Canadian Science Publishing | Canadian Journal of Earth Sciences

Nd isotope mapping of the Grenvillian Allochthon Boundary Thrust in Algonquin Park, Ontario

Journal:	*Canadian Journal of Earth Sciences*
Manuscript ID	cjes-2018-0142.R1
Manuscript Type:	Article
Date Submitted by the Author:	26-Sep-2018
Complete List of Authors:	Dickin, Alan; School of Geography and Geology Strong, Jacob; School of Geography and Geology
Keyword:	Nd isotopes, Model ages, Grenville Province
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

Nd isotope mapping of the Grenvillian Allochthon Boundary Thrust in Algonquin Park, Ontario

A.P. Dickin and J.W.D. Strong

School of Geography and Earth Sciences, McMaster University, Hamilton ON, Canada

Abstract

Over fifty new Nd isotope analyses are presented for high-grade orthogneisses from Algonquin Park and surrounding region in order to map major Grenvillian thrust boundaries. Nd model ages display a consistent geographical pattern that allows detailed mapping of the boundary between the Algonquin and Muskoka domains, here interpreted as the local trajectory of the Ottawan-age Allochthon Boundary Thrust (ABT). The ABT is underlain by a domain with Paleoproterozoic Nd model ages, interpreted as a tectonic duplex entrained onto the base of the main allochthon. The boundaries determined using Nd isotope mapping are consistent with field mapping and with remotely sensed aeromagnetic and digital elevation data. The precise location of the ABT can be observed in a road-cut on Highway 60, on the north shore of the Lake of Two Rivers in the centre of Algonquin Park.

Introduction

Algonquin Park forms part of the Canadian Shield located in the Grenville Province of Ontario (Fig. 1). The Grenville Province represents the deeply exhumed remains of an ancient orogenic belt with similarities to the modern Himalayas. Like the Himalayas, the Grenville Province experienced crustal thickening due to a continental collision, and then underwent gravitational collapse by thrusting. However, the exact locus of this thrusting has proven difficult to determine.

In their early work on this subject, Rivers et al. (1989) recognised the principal locus of Ottawan-age (1080 Ma) thrusting as a major shear zone separating a belt of relatively *in situ* crustal basement to the NW from a belt of laterally transported ‘allochthonous’ thrust sheets to the SE. This boundary, termed the Allochthon Boundary Thrust (ABT) was believed to follow round the north side of Parry Sound domain on Georgian Bay, before traversing eastward with a trajectory sub-parallel to the Monocyclic Belt Boundary (MBB, Fig.1).

This model was abandoned in later work (e.g. Rivers et al., 2002), and a more northerly trajectory was proposed, based on the discovery of allochthonous rocks near North Bay, Ontario (Ketchum and Davidson, 2000). However, it was shown in several subsequent papers (Dickin and McNutt, 2003; Dickin et al., 2012; 2014) that the allochthonous rocks at North Bay (NB, Fig. 1) represent a tectonic outlier or klippe. Hence, Dickin et al. (2017) reinstated the southerly trajectory for the ABT originally proposed by Rivers et al. (1989) in the Georgian Bay area. However, this work did not examine the trajectory of the ABT eastward into Algonquin Park, which is the focus of the present study.

The Geology of Algonquin Park

Based on its large size (7723 square km) and proximity to major population centres, Algonquin Park could form a public showcase of the geology of the Precambrian Shield. However, its geology has been difficult to unravel for a number of reasons. Some difficulties arise from limited vehicle access to the park interior and extensive glacial cover. However, the main difficulty is the high degree of crustal exhumation experienced by Grenvillian gneisses. As a result, most of the rocks in Algonquin Park consist of high-grade granitoid orthogneisses with few distinguishing features. In fact, a geological overview of Algonquin Park has never been achieved.

In the beginning of modern geological mapping in the gneiss belt of Ontario, geological structures were mapped with the assistance of aerial photography, which vividly picked out the locations of major deformation zones in the Parry Sound region (Davidson et al., 1982; Culshaw et al., 1983). These deformation zones were interpreted as tectonic boundaries between distinct 'lithotectonic' domains. This work established a series of distinct units, including the Parry Sound domain itself, and the Algonquin domain to the east (Fig. 2).

The Algonquin domain was separated from the Muskoka domain to the south by a major shear zone (solid black line, Fig. 2), and from the Kiosk domain to the north by another less-distinct shear zone (dotted black line). The Algonquin domain was also subdivided into a number of sub-domains (Culshaw et al., 1983), which were well established to the west of the park, but became less clearly defined within the park itself. Around the same time, Lumbers (1982), working on the eastern side of Algonquin Park, coined the term 'Algonquin Batholith' to signify the igneous protolith of rocks in this area. However, these rocks do not form a batholith in the conventional sense, and the term is therefore not helpful.

During the 1990s, the main research focus continued to be in the Parry Sound area to the west. Here, the GLIMPCE and Lithoprobe seismic reflection profiles supported the structural model of this region as a stack of thrust slices (Culshaw et al., 1983; Culshaw et al., 1997). However, the geology of Algonquin Park was largely neglected during this period.

A significant discovery made by Ketchum and Davidson (2000), following earlier work by Davidson and Grant (1986) and Culshaw et al. (1994), was that different levels in the thrust stack could be distinguished by the presence of different metabasic intrusive bodies. Specifically, the lowest structural level (Britt domain of Davidson, 1984) contained metamorphosed equivalents of 1240 Ma Sudbury diabase dykes, whereas higher structural levels (including Algonquin and Muskoka domains) contained ca. 1160 Ma coronitic olivine metagabbro (black stars in Fig. 2). The latter two structural decks were therefore argued to be allochthonous relative to the underlying Britt parautochthon.

