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An application of Nd isotope mapping in structural geology: delineating an allochthonous Grenvillian terrane at North Bay, Ontario

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Abstract – Fifty new Nd isotope analyses are presented from the North Bay area of the Grenville Province in Ontario. These data are used to map the extent of an allochthonous Grenvillian terrane which is an outlier of the Allochthonous Polycyclic Belt of the Grenville Province. Amphibolite facies orthogneisses from the allochthonous terrane have depleted mantle Nd model ages (T_{DM}) below 1.8 Ga, whereas the gneisses of the structurally underlying parautochthon almost invariably have model ages above 1.8 Ga. The distribution of model ages is consistent with the distribution of distinct types of metabasic rock, used by other researchers as the criterion for recognizing rocks of the allochthonous and parautochthonous belts of the Grenville Province. The agreement between these different types of evidence demonstrates that Nd isotope mapping is a reliable and powerful tool for mapping terrane boundaries in high-grade metamorphic belts.

Keywords: Nd, isotopes, mapping, Grenville Province, allochthons, klippe.

1. Introduction

Nd isotope mapping is a powerful tool for the identification and delineation of accreted terranes in high-grade metamorphic belts such as the Grenville Province of the Canadian Shield. However, the method is still regarded in some circles as controversial (see, e.g. Cruden & Easton, 2001). The present case study represents a test case for isotope mapping because at North Bay, in the Grenville Province of Ontario, the results of Nd isotope mapping can be compared with an independent method of terrane mapping based on the distribution of meta-basic gneisses (Ketchum & Davidson, 2000).

The Grenville Province represents the remains of a 1.2–1.0 Ga collisional orogeny established on the margin of the Canadian Shield (Fig. 1a). It was divided into two major longitudinal belts by Rivers *et al.* (1989), as shown in Figure 1b. The parautochthonous belt comprises crustal terranes that are more or less contiguous with the Archaean–Palaeoproterozoic foreland of Laurentia. Within this belt, U–Pb igneous crystallization ages vary widely, with prominent age peaks around 1.45, 1.7 and 2.7 Ga in the Ontario segment (e.g. Davidson, 1998). In contrast, the terranes that make up the allochthonous belt in Ontario were transported large distances to the northwest during the Grenville collision, and well-established igneous crystallization ages only reach back to 1.45 Ga (Nadeau & van Breemen, 1998). The allochthon is here assumed to be a C-type crystalline sheet according to the terminology of Hatcher & Hooper (1992). In places, it contains within it smaller F-type thrust sheets, as described by Hatcher & Hooper; however, we are not concerned in this paper with that type of second-order domain.

The parautochthonous and allochthonous belts are separated by a major shear zone, the Allochthon Boundary Thrust. This thrust is readily located along much of the length of the Grenville Province from aeromagnetic data because it separates magnetically ‘quiet’ Archaean rocks to the northwest from magnetically ‘noisy’ Mesoproterozoic rocks to the southeast (Rivers *et al.* 1989). In addition, the location of the thrust has been confirmed from detailed structural studies at a few localities (e.g. Rivers & Chown, 1986). However, in the Central Gneiss Belt of Ontario and western Quebec, the long history of plutonism, through much of the Mesoproterozoic, has obscured the location of the Allochthon Boundary Thrust so that it is hard to delineate using aeromagnetic data. In addition, the deep level of exhumation and erosion has often juxtaposed very similar high-grade plutonic orthogneisses on both sides of the thrust, so that lithological variations across the boundary are quite subtle. This makes the boundary hard to map using conventional ground-based techniques, hence the need for isotopic analysis.

2. Distribution of metabasic rocks

The difficulties of mapping the Allochthon Boundary Thrust using conventional geological evidence led J. Ketchum to develop a new method of locating the boundary, based on the distribution of three suites of

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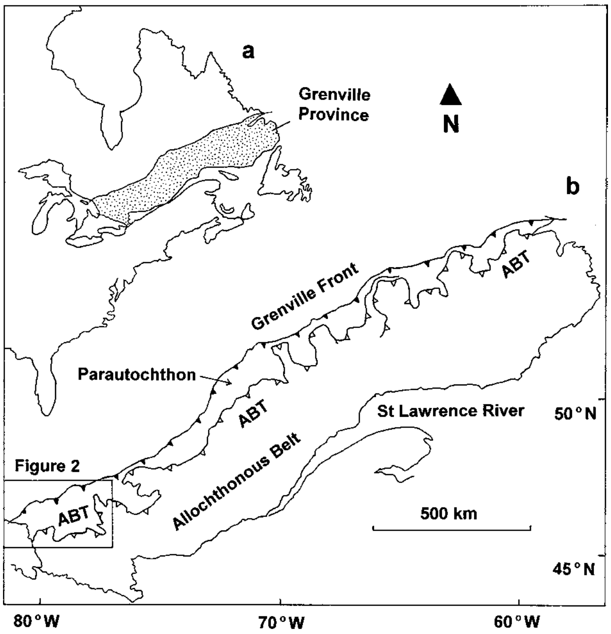

Figure 1. General view of the Grenville Province. (a) locates the province geographically within North America. (b) shows its division into two major tectonic belts (after Rivers *et al.* 1989). Box shows area of Figure 2. ABT = Allochthon Boundary Thrust.

metabasic rocks (J. W. F. Ketchum, unpub. Ph.D. thesis, Dalhousie Univ., 1994). This method was developed during studies of the Shawanaga Shear Zone (SSZ, Fig. 2a), which is established as the trace of the thrust on the shore of Georgian Bay (Jamieson *et al.* 1992; Culshaw *et al.* 1994). The method was then applied by Ketchum & Davidson (2000) to map the Allochthon Boundary Thrust eastwards into Quebec, where its position has been in doubt.

