Geological Survey
of Canada

Current Research
2000-E12

Geochemistry and Nd isotopes of granitoid rocks in the Shikag–Garden lakes area, Ontario: recycled Mesoarchean crust in the central Wabigoon Subprovince

K.Y. Tomlinson and J.A. Percival

2000

Natural Resources Canada Ressources naturelles Canada

Canada

Catalogue No. M44-2000/E12E-IN
ISBN 0-660-18215-7

Authors' address

K.Y. Tomlinson *(ktomlins@nrcan.gc.ca)*
J.A. Percival *(joperciv@nrcan.gc.ca)*
Continental Geoscience Division
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

Geochemistry and Nd isotopes of granitoid rocks in the Shikag–Garden lakes area, Ontario: recycled Mesoarchean crust in the central Wabigoon Subprovince[1]

K.Y. Tomlinson and J.A. Percival

Continental Geoscience Division, Ottawa

Tomlinson, K.Y. and Percival, J.A. 2000: Geochemistry and Nd isotopes of granitoid rocks in the Shikag–Garden lakes area, Ontario: recycled Mesoarchean crust in the central Wabigoon Subprovince; Geological Survey of Canada, Current Research 2000-E12; 11 p. (online; http://www.nrcan.gc.ca/gsc/bookstore)

Abstract: Neoarchean granitoid rocks from the Shikag–Garden lakes area of the central Wabigoon Subprovince were analyzed to examine the role of recycling of older crust in their petrogenesis. The ε_{Nd} values calculated at 2.7 Ga range from +1.2 to –6.9 with Nd model ages ranging from 2.80–3.97 Ga. Isotopic modelling calculations suggest that most of the rocks have incorporated older material with a predominant ca. 3.4 Ga component. These data suggest similarities with the Winnipeg River Subprovince, remnants of which may extend in the subsurface across the northern part of the central Wabigoon Subprovince as far south as the Garden Lake greenstone belt. Neoarchean magmatism obliterated most direct evidence for the existence of the Paleoarchean and Mesoarchean terrane, but its antiquity is reflected in the Nd isotopes of the granitoid rocks.

Résumé : Des roches granitoïdes néoarchéennes de la région des lacs Shikag–Garden dans la Sous-province de Wabigoon centrale ont été analysées afin d'examiner le rôle du recyclage de croûte plus ancienne dans leur pétrogenèse. Les valeurs de ε_{Nd} calculées à 2,7 Ga varient de +1,2 à –6,9 pour des âges modèles Nd variant de 2,80 à 3,97 Ga. Les calculs d'après les modèles isotopiques font penser que la plupart des roches ont incorporé un matériau plus ancien à composante prédominante datant d'environ 3,4 Ga. Ces données suggèrent des similitudes avec la Sous-province de Winnipeg River dont des vestiges pourraient s'avancer dans la subsurface dans la partie septentrionale de la Sous-province de Wabigoon centrale vers le sud jusqu'à la ceinture de roches vertes de Garden Lake. Le magmatisme néoarchéen a oblitéré la plupart des indications directes de l'existence du terrane paléoarchéen et mésoarchéen, mais son caractère ancien se reflète dans les isotopes du Nd des roches granitoïdes.

---

[1] Contribution to Western Superior NATMAP Project

INTRODUCTION

One of the principle objectives of Western Superior NATMAP is to examine the relationship between Neoarchean and Mesoarchean rock packages. The central Wabigoon Subprovince is a key area for studying such relationships (Fig. 1a). In the northern part of the central Wabigoon, 3075 Ma tonalite intrudes the Caribou Lake greenstone belt (Davis et al., 1988). These rocks occur along strike from even older gneiss bodies in the Winnipeg River Subprovince (up to 3225 Ma tonalite gneiss, Davis et al., 2000; Corfu, 1988). Similarly, sedimentary units within the

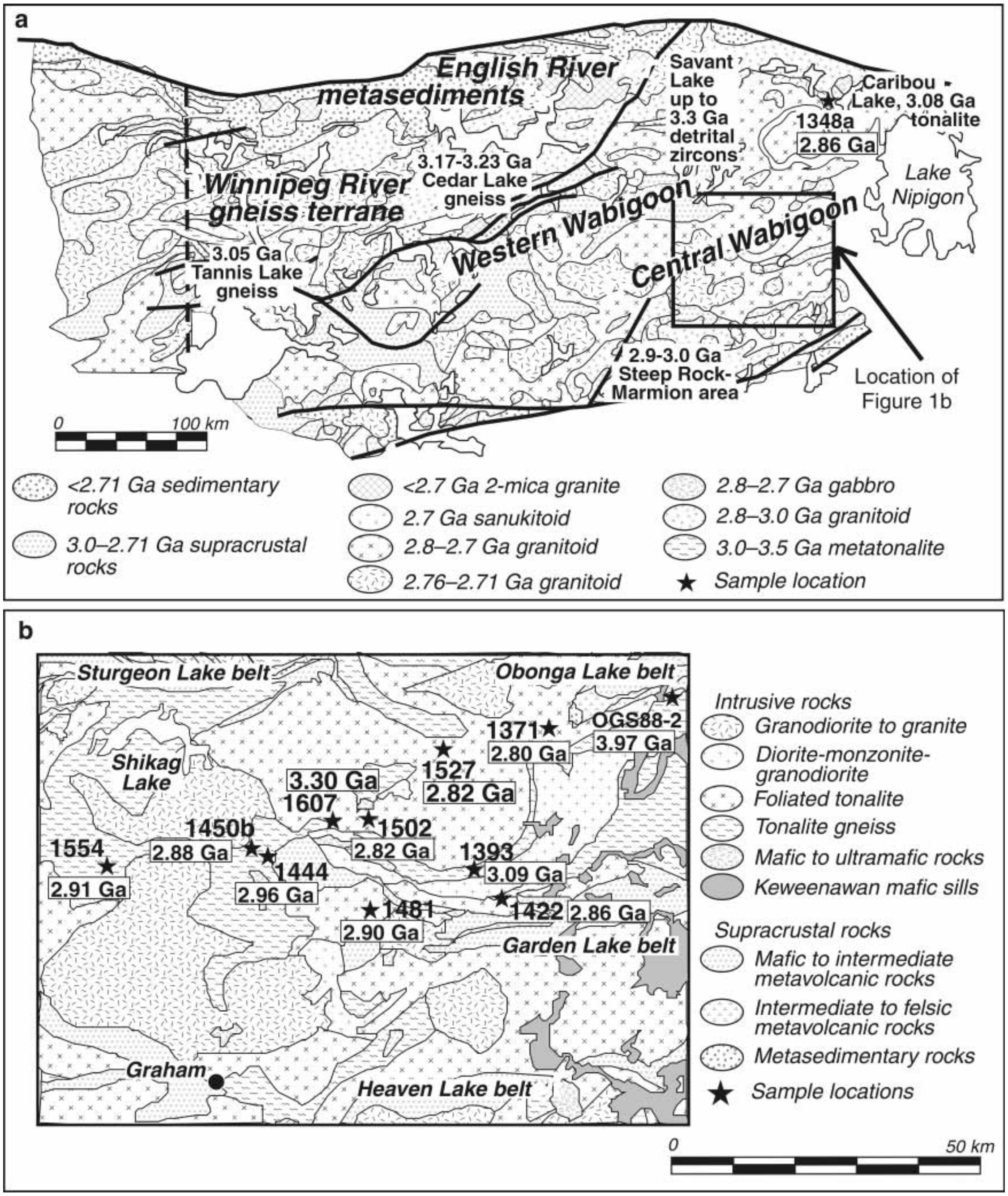

Figure 1. a**) General geology of the Wabigoon, Winnipeg River, and English River subprovinces with selected U-Pb geochronology highlighting Mesoarchean ages (*see *text for references). One sample located outside the Shikag–Garden lakes area is also shown with its Nd model age.* ***b) *Geology of the Shikag–Garden lakes area showing location of samples analyzed (base map* after *Ontario Geological Survey (1991)). Neodymium model ages are shown in boxes for each sample (*see *text for discussion).*