Ketchum and Davidson (2000) joined the most northwesterly outcrops of the allochthonous units to redefine the trend of the ABT (green dashed line passing through North Bay in Fig. 2). This trajectory was much further north than originally proposed by Rivers et al. (1989), and now included all of Algonquin Park within the allochthon. This proposal was described by the original authors as a speculative model, but was adopted by most subsequent workers, beginning with Rivers et al. (2002). However, there was little scientific basis for this interpretation of Algonquin Park, since the region along the northern edge of the park (including the Kiosk type-locality) contains very little meta-basic rock, and is therefore of equivocal affinity in this model.

Since it is based on the presence of younger metabasic rocks, the mapping approach of Ketchum and Davidson (2000) is a proxy method. It characterizes the crust on either side of the ABT boundary by one aspect of their different geological histories, rather than by actual field mapping of the boundary itself. Nd isotope mapping is another proxy approach to mapping the ABT, based on the observation that crust on either side of the boundary has distinct ranges of Nd model ages, reflecting different crustal formation ages (Dickin, 2000). However, unlike the sporadic distribution of metabasic rocks, Nd model ages can be determined on any granitoid orthogneiss. This makes Nd isotope mapping a much more geographically precise method for mapping terrane boundaries such as the ABT.

Dickin and McNutt (2003) showed that in the North Bay area, where metabasic outcrops are numerous (Fig.2), Nd isotope mapping yields results fully consistent with the distribution of metabasic rocks. They concluded that allochthonous rocks in this area form a tectonic outlier or klippe (NB Fig 3), and are not attached to the main allochthon to the south.

Where metabasic rocks are sparse, such as the northern part of Algonquin Park, Nd isotope mapping offers the only effective method for distinguishing parautochthonous and allochthonous crustal affinities. Hence, Dickin et al. (2014) showed that all of the northern part of Algonquin Park consists of Paleoproterozoic parautochthonous crust, except for a small allochthonous klippe near Brent (to be discussed below).

The duplex model

The area in Fig 1 marked by a question-mark corresponds to the Lac Dumoine thrust sheet, which is shown in Fig. 3 based on later geological mapping. The location of the ABT under this thrust sheet was first mapped in detail by Indares and Dunning (1997) at Lac Watson (LW, Fig. 3). However, these authors also showed that an additional structural deck was present in this region, between Archean basement (pink in Fig. 3) and the Mesoproterozoic allochthon (pale green). Nd isotope mapping of this structural deck by Herrell et al. (2006) revealed Paleoproterozoic Nd model ages (averaging 1.9 Ga). This work was extended by Dickin et al. (2012), who showed that this unit forms a nearly continuous band of Paleoproterozoic crust (yellow in Fig. 3) round the main Mesoproterozoic allochthon. Hence they proposed that this deck represents a tectonic duplex entrained onto the base of the allochthon during NW-directed Ottawan-age thrusting.

In the Parry Sound region the crustal structure is more complex, since Parry Sound domain itself represents an additional structural deck overlying the main allochthon. Lithoprobe transects (White et al., 1994) showed that dense rock in Parry Sound domain caused loading of the crust in this area, down-buckling the underlying allochthon (see cross-section in Fig. 3). However, reinterpretation of Lithoprobe line 31 by Dickin et al. (2014; 2017) showed that the overall trajectory of the ABT has a ramp-flat style, with only local down-buckling under Parry Sound domain. This explains the appearance of parautochthonous Paleoproterozoic rocks at the surface in the Lower Rosseau domain (Fig. 3 cross section). Hence, the main ramp of the ABT is located under the Muskoka allochthon, southeast of the Lower Rosseau window (heavy dashed line in Fig. 3 cross-section).

Detailed Nd isotope mapping in the Parry Sound area (Dickin et al., 2017) showed that a tectonic duplex was also present under the main allochthon in this region (mauve in Fig. 3), but with somewhat younger Nd model ages (averaging ca. 1.7 Ga) than in the Quebec part of the duplex. However, the underlying Parautochthon is also younger in the Parry Sound area, since it corresponds to a Penokean arc that was accreted onto the Archean craton to the north (Dickin and McNutt, 1989). Hence, there appears to be a change in the age of *both* the parautochthon and the duplex across Algonquin Park, from 2.7 / 1.9 Ga in the Lac Dumoine region to 1.9 / 1.7 Ga in the Parry Sound region. This change is attributed to the derivation of crust in the Parry Sound region from a more outboard location in the pre-Grenvillian continental margin.

Detailed Nd isotope mapping in the Nobel area (Fig. 3 cross-section) showed that the boundary between late Paleoproterozoic (mauve) and Mesoproterozoic (green) crust corresponds precisely to the ABT boundary mapped by Culshaw et al. (2004). This boundary (heavy dashed line in the cross section) is also the principal locus for pods of retrogressed eclogite, indicative of exhumation from the deep crust. This implies that the ABT in this area represents the horizontal extension of a crustal-scale ramp. However, an outcrop of coronitic olivine metagabbro (Heaman and LeCheminant, 1993) is found structurally *below* the ABT boundary in the Nobel area (Culshaw et al., 2004; Dickin et al., 2017). Hence, the boundary that separates rocks containing coronitic olivine metagabbro from rocks containing metamorphosed Sudbury diabase is not the ABT itself (as proposed by Ketchum and Davidson, 2000), but the sole thrust of the duplex. On the other hand, Nd model age distributions show that the eclogite-bearing ABT boundary below Parry Sound domain is equivalent to the basal shear zone of the Muskoka domain (Dickin et al., 2017). Hence, we are led back to the original conception of Davidson (1984) based on field mapping, that the sole thrust of the Muskoka domain is the major structural discontinuity of the gneiss belt, and is the local expression of the ABT.

