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Neodymium isotopic data from the central Wabigoon Subprovince, Ontario: implications for crustal recycling in 3.1 to 2.7 Ga sequences[1]

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Abstract: Neodymium isotopic data on Mesoarchean supracrustal rocks of the central Wabigoon Subprovince suggest that the southern part of this terrane was relatively juvenile at 3.0–2.9 Ga whereas the northern part contains an older recycled crustal component that is at least 3.3–3.2 Ga. Neodymium isotopic data from Neoarchean supracrustal rocks of the central Wabigoon Subprovince indicate that volcanism at 2.73–2.70 Ga was ensialic and that rocks in the northern part of the central Wabigoon Subprovince have also recycled 3.3–3.2 Ga felsic crust whereas those to the south have recycled crust no older than 3.0 Ga.

Résumé : D'après des données sur les isotopes de Nd provenant de roches supracrustales mésoarchéennes de la sous-province de Wabigoon centrale, la partie méridionale de ce terrane était relativement jeune à 3,0–2,9 Ga alors que la partie septentrionale contient une composante crustale recyclée plus ancienne âgée d'au moins 3,3–3,2 Ga. Les données sur les isotopes de Nd dans des roches supracrustales néo-archéennes dans la sous-province de Wabigoon centrale indiquent que le volcanisme de 2,73–2,70 Ga était ensialique et que les roches dans la partie septentrionale de la sous-province de Wabigoon centrale ont également une croûte felsique recyclée de 3,3–3,2 Ga) alors que celles qui se trouvent au sud ont une croûte recyclée dont l'âge ne dépasse pas 3,0 Ga.

[1] Contribution to Western Superior NATMAP Project 97-0014

INTRODUCTION

The central part of the Wabigoon Subprovince of the western Superior Province is a predominantly plutonic domain with several small greenstone belts (Thurston and Davis, 1985; Fig. 1). In this respect it contrasts with the western and eastern portions of the Wabigoon Subprovince, which contain abundant supracrustal rocks (predominantly 2.78–2.70 Ga) intruded by syn- to postvolcanic granitoid rocks (Davis et al., 1988; Stott and Davis, 1999). The central Wabigoon Subprovince contains evidence of Mesoarchean supracrustal and granitoid rocks (>3.0 Ga in the north and 3.0 to 2.9 Ga in the south; Davis et al., 1988; Davis and Jackson, 1988; Tomlinson et al., 1999a), in addition to Neoarchean volcanic sequences (2.73 to 2.70 Ga, Tomlinson et al., 1998) and granitoid rocks. It is therefore an important area to study the relationship between Mesoarchean and Neoarchean supracrustal sequences and to establish whether Neoarchean volcanism occurred in an ensialic setting, with deposition upon Mesoarchean basement, or whether the Neoarchean greenstone sequences are allochthonous. The Mesoarchean basement rocks can also be studied to examine whether they are isotopically juvenile or whether they show evidence of an older continental crustal component, and if there is a contrast between Nd isotopic compositions of the Mesoarchean rocks in the northern and southern parts of the central Wabigoon Subprovince.

GEOLOGY AND GEOCHRONOLOGY

Mesoarchean rocks of the south-central Wabigoon Subprovince

The 3003 Ma tonalitic Marmion batholith (Davis and Jackson, 1988) is unconformably overlain by the Steep Rock greenstone belt (Fig. 1) comprising quartz arenite and conglomerate, stromatolitic limestone, banded iron formation, komatiitic pyroclastic rocks, and mafic lavas (Wilks and Nisbet, 1988). The quartz arenite and ultramafic pyroclastic rocks contain 3.0 Ga zircons derived from the tonalitic basement (D. Davis, unpub. data, 1996; Tomlinson et al., 1998). The mafic volcanic rocks correlate with those in the neighbouring Finlayson greenstone belt, where a rhyolite has been

