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Abstract

Many occurrences of metadiabase in the parautochthonous belt of the Grenville Province in Ontario have a geochemical signature indistinguishable from that of Sudbury diabase in the adjacent Superior and Southern provinces, and some bodies close to the Grenville Front are known to have the same ca. 1.24 Ga age. However, dating of baddeleyite in metadiabase with Sudbury-type chemistry from a small mass enclosed in orthogneiss near Key Harbour shows it to be at least 200 Ma older than Sudbury diabase, which casts doubt on the use of rock chemistry as a correlation tool for tracing the extent of Sudbury metadiabase within the parautochthon. Despite this, the common chemical signature of metadiabase of whatever age in the parautochthonous footwall of the allochthon boundary thrust zone serves as a distinction from the 1.17–1.15 Ga coronitic metagabbro in the hanging wall, the two being spatially mutually exclusive.

Résumé

De nombreuses métadiabases observées dans le Parautochtone de la Province de Grenville en Ontario présentent une signature géochimique qui ne peut être différenciée de celle des diabases de Sudbury présentes dans les secteurs limitrophes de la Province du lac Supérieur et de la Province du Sud. En outre, certaines de ces métadiabases situées à proximité du front de Grenville sont également du même âge (env. 1,24 Ga) que les diabases de Sudbury. Cependant, la datation de la baddeleyite contenue dans la métadiabase d'une petite masse encaissée dans des orthogneiss près de Key Harbour indique un âge plus ancien d'au moins 200 millions d'années que celui des diabases de Sudbury, bien que les deux lithologies présentent des compositions chimiques semblables. Ce résultat remet donc en question l'utilité de la composition chimique des roches comme outil de corrélation afin de définir l'étendue des diabases de Sudbury dans le Parautochtone. Malgré cela, la signature chimique habituelle des métadiabases de tous âges présentes dans le Parautochtone, dans le mur de la zone limite de chevauchement de l'Allochtone, permet de différencier celles-ci des métagabbros coronitiques âgés de 1,17 à 1,15 Ga que l'on observe dans le toit de cette zone tectonique, les deux groupes occupant des espaces distincts.

INTRODUCTION

It can be implied that where specific rock units are present on both sides of a tectonic boundary, the two blocks of crust containing them were adjacent to one another when these rocks were deposited or emplaced. Conversely, the restriction of a particular rock unit to one side of a tectonic boundary may indicate that one block is allochthonous with respect to the other. In the Grenville Province, the Grenville Front is an example of the first case, and the allochthon boundary thrust zone farther southeast within the province, an example of the second (Rivers et al., 1989). Bethune (1993, 1997) and Dudás et al. (1994) confirmed earlier suggestions (e.g. Palmer et al., 1977; Frarey, 1985) that olivine diabase dykes of the

Sudbury swarm occur on both sides of the Grenville Front, and Ketchum and Davidson (2000), using the distinctive chemistry of these dykes to trace them southeastward within the Grenville Province, established that they do not occur in the hanging wall of the allochthon boundary thrust.

In the Southern Province, southeast-trending, vertical, olivine diabase dykes of the Sudbury swarm (Fahrig et al., 1965) are unmetamorphosed and are deformed only to the extent that they are cut by faults that have only minor lateral offsets. Primary baddeleyite in diabase of this swarm has been dated at ca. 1.24 Ga (Krogh et al., 1987; Dudás et al., 1994), an age that precedes major deformation and metamorphism in the neighbouring part of the Grenville Province (**Fig. 1**). In the region between Georgian Bay and Sudbury, dykes of this swarm, despite disruption at the Grenville Front, can be traced for several kilometres into the Grenville Province where they become increasingly deformed and metamorphosed (Bethune, 1993, 1997; Bethune and Davidson, 1997). For metadiabase in the Grenville Front tectonic zone (Fig. 1), Dudás et al. (1994) reported U-Pb baddeleyite ages similar to those obtained for Sudbury diabase in the Southern Province, and late Grenvillian (ca. 1000 Ma) metamorphic ages on secondary zircon from the same rocks.