As noted above, this was the model originally proposed by Rivers et al. (1989), but the trajectory of the Muskoka shear zone was unclear at its easterly end where it enters Algonquin Park (Fig. 2). The earliest proposed trajectory (solid black line, Culshaw et al., 1983) was approximately followed by Rivers and Schwerdtner (2015), shown by the pink dashed line. On the other hand, a more easterly trajectory proposed by Davidson (1984) was closely followed by Culshaw et al. (2016), shown by the orange dotted line in Fig. 2.

The area in the southerly part of Algonquin Park where these models differ is a very inaccessible area, but the alternative trajectories are separated by only a few km where they cross Highway 60 in Algonquin Park, which has an abundance of road cuts. This is an ideal opportunity to test these models using detailed Nd isotope mapping, and it offers the possibility of a road section displaying the ABT for easy viewing.

Sampling and analytical techniques

The objective of Nd isotope mapping is to characterize the protolith age (crustal formation age) of large areas of crust as an indication of the geological relationships between highly metamorphosed lithotectonic terranes. The protolith age is one of the most fundamental features of a crustal terrane, but clearly there are other events in the geological history of terranes that are also indicative of relationships between them.

Another feature that may characterise lithotectonic terranes and domains is their magmatic / plutonic history. In the SW Grenville Province, the most widely distributed igneous crystallisation event occurred around 1.45 Ga (Slagstad et al., 2004, 2009, and references therein). Rocks with U-Pb ages corresponding to this event are found in most of the lithotectonic domains shown in Fig. 3, except for the Monocyclic Belt in the SE corner. Some older U-Pb ages are also found in the northern part of the study area (Nadeau and van Breemen, 1998, and references therein). However, these U-Pb ages are much too thinly scattered to be used to map the complexly deformed terrane boundaries in this region. In contrast, Nd isotope analysis represents a cost-effective technique for mapping lithotectonic terrenes, based on the robustness of Nd isotope signatures in highly metamorphosed terranes (e.g. Dickin, 2000). This method allows very high spatial resolution, which is unmatched by any other geological age discriminant in the Grenville Province.

Since the objective of this study was to characterize the protolith age of the crust as an estimate of its regional crustal formation age, sampling was limited to granitoid orthogneisses that are believed to form by anatexis of mafic juvenile arc crust. Previous studies have shown that granitoids of this type have Nd isotope signatures that are consistent and predictable (e.g.

McNutt and Dickin, 2012), thus allowing reliable estimates to be made of the formation age of the crust using the depleted mantle model of DePaolo (1981).

The lithologies of the analysed samples were determined by hand-lens examination. All of the sampled rocks are clearly orthogneissic, and their lithologies are summarised in Table 1 using the Streckeisen classification. Gneisses in the range diorite – monzodiorite – quartz monzodiorite – granodiorite are dominant in the allochthon. On the other hand, the duplex is slightly more siliceous and alkaline, being dominated by monzogranite gneiss. The smaller sample set from the parautochthon is dominantly granodioritic. These lithologies are all typical of ensialic arc magmatism (Martin and Dickin, 2005).

In contrast to granitoid rocks, sampling of mafic gneisses was avoided as far as possible, because of the increased likelihood of a younger mantle-derived component in these rock-types. Metasedimentary gneisses were also excluded because of their uncertain sedimentary provenance. Most analysed samples contain amphibole, but feldspars are commonly green-coloured. Therefore, although the dominant metamorphic grade is upper amphibolite facies, many samples are probably retrogressed from granulite facies.

On average, 1 kg of rock was crushed, after the removal of weathered, veined or migmatized material, and careful attention was given to obtain a fine powder representative of the whole rock. Sm-Nd analysis followed our established procedures. After a four-day dissolution at 125^{o}C using HF and HNO_3, samples were converted to the chloride form before being split, and one aliquot spiked with a mixed ^{150}Nd-^{149}Sm spike. Analysis by this technique yielded Sm/Nd = 0.2280 +/- 2 for BCR-1. Standard cation and reverse phase column separation methods were used. Nd isotope analyses were performed on a VG isomass 354 mass spectrometer at McMaster University using double filaments and a 4 collector peak switching algorithm, and were normalised to a $^{146}Nd/^{144}Nd$ ratio of 0.7219. Average within-run precision on the samples was ± 0.000012 (2σ), and an average value of 0.51185 +/- 2 (2σ population) was determined for the La Jolla Nd standard. Because the work extended over several years, some samples were duplicated to check for long-term reproducibility of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios, which are estimated at 0.1% and 0.002% (1σ) respectively, leading to an analytical uncertainty on each model age of ca. 20 Ma (2σ).

Results

New Nd data for over fifty samples from the Algonquin region are presented in Table 1, where they are used to calculate TDM ages using the depleted mantle model of DePaolo (1981). As discussed by Dickin et al. (2016), this model yields formation ages for crustal terranes in the SW Grenville Province that are very well supported by U-Pb dating (Slagstad et al., 2004; 2009; McNutt and Dickin, 2012), thus validating the accuracy of the model.

Samples are grouped in Table 1 according to the new structural domains proposed in this study, and are shown on a coloured map in Fig. 4, where new data points from Table 1 are numbered, whereas published data points are un-numbered (Dickin and McNutt 1990; Dickin et al., 2008; 2010; Slagstad et al., 2009; Moore and Dickin, 2011). The new data form three main age categories: 1.45 – 1.64 Ga in the Muskoka allochthon, 1.65 – 1.79 Ga in the Algonquin duplex and 1.8 – 1.99 Ga in small domains near Cache Lake, Oxtongue Lake and Heron Lake that are interpreted as tectonic slivers brought to the surface from the underlying parautochthon. In addition, a few samples within the allochthonous domain have younger TDM ages in the range 1.35 – 1.44 Ga.

The crustal structures shown in Fig. 4 will be discussed in detail below. However, it is first important to visualize the Nd isotope data on the Sm/Nd isochron diagram (Fig. 5), in order to see the isotopic distribution of points that define the three main age suites. These suites are compared in Fig. 5 with corresponding suites of published data, and with 1.75 and 1.45 Ga reference lines.