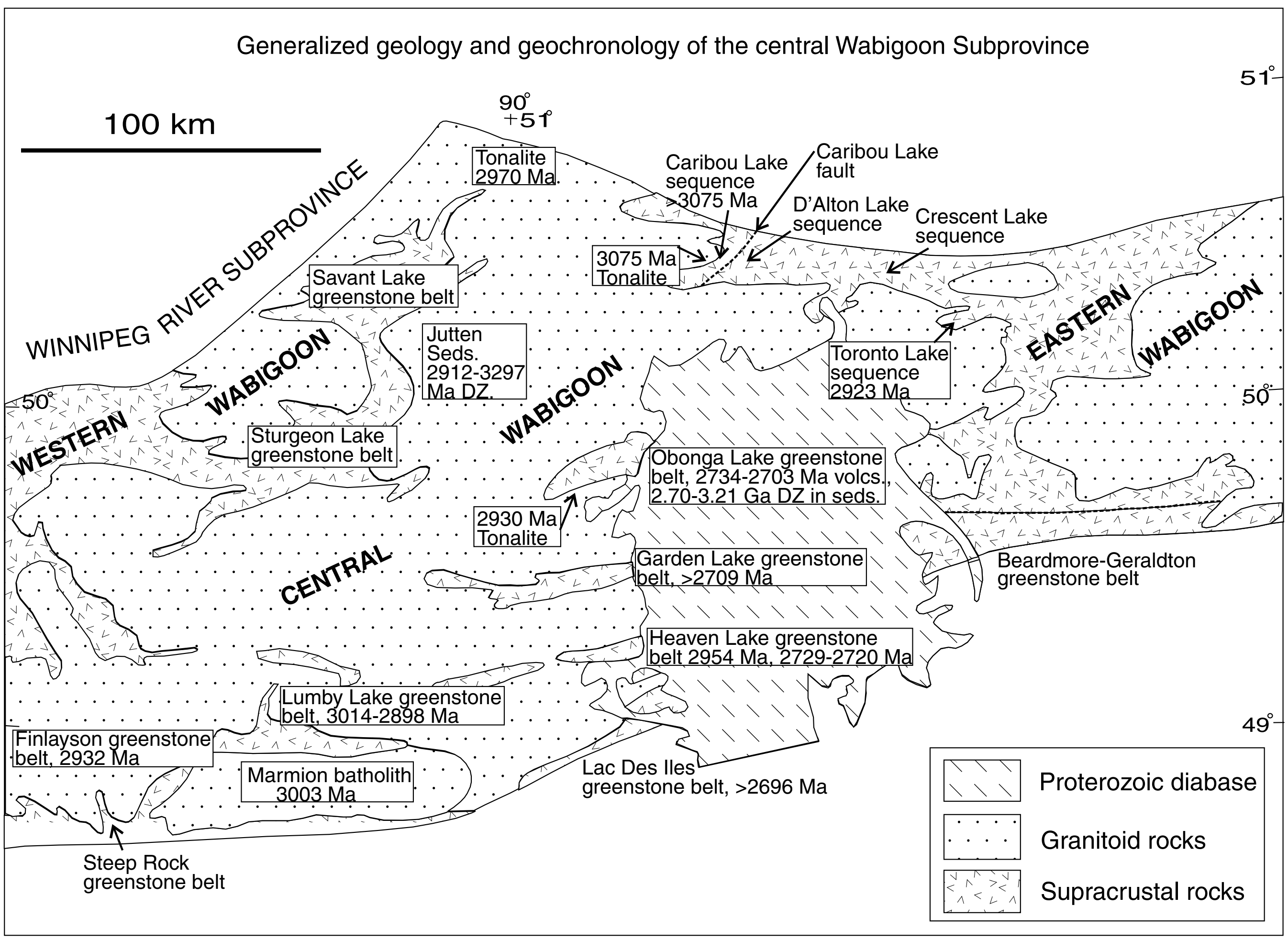

Figure 1. Location of greenstone belts discussed in the text with available geochronological data (see text for references).

dated at 2932 Ma (D.W. Davis, unpub. data, 1993). The volcanic rocks are also continuous into the Lumby Lake greenstone belt to the northeast (Fig. 1) where thin, felsic horizons within the mafic-ultramafic sequence have been dated at <2963 Ma and 2898 Ma (Tomlinson et al., 1999a). Inherited zircons indicate that this sequence erupted through the Marmion batholith and basal felsic volcanic units that are in part coeval with the tonalitic plutonism. These basal felsic units have been dated at 3014 Ma, 3001 Ma, and 2999 Ma (Davis and Jackson, 1988; Tomlinson et al., 1999a). In the Lumby Lake greenstone belt, komatiitic rocks occur towards the top of the stratigraphy (Tomlinson et al., 1999b). The carbonate-banded iron formation-basalt-komatiite association is characteristic of the Mesoarchean rocks of the southern-central Wabigoon Subprovince and is also found in the 2954 Ma mafic-ultramafic lower sequence of the nearby Heaven Lake greenstone belt (Tomlinson et al., 1998; Fig. 1). This Steep Rock–Lumby Lake–Heaven Lake 3.01–2.90 Ga domain represents the largest area of exposed Mesoarchean crust within the central Wabigoon Subprovince. Its relationship to Mesoarchean rocks in the northern part of the central Wabigoon Subprovince is unknown due to extensive Neoarchean granitoid plutonism in the intervening area.

Mesoarchean rocks of the north-central Wabigoon Subprovince

Mesoarchean rocks occur along the northern margin of the central Wabigoon Subprovince (Fig. 1). Mafic volcanic rocks of the Caribou Lake greenstone belt (northwest of the Caribou Lake fault) are intruded by 3075 Ma tonalite (Davis et al., 1988). The lava sequence contains rare, thin units of banded iron formation, chert, and serpentinite (thought to be altered volcanic flows). Southeast of the Caribou Lake fault, the mafic volcanic sequence in the D'Alton Lake area (Fig. 1) comprises mafic flows and rare thin serpentinite units, chert, banded iron formation, and spinifex-textured ultramafic flows. The sequence is in fault contact with the >3075 Ma supracrustal sequence and is itself undated, but is continuous to the east into the Crescent Lake and Toronto Lake area (Fig. 1) where a thin rhyolite has been dated at 2923 Ma (Davis, 1998). It is unclear from field data whether these sequences may have originally overlain older granitoids.

Neoarchean supracrustal rocks

From north to south, the Obonga Lake, Garden Lake, Heaven Lake, and Lac des Iles belts in the central Wabigoon Subprovince (Fig. 1) contain Neoarchean supracrustal rocks. No unconformable relationships with basement are observed in any of these belts as their margins are generally intruded by younger granitoid rocks or represented by high-strain zones. These belts may be allochthonous or they may be autochthonous and have interacted with Mesoarchean basement.

The Obonga Lake greenstone belt (north-central Wabigoon Subprovince)

The Obonga Lake greenstone belt contains two volcanic assemblages. Lavas of the northern assemblage are south-facing, predominantly mafic, and interbedded with greywacke and rare quartz-rich sedimentary rocks. A single rhyolite has been dated at 2703 Ma and a sedimentary unit interbedded with mafic pillow lavas is <2724 Ma (Tomlinson et al., 1999a). Along the northern margin of the assemblage, a tectonized granodiorite contains 2921 to 2855 Ma zircons (Tomlinson et al., in press; Percival and Stott, 2000) and a sedimentary unit contains detrital zircons in the range of 3.21 to 2.70 Ga (J. Percival and V. McNicoll, unpub. data, 2000). The southern assemblage faces predominantly northward and contains a higher proportion of felsic volcanic rocks interbedded with mafic lavas. Four rhyolite units have been dated at 2743 to 2726 Ma (D.W. Davis and M. Moore, unpub. data, 1991; Tomlinson et al., 1999a). Granitoid basement rocks are locally preserved directly south of the greenstone belt and dated at 2930 Ma (D.W. Davis and M. Moore, unpub. data, 1991).

The Garden Lake greenstone belt

The Garden Lake greenstone belt comprises massive to pillowed mafic flows, lesser intermediate to felsic tuff, and conglomeratic sedimentary rocks. The sequence is cut by a 2709 Ma felsic porphyry (D. Davis, unpub. data, 1997) and shows similarities to other Neoarchean sequences in the central Wabigoon Subprovince (i.e. lack of komatiite and greater proportion of intermediate to felsic volcanic rocks) and is therefore considered to be Neoarchean.