north-central Wabigoon show evidence for old detrital sources, including 3297 Ma zircons in Jutten sedimentary rocks of the Savant Lake belt (D.W. Davis and M. Moore, unpub. report, 1991) and 3210 Ma zircons in sedimentary rocks of the Obonga Lake belt (V. McNicoll and J. Percival, unpub. data, 2000). In contrast, the south-central Wabigoon Subprovince has Mesoarchean ancestry dating from ca. 3.0 Ga. This includes supracrustal rocks of the Lumby Lake, Finlayson Lake, Steep Rock Lake, and Heaven Lake belts, dated at 2999–2898 Ma, which overlie (in part unconformably), the 3003 Ma Marmion tonalite batholith (Davis and Jackson, 1988; Wilks and Nisbet, 1988; D.W. Davis, unpub. report, 1993; Tomlinson et al., 1998, 1999; Tomlinson, in press).

The old crust of the central Wabigoon Subprovince has been invaded by younger volcanic and plutonic rocks, to the extent that original relationships have been modified or obscured. The Obonga Lake, Garden Lake and Heaven Lake greenstone belts (Fig. 1b) contain volcanic rocks in the range 2.73–2.70 Ga (Tomlinson et al., 1998, 1999). Granitoid rocks of 2.77–2.69 Ga are also widespread throughout the central Wabigoon Subprovince (Percival et al., 1999b). The young granitoid plutons can be used as crustal probes to explore possible interaction with older basement rocks such as those described above. The interaction with old crust should be reflected in the Nd isotope characteristics of the Neoarchean granitoid rocks and hence the technique can be used to map the extent of old crust within the central Wabigoon Subprovince. The Shikag–Garden lakes area (Fig. 1b) is of particular interest because it may straddle the juncture of three distinct terranes: 1) to the north, ca. 3.2–3.07 Ga rocks continuous with the Winnipeg River Subprovince; 2) to the south, the ca. 3.0–2.9 Ga rocks of the Marmion batholith and associated supracrustal rocks (Fig. 1a); and 3) to the west, juvenile 2.78–2.70 Ga oceanic rocks (Sanborn-Barrie and Skulski, 1999) of the western Wabigoon Subprovince.

In this study, we used major and trace-element geochemistry to characterize the granitoid rocks of the Shikag–Garden lakes area and to examine their petrogenesis and tectonic setting. We measured Nd isotopes to examine crustal recycling and to estimate the age of crustal sources contributing to the granitoid rocks. The data were subsequently interpreted to shed light on the distribution of basement terranes in the central Wabigoon Subprovince.

GEOLOGY OF THE SHIKAG–GARDEN LAKES AREA

The Shikag–Garden lakes area (Fig 1b; south of the Sturgeon Lake and Obonga Lake corridor (Percival et al., 1999b, c)), is dominated by large bodies of homogeneous plutonic rock (Sage et al., 1973). Road-based reconnaissance (Percival et al., 1999a) revealed mainly foliated tonalite and granodiorite, generally characterized by a single penetrative east-trending foliation, and local units with older, north-trending structures crenulated by east-plunging folds. Several mafic plutons (Sage et al., 1973) have similar structural character. A newly mapped approximately10 km wide anorthositic body (Percival et al., 1999a) consists mainly of foliated gabbroic anorthosite and minor gabbro. Tonalitic gneiss carrying an early layering in addition to one or two sets of folds, occurs sporadically as enclaves in tonalite-granodiorite through the northern part of the area. Although pegmatite dykes and small bodies of leucogranite are ubiquitous, larger bodies of granite are present in the south. They are generally massive and inferred to postdate penetrative regional deformation; however, east- and southeast-striking, ductile shear zones with dextral shear sense were observed in a few locations.

The western limit of the central Wabigoon region, with its characteristic lithological heterogeneity, including tonalitic gneiss bodies, may be located south of Shikag Lake, defined by a prominent zone of north-striking, gently east-dipping foliation (Rogers, 1964). North-striking foliation and gneissosity in this approximately 5 km wide zone is crenulated by east-trending fold hinges. To the west, plutonic rocks take the form of large bodies of homogeneous tonalite and trondhjemite (Sage et al., 1973) characteristic of the western Wabigoon Subprovince.

METHODOLOGY AND SAMPLE SELECTION

Eleven samples have been analyzed from the Shikag–Garden lakes area (Fig. 1b). Based on field identification these include: one tonalite gneiss, two tonalite samples, two gabbro-anorthosite samples, four granodiorite samples, one quartz diorite, and one granite. In addition, one sample of tonalite gneiss has been analyzed from southwest of the Caribou Lake greenstone belt (Fig. 1a). Sample descriptions are given in Appendix 1. The age of the units is unknown with the exception of sample OGS88-2 from south of the Obonga Lake greenstone belt which contains zircons that have been dated at 2930 ± 3 Ma (D.W. Davis and M. Moore, unpub. report, 1991). It is possible that this represents an inherited age as field relationships indicate that this is a late intrusion (*see* Appendix 1) (Percival and Stott, 2000).

Although U-Pb age constraints are not available for most units, they can be ordered in terms of relative age. The structurally oldest unit is tonalite gneiss enclaves (samples PBA99-1348a, PBA99-1410b), the gneissic fabric of which suggests an early deformation event prior to incorporation in younger plutonic rocks. Whereas anorthositic rocks (samples PBA99-1444, PBA99-1502) also occur as enclaves, they generally carry only a single foliation and are therefore probably younger than the tonalitic gneiss. The main plutonic phases, tonalite and granodiorite (samples PBA99-1371, PBA99-1393, PBA99-1422, PBA99-1481, PBA99-1527, PBA99-1554), are both medium to coarse grained and weakly to moderately foliated. Crosscutting relationships were not observed between tonalite and granodiorite and the two units may be compositionally gradational. Regional deformation is inferred to be coeval with that to the north, at ca. 2.70 Ga (Percival et al., 1999c). A suite of late, generally massive granite bodies (samples PBA99-1607, OGS88-2) cut all of the previously mentioned units and structures.

Major and trace elements were analyzed by ICP-MS at the Geoscience Laboratories of the Ministry of Northern Development and Mines, Sudbury. Major and trace element data are reported in Table 1 (*see* below). Neodymium isotopes were measured at the Geological Survey of Canada, Ottawa (methodology reported in Tomlinson (in press)) and the data are presented below (*see* Table 2).

GEOCHEMICAL RESULTS

Major elements

The granitoid rocks are classified on a CIPW normative albite-anorthite-orthoclase diagram in Figure 2a. Most of the samples are tonalitic to granodioritic but two samples are true granites. One of these granite samples is OGS88-2, described as aplitic granodiorite in the field (*see* Appendix 1). For ease of discussion, this obviously chemically evolved sample will be referred to as a granite for the rest of this manuscript and in the figures and tables. On an AFM diagram (Fig. 2b) all samples are calc-alkaline.