Whole-rock geochemistry of Sudbury diabase is distinctly enriched in K, Fe, P, Ba, S, light rare-earth elements and other high field-strength elements compared to diabase of most other dyke swarms in the Canadian Shield (Fahrig et al., 1965; Condie et al., 1987). Bethune (1993) showed that this characteristic chemistry is maintained in metadiabase in the hanging wall of the Grenville Front. Ketchum and Davidson (2000) used this characteristic among unconnected metadiabase masses and dyke remnants in Britt domain and elsewhere to extend the range of the Sudbury swarm for 100 km or more southeast of the front, far beyond the limit established on the basis of age determination (Fig. 1). They also showed that mafic rocks with this chemistry do not appear to continue beyond a major, southeast-dipping high-strain zone, above which coarse-grained coronitic metagabbro, itself absent in the footwall of this zone, has a different, less enriched whole-rock chemistry and whose age has been determined to be ca. 70 to 90 Ma younger than Sudbury diabase (1170 ± 30 Ma, Davidson and van Breemen, 1988; van Breemen and Davidson, 1990; 1152 ± 2 Ma, Heaman and LeCheminant, 1993). This high-strain zone is also the locus of the first appearance, southeast of the front, of remnants of retrograded eclogite, and is taken as the locus of the allochthon boundary thrust zone, marking the southeastern boundary of parautochthonous rocks within this part of the Grenville Province.

At this point it is necessary to discuss an alternative age interpretation for the coronitic metagabbros discussed above. Whereas Indares and Dunning (1997) argue for an older age of 1211 Ma with large uncertainties and allowing overlap with Sudbury dyke ages, we consider this interpretation to be unlikely for the following reasons. Davidson and van Breemen's regression of U-Pb baddeleyite analyses from four samples was anchored to a zircon metamorphic age of 1060 Ma and did not take into account a likely component of recent Pb-loss. Their 1170 Ma upper intercept age was therefore likely to be high, not low. Heaman and LeCheminant subsequently found magmatic zircon in one of these metagabbros and a best fit regression line through five single zircon analyses, three of which were nearly concordant, yielded the age of 1152 Ma (*see* above). Their single baddeleyite analysis plots on the regression line with a $^{207}Pb/^{206}Pb$ model age of 1139 Ma, which is identical to the maximum $^{207}Pb/^{206}Pb$ age reported by Davidson and van Breemen. There is, therefore, consistent isotopic evidence for an 1160–1150 Ma igneous age for all these coronitic gabbros, not only from separate samples, but also from distinct U-Pb mineral systems. In addition, it is noted that the error ellipse of one of the baddelyite analyses reported by Indares and Dunning (1997, Fig. 3c) for coronitic metagabbro intersects concordia at 1142 Ma.

It is not practicable to date enough samples of metadiabase and metagabbro to pin down the boundary on a geochronological basis; even if it were, it is commonly observed in thin section that primary baddeleyite in these rocks has been completely converted to zircon during Grenvillian metamorphism, thus making it unlikely that primary igneous crystallization ages could be obtained. Using characteristic whole-rock chemistry as a proxy for precise age determination is thus probably the best alternative, although it does not necessarily follow that all chemically similar rocks have the same age.