The Heaven Lake greenstone belt (south-central Wabigoon Subprovince)

The 2954 Ma mafic to ultramafic sequence (*see* 'Mesoarchean rocks of the south-central Wabigoon Subprovince') is overlain by a sequence of intermediate to felsic volcanic rocks, quartz porphyry, and rare mafic flows. Felsic units have been dated at 2729 Ma and 2720 Ma, with zircon inheritance back to 2779 Ma (Tomlinson et al., 1998).

The Lac des Iles greenstone belt (southern margin of the central Wabigoon Subprovince)

The Lac des Iles belt contains alternating panels of mafic-intermediate volcanic rocks and clastic sedimentary rocks (north, south, and central panels, similar to the Beardmore-Geraldton belt that may be correlated across Lake Nipigon). A modern structural interpretation of this belt is lacking, but similarities with the Beardmore-Geraldton belt suggest that the sedimentary rocks overlie the volcanic rocks. A conglomerate at Max Creek contains detrital zircons as young as 2696 Ma (D. Davis, unpub. data, 1994). By analogy with other greenstone belts in the central Wabigoon Subprovince the volcanic rocks are also thought to be about 2.73 to 2.70 Ga.

NEODYMIUM ISOTOPIC METHODOLOGY

Sample powders, spiked with a mixed ^{148}Nd-^{149}Sm solution, were dissolved in an HF-HNO_3 mixture. Separation of the rare earth elements (REEs) was done by cation exchange chromatography using TruSpec$_{®}$ resin optimized for REE separation. Separation of Sm and Nd from other REEs followed HDEHP (Di (2-ethylexyl) orthophosphoric acid) teflon powder chromatography. Total procedural blanks were less than 200 pg for Nd and less than 20 pg for Sm. Mass analysis was carried out on a MAT-261 solid-source mass spectrometer in static multicollection mode. Neodymium isotopic compositions were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Repeated measurements of an AMES Nd standard solution yielded $^{143}Nd/^{144}Nd = 0.512195 \pm 17$ (2 s.d.), corresponding to a value of 0.511907 for the La Jolla Nd standard. The $^{143}Nd/^{144}Nd$ ratios were bias corrected to La Jolla $^{143}Nd/^{144}Nd = 0.511860$. Measurement of rock standard BCR-1 yielded $^{143}Nd/^{144}Nd = 0.512623 \pm 6$ (Table 1). Values of $^{147}Sm/^{144}Nd$ are reproducible to 0.5%. Within-run 2 σ errors on $^{143}Nd/^{144}Nd$ are given in Tables 1 and 2. Values of ε_{Nd} were calculated assuming chondritic uniform reservoir (CHUR) $^{147}Sm/^{144}Nd = 0.1967$ and present-day $^{143}Nd/^{144}Nd = 0.512638$. Values of ε_{Nd} are calculated at the known or estimated age of crystallization of the rock. The combined errors in the $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios yield an average uncertainty of ± 0.5 ε units at 2.7 to 3.0 Ga. Neodymium-model ages (T_{DM}) were calculated using the model of DePaolo (1981). The data are presented in Table 1

Table 1. Neodymium isotopic data from Mesoarchean rocks.

sample #	Lithological unit	Sm (ppm)	Nd (ppm)	measured $^{143}Nd/^{144}Nd$	2 sigma error	measured $^{147}Sm/^{144}Nd$	Age (Ga)	Epsilon Nd (t)	Nd model age T(DM)
Lumby Lake									
96KYT-82	Ultramafic lava	4.34	19.18	0.511617	±6	0.13667	2.93	**2.76**	2854
96KYT-48	Ultramafic pyroclastic	3.25	14.27	0.511546	±11	0.13340	2.93	**2.61**	2874
Heaven Lake									
96KYT-277	Komatiite	0.90	2.38	0.513304	±17	0.22830	2.95	**0.97**	
96KYT-257	Mafic lava	2.95	8.62	0.512900	±9	0.20692	2.95	**1.23**	
96KYT-256	Mafic lava	2.07	6.34	0.512732	±12	0.19723	2.95	**1.65**	
96KYT-267	Mafic lava	2.93	9.40	0.512557	±12	0.18823	2.95	**1.66**	
96KYT-268	Mafic lava	4.36	14.65	0.512410	±9	0.17976	2.95	**2.01**	
96KYT-252	Felsic volcanic rock	2.13	10.52	0.511237	±3	0.12236	2.95	**0.96**	3054
96KYT-249	Felsic dyke	1.80	11.35	0.510735	±14	0.09602	2.95	**1.19**	3020
96KYT-249 (dup.)	Felsic dyke	1.78	11.20	0.510723	±4	0.09614	2.95	**0.90**	3039
Caribou Lake									
96KYT-200	Mafic lava	1.63	4.75	0.512894	±10	0.20718	3.1	**0.81**	
96KYT-218	Amphibolite	1.87	5.48	0.512889	±10	0.20670	3.1	**0.91**	
96KYT-217	Amphibolite	2.05	6.18	0.512804	±12	0.20085	3.1	**1.59**	
96KYT-207	Mafic lava	2.32	7.75	0.512279	±10	0.18076	3.1	**-0.64**	
98KYT-40	Tonalite	4.84	18.99	0.511724	±11	0.15408	3.075	**-0.92**	3475
96KYT-210	Amphibolite	2.24	8.95	0.511583	±10	0.15105	3.1	**-2.36**	3674
96KYT-238	Basalt	6.68	29.44	0.511535	±5	0.13716	3.1	**2.29**	3049
98KYT-42	Tonalite	2.31	12.39	0.510973	±13	0.11248	3.075	**0.95**	3160
D'Alton Lake									
96KYT-102	Mafic lava	1.80	5.18	0.512961	±11	0.20986	2.93	**1.35**	
96KYT-97	Mafic lava	2.96	9.67	0.512490	±15	0.18529	2.93	**1.43**	
96KYT-183	Mafic lava	1.53	5.02	0.512492	±11	0.18370	2.93	**2.08**	
96KYT-87	Mafic lava	5.65	20.05	0.512203	±11	0.17035	2.93	**1.47**	
Crescent Lake									
96KYT-120	Mafic lava	1.74	5.08	0.512912	±9	0.20694	2.93	**1.49**	
96KYT-124	Mafic lava	2.02	6.09	0.512809	±5	0.20050	2.93	**1.92**	
96KYT-119	Amphibolite	2.38	7.28	0.512557	±9	0.19524	2.93	**-1.04**	
Toronto Lake									
96KYT-311	Mafic lava	3.04	9.61	0.512618	±13	0.19147	2.92	**1.59**	
Rock Standard									
BCR-1	USGS basalt	6.576	28.29	0.512620	±6	0.13809			
dup=duplicate analysis									

Table 2. Neodymium isotopic data from Neoarchean rocks.