Starting with the youngest suite, we can see that the new data for the main allochthon (bright green squares) are fully coincident with published data for the Muskoka domain (Slagstad et al., 2009; Dickin et al. 2010; 2017), and with a 1.45 Ga reference line that corresponds with the oldest U-Pb ages from the Muskoka domain (Slagstad et al., 2004; 2009). On the other hand, the average TDM model age of this suite (1.56 Ga, Table 1) reflects minor incorporation of slightly older crustal material during ensialic arc magmatism to form this suite.

The oldest crustal suite, interpreted as tectonic slivers of the parautochthon (yellow circles) mostly fall with the range of published data for the Paleoproterozoic Barilia terrane (Dickin et al., 2008), which lie on a 1.75 Ga reference line. The average TDM age of the Barilia suite is 1.9 Ga, attributed to an accreted Penokean arc terrane (Dickin and McNutt, 1989). This age has been supported by U-Pb detrital zircon ages from the north-west part of Algonquin Park (Culshaw et al., 2016). However, intensive ensialic arc magmatism after arc accretion led to the 1.75 Ga Sm-Nd isochron age for this suite, which is in agreement with the oldest U-Pb age of 1.74 Ga for this terrane (Krogh et al., 1992). The new samples of the parautochthon fall slightly above the Barilia reference line, attributed to slightly greater degrees of Mesoproterozoic magmatic reworking in these samples, reflecting their more southerly location relative to the main body of parautochthonous rocks to the north (Fig. 4). The degree of divergence from the 1.75 Ga reference line increases slightly as Sm/Nd falls. This is attributed to a preponderance of more felsic lithologies in the younger magmatic reworking, consistent with ensialic arc magmatism.

The intermediate age-suite corresponds to the crustal domain interpreted as a tectonic duplex. This suite has TDM ages between the other two suites (average = 1.73 Ga), and also defines an intermediate slope on the isochron diagram. Given that the rocks of the parautochthon and the allochthon are attributed to an older continental margin that was telescoped by Grenvillian tectonism, younger TDM ages are attributed to rocks that once lay further outboard on this margin. Therefore, the rocks of the duplex are attributed to a crustal segment that was originally outboard of the accreted Penokean arc, but inboard of the 1.45 Ga continental margin arc (Dickin and McNutt, 1990; Slagstad et al., 2009). Given the average TDM age of 1.73 Ga, it is considered that this crustal segment was most likely formed in a late Paleoproterozoic continental margin arc. A small amount of available U-Pb data support this interpretation (Nadeau and van Breemen, 1998).

An alternative way of assessing the Nd isotope data is by calculating ε Nd values at the average age of magmatic activity. The epsilon value can then be plotted against Nd concentration to evaluate petrogenetic/mixing models. It is important to calculate epsilon Nd at the same time for all samples, even if their crystallization ages differ, because we are looking for relative differences in the protolith composition (reflecting different crustal formation ages). The results in Fig. 6 show that the three age suites all have similar ranges of Nd content, but distinct epsilon Nd signatures consistent with different crustal extraction ages. The samples attributed to slices of parautochthonous crust fall within the upper part of the epsilon Nd envelope of Barilia, but with above-average Nd contents, consistent with being more magmatically reworked than *in situ* parautochthon to the north. This is consistent with the development of a 1.45 Ga ensialic arc on an older margin consisting of crust with southward-younging crustal formation ages (as proposed above).

Discussion

The major objective of this study was to establish the location of the eastward extension of the Muskoka Shear Zone in Algonquin Park, argued above to represent the local expression of the ABT. Four different published trajectories for parts of this boundary are shown in Fig. 4, all of which extend eastward from the established boundary south of Huntsville (Nadeau, 1991; Nadeau and van Breemen, 1998). These will be compared with the boundary derived from isotope mapping, shown as a change in background colour from lilac to green.

The first 15 km eastward from the agreed section runs through Kawagama Lake, which therefore gives limited scope for detailed study of the boundary. Davidson (1984) and Rivers and Schwerdtner (2015) preferred a more southerly trajectory, whereas Lumbers and Vertolli (2003) and Culshaw et al. (2016) preferred a slightly more northerly one. The boundary of Lumbers and Vertolli (2003) seems to be based on more detailed geological mapping, and is supported by the isotope data (Fig. 4, sample #2).

To the east of the Lumbers and Vertolli map, the trajectories of Culshaw et al. (1983) and Rivers and Schwerdtner (2015) are in close agreement, whereas the boundary of Culshaw et al. (2016) deviates strongly to the east, following Davidson (1984). These trajectories come closer together as they approach Highway 60, where we have very detailed coverage of the boundary. Relative to our new data, the misfit with Rivers and Schwerdtner (2015) is a little over 1 km, which is double the thickness of the boundary-line on their regional-scale map. Hence, the agreement is almost within cartographical error on the road, but our boundary diverges strongly from Rivers and Schwerdtner (2015) to the north of the highway. On the other hand, the original boundary of Culshaw et al. (1983) does not reach the highway, since their map stopped at 78.5 degrees longitude, which happens to be 2.5 km west of our boundary section on Highway 60.

Due to the difficulties of sampling away from Highway 60, it is necessary to use remotely sensed data to extrapolate the ABT boundary across country to the north and south. This is done in Fig. 7, which shows a close-up view of the sample localities and boundaries from Fig. 4 in the central area of Algonquin Park. The background was made by draping the first vertical derivative of the total magnetic field from Culshaw et al. (2016) over a shaded digital elevation model (DEM) map from the Government of Ontario. The new ABT trajectory (black dashed line) departs from that of Schwerdtner and Rivers (2015) around 45.5^{o} N, and displays a ca. 90^{o} bend in the vicinity of the Lake of Two Rivers (near sample #35, Fig. 7). Our trajectory is consistent with the structural grain from the aeromagnetic and DEM data, whereas the approximately N—S trajectory of Schwerdtner and Rivers (2015) cuts across the structural grain. The trajectory of Culshaw et al. (2016) is consistent with the structural grain, but is located too far east. Our proposed basement sliver in the vicinity of Cache Lake is also consistent with the structural grain (black dotted line).