In Britt domain, several masses of amphibolite and metadiabase are well exposed along the rocky shores of Georgian Bay in the vicinity of Key Harbour, some 50 km southeast of the Grenville Front (**Fig. 1**; Davidson and Bethune, 1988; Corrigan et al., 1994). A thin section of a sample collected from the little-altered core of one of these metadiabase masses revealed not only the presence of primary baddeleyite in the cores of partial pseudomorphs of polycrystalline zircon after formerly larger baddeleyite crystals, but also small grains or small aggregates (three or four prisms) of fresh baddeleyite, including long, thin, curved, hair-like crystals (**Fig. 2**), that are not associated with secondary zircon. It was noted that most unaltered baddeleyite occurs within the sodic outer parts of plagioclase laths, and that polycrystalline zircon pseudomorphs are generally associated with secondary biotite surrounding Fe-Ti oxide grains or occur at plagioclase grain boundaries. The host rock is a classic coronite; it contains relics of primary olivine surrounded by successive rinds of orthopyroxene, clinopyroxene, and garnet symplectite, and the cores of its primary plagioclase laths are clouded with dark spinel dust. It is in every way like metadiabase in the southeasternmost parts of continuously traced Sudbury dykes within the Grenville Province, some 20 km to the northwest (*see* Bethune and Davidson, 1997, Fig. 1). Moreover, its whole-rock chemistry conforms to that of typical Sudbury diabase (**Fig. 3**). The metadiabase body in question underlies all of an islet, some 20 m in diameter, in a channel along the north shore of Georgian Bay, 4 km west-northwest of Key Harbour. The nearest islands and peninsulas are underlain by uniform granitoid orthogneiss with K-feldspar megacrysts, migmatitic in part, and similar in aspect to the nearby Mann Island granodiorite, which has been dated at ca. 1442 Ma (Corrigan et al., 1994). A large sample of this metadiabase was collected for U-Pb analysis in order to test whether the Sudbury mafic dyke swarm continues southeast of the Grenville Front tectonic zone into Britt domain.

GEOCHRONOLOGY

The extract of non-magnetic heavy minerals from a sample of the metadiabase described above was composed mainly of zircon in the form of polygonal or columnar aggregates of 1–2 mm grains, the aggregates being pseudomorphous after single baddeleyite crystals, a very few of which retained small remnants of primary baddeleyite in their cores. In addition, clean, light brown, baddeleyite prism fragments made up about 2% of the extract. It is of interest to note that, unlike separates obtained by Davidson and van Breemen (1988) from coronitic metagabbro that contained mainly rough-surfaced baddeleyite crystals from which secondary zircon had broken away during crushing, all the baddeleyite grains mixed in with polycrystalline zircon pseudomorphs were broken pieces with smooth prism faces, some with one end retaining terminal crystal faces. In addition, the clean, hair-like crystals noted in thin section were not represented in the separates, and presumably did not survive the crushing procedure, so it is not known whether they represent a generation of baddeleyite different in age to that of the coarser prisms.

For analytical techniques, *see* Nadeau and van Breemen (2001). Three fractions of baddeleyite (A–C) and one of zircon aggregates lacking baddeleyite cores (D) were analyzed (**Table 1**); results are plotted in **Figure 4**. The zircon fraction is 1.4% discordant and has a $^{207}Pb/^{206}Pb$ age of 1013 ± 2.4 Ma, within the range of the $^{207}Pb/^{206}Pb$ ages (985–1032 Ma) obtained by Dudás et al. (1994) for zircon aggregates extracted from Sudbury metadiabase within the Grenville Front tectonic zone to the north. The three baddeleyite analyses, however, are more discordant (4.6–7.4%) and are not collinear, and for this reason do not yield a precise age. Their discordance is likely a mixture of two components: Pb-loss at some stage of Grenville metamorphism and recent Pb-loss as documented in Heaman (1997). The $^{207}Pb/^{206}Pb$ ages of 1287 Ma, 1343 Ma, and 1454 Ma indicate a minimum age of 1.45 Ga, which is too old to allow the metadiabase to be correlated with the Sudbury swarm. It is conceivable that the larger baddeleyite grains extracted for dating are inherited, although inherited baddeleyite in any rock type has yet to be reported. Assuming that the baddeleyite is primary, its isotopic analyses indicate that the metadiabase is at least 200 Ma older than Sudbury diabase. Assuming further that the country rock to the metadiabase is roughly coeval with other igneous rocks in the Britt domain (*see* below), the age of the metadiabase is likely close to 1.45 Ga.