Sample no.	Lithological unit	Sm (ppm)	Nd (ppm)	measured $^{143}Nd/^{144}Nd$	2 sigma error	measured $^{147}Sm/^{144}Nd$	Age (Ga)	Epsilon Nd (t)	Nd model age T(DM)
***Obonga Lake, north**									
PBA98-590B	Pyroxenite	1.38	4.03	0.512908	±9	0.20641	2.70	**1.90**	
PBA98-556	Gabbro	1.55	5.20	0.512367	±12	0.18002	2.70	**0.51**	
PBA98-561B	Gabbro	4.66	15.75	0.512407	±5	0.17876	2.70	**1.74**	
PBA98-522	Pyroxenite	0.39	1.40	0.512187	±8	0.16914	2.70	**0.79**	
98KYT-37	Rhyolite	4.04	27.11	0.510791	±3	0.09002	2.70	**1.09**	2795
98KYT-37 (dup.)	Rhyolite	4.04	27.11	0.510728	±8	0.09004	2.70	**-0.15**	2877
Obonga Lake, south									
95KYT-17	Mafic volcanic rock	1.70	5.22	0.512727	±10	0.19733	2.73	**1.52**	
95KYT-22	Mafic volcanic rock	1.50	4.60	0.512772	±8	0.19732	2.73	**2.41**	
95KYT-53	Mafic volcanic rock	4.22	20.25	0.511479	±8	0.12592	2.73	**2.28**	2739
95KYT-52	Mafic volcanic rock	4.14	20.03	0.511399	±8	0.12493	2.73	**1.06**	2852
95KYT-57	Mafic volcanic rock	8.26	50.62	0.510939	±5	0.09857	2.73	**1.35**	2807
95KYT-50	Rhyolite	8.56	40.16	0.511524	±5	0.12887	2.73	**2.12**	2754
95KYT-49	Rhyolite	7.59	36.47	0.511431	±10	0.12587	2.73	**1.35**	2825
95KYT-27	Rhyolite	2.30	13.05	0.511095	±7	0.10644	2.73	**1.63**	2790
PBA97-182	Tonalite	0.54	2.54	0.511303	±10	0.12847	2.70	**-2.32**	3161
Garden Lake									
96KYT-141	Amphibolite	1.05	3.26	0.512715	±17	0.19456	2.73	**2.27**	
96KYT-137	Amphibolite	3.08	9.60	0.512693	±12	0.19370	2.73	**2.14**	
96KYT-134	Mafic lava	2.16	7.07	0.512520	±6	0.18475	2.73	**1.91**	
96KYT-161	Amphibolite	3.05	10.59	0.512261	±9	0.17427	2.73	**0.53**	
96KYT-162	Amphibolite	4.20	14.62	0.512306	±8	0.17380	2.73	**1.58**	
96KYT-169	Amphibolite	3.93	13.68	0.512304	±11	0.17374	2.73	**1.56**	
96KYT-164	Amphibolite	1.52	5.34	0.512267	±12	0.17205	2.73	**1.43**	
96KYT-170	Mafic lava	3.71	13.24	0.512220	±4	0.16924	2.73	**1.50**	
96KYT-170 (dup.)	Mafic lava	3.71	13.24	0.512199	±6	0.16929	2.73	**1.07**	
96KYT-159	Mafic lava	2.50	9.98	0.511852	±13	0.15128	2.73	**0.63**	2956
96KYT-163	Amphibolite	10.06	51.93	0.511285	±6	0.11709	2.73	**1.59**	2798
96KYT-156	Intermediate lava	4.34	23.46	0.511044	±8	0.11178	2.73	**-1.26**	3024
96KYT-155	Intermediate lava	4.03	22.35	0.510966	±4	0.10890	2.73	**-1.77**	3056
96KYT-144	Feldspar porphyry	6.09	37.96	0.510868	±8	0.09699	2.71	**0.24**	2864
96KYT-142	Intermediate volcanic rock.	5.82	40.09	0.510695	±15	0.08771	2.73	**0.40**	2863
Heaven Lake									
97KYT-74	Mafic lava	2.14	6.69	0.512654	±11	0.19315	2.73	**1.57**	
97KYT-72	QF porphyry	1.65	9.20	0.511130	±13	0.10818	2.72	**1.59**	2785
97KYT-73	QF porphyry	2.18	13.02	0.511006	±9	0.10124	2.72	**1.60**	2782
97KYT-75	Felsic tuff	1.90	11.76	0.510951	±9	0.09741	2.73	**1.98**	2762
Lac Des Iles									
97KYT-71	Mafic lava	1.58	4.55	0.513006	±18	0.20975	2.73	**2.61**	
97KYT-70	Mafic lava	2.77	8.76	0.512652	±6	0.19130	2.73	**2.19**	
96KYT-285	Mafic lava	2.81	8.92	0.512622	±13	0.19029	2.73	**1.95**	
96KYT-281	Amphibolite	2.19	7.25	0.512501	±9	0.18227	2.73	**2.41**	
96KYT-290	Amphibolite	3.23	11.35	0.512288	±7	0.17222	2.73	**1.79**	
96KYT-298	Mafic lava	2.03	7.43	0.512149	±10	0.16471	2.73	**1.71**	
96KYT-297	Amphibolite	3.64	13.61	0.512086	±13	0.16171	2.73	**1.54**	
96KYT-293	Mafic lava	2.92	11.48	0.511965	±4	0.15353	2.73	**2.06**	2764
96KYT-294	Mafic lava	3.85	16.16	0.511808	±5	0.14389	2.73	**2.38**	2723
96KYT-300	Mafic lava	2.84	12.00	0.511790	±12	0.14287	2.73	**2.39**	2723
96KYT-286	Intermediate lava	4.62	24.70	0.511156	±9	0.11309	2.73	**0.48**	2886
96KYT-283	Dacitic lava	2.34	13.07	0.511073	±4	0.10822	2.73	**0.57**	2873