The first of the three suites of metabasic rocks identified by Ketchum (J. W. F. Ketchum, unpub. Ph.D. thesis, Dalhousie Univ. 1994) is termed olivine metadiabase, and is correlated with the 1.24 Ga Sudbury dyke swarm to the northwest of the Grenville Province. This suite is found only in the parautochthonous belt. The second suite is termed coronitic olivine metagabbro; it is found only in the allochthonous belt, where dated examples have given ages of *c.* 1.16 Ga (see references in Ketchum & Davidson, 2000). The third suite consists of retrogressed eclogite, and is normally found in the shear zone itself, or in the hanging wall just above the shear zone.

Because the olivine metadiabase (Sudbury) suite has not been found together with the coronitic olivine metagabbro suite, Ketchum & Davidson (2000) argued that the two suites must have been emplaced into crustal terranes some distance apart. This suggests that the boundary between the two suites is a site of major crustal convergence, and must therefore represent the Allochthon Boundary Thrust.

Ketchum & Davidson (2000) performed a regional reconnaissance of metabasic rocks in the Central Gneiss Belt of Ontario and western Quebec. They found that these rock types are fairly densely distributed along the Shawanaga Shear Zone, and to the south and east of Burk's Falls, but are more sporadically distributed to the northeast (Fig. 2a). Therefore, in order to use this method to map the Allochthon Boundary Thrust, Ketchum & Davidson were forced to interpolate widely between metabasic occurrences. The approach that they adopted to the north of Burk's Falls was essentially to join up the occurrences of metabasic rocks by drawing the trend of the Allochthon Boundary Thrust along pluton boundaries and regional foliation directions, but constrained to the southeastern side of areas of muscovite–quartzite gneiss which are widespread near the Ontario–Quebec border. The latter rocks are agreed by all workers to be part of the parautochthon (e.g. Davidson, 1998). As a result of these deductions, Ketchum & Davidson (2000) proposed a new location for the Allochthon Boundary Thrust in Ontario and western Quebec, as shown in Figure 2a.

3. Nd isotope mapping

Nd isotope mapping may also be useful to delineate the Allochthon Boundary Thrust, if this tectonic boundary separates terranes with distinct crustal formation ages. Because both parent and daughter isotopes in the Sm–Nd system are REE, they behave geochemically in a very similar manner and are very resistant to metamorphic disturbance. This makes Nd isotope mapping a powerful technique in the Grenville Province, where much other geological evidence has been erased by the intense metamorphism associated with the Grenvillian collision and earlier orogenic events. A detailed discussion of the merits of Nd model ages can be found in Dickin (1995).

Nd isotope data are used to calculate depleted mantle (T_{DM}) model ages using the Nd mantle evolution model of DePaolo (1981). This has been shown to yield crustal formation ages for juvenile gneiss terranes that are in excellent agreement with other geological evidence, including U–Pb dates for igneous crystallization. For example, Archaean basement within the northwest Grenville Province (southeast of Sudbury) has an average T_{DM} age of 2.73 Ga (Dickin, 1998*a*), in excellent agreement with U–Pb ages of 2.7 to 2.75 for the western Abitibi belt of the Superior Province (e.g. Jackson & Fyon, 1991).

The technique of Nd model age mapping was first applied to the Grenville Province by Dickin & McNutt (1989) in order to locate the boundary between Archaean and Palaeoproterozoic crust within the southwest Grenville Province. This revealed a step in model ages about 60 km southeast of the Grenville Front which was interpreted as a collisional suture between the Archaean craton to the north and an accreted Palaeoproterozoic arc to the south. The precise location of the proposed suture was refined by more