To pinpoint the exact location of the boundary on Highway 60, it is shown on a composite photograph of the outcrop in Fig. 8. Samples that yield ages typical of the allochthon and the duplex are located about 35 m apart, on either side of a boundary dipping at ca. 15^{o} E. The footwall of the boundary shows relatively fine-scale tectonic banding, including what appear to be calcareous-rich horizons a few decimeters thick. This could possibly represent a true supracrustal sequence dominated by meta-volcanics, with intervening volcaniclastic sediments.

In contrast, the layering structurally above the boundary is much more massive, with orthogneissic rock units typically 2 – 3 meters thick.

Immediately above the boundary, the outcrop contains a lozenge of rock which causes some deviation of foliations in the overlying units. However, the thinly foliated units underlying thrust boundary hardly deviate, except in a tight fold around the leading edge of the lozenge (Fig. 8). Hence it appears that this second-order structure has not significantly affected the main shear zone, which carried the main allochthon over the underlying Algonquin duplex.

Examination of road sections through the whole E—W section of Highway 60 shows that the rocks have very consistent dip. This can be confirmed by examination of rock-cuts on Google *Streetview*. The dip is consistently about 15 – 20 degrees east through most of the park, before the road turns southwards at its eastern end towards Whitney. This supports the claim of Rivers and Schwerdtner (2015) that the allochthon in this area is a synform. Rivers and Schwerdtner (2015) named this NW-directed nappe the Wallace domain. However, this seems an unsatisfactory name, since the (very small) hamlet of Wallace is actually located far from the relatively well-defined synformal thrust sheet in the southerly part of Algonquin Park. Therefore, we consider it more appropriate to refer to this nappe as the Opeongo domain, as proposed by (Culshaw et al., 2016). Although those authors did not define an easterly limit to this domain, their foliation measurements (from within the limits of our proposed domain) demonstrate that it has a synformal structure typical of a nappe.

In view of the consistent eastward dip along most of Highway 60, the repetition of three slivers of parautochthonous crust seems slightly problematical. However, we suggest that this pattern can be explained by imbrication of the tectonic duplex in this area, which is not surprising for such a rock package. For example, it was proposed by Dickin et al. (2017) that the

Algonquin duplex is a relatively thin structural unit, whose large outcrop area is a coincidence due to the horizontal structural dip of the allochthon in this area. However, in that case, it seems very likely that additional slivers of parautochthonous crust are present elsewhere, and also possibly additional klippen of the allochthon overlying it. However, mapping these structures away from the highway will be difficult.

A final brief discussion should be made of the lower boundary of the Algonquin duplex against parautochthonous crust to the north. Fig. 2 shows a large group of metabasic outcrops in the northern central part of Algonquin Park (Davidson and Grant, 1986). These metabasic rocks were identified by Ketchum and Davidson (2000) as coronitic olivine metagabbros indicative of the allochthon. To test this affinity, we sampled two localities (# 42 and 43) near the NE end of the area of metagabbro outcrops. The TDM ages, and especially the ε Nd (1.5 Ga) values, are typical of the Algonquin domain. Hence, we identify this area as part of the Algonquin duplex. In Fig. 4, we have shown this area connected to the main body of Algonquin domain as a NE-trending salient. However, it is also possible that this represents a tectonic outlier that is disconnected from the main body of Algonquin domain.

At the northern edge of the park, an area of rocks with Mesoproterozoic TDM ages typical of the allochthon was observed near Brent (Fig. 4). This is an area with good access, and detailed sampling allowed us to show that the Brent domain is an allochthonous klippe (Dickin et al., 2014). Unfortunately, the concentration of metabasic outcrops is in a more inaccessible area, and we have not yet been able to sample this region.

Conclusions

We conclude that the original field mapping of Culshaw et al. (1983) is the most consistent with our Nd isotope data. The structural interpretation of Culshaw et al. (1983) was largely followed by Davidson (1984) and Rivers et al. (1989), but was abandoned by Ketchum and Davidson (2000), Rivers et al. (2002) and Culshaw et al. (2016). However, tectonic mapping in deeply exhumed gneiss terranes can be somewhat subjective, since it may not be clear which of the observed shear zones is most significant. Hence, we conclude that terrane mapping in the Grenville Province needs to be tested and validated with Nd isotope data in order to reach reliable conclusions. In the present case, the original field mapping, not influenced by a preconceived structural model, was apparently the most perceptive. Based on the new isotope data and a re-examination of the highway section, we propose that the ABT, representing the principle thrust of the Ottawan orogeny, cuts across the Lake of Two Rivers with an approximately N—S trajectory, and is well exposed on Highway 60 with a 15^{o} E dip.

Acknowledgments

We are grateful to the Ontario Ministry of Natural Resources and Forestry for permission to sample in Algonquin Park, and we thank Alison Lake and her staff for arranging access and sampling permits. APD thanks Tom Nagy for assistance in the field, and JWDS thanks McMaster University for scholarship support. We acknowledge constructive comments from the journal editor and reviewers that helped improve this paper.

References

Culshaw, N.G., Corrigan, D., Ketchum, J.W.F., Wallace, P. and Wodicka, N. 2004. Precambrian geology, Naiscoot area. Ontario Geological Survey. Preliminary map P.3549, scale 1:50000.