Note: *additional data from the Obonga Lake greenstone belt in Tomlinson et al., in press.
dup=duplicate analysis

for Mesoarchean rocks and in Table 2 for Neoarchean rocks subdivided into greenstone belts with locations shown on Figure 1. Diagrams of ε_{Nd} versus time are shown in Figures 2 and 3 for Mesoarchean rocks and in Figures 4 and 5 for Neoarchean rocks. The depleted-mantle evolution curve (model of DePaolo, 1981) is shown for comparison and ε_{Nd} values vary from +2 at 3.1 Ga to +3 at 2.7 Ga. It is notable that previous isotopic studies on mantle-derived rocks in the Wabigoon Subprovince (west of the current study area) have shown some isotopic variations in 2.75 to 2.70 Ga rocks with initial ε_{Nd} values ranging from +1.0 to +3.3 (Ashwal et al., 1985; Morrison et al., 1985; Shirey and Hanson, 1986). These data have been explained by suggesting the presence of a heterogeneous mantle during the Neoarchean and particularly of an enriched mantle component. The DePaolo model may therefore represent an appropriate model for the depleted mantle (in agreement with studies such as Henry et al., 1998), but if the mantle is heterogeneous, a greater range of mantle values may be present than that represented by the depleted-mantle evolution curve shown in Figures 2 to 5.

NEODYMIUM ISOTOPIC DATA

Mesoarchean rocks of the south-central Wabigoon Subprovince

Komtiites enriched in light rare earth elements (LREEs) ($^{147}Sm/^{144}Nd$ =0.133–0.137) from the Lumby Lake belt have ε_{Nd} values of +2.6 to +2.8 (at 2.93 Ga), compared with model depleted-mantle values of +2.5 to +2.0 at 2.9–3.0 Ga (Fig. 2). In comparison, tonalite gneiss from the Marmion batholith south of the Lumby Lake belt has ε_{Nd} values of +2.4 to +2.5 (at 3.00 Ga; Henry et al., 1998), and a basal felsic tuff unit in the Lumby Lake belt has an ε_{Nd} value of +3.2 (at 3.00 Ga; Henry et al., 1998). Within the Mesoarchean part of the Heaven Lake greenstone belt, basalts have relatively chondritic REE ratios ($^{147}Sm/^{144}Nd$ =0.18–0.21) and ε_{Nd} values of +1.2 to +2.0 (at 2.95 Ga); a komatiite is LREE depleted with $^{147}Sm/^{144}Nd$ =0.22 and ε_{Nd} of +1.0 (at 2.95 Ga); and thin felsic units are LREE enriched ($^{147}Sm/^{144}Nd$ =0.096–0.122) with ε_{Nd} values of +1 to +1.2 (at 2.95 Ga). The model ages of the felsic rocks are 3054 to 3020 Ma. These data, with ε_{Nd} values all greater than +1, and Nd model ages similar to the reported U-Pb crystallization ages on zircons (*See* 'Geology amd geochronology') show that the rocks have not been contaminated by, or recycled, substantially older continental crust or sediment (i.e. not older than 3.1 Ga), which therefore indicates a lack of substantially older continental basement in the area.

Mesoarchean rocks of the north-central Wabigoon Subprovince

Lavas from Caribou Lake (Fig. 3) with chondritic REEs to depleted LREEs ($^{147}Sm/^{144}Nd$ =0.20–0.21) have ε_{Nd} values of +1.6 to +0.8 (at 3.1 Ga), whereas LREE-enriched lavas ($^{147}Sm/^{144}Nd$ =0.18–0.14) have ε_{Nd} values ranging from +2.3 to -2.4 (at 3.1 Ga). Tonalite from Caribou Lake dated at 3075 Ma (Davis et al., 1988) has initial ε_{Nd} values of -0.9 and +0.9 and Nd model ages of 3475 and 3160 Ma, suggesting an older crustal component in this region. D'Alton Lake lavas have chondritic to slightly enriched LREE profiles with $^{147}Sm/^{144}Nd$ =0.21–0.17 (and show small, mantle-normalized, negative Nb anomalies; Tomlinson et al., 1998) and ε_{Nd} values from +2.1 to +1.3 (at 2.93 Ga). The Caribou Lake tonalite would have an ε_{Nd} value of about -1 to -2 at 2.93 Ga and hence the geochemical and isotopic data would be consistent with small amounts of contamination by crust with characteristics similar to those of the Caribou Lake tonalite. Crescent Lake and Toronto Lake lavas have chondritic REE profiles ($^{147}Sm/^{144}Nd$ =0.191–0.207) with ε_{Nd} values from +1.9 to -1.0 (at 2.93–2.92 Ga; Table 1). They also show small, mantle-normalized, negative Nb anomalies (Tomlinson et al., 1998).

The ε_{Nd} values extending to such negative values in the northern part of the central Wabigoon Subprovince are consistent with varied degrees of contamination by much older (likely 3.3 to 3.2 Ga, but possibly as old as ~3.5 Ga; *see* 'Discussion') crust.