DISCUSSION

The identification of metadiabase with whole-rock chemistry indistinguishable from Sudbury diabase, yet which is in the order of 200 Ma older, casts serious doubt on the technique of using chemistry of unconnected dyke remnants for correlation purposes in order to determine how far into the Grenville Province remnants of the Sudbury swarm extend. None of the dated sample sites is anywhere near the allochthon boundary thrust zone (ABT in **Fig. 1**), and it is therefore crucial to find sample sites for metadiabase with preserved primary baddeleyite in the immediate footwall of this structure in order to test further whether Sudbury metadiabase remnants extend as far southeast as the allochthon boundary thrust zone.

The older age obtained for the Key Harbour metadiabase sample does not, however, invalidate Ketchum and Davidson's (2000) conclusion that metadiabase with enriched chemistry, distinct from the coarse-grained coronitic metagabbro in the hanging wall, is restricted to the footwall of the allochthon boundary thrust, and that the coronitic metagabbro is restricted to the hanging wall. The ca. 1450 Ma age of the Key Harbour metadiabase, although imprecise, places it in the age range of a number of orthogneiss plutons in the same region (Britt pluton, 1456.5 +8.5/-5.9 Ma, van Breemen et al., 1986; Mann Island pluton, 1442 +7/-6 Ma, Corrigan et al., 1994; King Island pluton, 1467 +11/-7 Ma, Davidson and van Breemen, 1994), and it is not unlikely that it is genetically related. The rocks of this metamorphosed plutonic suite that have been dated are all granitoid (megacrystic granodiorite, quartz monzonite). However, this plutonic suite includes rocks ranging from gabbro and anorthosite through diorite, monzodiorite, and granodiorite to syenite and granite, suggesting an A-type affinity, particularly in the continuous range of compositions at low silica content. If this character is confirmed by subsequent petrochemical study, then whether this suite represents a typical Andean-type magmatic arc, as suggested by Rivers (1997) and Rivers and Corrigan (2000) will need to be re-evaluated.

If the plutonic rocks and tectonic remnants of coeval metadiabase in the parautochthonous belt are related, then it is important to note that metaplutonic rocks of similar age (e.g. Krogh and Davis, 1969; van Breemen and Davidson, 1990; Timmermann et al., 1997; Nadeau and van Breemen, 1998) are present in the allochthonous terranes structurally above the allochthon boundary thrust zone; however, numerous chemical analyses of metamafic rocks in the allochthonous terranes (e.g. Grant, 1987) have not, so far, revealed any that have the enriched chemistry of metadiabase in the Grenville parautochthon, and all age determinations have yielded ages in the range 1170–1150 Ma.

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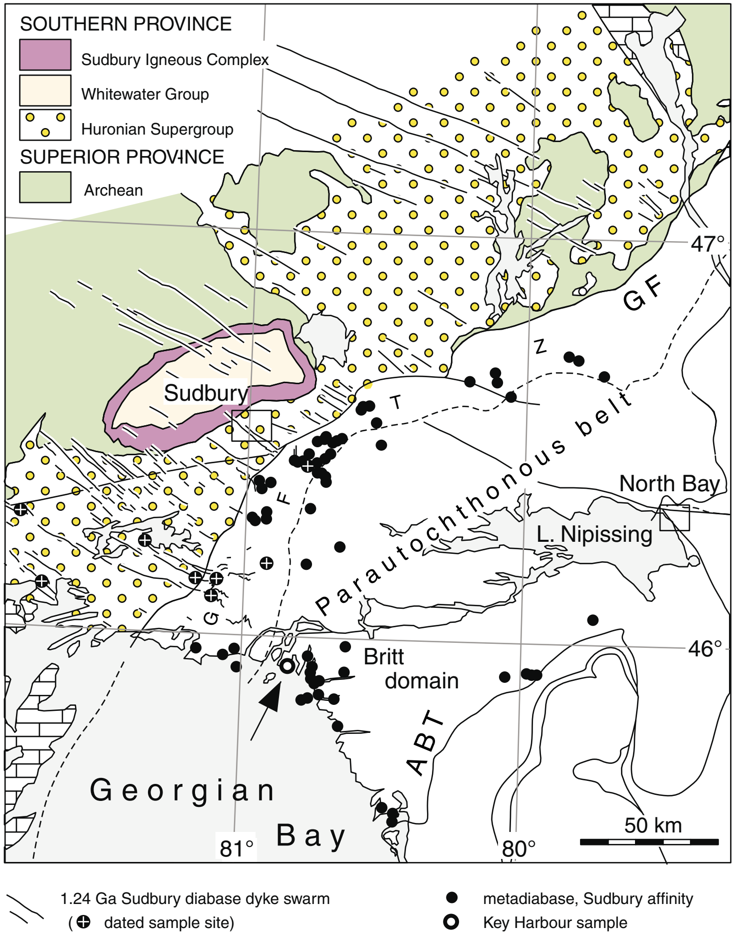

