks of the Silurian White Rock Formation. Although U-Pb dating of tantalite indicated that the pegmatite crystallized at  $378 \pm 1$  Ma, molybdenite from an adjacent quartz vein yielded a Re/Os age of  $354 \pm 3$  Ma (Kontak *et al.* 2003). This result indicates that mineralization in the Brazil Lake area is of similar age to the crystallization age of the Wedgeport pluton. Although it does not prove a genetic link between the two areas, the similar ages, younger than ages of other plutons known in the Meguma terrane, may be significant.

In addition to its anomalous age, the Wedgeport pluton also has anomalous petrochemical characteristics. It cannot be classified as any of the commonly accepted granite end-members, and its tectonic setting is not evident from its petrochemical features using commonly applied discrimination diagrams. However, a within-plate tectonic setting is most likely, both from the petrochemical features and the inferred tectonic situation of the Meguma terrane in the earliest Carboniferous. At that time, the Meguma terrane was being uplifted and unroofed, and shedding sedimentary material into Carboniferous basins. The northwestern part of the South Mountain Batholith was exposed by 357 Ma when the Wedgeport pluton was being emplaced, as conglomerate in the overlying units contains debris derived from the batholith. However, it is clear that the area around the Wedgeport pluton was still buried. The depth of emplacement of the Wedgeport pluton was likely epizonal, based on the presence of a well-developed contact metamorphic aureole containing cordierite and andalusite, and localized development of porphyritic, granophyric, and inequigranular textures near the margins.

The Wedgeport pluton appears to be a unique intrusion in the Meguma terrane, both in terms of its age and its composition, and remains an enigma in terms of its origin.

## ACKNOWLEDGEMENTS

This project was funded mainly by the Nova Scotia Department of Natural Resources through the Southwest Nova Mapping Project. Barr's contributions were funded by a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada. We thank Georgia Pe-Piper for providing locations for samples reported by Pe-Piper and Jansa



(1999). Ken Currie and Linda Ham provided helpful reviews which improved the manuscript.

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