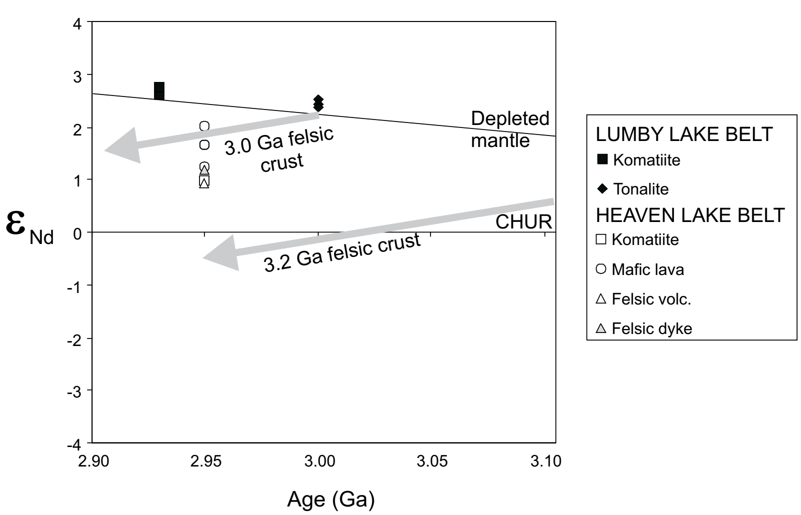

Figure 2.

Diagram of ε_{Nd} versus time for Mesoarchean greenstone belts of the southern part of the central Wabigoon Subprovince. Tonalite data for the Lumby Lake belt from Henry et al. (1998). CHUR = chondritic uniform reservoir

Neoarchean supracrustal rocks and interaction with Mesoarchean crust

The Obonga Lake greenstone belt (north-central Wabigoon Subprovince)

The mafic lavas of the northern assemblage (Fig. 4) are moderately LREE enriched ($^{147}Sm/^{144}Nd$ =0.18–0.15) with ε_{Nd} values ranging from +2.4 to +0.7 at 2.70 Ga, compared to a depleted mantle value of about +3 at 2.7 Ga. A felsic unit is more strongly enriched in LREE ($^{147}Sm/^{144}Nd$=0.09), shows a large mantle-normalized, negative Nb anomaly (Tomlinson et al., in press), and has an ε_{Nd} value of +1.1 (at 2.70 Ga). Analyses from a gabbro-pyroxenite intrusion in the northern assemblage show $^{147}Sm/^{144}Nd$=0.20–0.17 and ε_{Nd} values of +1.9 to +0.5 (at 2.70 Ga). The rocks with the lowest ε_{Nd} values are LREE enriched and also have mantle-normalized, negative Nb anomalies, whereas those with the highest ε_{Nd} values are depleted in LREEs and Th (Tomlinson et al., in press). These data suggest that some of the rocks come from a depleted mantle source and that others may have been contaminated by small amounts of much older felsic crust.

The southern assemblage comprises 1) mafic lavas (basalts to basaltic andesites) with LREE enrichment ($^{147}Sm/^{144}Nd$=0.16–0.10) and ε_{Nd} values of +2.3 to -0.9 (at 2.73 Ga), as well as significant negative Nb anomalies (Tomlinson et al., in press); 2) chondritic REE- to slightly LREE-depleted mafic lavas ($^{147}Sm/^{144}Nd$=0.21–0.19) with ε_{Nd} values of +2.7 to +1.7 (at 2.73 Ga), and 3) felsic volcanic rocks with $^{147}Sm/^{144}Nd$=0.129–0.106 and ε_{Nd} of +2.1 to +1.4 at 2.73 Ga (data in Table 2 and Tomlinson et al., in press). The slightly depleted mafic lavas suggest a juvenile depleted-mantle source, whereas some of the felsic volcanic rocks that are juvenile and enriched in LREEs (and have negative Nb anomalies; Tomlinson et al., in press) suggest a juvenile metasomatized mantle source. In contrast, detailed modelling of geochemical and isotopic data from the LREE-enriched mafic lavas with the lowest ε_{Nd} values and negative Nb anomalies indicates contamination of a primitive, unfractionated, mafic liquid by about 15% tonalitic crust that had an ε_{Nd} value of about -4 to -5 at 2.73 Ga and was therefore approximately 3.3 to 3.2 Ga (Tomlinson et al., in press). This greenstone belt is apparently complex with a number of different mantle and crustal sources, but the suggested age of the contaminant is significant. These rocks are adjacent to 2930 Ma basement and hence the isotopic data suggest that there has been reworking of much older crust

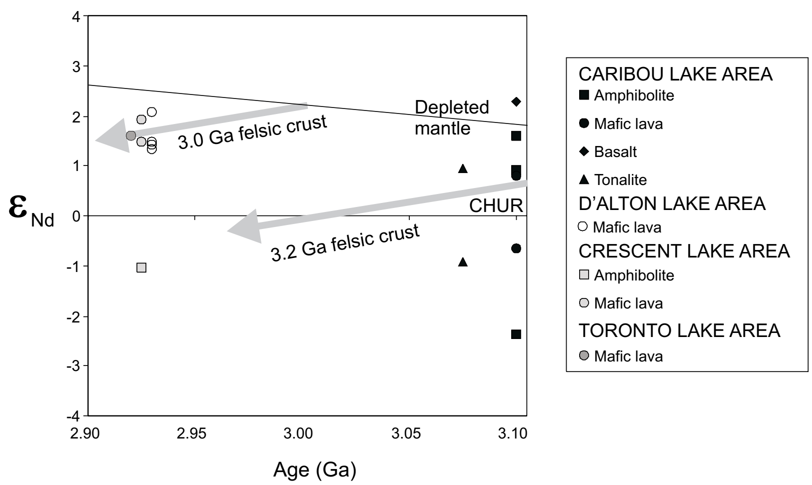

Figure 3.

Diagram of ε_{Nd} versus time for Mesoarchean greenstone belts of the northern part of the central Wabigoon Subprovince. Crescent Lake samples are plotted at 2.925 Ga to separate them from the D'Alton Lake samples. CHUR = chondritic uniform reservoir

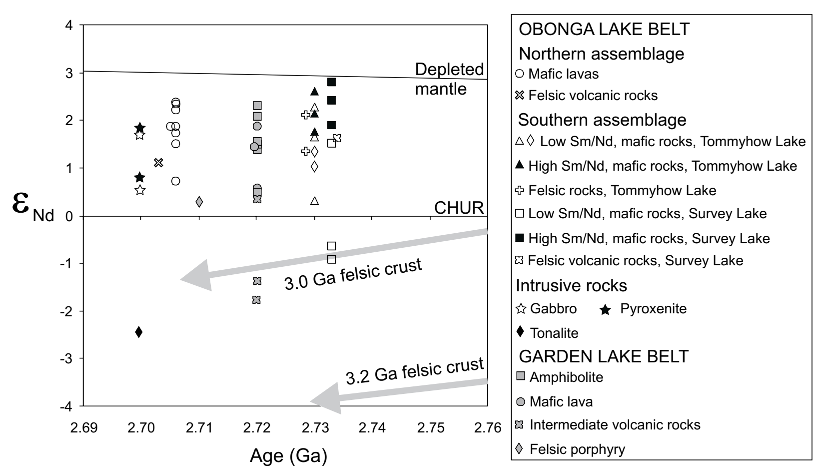

Figure 4.