Harker variation diagrams are shown in Figure 3 for selected major elements. The gabbro-anorthosite samples have 51.3 and 61.4 weight per cent SiO_2, granodiorite sample PBA99-1554 has 66.5 weight per cent SiO_2, the granite samples have 75.4 and 77.5 weight per cent SiO_2, and the other samples have silica values that cluster within the narrow range 68.5–71.3. Several samples have high alumina contents (i.e. >15 weight per cent Al_2O_3 at 70 weight per cent SiO_2), including the gabbro-anorthosite samples (20–22 weight per cent Al_2O_3). In terms of K_2O (classification of Le Maitre (1989)), the samples span all the fields, with the gabbro-anorthosite samples, the quartz diorite, and a tonalite in the low-K field; the granite samples and one granodiorite in the high-K field; and the remainder in the medium-K field (Fig. 3).

Multi-element diagrams

Primitive mantle normalized multi-element diagrams (normalizing values of Sun and McDonough (1989)) are shown in Figure 4, with the samples grouped according to lithology. The granite samples have the lowest $(La/Yb)_N$ at less than 8, the gabbro-anorthosite samples and the quartz diorite have higher $(La/Yb)_N$ of 9.4–19.6 and the tonalite, tonalite gneiss, and granodiorite samples all have $(La/Yb)_N$ of more than 20 (Table 1). General features of the multi-element profiles for all samples are high abundances of the large-ion lithophile elements (LILE) Cs, Rb, Ba, and K, and generally high Th and U. Most samples display negative Nb and Ti anomalies indicating Ti-magnetite fractionation. In addition, the anorthosite samples show positive Sr anomalies (consistent with Ca-plagioclase accumulation); the granite samples show negative Ba, Sr, and Eu anomalies (consistent with removal of K-feldspar); the tonalite, tonalite gneiss, and granodiorite samples show depletion in the heavy REEs (consistent with partial melting in the presence of garnet); and the Obonga Lake granite shows an increase from the middle to the heavy REEs, suggesting fractionation of hornblende.

Neodymium isotopes

Epsilon Nd values have been calculated for the samples at 2.70 Ga as their age is unknown (Table 2). The exception is sample OGS88-2 (Obonga Lake granite); the ε_{Nd} value was calculated at 2.93 Ga. Depleted mantle model ages (T_{DM}; DePaolo, 1981) are also presented in Table 2 and shown on Figure 1b. Epsilon Nd values are plotted against time in Figure 5, along with comparative data from the 3.0 Ga Marmion batholith (Henry et al., 1998), 3.05 Ga Tannis Lake gneiss, and 3.17 Ga Cedar Lake gneiss in the Winnipeg River Subprovince (Corfu, 1988; Henry et al., 1997), 3.075 Ga Caribou Lake tonalite, and 2.95 Ga felsic volcanic rocks of the Heaven Lake belt (Tomlinson, in press). A Sm^{147}/Nd^{144} ratio of 0.11 was used to project crustal evolution lines for felsic crust of 3.0 Ga, 3.075 Ga, and 3.4 Ga.

The ε_{Nd} values of the samples analyzed are generally low. Three samples have positive ε_{Nd} values, including tonalite 1371 (ε_{Nd}=+1.2, T_{DM}=2.80 Ga), gabbro-anorthosite 1444 (ε_{Nd}=+1.1, T_{DM}=2.82 Ga), and quartz diorite 1527 (ε_{Nd}=+0.8, T_{DM}=2.82 Ga). These rocks extend southwest from the western end of the Obonga Lake belt (Fig. 1b). Of the remaining samples, six have ε_{Nd} values between 0.0 and –1.1 with T_{DM} ages of 2.86–2.96 Ga. The other three samples have even lower εNd values at –2.7 for granite 1607 (T_{DM}=3.30 Ga), –3.0 for tonalite 1393 (T_{DM}=3.09 Ga), and –6.9 (at 2.93 Ga) for granite OGS88-2 (T_{DM}=3.97 Ga). In comparison, Figure 5 shows that at 2.7 Ga, tonalitic crust of the Marmion batholith would have an ε_{Nd} value of around –1, tonalitic crust at Caribou Lake would have an ε_{Nd} value of around –3, and tonalitic gneiss units of the Winnipeg River Subprovince (which have been shown by Henry et al. (1997) to have a depleted mantle model age of 3.4 Ga) would have an ε_{Nd} value of around –7. An even older crustal component has been recognized in the Winnipeg River Subprovince by Davis et al. (2000) using Hf isotopes on a single zircon dated at 3.225 Ga from the Cedar Lake gneiss. Its ε_{Hf} value of –2 suggests a 3.5 Ga crustal protolith.

Low ε_{Nd} values in the samples analyzed and corresponding old Nd model ages may be explained in several different ways. 1) The rocks may be older than 2.7 Ga (the arbitrary age for which the ε_{Nd} values were calculated). If the rocks are actually 3.0–2.8 Ga, then they could have formed through melting of juvenile mafic to felsic crust. This interpretation is unlikely based on the lack of zircon ages in this range (Percival et al., 1999b). 2) The rocks may be ca. 2.7 Ga and represent melts of old (3.3–2.8 Ga) felsic crust (with the exception of sample OGS88-2, which requires a much older protolith). 3) The rocks may be ca. 2.7 Ga and could have formed by melting of mafic crust and assimilation of much older felsic crust. In this scenario, the Nd model ages would represent mixtures of a ca. 2.7 Ga mafic derived (i.e. tonalitic) component with a relatively high (likely positive) ε_{Nd} value, and a much older felsic contaminant with low ε_{Nd}.

Table 1. Major and trace element data for samples from the Shikag–Garden lakes area.