Culshaw, N., Davidson, A. and Nadeau, L., 1983. Structural subdivisions of the Grenville province in the Parry Sound-Algonquin region, Ontario. Current Research, Part B, Geological Survey of Canada, Paper 83-1B, 243-252.

Culshaw, N., Foster, J., Marsh, J., Slagstad, T. and Gerbi, C., 2016. Kiosk domain, Central Gneiss Belt, Grenville Province, Ontario: A Labradorian palimpsest preserved in the ductile deep crust. Precambrian Research 280, 249-278.

Culshaw, N.G., Jamieson, R.A., Ketchum, J.W.F., Wodicka, N., Corrigan, D. and Reynolds, P.H. 1997. Transect across the northwestern Grenville orogen, Georgian Bay, Ontario: Polystage convergence and extension in the lower orogenic crust: Tectonics 16, 966-982.

Culshaw, N.G., Ketchum, J.W.F., Wodicka, N. and Wallace, P. 1994. Deep crustal ductile extension following thrusting in the southwestern Grenville Province, Ontario. Canadian Journal of Earth Sciences 31, 160-175.

Davidson, A., 1984. Tectonic boundaries within the Grenville Province of the Canadian Shield. Journal of Geodynamics, 1, 433-444.

Davidson, A., Culshaw, N. and Nadeau, L., 1982. A tectono-metamorphic framework for part of the Grenville Province, Parry Sound region, Ontario. Current Research, Part A, Geological Survey of Canada, Paper 82-1A, 175-190.

Davidson, A. and Grant, S.M., 1986. Reconnaissance geology of western and central Algonquin Park and detailed study of coronitic olivine metagabbro, Central Gneiss Belt, Grenville

Province of Ontario. Current research, Part B, Geological Survey of Canada, Paper 86-1B, 837-848.

DePaolo, D.J. 1981. Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. Nature 291, 193-196.

Dickin, A.P. 2000. Crustal formation in the Grenville Province: Nd-isotope evidence. Canadian Journal of Earth Sciences 37, 165-181.

Dickin, A.P., Cooper, D., Guo, A., Hutton, C., Martin, C., Sharma, K.N.M. and Zelek, M. 2012. Nd isotope mapping of the Lac Dumoine thrust sheet: implications for large scale crustal structure in the SW Grenville Province. Terra Nova 24, 363-372.

Dickin, A.P., Herrell, M., Moore, E., Cooper, D. and Pearson, S. 2014. Nd isotope mapping of allochthonous Grenvillian klippen: evidence for widespread 'ramp-flat' thrust geometry in the SW Grenville Province. Precambrian Research 246, 268-280.

Dickin, A., Hynes, E., Strong, J. and Wisborg, M. 2016. Testing a back-arc 'aulacogen'model for the Central Metasedimentary Belt of the Grenville Province. Geological Magazine, 153, 681-695.

Dickin A.P. and McNutt, R.H. 1989. Nd model age mapping of the southeast margin of the Archean foreland in the Grenville province of Ontario. Geology 17, 299-302.

Dickin, A.P. and McNutt, R.H. 1990. Nd model-age mapping of Grenville lithotectonic domains: Mid-Proterozoic crustal evolution in Ontario, In: Gower, C.F., Rivers, T. and Ryan, B., eds., Mid-Proterozoic Laurentia–Baltica: Geological Association of Canada Special Paper 38, 79-94.

Dickin, A.P. and McNutt, R.H. 2003. An application of Nd isotope mapping in structural geology: delineating an allochthonous Grenvillian terrane at North Bay, Ontario. Geological Magazine, 140, 539-548.

Dickin, A.P., McNutt, R.H., Martin, C. & Guo, A. 2010. The extent of juvenile crust in the Grenville Province: Nd isotope evidence. Geological Society of America Bulletin, 122, 870-883.

Dickin, A.P., Moretton, K. and North, R. 2008. Isotopic mapping of the Allochthon Boundary Thrust in the Grenville Province of Ontario, Canada. Precambrian Research 167, 260-266.

Dickin, A., Strong, J., Arcuri, G., Van Kessel, A. and Krivankova-Smal, L., 2017. A revised model for the crustal structure of the SW Grenville Province, Ontario, Canada. Geological Magazine, 154, 903-913.

Heaman, L.M. and LeCheminant, A.N. 1993. Paragenesis and U-Pb systematics of baddeleyite (ZrO2). Chemical Geology 110, 95-126.

Herrell, M.K., Dickin, A.P. and Morris, W.A. 2006. A test of detailed Nd isotope mapping in the Grenville Province: delineating a duplex thrust sheet in the Kipawa Mattawa region. Canadian Journal of Earth Sciences 43, 421-432.

Indares A. and Dunning, G. 1997. Coronitic metagabbro and eclogite from the Grenville Province of western Quebec: interpretation of U-Pb geochronology and metamorphism: Canadian Journal of Earth Sciences 34, 891-901.

Ketchum, J.W.F. and Davidson, A. 2000. Crustal architecture and tectonic assembly of the Central Gneiss Belt, southwestern Grenville Province, Canada: a new interpretation. Canadian Journal of Earth Sciences 37, 217-234.

Krogh, T. E., Culshaw, N., and Ketchum, J. 1992. Multiple ages of metamorphism and deformation in the Parry Sound — Pointe au Baril area. Lithoprobe (Abitibi-Grenville Workshop IV) Report 33, p. 39.

Lumbers, S.B. 1982, Summary of metallogeny, Renfrew County area: Ontario Geological Survey Report 212, 58 p.

Lumbers, S.B and Vertolli, V.M. 2003 Precambrian geology, Kawagama Lake area. Ontario Geological Survey. Preliminary map P.3525, scale 1:50 000.

Martin, C. and Dickin, A. P. 2005. Styles of Proterozoic crustal growth on the southeast margin of Laurentia: evidence from the central Grenville Province northwest of Lac St.-Jean, Quebec. Canadian Journal of Earth Sciences 42, 1643-1652.