Diagram of ε_{Nd} versus time for Neoarchean greenstone belts of the northern part of the central Wabigoon Subprovince. The Garden Lake volcanic rocks are plotted at 2.72 Ga to separate them from the Obonga Lake samples. The Obonga Lake samples are plotted at a slight spread of ages to make the diagram clearer. Some of the Obonga Lake data is from Tomlinson et al. (in press). CHUR = chondritic uniform reservoir than that currently exposed at the surface in this region. In support of this, an undated tonalite directly southwest of the greenstone belt has an ε_{Nd} value of -2.3 at 2.70 Ga and a Nd model age of 3.16 Ga, also suggesting recycling of rocks rather older than 3.0 Ga.

The Garden Lake greenstone belt

Volcanic rocks in the Garden Lake greenstone belt (Fig. 4) are of a variety of types, as follows: mafic rocks with chondritic REE profiles ($^{147}Sm/^{144}Nd$ =0.194–0.195) and ε_{Nd} of +2.1 to +2.3 (at 2.73 Ga); mafic rocks with LREE enrichment ($^{147}Sm/^{144}Nd$ =0.18–0.12), negative Nb anomalies (K. Tomlinson, unpub. data,1997) and with ε_{Nd} of +1.6 to +0.5 (at 2.73 Ga); and intermediate to felsic rocks with the greatest degree of LREE enrichment ($^{147}Sm/^{144}Nd$ =0.11–0.09) and ε_{Nd} of +0.4 to -1.8 (at 2.73–2.71 Ga; Table 2). The relationship between increasing LREE enrichment and decreasing ε_{Nd} suggests control by crustal contamination, with the most juvenile rocks representing uncontaminated liquids from a slightly depleted mantle source and the other groups of lavas having been contaminated by increasing amounts of felsic crust. Neodymium model ages of the rocks with the lowest ε_{Nd} values are 3056 Ma and 3024 Ma, presumably representing mixing of young-juvenile and older crustal components; hence the basement to this belt is also likely to have been 3.3 to 3.2 Ga.

The Heaven Lake greenstone belt (south-central Wabigoon Subprovince

The Neoarchean felsic volcanic rocks and porphyries of the Heaven Lake greenstone belt (Fig. 5) are LREE enriched ($^{147}Sm/^{144}Nd$ =0.097–0.108) with ε_{Nd} values of +2.0 to +1.6 (at 2.73–2.72 Ga; Table 2). A mafic lava has a chondritic REE profile ($^{147}Sm/^{144}Nd$ =0.193) and ε_{Nd} of +1.6 (at 2.73 Ga). These ε_{Nd} values are higher than those of the contaminated rocks in the Obonga Lake and Garden Lake greenstone belts (which typically have ε_{Nd} values <+1), but less than those of the most juvenile Neoarchean volcanic rocks in the central Wabigoon Subprovince (chondritic REEs to depleted LREEs with ε_{Nd} values typically greater than +2). The ε_{Nd} values of +1.6 in the Heaven Lake belt therefore do not suggest a juvenile depleted-mantle source, but rather either an enriched, Neoarchean mantle source, or a recycled 3.0 Ga felsic crustal component, which may be likely given that the belt is adjacent to 3.0 Ga rocks of the Marmion batholith.

The Lac des Iles greenstone belt (southern margin of the central Wabigoon Subprovince)

Several types of lava exist within the Lac des Iles greenstone belt (Fig. 5). The most juvenile mafic lavas make up the southern panel of the greenstone belt with chondritc REE to depleted LREE profiles ($^{147}Sm/^{144}Nd$ =0.21–0.91) and ε_{Nd} values of +2.2 to +2.6 (at 2.73 Ga). Andesitic to dacitic units in the northern panel of the greenstone belt have the steepest REE profiles ($^{147}Sm/^{144}Nd$ =0.113–0.108) and ε_{Nd} of +0.5 to +0.6 at 2.73 Ga (and Nd model ages of 2886–2873 Ma). The remaining units are basalts to basaltic andesites of the northern and central panels: slightly enriched LREE ($^{147}Sm/^{144}Nd$ =0.190–0.182) and ε_{Nd} of +2.0 to +2.4 (at 2.73 Ga); more enriched LREE ($^{147}Sm/^{144}Nd$ =0.17–0.14) and ε_{Nd} of +1.8 to +2.4 (at 2.73 Ga); and similarly enriched LREE ($^{147}Sm/^{144}Nd$ =0.162–0.165) and ε_{Nd} of +1.5 to +1.7 (at 2.73 Ga). This belt contains juvenile components that are both LREE depleted and LREE enriched (with high Th/Nb, K. Tomlinson, unpub. data, 1997), suggesting a combination of depleted-mantle and subduction-zone sources. In addition, an older crustal component is required for rocks with low ε_{Nd} values, particularly the andesitic to dacitic units with 2.87–2.88 Ga Nd model ages that suggest a mixture of a 2.7 Ga juvenile component and a 3.0 Ga felsic crustal component, which may be represented by the nearby Marmion batholith (Fig. 1).