Sample	PBA99-1348a	PBA99-1371	PBA99-1393	PBA99-1422	PBA99-1444	PBA99-1450b	PBA99-1481	PBA99-1502b	PBA99-1527	PBA99-1554	PBA99-1607	OGS88-2
Lithology	**Tonalite gneiss**	**Tonalite**	**Tonalite**	**Granodior.**	**Gabbro-anorth.**	**Tonalite gneiss**	**Granodior.**	**Gabbro-anorth.**	**Quartz diorite**	**Granodior.**	**Granite**	**Granite**
(wt.%)												
SiO_2	69.44	68.85	68.80	68.47	61.42	71.25	68.62	51.29	68.47	66.46	75.39	77.49
Al_2O_3	15.56	15.42	15.64	15.31	20.70	14.69	14.82	21.95	15.92	15.05	13.51	12.84
MnO	0.03	0.05	0.03	0.06	0.06	0.03	0.05	0.07	0.06	0.07	0.01	0.01
MgO	0.61	0.89	1.00	1.25	1.65	0.75	0.99	3.47	1.27	1.75	0.15	0.23
CaO	2.89	3.32	3.80	3.35	6.36	2.76	2.88	10.94	4.50	4.30	0.69	0.30
Na_2O	4.46	4.51	4.81	4.17	5.40	3.89	4.00	3.58	4.27	3.96	3.58	3.36
K_2O	2.48	1.69	1.17	2.38	0.59	2.71	3.36	0.34	0.88	1.65	5.34	4.77
P_2O_5	0.07	0.07	0.09	0.14	0.20	0.10	0.12	0.02	0.08	0.19	0.01	0.02
TiO_2	0.22	0.30	0.33	0.40	0.17	0.34	0.32	0.23	0.40	0.51	0.05	0.10
Fe_2O_3	2.04	2.81	2.84	3.54	3.40	2.82	2.76	6.58	4.18	5.28	0.58	1.20
LOI	0.69	0.56	0.74	0.95	0.86	0.76	0.53	0.31	0.50	0.90	0.54	0.75
TOTAL	98.49	98.47	99.25	100.02	100.81	100.10	98.45	98.78	100.53	100.12	99.85	101.07
(ppm)												
Ba	1242	566	225	906	294	816	817	155	266	477	332	691
Co	3.74	6.53	7.14	8.10	10.64	5.70	6.01	53.68	8.97	10.82	N.D.	N.D.
Cr	26	21	57	42	60	36	31	92	19	44	12	17
Cu	11.6	14.6	45.9	50.3	35.7	26.7	21.1	954.6	14.1	33.5	9.2	5.1
Ga	15.75	18.24	17.56	16.41	20.55	15.72	15.55	17.26	16.64	18.82	17.35	14.75
Li	15.5	30.2	19.0	19.2	8.7	13.7	39.2	21.6	14.8	28.1	13.5	6.3
Ni	6.9	30.1	20.7	16.6	34.4	47.4	10.2	474.7	30.2	18.4	N.D.	4.12
Sc	1.5	3.3	4.0	6.3	3.8	2.1	4.5	14.7	5.7	12.3	1.8	3.8
V	44	53	60	76	46	53	65	134	73	93	15	21
W	0.41	0.56	1.44	0.91	0.46	1.04	0.67	0.50	0.42	1.60	0.43	0.71
Zn	27	38	37	39	32	31	32	25	36	51	13	10
La	20.85	14.52	13.77	48.76	12.82	47.57	27.83	4.33	18.68	51.17	10.88	20.38
Ce	33.55	26.94	24.71	80.80	24.42	75.10	51.84	9.03	32.11	82.99	22.11	56.17
Pr	3.59	3.31	2.87	11.61	3.02	8.79	6.57	1.13	3.89	10.94	2.43	5.13
Nd	11.06	11.51	9.48	39.98	11.04	25.85	21.70	4.31	13.02	36.70	7.45	16.90
Sm	1.19	2.09	1.62	5.84	1.88	2.90	3.16	0.86	2.19	5.74	1.69	3.83
Eu	0.81	0.65	0.50	1.24	0.76	0.82	0.82	0.47	0.73	1.53	0.24	0.30
Gd	0.62	1.39	1.11	3.71	1.37	1.53	2.02	0.65	1.87	4.34	1.48	3.64
Tb	0.06	0.16	0.14	0.49	0.17	0.17	0.26	0.10	0.29	0.60	0.26	0.77
Dy	0.40	0.94	0.84	2.97	1.09	1.13	1.70	0.60	1.80	3.61	1.66	5.31
Ho	0.05	0.17	0.13	0.53	0.20	0.16	0.31	0.11	0.38	0.66	0.37	1.31
Er	0.23	0.48	0.41	1.56	0.60	0.58	0.91	0.36	1.06	1.84	1.11	3.94
Tm	0.01	0.05	0.04	0.20	0.07	0.06	0.12	0.04	0.15	0.22	0.16	0.66
Yb	0.22	0.46	0.37	1.30	0.47	0.45	0.81	0.33	1.02	1.27	0.98	4.34
Lu	0.03	0.07	0.06	0.20	0.08	0.08	0.14	0.06	0.18	0.21	0.16	0.73
Rb	65.84	50.26	40.17	64.32	21.32	76.46	90.42	15.99	22.92	57.77	240.11	168.90
Sr	531.7	293.7	437.4	616.6	823.8	438.2	457.5	723.0	268.5	413.9	70.0	31.1
Nb	2.41	8.82	2.05	7.56	1.57	4.71	5.43	0.84	5.09	7.30	13.59	17.02
Cs	0.65	1.90	1.58	1.41	0.89	1.01	2.66	1.61	0.30	1.52	2.39	0.66
Hf	3.86	3.95	3.16	3.71	0.96	6.13	3.58	0.28	3.87	3.94	2.52	5.93
Ta	0.15	0.96	0.24	0.84	0.22	0.33	0.55	0.15	0.38	0.36	1.54	2.37
Th	2.66	3.63	2.28	8.32	1.52	8.88	8.28	0.76	2.37	5.69	22.20	23.32
U	0.37	1.11	0.77	1.87	0.73	0.61	0.88	0.25	0.39	1.48	4.33	3.79
Y	2.00	5.70	4.47	16.15	6.21	5.11	9.26	3.01	11.03	18.56	11.57	37.26
Zr	137.44	130.26	117.86	125.97	30.27	217.29	120.54	8.50	133.67	137.89	49.85	145.80
Sr/Y	265.85	51.53	97.85	38.18	132.66	85.75	49.41	240.20	24.34	22.30	6.05	0.83
Rb/Sr	0.124	0.171	0.092	0.104	0.026	0.174	0.198	0.022	0.085	0.140	3.430	5.431
K/Rb	313	279	242	307	230	294	308	176	319	237	185	234
$(La/Yb)_N$	68.01	22.65	26.71	26.92	19.57	75.86	24.66	9.42	13.14	28.91	7.97	3.37

Notes: Gabbro-anorth. = gabbro-anorthosite; Granodior. = granodiorite; N.D. = not detected

Table 2. Neodymium isotope data for granitoid rocks of the Shikag–Garden lakes area.

Sample	Measured $^{143}Nd/^{144}Nd$	2 sigma error	Measured $^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (T)	Age (Ga)	Epsilon Nd (T)	Sm (ppm)	Nd (ppm)	DePaolo T_{DM} (Ga)
PBA99-1348A Tonalite gneiss	0.510309	7	0.0669	0.509116	2.7	**-0.34**	1.44	12.96	**2.86**
PBA99-1371 Tonalite	0.511150	9	0.1099	0.509193	2.7	**1.16**	1.94	10.69	**2.80**
PBA99-1393 Tonalite	0.510731	9	0.0982	0.508981	2.7	**-3.00**	1.65	10.15	**3.09**
PBA99-1422 Granodiorite	0.510731	6	0.0896	0.509134	2.7	**0.00**	6.06	40.88	**2.86**
PBA99-1444 Gabbro-anorthosite	0.510913	7	0.1030	0.509077	2.7	**-1.11**	2.94	17.26	**2.96**
PBA99-1450B Tonalite gneiss	0.510316	10	0.0683	0.509099	2.7	**-0.69**	3.32	29.39	**2.88**
PBA99-1481 Granodiorite	0.510710	6	0.0900	0.509107	2.7	**-0.52**	3.59	24.11	**2.90**
PBA99-1502B Gabbro-anorthosite	0.511280	12	0.1174	0.509188	2.7	**1.06**	1.04	5.33	**2.82**
PBA99-1527 Quartz diorite	0.511060	10	0.1058	0.509176	2.7	**0.83**	2.48	14.18	**2.82**
PBA99-1554 Granodiorite	0.510836	9	0.0970	0.509109	2.7	**-0.50**	5.72	35.62	**2.91**
PBA99-1607 Granite	0.511534	9	0.1425	0.508996	2.7	**-2.72**	1.86	7.88	**3.30**
OGS88-2 Granite	0.511199	13	0.1404	0.508484	2.93	**-6.86**	3.79	16.32	**3.97**
Additional modelling parameters:									
3.4 Ga tonalite			0.1100	0.508777	2.7	-7.00		13	