Figure 1. Generalized map of the Grenville Front in Ontario showing the distribution of Sudbury dykes in the adjacent Superior and Southern provinces, occurrences of metadiabase in the Grenville Province that have the same chemical characteristics as Sudbury diabase, the locations of previously dated samples on both sides of the front, and the location (arrow) of the metadiabase dated in this report. GF is the Grenville Front, GFTZ the Grenville Front tectonic zone, and ABT is the allochthon boundary thrust zone.

Figure 2. Photomicrograph of hair-like baddeleyite crystal enclosed by sodic plagioclase in coronitic metadiabase from the sample site near Key Harbour.

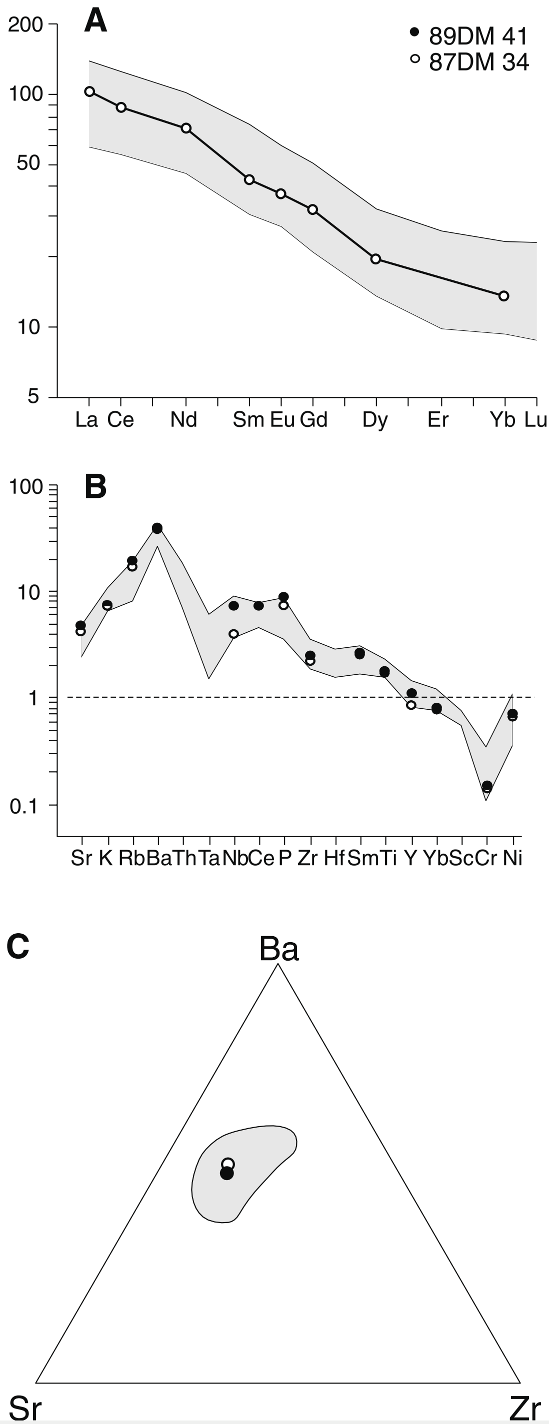

Figure 3. A) Rock/mid-ocean-ridge basalt spidergram (Pearce, 1983; two partial analyses), **B)** rare-earth-element profile (Nakamura, 1974; one analysis), and **C)** Ba/Sr/Zr plot (two analyses) for metadiabase from the sample site near Key Harbour. Ranges for Sudbury diabase are taken from Ketchum and Davidson (2000).