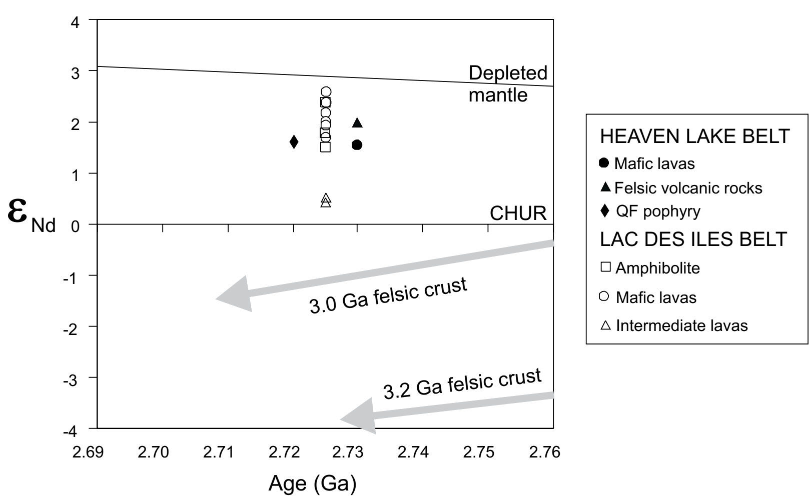

Figure 5.

Diagram of ε_{Nd} versus time for Neoarchean greenstone belts of the southern part of the central Wabigoon Subprovince. The Lac des Iles samples are plotted at 2.725 Ga to separate them from the Heaven Lake samples. CHUR = chondritic uniform reservoir

DISCUSSION

Crustal recycling in the north-central Wabigoon Subprovince

Data from the >3075 Ma Caribou Lake greenstone belt, the 3075 Ma Caribou Lake tonalite, the ~2.92 Ga D'Alton Lake–Crescent Lake–Toronto Lake sequences, and the Neoarchean Obonga Lake and Garden Lake greenstone belts and an adjacent tonalite sample suggest that basement in the northern half of the central Wabigoon Subprovince likely contained a significant pre-3.2 Ga felsic component. The basement has apparently been extensively reworked during ~2.92 Ga and 2.73–2.69 Ga magmatic events and is not exposed at the surface within the north-central Wabigoon Subprovince. Evidence for reworking of this older crust is provided by the detrital zircon populations in sedimentary units of the Obonga Lake greenstone belt (3210 Ma and 3050 Ma; J. Percival and V. McNicoll, unpub. data, 2000) and in the nearby Jutten sedimentary sequence of the Savant Lake and Sturgeon Lake greenstone belts (3199 Ma, 3258 Ma, and 3297 Ma; D.W. Davis and M. Moore, unpub. data, 1991), which is interpreted to have formed as a continental margin sequence upon Mesoarchean basement of the central Wabigoon Subprovince (Sanborn-Barrie and Skulski, 1999).

Rocks that may represent this ancient component occur to the west in the Winnipeg River Subprovince where tonalite gneiss has been dated at 3170 Ma (Corfu, 1988) and 3225 Ma (Davis et al., 2000). These rocks may be continuous into the northern part of the central Wabigoon Subprovince as suggested by the occurrence of tonalite to the north of the Savant Lake greenstone belt that has been dated at ~2.97 Ga and has a 3.4 Ga Nd model age (T. Skulski, unpub. data, 1999). The Winnipeg River gneiss units themselves show evidence of recycling of older crust with an ε_{Hf} value of -2 from a 3.2 Ga zircon implying a 3.5 Ga crustal protolith (Davis et al., 2000). Henry et al. (1997) also documented 3.4 Ga Nd model ages from 3.05 Ga rocks from the Winnipeg River Subprovince. The oldest detrital zircons in the north-central Wabigoon Subprovince would therefore suggest reworking of a 3.3 to 3.2 Ga basement, but correlations with the Winnipeg River Subprovince basement rocks suggest that such basement may itself have recycled even older crust, up to 3.5 Ga.

The Neoarchean Obonga Lake and Garden Lake greenstone belts both contain isotopically juvenile components, in addition to the much older recycled crustal components. This suggests that mantle-derived rocks that avoided felsic crustal contamination make up parts of these greenstone belts. The observed crustal contamination signature is a result of the following factors: the composition of the basement (which can vary considerably), the thermal energy of the magma, the difference between the magma temperature and the melting temperature of the wall rocks, the nature of flow of the magma (laminar or turbulent), the length of time the magma resides in a magma chamber or conduits, whether the conduits are lined with juvenile magma, and the eruption rate (Wilson, 1988). It is therefore to be expected that rocks that erupted through Mesoarchean basement will show variations in the degree of felsic crustal contamination. The observed variation in the isotopic signatures in these greenstone belts may therefore result from variations in these factors. The uncontaminated rocks may be useful for indicating the original mantle source of a particular volcanic sequence (*see* below).

Crustal recycling in the south-central Wabigoon Subprovince

Data from the Lumby Lake and Heaven Lake greenstone belts and the Marmion batholith of the south-central Wabigoon Subprovince, suggest that these sequences are relatively juvenile at 3–2.9 Ga and thus significantly older basement rocks did not exist in this region. This is in strong contrast to the north-central Wabigoon Subprovince. Data from Neoarchean sequences of the Heaven Lake and Lac des Iles greenstone belts support this and suggest that contaminated units have recycled felsic crust no older than 3.0 Ga.

Mantle sources and tectonic setting of Neoarchean volcanism in the central Wabigoon Subprovince

The crustally contaminated rocks of the Neoarchean greenstone belts in the central Wabigoon Subprovince indicate that volcanism was ensialic, although occurring in a subaqueous environment. The contamination masks the original mantle sources involved, but by examining the geochemical signatures of the least contaminated (most juvenile) rocks in these belts, the mantle sources and hence possible tectono-magmatic setting may be determined.

The most juvenile Neoarchean rocks in the Obonga Lake, Garden Lake, Heaven Lake, and Lac des Iles belts are complex with both LREE-depleted and LREE-enriched signatures (with negative Nb anomalies), suggesting the presence of both depleted-mantle and metasomatically enriched-mantle (subduction zone) sources. In addition, in the Obonga Lake greenstone belt, an increasing deep asthenospheric signature (enriched-mantle source) is observed in the younger rocks (2.70 Ga) (Tomlinson et al., in press). Neoarchean volcanism therefore seems to have occurred in an environment where both subduction-related and depleted-mantle sources were available and where a deep asthenospheric source became more prominent with time. Such an environment may have been an extensional-arc-related setting such as a continental back-arc, and may be related to subduction in the Sturgeon–Savant lakes and Lac des Iles areas.

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