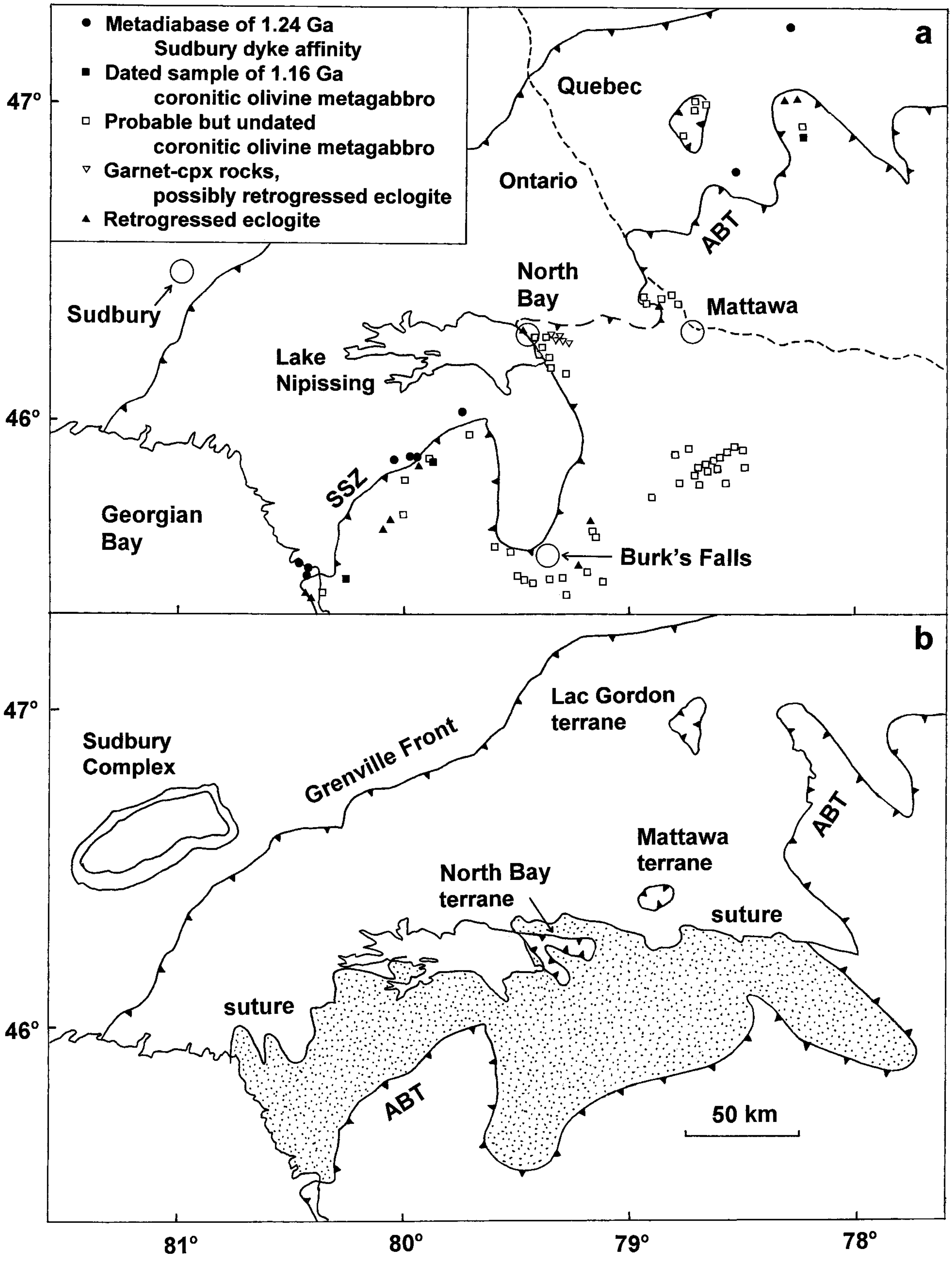

Figure 2. Maps of the Sudbury–North Bay area showing alternative views of the southwest Grenville Province and part of the adjacent foreland. (a) based on Ketchum & Davidson (2000); (b) on Dickin (2000) and Dickin & Guo (2001). Stippled area = juvenile Palaeoproterozoic arc terrane (Barilia); SSZ = Shawanaga Shear Zone; ABT = Allochthon Boundary Thrust.

detailed isotope mapping (Holmden & Dickin, 1995; Dickin, 1998*b*; Dickin & Guo, 2001), leading to the suture line shown in Figure 2b. This runs from Georgian Bay to Lake Nipissing, thereafter running eastwards in close proximity to the Mattawa fault.

Comparison of parts a and b of Figure 2 shows that the Archaean–Proterozoic suture apparently crosses the trend of the Allochthon Boundary Thrust proposed by Ketchum & Davidson (2000). However, in a review of crustal formation ages for the whole of the Grenville Province, Dickin (2000) proposed a location for the Allochthon Boundary Thrust well to the south of the suture, which was slightly revised by Dickin & Guo (2001) following more detailed studies in the Mattawa area. This location for the Allochthon Boundary Thrust (Fig. 2b) consistently separates Nd model ages into two groups. In the footwall to the north of the thrust, model ages for plutonic orthogneisses are consistently greater than 1.8 Ga, whereas to the south of the boundary these rocks yield model ages consistently less than 1.8 Ga (using the depleted mantle model of DePaolo, 1981).

The location for the Allochthon Boundary Thrust based on Nd isotope mapping (Fig. 2b) is fully consistent with the distribution of metabasic rocks shown in Figure 2a. However, there are three terranes of younger gneisses (model ages consistently less than 1.8 Ga) which are surrounded by older gneisses (model ages consistently greater than 1.8 Ga). Because these three terranes also have metabasic rocks indicative of the allochthonous belt (Fig. 2a), they must represent structural outliers detached from the main body of the allochthonous belt by erosion.

The focus of the present work is to examine precisely the extent of the proposed North Bay allochthonous terrane using Nd isotope mapping, and to compare the results with the distribution of metabasic rocks and with mapped regional foliation directions. Unlike the terranes in the Mattawa–Lac Gordon area, which are surrounded by Archaean or reworked Archaean crust (Fig. 2b), the North Bay terrane is more or less entirely surrounded by Palaeoproterozoic crust. This means that the difference in model ages between the two (averaging about 300 Myr) is less than in some of our previous studies. However, since the reproducibility of model ages is about 20 Myr, an age difference of 300 Myr should be ample to resolve the boundary between the two terranes.

4. Geology of the North Bay area

The North Bay area lies within the ‘sea of gneisses’ that forms the Central Gneiss Belt of Ontario (Davidson, 1986). This area was mapped very precisely by Lumbers (1971), but the dominant rock type of grey gneiss was mistaken at that time for metasedimentary gneiss. These rocks are now known (e.g. Holmden & Dickin, 1995; Dickin & Guo, 2001) to be largely granitoid orthogneisses, with subordinate amounts of mafic gneiss. Rocks with significant amounts of garnet are rare in the parautochthon, but are more common in the allochthon. Some of these are paragneisses, but the presence of garnet alone does not mean that a rock is necessarily of metasedimentary origin.