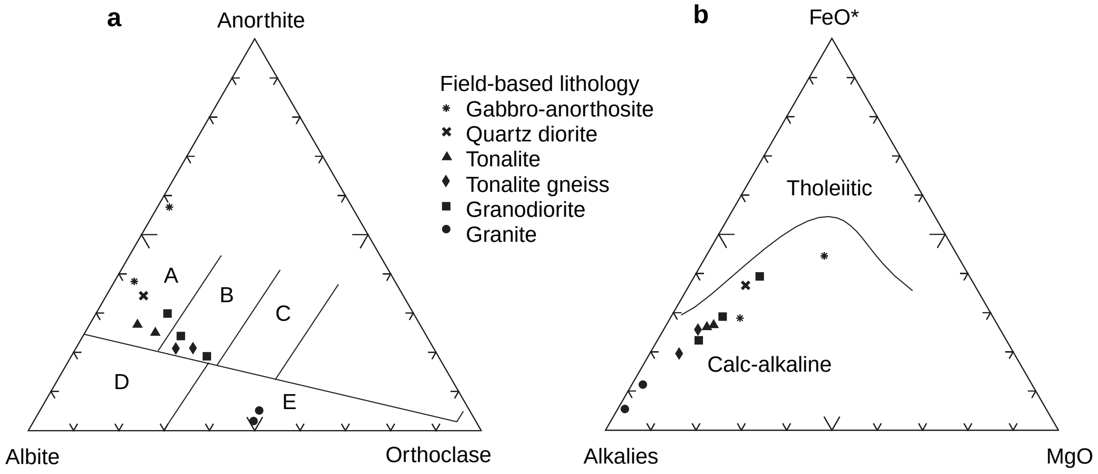

***Figure 2.** Classification of granitoid rocks from the Shikag-Garden lakes area **a)** CIPW normative diagram (A=tonalite, B=granodiorite, C=adamellite, D=trondhjemite, E=granite), **b)** AFM diagram.*

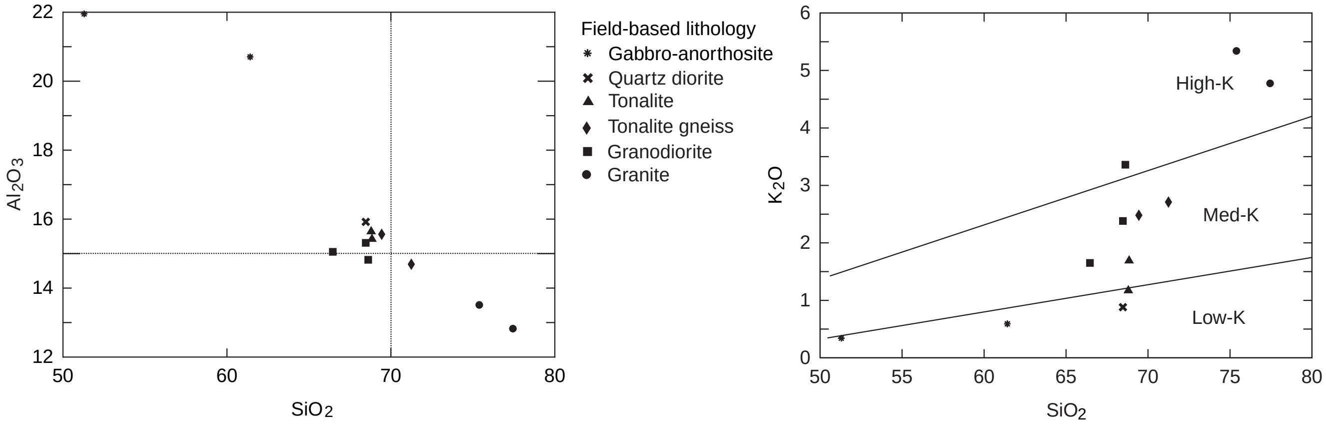

***Figure 3.** Harker variation diagrams for selected major elements. Subdivisions of high-, medium-, and low-K are from Le Maitre (1989).*

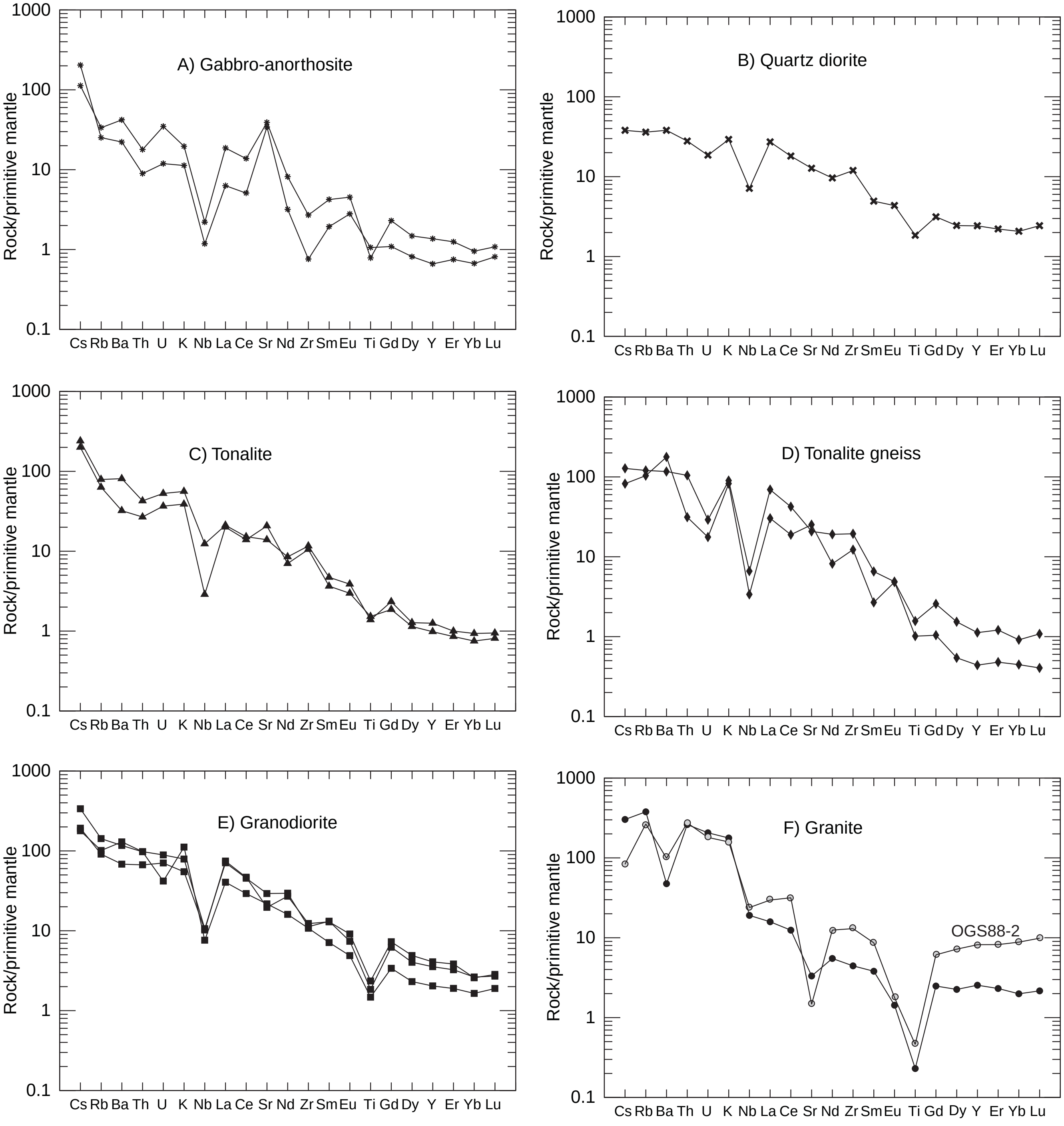

Figure 4. *Primitive mantle normalized multi-element diagrams. Normalizing values of Sun and McDonough (1989).*