McNutt, R. H. and Dickin, A. P. 2012. A comparison of Nd model ages and U–Pb zircon ages of Grenville granitoids: constraints on the evolution of the Laurentian margin from 1.5 to 1.0 Ga. Terra Nova, 24, 7-15.

Moore, E.S. and Dickin, A.P. 2011. Evaluation of Nd isotope data for the Grenville Province of the Laurentian Shield using a Geographic Information System (GIS). Geosphere 7, 415-428.

Nadeau, L. 1991. Tectonic evolution of the Central Grenville Belt, Huntsville area, Ontario. Friends of the Grenville Annual Field Excursion, Guidebook.

Nadeau, L. and van Breemen, O. 1998. Plutonic ages and tectonic setting of the Algonquin and Muskoka allochthons, Central Gneiss Belt, Grenville Province, Ontario. Canadian Journal of Earth Sciences 35, 1423-1438.

Rivers, T., Ketchum, J., Indares, A. and Hynes, A. 2002. The High Pressure belt in the Grenville Province: architecture, timing, and exhumation. Canadian Journal of Earth Sciences 39, 867-893.

Rivers, T., Martignole, J., Gower, C.F. and Davidson, A. 1989. New tectonic divisions of the Grenville Province, southeastern Canadian Shield. Tectonics 8, 63-84.

Rivers, T. and Schwerdtner, W. 2015. Post-peak Evolution of the Muskoka Domain, Western Grenville Province: Ductile Detachment Zone in a Crustal-scale Metamorphic Core Complex. Geoscience Canada 42, 403-436.

Slagstad, T., Culshaw, N.G., Daly, J.S. and Jamieson, R.A. 2009. Western Grenville Province holds key to midcontinental Granite-Rhyolite Province enigma. Terra Nova 21, 181-187.

Slagstad, T., Culshaw, N.G., Jamieson, R.A. and Ketchum, J.W. 2004. Early Mesoproterozoic tectonic history of the southwestern Grenville Province, Ontario: constraints from geochemistry and geochronology of high-grade gneisses. Geological Society of America Memoirs 197, 209-241.

White, D. J., Easton, R. M., Culshaw, N. G., Milkereit, B., Forsyth, D. A., Carr, S. and Davidson, A. 1994. Seismic images of the Grenville Orogen in Ontario. Canadian Journal of Earth Sciences 31, 293-307.

Table caption

Table 1. Nd isotope data for analysed samples from the Algonquin Park region

Table 1 footnote

Petrology key: TN = Tonalite, GD = granodiorite, MG = monzogranite, GR = granite, QD = quartz diorite, QMD = quartz monzodiorite, DI = diorite, MD = monzodiorite.

Figure captions

Fig. 1. Map of the SW Grenville Province showing the location of Algonquin Park (AP) relative to the structural belts proposed by Rivers et al. (1989): APB = Allochthonous Polycyclic Belt; NB = North Bay; PS = Parry Sound. Major thrusts: ABT = Allochthon Boundary Thrust; MBB = Monocyclic Belt Boundary.

Fig. 2. Lithotectonic domains of the Parry Sound region and the Algonquin region after Davidson et al. (1982) and Culshaw et al. (1983). Solid and dotted black lines = primary and secondary shear zones from those papers. Dashed violet line and dotted orange line = alterative trajectories of the Muskoka sole thrust from Rivers and Schwerdtner (2015) and Culshaw et al. (2016). Green dashed line = ABT of Ketchum and Davidson (2000). Stars = coronitic olivine metagabbro (Ketchum and Davidson, 2000).

Fig. 3. Tectonic map and cross-section of the SW Grenville Province showing terranes categorized by average TDM age: (pink = 2.7 Ga; yellow = 1.9 Ga; mauve = 1.7 Ga; green =

1.55 Ga). LW = Lac Watson; NB = North Bay. Red stars = eclogite; red dots = seismic lines. Solid blue line = line of cross-section.

Fig. 4. Tectonic map of the Algonquin Park area showing sample localities numbered as in Table 1 and categorized by TDM model age. Muskoka domain boundary as follows: dashed blue line = Culshaw et al. (1983); solid black = Lumbers and Vertolli (2003); dotted violet = Rivers and Schwerdtner (2015); dotted orange = Culshaw et al. (2016).

Fig. 5. Sm—Nd isochron diagram for samples in Table 1 compared with published age suites: Barilia Parautochthon (Dickin et al., 2008); Slagstad et al. (2009) excluding sample E; Muskoka (samples 1-15 from Dickin et al., 2010; samples 60-65 from Dickin et al. 2017).

Fig. 6. Plot of Epsilon Nd at 1.5 Ga as a function of Nd content for new and published data (symbols as in Fig. 5).

Fig. 7. Map of central Algonquin Park, showing boundaries in Fig. 4 against a background of the first vertical derivative of the total magnetic field draped over a shaded DEM map. Dashed blue line = Culshaw et al. (1983); solid violet = Rivers and Schwerdtner (2015); dotted orange line = Culshaw et al. (2016); dashed black line = ABT proposed here.

Fig. 8. View of the north side of the road-cut along Lake of Two Rivers, showing the location of the ABT between a sample of the allochthon (right) and duplex (left) that are ca. 35 m apart. Tom Nagy (pictured) is 1.85 m tall.