Before the work of Ketchum & Davidson (2000), the North Bay area was not considered as part of the allochthon. However, these workers found a retrogressed eclogite outcrop near the shore of Lake Nipissing in North Bay, and also identified coronitic olivine metagabbros with chemical signatures characteristic of the allochthon to the east and southeast of North Bay (Fig. 2a). Ketchum & Davidson suggested that the western margin of the allochthon at North Bay was located immediately to the east of Lake Nipissing, but that it turned abruptly to the east immediately north of the town, lying between Highway 17 and the post-Grenvillian Mattawa fault.

A critical observation made by Ketchum & Davidson was that their proposed location for the Allochthon Boundary Thrust at North Bay lay between localities with model ages greater than 1.8 Ga to the north and less than 1.8 Ga to the south, based on previous Nd isotope mapping by Dickin & McNutt (1989) and Holmden & Dickin (1995). At the time when these samples were analysed for Nd, the significance of model ages less than 1.8 Ga as indicators for rocks of the allochthon was not appreciated. Hence, these results were simply presented as part of the overall data set, without explanation. However, since the evidence from mafic rock distributions has now revealed the significance of these model ages, this case study provides an opportunity to demonstrate the reliability of these ages as indicators of crustal formation age, and the effectiveness of model age mapping to accurately determine the location of the Allochthon Boundary Thrust.

5. Sampling and analytical methods

Representative samples were collected, where possible, from homogeneous outcrops showing minimal migmatitic segregation. Localities in Table 1 are quoted to the nearest 100 m relative to the NAD 83 datum, within the 100 km grid square denoted PM/PB. Samples were crushed very carefully to achieve powders representative of 1–2 kg of rock, with larger samples for coarse-grained material. Experimental techniques are exactly as in Dickin & Guo (2001). Nd isotope analyses were measured by dynamic multi-collection, normalized to $^{146}Nd/^{144}Nd = 0.7219$, and are quoted relative to a value of 0.51185 for the La Jolla standard. Average within run precizion was ± 0.000012 (2 sigma), and the analytical uncertainty on model ages averages ± 20 Myr, based on analysis of duplicate sample dissolutions in this and previous studies.

Table 1. Sm–Nd data for gneissic rocks from the North Bay–Bonfield area

Map no.	Field no.	Grid reference	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd} 1.70	T_{DM} (Ga)
Dickin & McNutt (1989); Holmden & Dickin (1995)								
1	MR66.0	PB 177/331	2.53	0.41	.0971	.511728	4.0	1.72
2	MR71.2	PB 205/294	98.30	18.63	.1146	.511923	4.0	1.72
3	MR77.1	PB 238/247	51.96	10.01	.1164	.512029	5.6	1.59
4	NB4	PB 163/312	29.72	5.66	.1151	.512031	6.0	1.56
Palaeoproterozoic crust at North Bay								
5	BO74*	PB 191/267	54.90	9.01	.0993	.511670	2.3	1.83
6	BO85	PB 219/245	50.51	8.89	.1064	.511715	1.7	1.89
7	BO83	PB 223/240	48.26	7.99	.1000	.511647	1.7	1.87
8	BO23	PB 266/205	74.76	12.24	.0990	.511631	1.6	1.88
9	BO29	PB 272/199	80.81	14.19	.1062	.511722	1.9	1.87
10	BO50	PB 282/169	45.22	8.98	.1200	.511814	0.6	2.00
11	BO52	PB 293/170	79.43	14.12	.1074	.511717	1.5	1.90
12	BO41	PB 375/028	45.51	8.97	.1191	.511820	0.9	1.97
13	BO44*	PB 292/235	83.95	17.77	.1280	.511809	−1.2	2.20
14	BO45	PB 310/243	58.13	10.09	.1049	.511677	1.3	1.91
15	BO43	PB 317/243	45.47	8.58	.1140	.511765	1.0	1.95
16	BO55	PB 373/224	35.49	6.44	.1096	.511704	0.8	1.96
17	BO57	PB 412/208	28.30	4.78	.1021	.511652	1.4	1.90
18	BO70*	PB 206/315	27.11	4.88	.1089	.511721	1.2	1.92
19	BO34	PB 325/298	41.82	7.32	.1058	.511714	1.8	1.88
20	BO14	PB 347/302	51.17	8.99	.1062	.511731	2.0	1.86
21	BO18	PB 387/295	28.56	6.10	.1291	.511998	2.2	1.88
22	BO17	PB 412/296	54.19	9.88	.1102	.511757	1.7	1.89
23	BO58	PB 439/301	34.32	5.38	.0948	.511558	1.1	1.90
24	BO88	PB 140/346	35.83	6.78	.1143	.511815	1.9	1.88
25	BO87	PB 146/327	62.45	11.87	.1148	.511801	1.5	1.91
26	BO10	PB 158/327	82.19	15.49	.1139	.511779	1.3	1.93
27	BO67	PB 177/333	70.25	14.97	.1288	.511910	0.6	2.04
28	BO69	PB 187/327	109.45	19.08	.1054	.511674	1.1	1.93
29	BO9	PB 385/372	77.02	14.53	.1140	.511820	2.1	1.87
30	BO6	PB 394/375	38.22	6.89	.1089	.511744	1.7	1.89
31	BO8	PB 443/365	38.99	6.37	.0988	.511625	1.6	1.88
North Bay terrane								
32	BO80	PB 183/290	58.10	10.20	.1061	.512018	7.7	1.45
33	BO71	PB 222/299	125.08	21.73	.1050	.511940	6.4	1.54
34	BO73*	PB 228/308	35.01	6.52	.1126	.512008	6.0	1.56
35	BO35*	PB 261/290	29.85	3.97	.0803	.511719	7.5	1.51
36	BO12	PB 268/303	20.59	5.04	.1479	.512287	3.8	1.75
37	BO13	PB 305/301	71.29	13.66	.1158	.512092	7.0	1.48
38	BO15*	PB 336/303	24.63	5.17	.1265	.512170	6.2	1.52
39	BO16	PB 396/291	96.37	17.93	.1125	.511987	5.7	1.59
40	BO59	PB 341/258	71.11	14.17	.1205	.512018	4.5	1.67
41	BO60	PB 357/258	11.06	2.31	.1265	.512057	4.0	1.72
42	BO37	PB 424/257	48.80	9.26	.1147	.512031	6.0	1.56
43	BO76	PB 230/243	72.27	13.35	.1117	.511975	5.6	1.59
44	BO20	PB 249/226	38.06	7.34	.1166	.511940	3.9	1.73
45	BO51	PB 270/211	55.72	10.69	.1160	.511990	5.0	1.64
46	BO48	PB 269/209	5.34	1.03	.1171	.511912	3.2	1.78
47	BO25	PB 272/204	39.31	7.56	.1163	.512015	5.4	1.61
48	BO31	PB 286/183	40.94	8.20	.1210	.512024	4.5	1.67
49	BO82	PB 291/176	58.55	11.92	.1230	.512112	5.8	1.56
50	BO81	PB 291/175	62.61	13.75	.1328	.512208	5.6	1.57
51	BO40	PB 301/165	230.7	40.07	.1050	.512008	7.7	1.45
52	BO78	PB 333/151	41.28	7.62	.1116	.512026	6.6	1.51
53	BO79	PB 336/143	42.71	8.03	.1136	.511964	5.0	1.64
54	BO42	PB 378/139	81.12	12.07	.0899	.511785	6.7	1.55
Archaean crust								
55	NB101	PB 124/326	2.55	0.67	.1588	.512048	−3.2	2.80
56	NB109	PB 094/342	16.18	2.81	.1049	.511083	−10.4	2.77