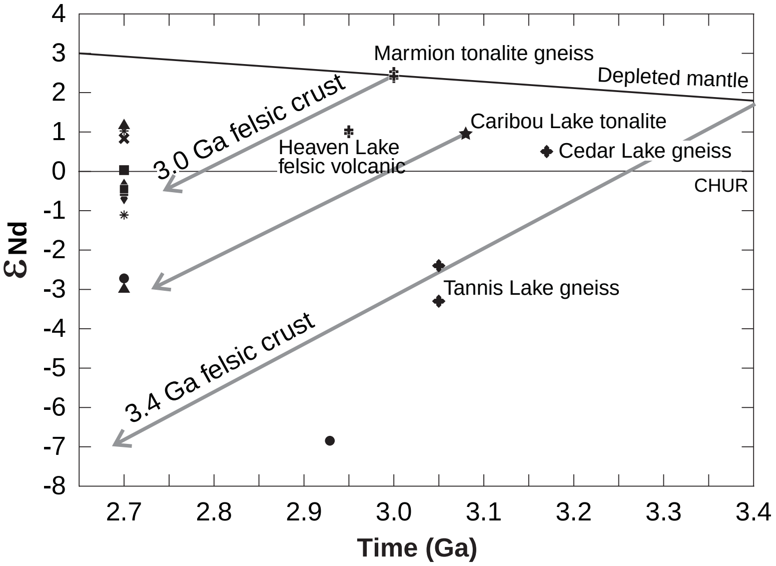

Figure 5.

*Epsilon Nd versus time diagram. Epsilon Nd values are calculated at 2.7 Ga for rocks of unknown age. Several older crustal sources are shown for comparison (*see *text for references).*

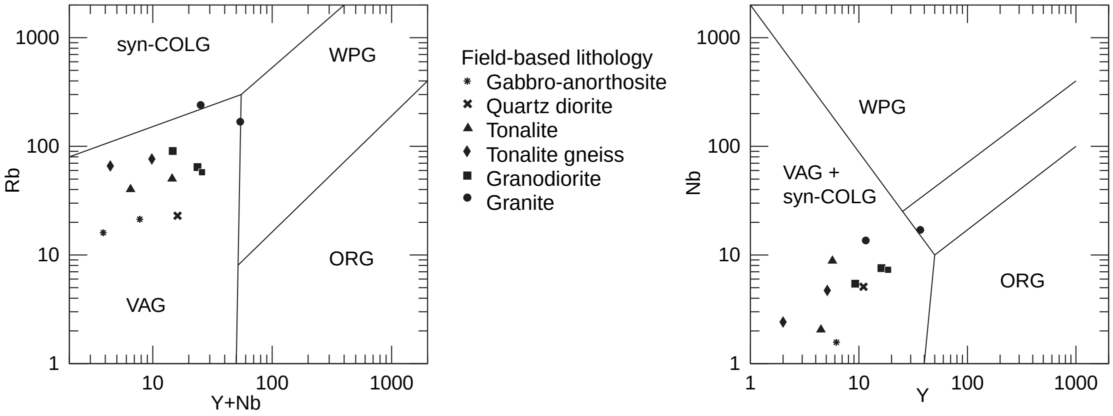

***Figure 6.** Tectonic discrimination diagrams for granitoid rocks (*after *Pearce et al., 1984). WPG=within-plate granite, ORG=ocean-ridge granite, VAG=volcanic-arc granite, syn-COLG=syncollisional granite.*

DISCUSSION

Archean tonalite-trondhjemite-granodiorite suites with fractionated rare-earth element patterns are generally considered to have been generated by partial melting of amphibolite with garnet and/or hornblende in the residue, commonly from a subducting slab of oceanic crust, or from underplated mafic material (Martin, 1986; Windley, 1995). Characteristic features of such rocks include high Al_2O_3 (>15% at 70% SiO_2; Fig. 3), low Yb, Y, and Nb; $(La/Yb)_N>20$; Sr>300 ppm; lack of a negative Eu anomaly (Fig. 4); and in addition, Sr/Y>40; Rb/Sr<0.15; and K/Rb<550 (Drummond and Defant, 1990; Defant and Drummond, 1990). Several of the samples analyzed display all or most of these characteristics (Table 1), particularly the tonalite, tonalite gneiss, and granodiorite units. In addition, on Rb versus Y+Nb and Nb versus Y tectonic discrimination diagrams (Pearce et al., 1984), all samples fall within the “volcanic arc granite” field (Fig. 6). It is therefore likely that the tonalite-trondhjemite-granodiorite samples were generated by partial melting of mafic crust, possibly in a subduction zone environment. The more evolved granodioritic to granitic rocks were likely generated by moderate amounts of intracrustal melting (Taylor and McLennan, 1985) possibly within a maturing continental arc. The more primitive gabbro-anorthosite rocks, by analogy with other Archean anorthosite, may have been generated by fractional crystallization of Al-rich basaltic melts (Ashwal and Myers, 1994).

If the tonalite-trondhjemite-granodiorite rocks were generated by partial melting of mafic crust, then their ε_{Nd} values, which range from +1.2 to –3 (at 2.70 Ga), and their Nd model ages, in the range 3.09–2.80 Ga, would suggest contamination by variable amounts of older felsic crust. Similar inferences can be drawn for the gabbro-anorthosite, with ε_{Nd} values of +1.1 and –1.1, and Nd model ages of 2.82 Ga and 2.96 Ga. Contamination of Neoarchean tonalitic magma with Mesoarchean tonalitic crust would have imperceptible effects on the major and trace element composition of the resulting rock, but would reduce the ε_{Nd} value significantly if the contaminant was much older. Contamination of gabbro-anorthosite magma with Mesoarchean crust of predominantly tonalitic composition would have a greater effect on the major and trace element compositions, as well as a large effect on the Nd isotopic composition. In order to explore the effects of contamination in producing the range of observed Nd isotopic compositions, modelling was performed using simple isotopic mixing equations (DePaolo, 1988). Taking the most juvenile tonalite (ε_{Nd} of +1.2) as the starting composition, assimilation of 95% Caribou Lake type tonalite (3.075 Ga rock with 3.16 Ga Nd model age) would be required to produce the tonalite with the lowest ε_{Nd} value (–3). This is unrealistic because a tonalitic magma could not assimilate that volume of material without crystallizing. If 3.4 Ga tonalitic crust is used as the contaminant, then 45% assimilation is required. If a more evolved granodioritic composition is used as the contaminant (with 30 ppm Nd), then only 25–30% assimilation is required to produce the low ε_{Nd} value. Less contaminated samples (i.e. those with ε_{Nd} values of 0 to –1) could have been generated through contamination by 25–45% Caribou Lake tonalite, 12–25% 3.4 Ga tonalite, or 5–12% 3.4 Ga granodiorite.

Taking the most juvenile gabbro-anorthosite (ε_{Nd} of +1.1) and modelling contamination by tonalitic crust to produce gabbro-anorthosite with ε_{Nd} of –1.1 would require assimilation of about 30% Caribou Lake type tonalite or about 13% 3.4 Ga tonalite.