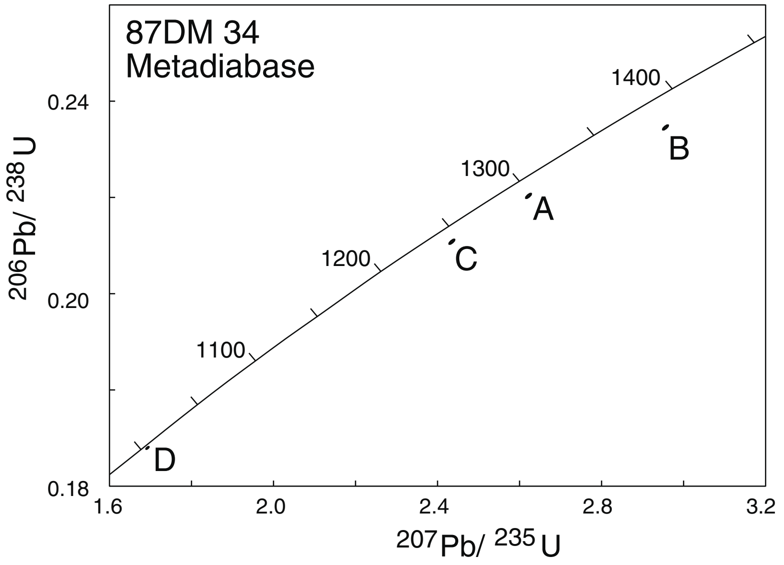

Figure 4. Uranium-lead concordia diagram for baddeleyite and zircon fractions extracted from metadiabase.

Table 1. U-Pb isotopic data for baddeleyite and zircon.

Fraction[1]		Weight[2] µg	U ppm	Pb[3] ppm	$^{206}Pb/^{204}Pb$ [4]	Pb[5] pg	$^{208}Pb/^{206}Pb$ [6]	$^{207}Pb/^{235}U$ [6]	$^{206}Pb/^{238}U$ [6]	$^{207}Pb/^{206}Pb$ [6]	$^{207}Pb/^{206}Pb$ [7]	Disc[8]
Metadiabase pod (87DM 34; z4313) Zone 17 Easting 516725 Northing 5082925												
A, b,	10 x 50–20 x 100	0.014	171	36	5162	6	0.018	0.2204 ± .09	2.620 ± .11	0.08622 ± .04	1343.0 ± 1.5	4.8
B, b,	30 x 60–50 x 100	0.016	317	71	12587	6	0.014	0.2344 ± .09	2.953 ± .10	0.09136 ± .03	1454.2 ± 1.1	7.4
C, b,	30 x 70	0.022	267	53	7100	11	0.015	0.2107 ± .09	2.433 ± .10	0.08374 ± .03	1286.5 ± 1.3	4.6
D, z,	20 x 90–50 x 200	0.018	143	25	4519	6	0.124	0.1677 ± .09	1.687 ± .11	0.07297 ± .06	1013.0 ± 2.4	1.4

[1]b=baddeleyite, z=zircon; approximate grain dimensions are in microns; all fractions are non-magnetic on a Frantz isodynamic magnetic separator at 1.8 amps with a side slope of 5°; [2]error on weight = ±1 µg; [3]radiogenic Pb; [4]measured ratio corrected for spike and Pb fractionation of 0.09 ± 0.03 per cent per AMU; [5]total common Pb on analysis corrected for fractionation and spike; [6]corrected for blank Pb and U, common Pb, errors quoted are 1σ in per cent; [7]age errors quoted are 2σ in Ma; [8]discordance in per cent along a discordia to origin.