* Average of two repeat dissolutions.

6. Results

Nd isotope data are presented in Table 1, divided into an parautochthonous terrane with T_{DM} ages above 1.8 Ga (Palaeoproterozoic crust), and an allochthonous terrane with T_{DM} ages below 1.8 Ga (the North Bay terrane). The results are plotted in Figure 3 on a Sm/Nd isochron diagram, along with published data from Holmden & Dickin (1995) and Dickin & Guo (2001). In this diagram, Palaeoproterozoic gneisses from the

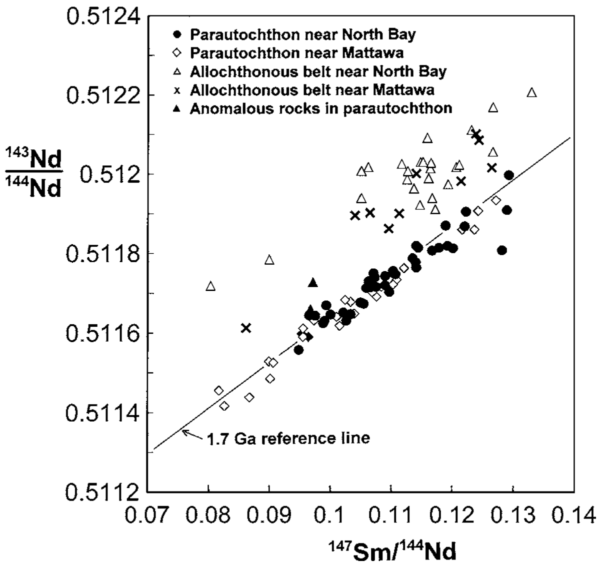

Figure 3. Sm–Nd isochron diagram comparing rocks from the North Bay and the Mattawa areas that fall respectively within the Palaeoproterozoic parautochthon or the allochthonous belt. Two anomalous rocks (see text for discussion) from the parautochthon are shown by solid triangles.