The above modelling calculations for tonalite and gabbro-anorthosite show that for realistic amounts of crustal assimilation, it is necessary for ca. 3.4 Ga crust to have been a significant source component. This suggests that ca. 3.4 Ga material was probably widespread in the Shikag–Garden lakes area during Neoarchean plutonism. Further evidence for 3.5–3.4 Ga crust is found in adjacent areas; as inferred from Nd and Hf isotopic data from the Winnipeg River Subprovince (Henry et al., 1997; Davis et al., 2000), and from detrital zircons (up to 3445 Ma, Fralick and Davis, 1999) in the northwestern Wabigoon Subprovince (Fig. 1a).

The most evolved samples analyzed (1607 and OGS88-2) are chemically granite and hence both may have been produced by intracrustal melting. These rocks both have high Sm^{147}/Nd^{144} ratios for granite (0.14) that may suggest disturbance of the isotopic system; however, they are relatively fresh and undeformed rocks therefore this is thought to be unlikely. Their Nd model ages of 3.30 Ga and 3.97 Ga, respectively, suggest melting of crustal protoliths of this age. The presence of 3.3 Ga crust in the north-central Wabigoon Subprovince has been inferred from the age of detrital zircons (up to 3297 Ma, D.W. Davis and M. Moore, unpub. report, 1991); however rocks as old as 3.97 Ga have not been reported from this part of the western Superior Province. Rocks with model ages approaching this value have been reported from the Assean Lake area at the northwestern margin of the Superior Province (Böhm et al., 2000).

The isotope data suggest that the Shikag–Garden lakes area is underlain by crust of Mesoarchean and Paleoarchean age, including a significant ca. 3.4 Ga component. In this regard, the north-central Wabigoon Subprovince resembles the Winnipeg River Subprovince and the two may have common ancestry. In light of this finding, the study area is unlikely to contain a terrane boundary with either the juvenile oceanic terrane of the western Wabigoon Subprovince to the west, or 3.0 Ga Marmion batholith type rocks to the south. The cryptic boundaries of these terranes are inferred to lie further west and south, respectively.

ACKNOWLEDGMENTS

We thank Tom Skulski for critically reviewing an earlier version of this manuscript.

REFERENCES

Ashwal, L.D. and Myers, J.S.
1994: Archean anorthosites; *in* Archean Crustal Evolution, (ed.) Condie K.C. Elsevier, Amsterdam, Netherlands, p. 315–355.

Böhm, C.O., Heaman, L.M., and Creaser, R.A.
2000: Discovery of pre-3.5 Ga exotic crust at the northwestern Superior Province margin, Manitoba; Geology, v. 28, p. 75–78.

Corfu, F.
1988: Differential response of U-Pb systems in coexisting accessory minerals, Winnipeg River Subprovince, Canadian Shield: implications for Archean crustal growth and stabilization; Contributions to Mineralogy and Petrology, v. 98, p. 312–325.

Cortis, A.L., Stott, G.M., Osmani, I.A., Atkinson, B., and Thurston, P.C.
1988: A geological re-evaluation of northwestern greenstone belts; *in* Summary of Fieldwork and Other Activities; 1988, Ontario Geological Survey, Miscellaneous Paper 141, p. 25–52.

Davis, D.W. and Jackson, M.C.
1988: Geochronology of the Lumby Lake greenstone belt: a 3 Ga complex within the Wabigoon Subprovince, northwest Ontario; Geological Society of America Bulletin, v. 100, p. 818–824.

Davis, D.W., Amelin, Y., Nowell, G.M., and Parrish, R.R.
2000: A Hf isotopic study on zircons from the Western Superior Lithoprobe Transect; *in* Western Superior LITHOPROBE-NATMAP Annual Meeting, February, 2000, Abstracts.

Davis, D.W., Sutcliffe, R.H., and Trowell, N.F.
1988: Geochronological constraints on the tectonic evolution of a late Archean greenstone belt, Wabigoon Subprovince, northwestern Ontario, Canada; Precambrian Research, v. 39, p. 171–191.

Defant, M.J. and Drummond, M.
1990: Derivation of some modern arc magmas by melting of young subducted lithosphere; Nature (London), v. 347, p. 662–665.

DePaolo, D.J.
1988: Neodymium Isotope Geochemistry An Introduction; Springer-Verlag, Berlin, 187 p.
1981: Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic; Nature, v. 291, p. 193–196.

Drummond, M. and Defant, M.J.
1990: A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons; Journal of Geophysical Research, v. 95, p. 21 503–21 521.

Fralick, P. and Davis, D.W.
1999: The Seine-Coutchiching problem revisited: sedimentology, geochronology and geochemistry of sedimentary units in the Rainy Lake and Sioux Lookout areas; *in* Western Superior Transect 1999 Annual Meeting, LITHOPROBE Report #70, (ed.) R.M. Harrap and H. Helmstaedt; LITHOPROBE Secretariat, University of British Columbia, p. 66–75.

Henry, P., Stevenson, R.K., and Gariepy. C.
1998: Late Archean mantle composition and crustal growth in the Western Superior Province of Canada: Neodymium and lead isotopic evidence from the Wawa, Quetico and Wabigoon subprovinces; Geochimica et Cosmochimica Acta, v. 62, p. 143–157.

Henry, P., Stevenson, R.K., Larbi, Y. and Gariepy. C.
1997: Use of Nd isotopes to quantify 700 Ma of crustal growth from 3.4 to 2.7 Ga in the western Superior Province (Ontario, Canada); *in* 1997 Western Superior Transect Third Annual Workshop, LITHOPROBE Report #63, (ed.) R.M. Harrap and H. Helmstaedt; LITHOPROBE Secretariat, University of British Columbia, p. 27–36.

LeMaitre, R.W.
1989: A Classification of Igneous Rocks and Glossary of Terms; Blackwell, Oxford, United Kingdom, 193 p.

Martin, H.
1986: Effect of steeper Archean geothermal gradient on geochemistry of subduction zone magmas; Geology, v. 14, p. 753–756.

Ontario Geological Survey
1991: Bedrock geology of Ontario, west-central sheet; Ontario Geological Survey, Map 2542, scale 1:1 000 000.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G.
1984: Trace element discrimination diagrams for the tectonic interpretation of granitic rocks; Journal of Petrology, v. 25, p. 956–983.

Percival, J.A. and Stott, G.M.
2000: Toward a revised stratigraphic and structural framework for the Obonga Lake greenstone belt, Ontario; Geological Survey of Canada, Current Research, 2000-C22, 8 p. (online; http://www.nrcan.gc.ca/gsc/bookstore).

Percival, J.A., Breaks, F.W., Brown, J.L., Corkery, M.T., Devaney, J., Dubé, B., McNicoll, V., Parker, J.R., Rogers, N., Sanborn-Barrie, M., Sasseville, C., Skulski, T., Stone, D., Stott, G.M., Syme, E.C., Thurston, P.C., Tomlinson, K.Y., and Whalen, J.B.
1999a: Evolution of Archean continental and oceanic domains in the western Superior Province: 1999 NATMAP results; *in* Summary of Field Work and Other Activities 1999, Ontario Geological Survey, Open File Report 6000, p. 17-1–17-16.

Percival, J.A., Castonguay, S., Whalen, J.B., Brown, J.L., McNicoll, V., and Harris, J.R.
1999b: Geology of the central Wabigoon region in the Sturgeon Lake-Obonga Lake corridor, Ontario; *in* Current Research 1999-C; Geological Survey of Canada, p. 197–208.
1999c: Geology, Sturgeon Lake–Obonga Lake area, Ontario; Geological Survey of Canada, Open File 3738, scale 1:100 000.

Rogers, D.P.
1964: Metionga Lake area; Ontario Department of Mines, Geological Report 24, 53 p.

Sage, R.P., Breaks, F.W., Stott, G.M., McWilliams, G.M., and Robertson, D.
1973: Operation Ignace-Armstrong, Ignace-Graham sheet, Ontario Division of Mines Map P.964, scale 1 inch to 2 miles.

Sanborn-Barrie, M. and Skulski, T.
1999: Tectonic assembly of continental margin and oceanic terranes at 2.7 Ga in the Savant Lake-Sturgeon Lake greenstone belt, Ontario; *in* Current Research 1999-C; Geological Survey of Canada, p. 209–220

Sun, S.S. and McDonough, W.F.
1989: Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes; *in* Magmatism in the Ocean Basins, (ed.) A.D. Saunders and M.J. Norry; Geological Society, Special Publication no. 42, p. 313–345.

Taylor, S.R. and McLennan, S.M.
1985: The Continental Crust: its Composition and Evolution; Blackwell Scientific Publications, Oxford, London, Edinburgh, 312 p.

Tomlinson, K.Y.
In press: Neodymium isotopic data from the central Wabigoon Subprovince, Ontario: implications for crustal recycling in 3.1 to 2.7 Ga sequences; *in* Geological Survey of Canada, Radiogenic Age and Isotopic Studies; Report 13.

Tomlinson, K.Y., Davis, D.W., Hughes, D.J., and Thurston, P.C.
1998: The central Wabigoon Subprovince: geochemistry, geochronology and tectonic reconstruction; *in* Western Superior LITHOPROBE 1998 Annual Meeting, LITHOPROBE Report #65, (ed.) R.M. Harrap and H. Helmstaedt; LITHOPROBE Secretariat, University of British Columbia, p. 35–47.

Tomlinson, K.Y., Davis, D.W., Thurston, P.C., Hughes, D.J., and Sasseville, C.
1999: Geochemistry, Nd isotopes and geochronology from the Central Wabigoon Subprovince and North Caribou Terrane: regional correlations leading towards a Mesoarchean reconstruction; *in* Western Superior Transect 1999 Annual Meeting, LITHOPROBE Report #70, (ed.) R.M. Harrap and H. Helmstaedt; LITHOPROBE Secretariat, University of British Columbia, p. 136–146.

Wilks, M.E. and Nisbet, E.G.
1988: Stratigraphy of the Steep Rock Group, northwestern Ontario: a major Archean unconformity and Archean stromatolites; Canadian Journal of Earth Sciences, v. 25, p. 370–391.

Windley, B.F.
1995: The Evolving Continents; third edition, Pergamon Press, 526 p.

Geological Survey of Canada Project 970014

APPENDIX 1

Sample descriptions

TONALITE GNEISS SUITE

PBA99-1348a Caribou Lake tonalite gneiss (UTM zone 16, 337472E, 5575450N):

This rock represents the oldest phase of a gneiss complex. It is a thinly layered (S_1) biotite tonalite gneiss, cut by several younger igneous phases: 1) concordant (S_1) granitic leucosome; 2) sheets of foliated (S_2), homogeneous tonalite; 3) gabbroic dykes (dismembered and cut by 4); 4) dykes and masses of late granitic pegmatite.

PBA99-1450b Moberly area tonalite gneiss (UTM zone 15, 684204E, 5495722N):

This rock is the oldest phase in a complex gneissic outcrop. The biotite tonalite gneiss contains a well developed S_1 gneissosity affected by F_2 folds and is cut by a variety of mafic dykes, themselves dismembered by younger dykes of granite.

ANORTHOSITE SUITE

PBA99-1444 Moberly Lake gabbroic anorthosite (UTM zone 15, 687525E, 5495906N):

The sample is from an enclave of gabbroic anorthosite within a body of foliated granodiorite, itself cut by dykes of granite. Also present are enclaves of gabbro.

PBA99-1502 Empire Lk gabbroic anorthosite (UTM zone 15, 701062E, 5509495N):

This sample is from a gabbroic anorthosite layer within a layered, coarse-grained body that ranges in composition from anorthosite, through gabbro, to pyroxenite. It is a massive to weakly foliated orthopyroxene-clinopyroxene-hornblende rock containing local magnetite.

TONALITE-GRANODIORITE SUITE

PBA99-1371 Kashishibog area tonalite (UTM zone 16, 292975E, 5520472N):

This homogeneous, well foliated medium-grained biotite tonalite to granodiorite contains large (to 5 mm) crystals of allanite. The dominant foliation dips shallowly and is folded into open, upright folds.

PBA99-1393 Garden Lake area tonalite (UTM zone 15, 708577E, 5491834N):

The rock is a homogeneous biotite tonalite with a single foliation and weak rodding lineation. The unit ranges in composition to granodiorite.

PBA99-1422 Garden Lake area granodiorite (UTM zone 16, 287312E, 5491556N):

This sample comes from an outcrop that grades from quartz diorite, through tonalite, to granodiorite. It is a homogeneous, medium-grained hornblende-biotite granodiorite with a single foliation and weak rodding lineation. The outcrop is transected by dykes and veins of aplite.

PBA99-1481 Empire Lake granodiorite (UTM zone 15, 698020E, 5488290N):

This is a medium-grained to K-feldspar porphyritic biotite granodiorite with a well developed S_1 foliation, locally transposed into east-west S_2. It is cut by dykes of homogeneous, weakly foliated biotite tonalite.

PBA99-1527 Empire Lake quartz diorite (UTM zone 15, 705709E, 5516137N):

This is a medium-grained, foliated hornblende-biotite quartz diorite that grades to tonalite. It contains sparse mafic layers and is cut by boudinaged mafic dykes.

PBA99-1554 McCausland area granodiorite (UTM zone 15, 655600E, 5489555N):

This rock is from a broad, gently east-dipping high-strain zone. It is a hornblende-biotite-epidote granodiorite with a well developed mineral and rodding lineation. The granodiorite contains sparse mafic enclaves and is cut by mafic and pegmatitic dykes.

GRANITE SUITE

PBA99-1607 Empire Lake granite (UTM zone 15, 696112E, 5507305N):

This medium-grained, homogeneous, massive biotite granite contains sparse enclaves of foliated to gneissic granodiorite.

OGS88-2 South Obonga Lake belt granodiorite (UTM zone 16, 312400E, 55259750N):

Fine- to medium-grained, pink aplitic granodiorite which cuts medium-grained homogenous, foliated, quartz porphyritic trondhjemite, and is itself cut by two generations of mafic dykes (Percival and Stott, 2000). The pink granodiorite phase was first interpreted as altered (regolithic) pink trondhjemite by Cortis et al. (1988) who collected a sample for geochronology. The sample was dated at 2930 Ma by D.W. Davis and M. Moore (unpub. report, 1991). The sample site was then revisited by Percival and Stott (2000) who recognized the pink, dated phase as aplitic granodiorite which was cutting an even older phase of trondhjemite (undated). Sample OGS88-2 analyzed here (chemically a granite) is an offcut of the original sample collected and described by Cortis et al. (1988) and dated by D.W. Davis and M. Moore (unpub. report, 1991).