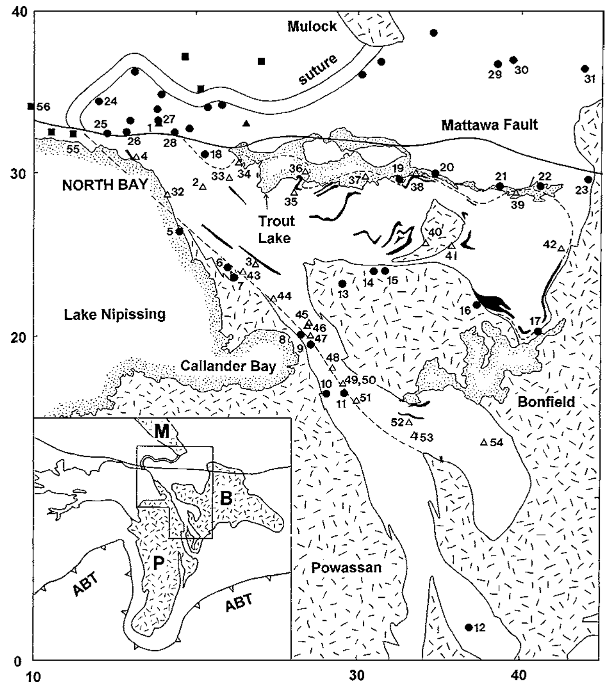

Figure 4. Map of the North Bay area showing the extent of the allochthonous terrane defined by T_{DM} ages below 1.8. Symbols as in Figure 3, and also: solid squares = Archaean gneisses; black shading = metabasic rocks; stipple = major granites; dashed line = proposed location of the Allochthon Boundary Fault. 10 km grid lines, shown by tick marks, are based on the North American Universal Transverse Mercator (UTM) grid, using the 1927 datum (NAD 27). The inset map gives the regional context and identifies the Allochthon Boundary Fault (ABT), the Powassan Batholith (P), the Bonfield batholith (B) and the Mulock Pluton (M).

North Bay parautochthon (solid symbols) are compared with data from the corresponding terrane at Mattawa, indicated by open diamonds (Dickin & Guo, 2001). The two data sets are strongly colinear, although the North Bay data display slightly more scatter, possibly due to more intense magmatic reworking in this area. The array clusters round a 1.7 Ga reference line, and was interpreted by Dickin & Guo (2001) as the result of north-dipping subduction under a recently accreted juvenile arc terrane. The minimum age of this terrane is 1.74 Ga, based on U/Pb dating of a plutonic orthogneiss from Pointe au Baril (Krogh, Culshaw & Ketchum, 1992). Hence this terrane (shown stippled in Fig. 2b) was named Barilia by Dickin (2000).

Allochthonous gneisses at North Bay (open triangles) and the Mattawa area (crosses) have Nd signatures lying above the Palaeoproterozoic array, but with much more scatter. As a result, Dickin & Guo (2001) attributed these data to a long-lived ensialic arc in which juvenile mantle-derived magmas mixed with older crustal material in events spanning a long period of time from *c.* 1.7 to 1.4 Ga. It has not been possible to identify any patterns of model age distribution within the allochthonous belt of the Central Gneiss Belt, suggesting that the arc was stationary over this area for a long period.

Two anomalous samples, indicated by solid triangles, have model ages younger than 1.8 Ga, but plot within the area of the parautochthon. The anomalous samples are MR66 in Table 1 and sample CH19 from Holmden & Dickin (1995). The first of these was analysed in the reconnaissance study of grey gneisses by Dickin & McNutt (1989), but turns out to be a younger anorthosite body analysed in error. This is shown, for example, by its anomalously low Nd content of 2.5 ppm. There is no simple explanation for the anomalously low model age measured on CH19, but at 1.78 Ga it is only slightly below the cut-off of 1.8 Ga, and may be due to minor remobilization of Sm and Nd during Mesoproterozoic thermal events.

Sample localities from Table 1 and relevant data from Holmden & Dickin (1995) are plotted on a map of the North Bay area (Fig. 4) in order to examine the geographical distribution of the parautochthonous and allochthonous terranes. With the exception of the two anomalous samples just mentioned, a single line of demarcation, interpreted as the Allochthon Boundary Thrust, can be drawn between all samples with T_{DM} ages above and below 1.8 Ga. We will now discuss the detailed distribution of parautochthonous and allochthonous rocks in Figure 4, beginning at the lake shore in North Bay.

Within the city of North Bay, allochthonous rocks are exposed at a few localities on the lake shore, but moving southeastwards the Powassan batholith is encountered, within which screens of country rocks (localities 5–7) yield model ages characteristic of the parautochthon. These findings are consistent with Ketchum & Davidson (2000), as shown in Figure 2a. However, moving further to the southeast, T_{DM} ages above 1.8 Ga are observed to the east of the Powassan batholith (localities 8–11), suggesting that here the Allochthon Boundary Thrust trends to the southeast rather than following the margin of the Powassan batholith to the south. This is confirmed by the Nd model age from locality 12 (1.97 Ga), which lies in the south of the field area between two of the arms of the Bonfield batholith.

In order to determine the structural position of the Bonfield batholith, five screens of grey gneiss were analysed within or at the northern margin of the pluton (localities 13–17). These all yield T_{DM} ages over 1.8 Ga, supporting the suggestion of Dickin & Guo (2001) that the Bonfield pluton is located structurally below the Allochthon Boundary Thrust, within the parautochthonous footwall. Hence, these samples provide very strong evidence that the allochthonous terrane at North Bay is an erosional outlier, and that the main trace of the Allochthon Boundary Thrust is located to the southeast, as proposed by Dickin (2000). Further evidence for this interpretation is provided by two samples of grey gneiss collected from near Lake Kawawamog, east of the Powassan batholith (R. B. North, unpub. M.Sc. thesis, McMaster Univ., 2001). These support a location for the main trace of the Allochthon Boundary Thrust near the line shown in Figure 2b.

Mapping by Lumbers (1971) indicated that folding patterns to the north of the Bonfield batholith were very complex. Hence, samples were collected along the length of Trout Lake south of the Mattawa fault in order to constrain the northern boundary of the allochthonous North Bay terrane. These samples demonstrate that the sole thrust of the terrane can be drawn as a single surface between localities 18–23 on the north side and 33–39 on the south side, consistent with mapped foliation directions. The outcrop of the sole thrust lies 1 to 4 km south of the Mattawa fault along the whole length of Trout Lake, but finally adopts a northeast trend within the city of North Bay, parallel to the opposite margin of the terrane on the Nipissing lakeshore. Immediately north of the city, both margins of the allochthonous terrane are cut off by the Mattawa fault, and (as observed by Ketchum & Davidson, 2000), allochthonous rocks do not seem to re-appear to the north of the fault. This is demonstrated by localities 25–28, which give T_{DM} ages of 1.91–2.04 Ga. Since the Mattawa fault is a post-Grenvillian normal fault associated with the Ottawa–Bonecherre graben, it is inferred that uplift on the north side of the fault was sufficient to allow erosion to remove all traces of the terrane.

Finally, two new samples from west of North Bay gave Archaean model ages (Table 1). When combined with mapped foliation directions (Lumbers, 1971), these set tighter limits on the westward extension of parautochthonous Palaeoproterozoic rocks north of the Mattawa fault, and allochthonous Mesoproterozoic rocks south of the Mattawa fault. Hence it appears (Fig. 4) that the suture and the Allochthon Boundary Thrust are here nearly colinear. Probably the trajectory of the suture was folded around the nose of the northward-thrusted allochthon. Thus, the suture is predicted to follow an ‘S’-shaped pattern before tracking to the southwest across Lake Nipissing. However, further sampling will require drilling of the lake bed.

7. Discussion

Having mapped the boundaries of the allochthonous North Bay terrane using Nd isotope data, we can now compare these results with the mapping of Lumbers (1971). As noted by Ketchum & Davidson (2000), their sampling was itself based on the original mapping of Lumbers in this area. However, since Lumbers interpreted the whole Central Gneiss Belt as largely metasedimentary, hornblende gneisses at North Bay were mapped as metasedimentary ‘calc-silicate gneiss’. As mentioned in Section 4, it is now realized that the Central Gneiss Belt largely has an igneous protolith, and similarly the calc-silicate gneisses are recognized as metabasic intrusions.

Examination of Figure 4 shows that the outcrop pattern of the metabasic intrusions matches very well with the extent of the allochthonous terrane determined from Nd isotope mapping, suggesting that the majority of these outcrops represent coronitic metagabbro of the 1.16 Ga suite identified by Ketchum & Davidson as indicators of allochthonous rocks. This is confirmed by the distribution of geochemically analysed samples (Fig. 5), which almost exactly matches the extent of the terrane. As argued by Ketchum & Davidson, “The mutually exclusive distribution of the mafic suites points to a significant separation of allochthonous and parautochthonous components prior to the Grenvillian orogeny”, and hence demonstrates that the terrane boundary identified by Nd isotope mapping is tectonic (that is, the Allochthon Boundary Thrust), and not an intrusive contact.

Based on the distribution of Nd model ages and metabasic rock types, we conclude that the allochthonous terrane at North Bay represents a structural klippe. This is consistent with the terminology of Hatcher (1995), where it is applied to the erosional outliers of thrust sheets, resulting from either dissection of a flat sheet, or planation of a folded thrust sheet.

In order to make further deductions about the three-dimensional shape of the klippe, we can examine the strike and dip measurements recorded by Lumbers (1971) in the vicinity of its margins. It is apparent from Figure 4 that the northern margin of the klippe along Trout Lake is strongly folded, and this gives rise to large variations in the dip as well as the strike of the foliation, although the average dip direction is southwards (170°)

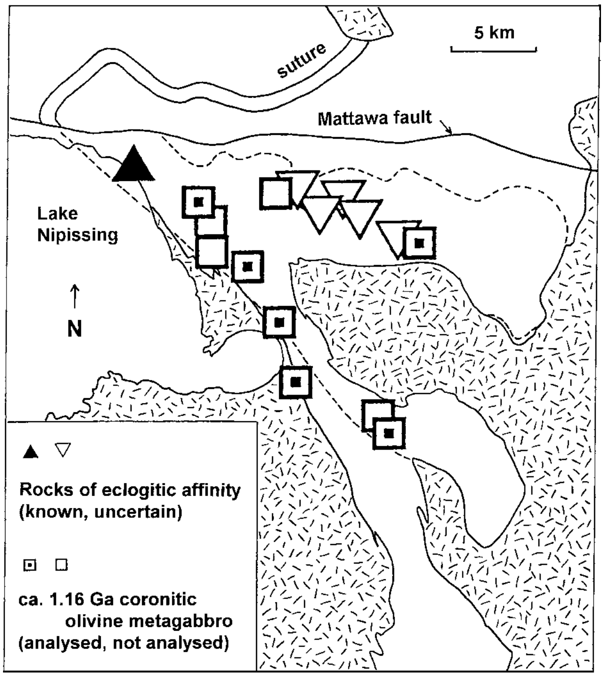

Figure 5. Map of the North Bay area showing the distribution of metabasic rocks. Symbols representing probable and analysed coronitic olivine metagabbro are superimposed directly from the map of Ketchum & Davidson (2000), since no locality data were given in that work.

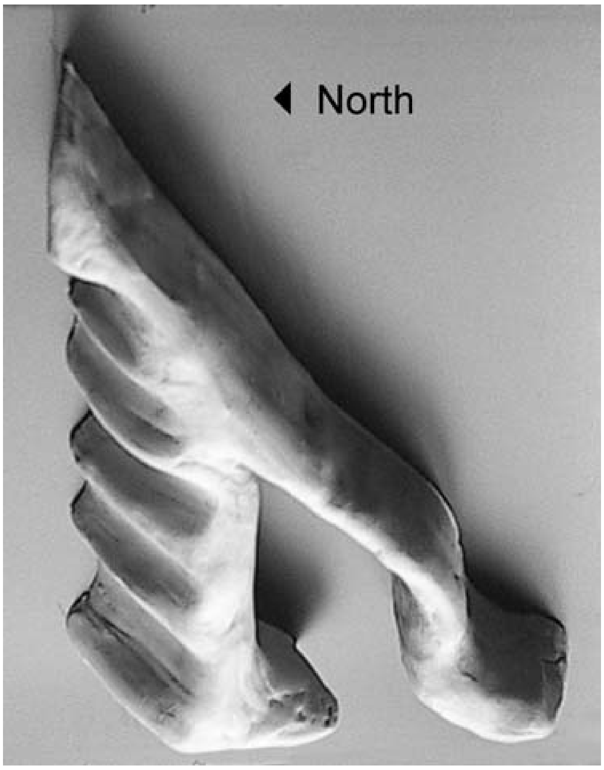

Figure 6. Reconstructed view of the North Bay klippe looking upwards and to the east from a point on the Mattawa fault north of Lake Nipissing, near the base of the crust. This view shows the proposed structure of the lobate isoclinal synform, whose outer surface is interpreted as the trace of the Allochthon Boundary Thrust. The field of view is 30 km wide.

at an angle of 60°. On the other hand, the strike along the northern margin of the Bonfield batholith (near localities 14–15) is much more consistent, but curiously enough, the average value is very similar, with a 190° dip direction and a 65° angle of dip. Hence, the klippe is essentially an inclined sheet, with its southern margin over-ridden by the Bonfield batholith. However, based on the preferred occurrence of metabasic rocks along the north and southeast margins of the klippe, we suggest that it is actually an isoclinally folded thrust sheet which originally had a layer of mafic rock at its base. We suggest that this sheet was probably thrust to the northwest as a semi-flat sheet approximately 2 km thick, and subsequently folded as a result of additional orogenic convergence. The over-riding (rigid) lobe of the Bonfield batholith was probably responsible for disruption or removal of the metabasic rocks along the northern margin of the pluton, whereas they are less disrupted between the arms of the batholith (near locality 17).

The other lobe of the klippe, along the Nipissing lakeshore, has a steeper dip. The eastern margin, against the Bonfield batholith, dips at an average angle of 80° to the southwest. The western margin of the klippe has the same strike, but here the dip is almost exactly vertical. However, within the margin of the Powassan batholith southeast of Callander Bay, the dip is 75° to the east. Hence, it appears that this arm of the klippe forms the core of a vertical isoclinal synform. Again, the approximate thickness of the klippe before doubling was approximately 2 km, although it has been thinned by compression between the more rigid Powassan and Bonfield batholiths.

An attempt has been made to portray the three-dimensional form of the folded klippe in Figure 6 by means of a photograph of a clay model. This is a preliminary model which, it is hoped, can be refined in the future using geophysical data. The 'view point' is from the interior of the earth, looking upwards to the east from a location on the Mattawa fault, by the north shore of Lake Nipissing (that is, the North direction is to the left). The prominent shadows pick out the corrugated dipping surface of the klippe along the south shore of Trout Lake, whereas the thinner, vertical arm of the klippe is to the right. At the top left, the klippe is truncated by the Mattawa fault.

Three localities along the margin of the klippe were studied in more detail in an attempt to determine the width of the basal shear zone. The southwest margin of the klippe was chosen for this purpose because it has the most consistent strike. These localities included the E–W section of Highway 11B south of the city (samples 7 and 43), the disused railroad southeast of Callander Bay (11 and 50), and the four-lane highway northeast of Callander Bay (9 and 47). Unfortunately, the boundary zone was not exposed at the first two localities, due to the presence of glacial deposits, which obscure more than 50 % of the bedrock geology in the North Bay area. However, on the four-lane section of Highway 11, allochthonous and parautochthonous rocks were seen in close proximity. Here the northeast margin of the Powassan batholith contains several discrete zones of intense shear, separated by panels of less deformed and more massive, coarse grained granitic gneiss. Sample BO29 (locality 9) was collected to the north of one of these major shear zones, whose grid reference in the UTM 100 km grid square 'PB' is 27.24 km E and 19.93 km N. However, the model age of this sample (1.87 Ga) shows that it is still in the footwall of the Allochthon Boundary Thrust. Going 0.2 km to the north, on the other side of a service connection between the north and south lanes, Mesoproterozoic grey gneisses containing abundant metagabbro pods were seen. Hence the actual trace of the thrust must be covered by the service road, in the gap between the two outcrops. Probably the main shear zone is a zone of preferential erosion, because at most localities which straddle the boundary it seems to be represented by a gully.

8. Conclusions

Nd isotope data have been successfully used to map the extent of an allochthonous klippe of rocks with largely Mesoproterozoic crustal formation ages at North Bay, surrounded by rocks which were formed as part of a Palaeoproterozoic juvenile arc terrane. The extent of the allochthonous terrane determined by isotope mapping is consistent with a distinctive suite of metagabbroic rocks which were shown by Ketchum & Davidson (2000) to be restricted to the Grenvillian allochthonous belt. This provides evidence that this klippe is an erosional remnant of a far-travelled thrust sheet, whose main mass lies 50 km to the southeast. Nd isotope mapping is shown to be a powerful technique for terrane mapping in high-grade orogenic belts, where other geological evidence normally used to distinguish tectonic units has been obscured by intense metamorphism.

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