Map#	Sample	UTM N NAD 83	UTM E zone 17	Nd ppm	Sm ppm	147Sm/ 144Nd	143Nd/ 144Nd	TDM Ga	E Nd 1.5 Ga	Rock type
Allochthon										
1	KA10	5012860	673070	43.9	9.74	0.1342	0.512186	1.64	3.1	QMD
2	KA24	5020210	679887	10.8	1.93	0.1078	0.511969	1.54	4.0	GD
3	BA28	5050750	697700	24.0	5.86	0.1251	0.512119	1.59	3.6	QD
4	AL57	5050200	698915	31.6	5.78	0.1104	0.511982	1.56	3.7	GD
5	AL40	5051294	704295	20.0	4.00	0.1211	0.512058	1.62	3.1	MD
6	AL21	5058910	704740	30.0	6.06	0.1219	0.512062	1.63	3.1	QMD
7	BA23	5052200	707200	46.2	8.06	0.1054	0.512024	1.43	5.5	DI
8	BA22	5050500	710900	55.8	11.27	0.1221	0.512094	1.58	3.7	DI
9	BA20	5042700	714800	26.2	5.19	0.1197	0.512051	1.61	3.3	MD
10	BA18	5040100	719600	40.5	8.56	0.1278	0.512160	1.56	3.9	MD
11	BA17	5038200	719550	32.4	5.92	0.1103	0.511932	1.64	2.8	GD
12	BA71	5042448	722029	49.6	9.59	0.1167	0.512125	1.44	5.3	MG
13	BA78	5040290	728444	33.9	6.39	0.1140	0.512085	1.46	5.0	QD
14	BA73	5030266	721936	67.7	11.27	0.1007	0.511877	1.56	3.5	GD
15	WH6	5019940	731071	21.1	4.65	0.1332	0.512253	1.49	4.6	QD
							Mean	1.56	3.9	
Duplex										
16	DW23	5017027	659701	35.2	6.84	0.1172	0.511960	1.71	2.0	MG
17	DW24	5021112	659163	41.1	8.16	0.1198	0.511963	1.75	1.5	GD
18	KA6	5013590	666410	77.8	15.89	0.1234	0.512013	1.74	1.8	MG
19	KA1	5016540	666740	80.8	17.08	0.1277	0.512065	1.73	2.0	QSY
20	KA3	5022450	669040	32.9	5.67	0.1042	0.511782	1.75	1.0	MG
21	KA5	5023990	673960	23.2	5.03	0.1309	0.512090	1.75	1.9	QMD
22	KA20	5024200	679700	36.4	5.76	0.0955	0.511697	1.73	1.0	MG
23	DW25	5030510	666796	40.5	5.79	0.0862	0.511650	1.66	1.9	QMD
24	D9	5031500	678100	45.6	7.94	0.1054	0.511815	1.73	1.4	QMD
25	AL46	5040593	676100	52.2	9.49	0.1099	0.511883	1.70	1.9	MG
26	BA25	5041800	677600	46.0	9.49	0.1248	0.512004	1.78	1.4	DI
27	AL45	5044100	679050	65.2	12.77	0.1183	0.511922	1.79	1.0	GR
28	BA26	5045950	681000	37.0	5.86	0.0957	0.511708	1.72	1.2	MG
29	AL60	5043120	680507	42.1	6.11	0.0877	0.511662	1.67	1.8	GR
30	AL61	5042154	681922	31.7	5.09	0.0971	0.511737	1.70	1.5	MG
31	AL32	5048450	689640	25.9	4.90	0.1145	0.511926	1.71	1.8	GD
	AL32R			23.8	4.52	0.1147	0.511922	1.72	1.7	
32	AL31	5049450	692650	57.1	11.06	0.1170	0.511930	1.75	1.4	MG
33	AL30	5050990	695760	41.4	8.28	0.1208	0.512002	1.70	2.1	MG
34	AL43	5051010	696841	35.5	6.68	0.1139	0.511915	1.72	1.7	MG
35	AL42	5050899	697037	27.2	4.09	0.0908	0.511650	1.73	1.0	MG
36	AL20	5062140	704210	50.0	10.57	0.1277	0.512066	1.73	2.0	QD
37	AL27	5064730	704540	25.6	4.43	0.1046	0.511804	1.73	1.3	MG
38	BA48	5050800	726500	50.7	10.25	0.1222	0.512004	1.73	1.9	MG
39	BA70	5045014	733793	63.3	12.39	0.1184	0.511954	1.74	1.6	QD
40	AL47	5039200	683624	59.8	12.55	0.1269	0.512033	1.77	1.5	DI
41	AL34	5047150	685990	30.8	5.97	0.1171	0.511899	1.80	0.8	MG
	AL34R			32.0	6.18	0.1166	0.511906	1.78	1.0	
42	CL5N	5091930	695880	75.8	15.97	0.1274	0.512035	1.78	1.5	GD
43	AQ33	5091200	697600	120.3	23.15	0.1164	0.511933	1.73	1.6	MG
							Mean	1.73	1.5	
Cache Lake										
44	AL33	5047200	686750	85.3	12.18	0.0868	0.511547	1.80	-0.3	MG
45	BA27	5047600	688200	31.5	6.55	0.1259	0.511969	1.86	0.5	QD
46	CL4	5048130	689110	60.5	10.67	0.1065	0.511771	1.81	0.3	GD
47	CL1	5044954	688470	29.9	5.72	0.1155	0.511837	1.87	-0.1	MG

Oxtongue Lake										
48	KA11	5016994	662152	43.7	8.70	0.1201	0.511847	1.95	-0.8	GD
49	DW20	5024707	662006	36.4	6.73	0.1118	0.511827	1.81	0.4	GD
50	DW26	5027248	663040	36.0	8.13	0.1365	0.512088	1.88	0.8	GD
Heron Lake										
51	AL49	5036508	672009	23.0	5.29	0.1390	0.512070	1.98	-0.1	MD
52	AL48	5038800	674614	28.2	6.03	0.1292	0.511986	1.90	0.2	DI
							Mean	1.87	0.1	
Boundary zone										
	AL51	5050816	697535	42.1	8.05	0.1155	0.511921	1.74	1.5	QMD
	AL53	5050797	697575	33.4	5.47	0.0988	0.511820	1.62	2.8	GD

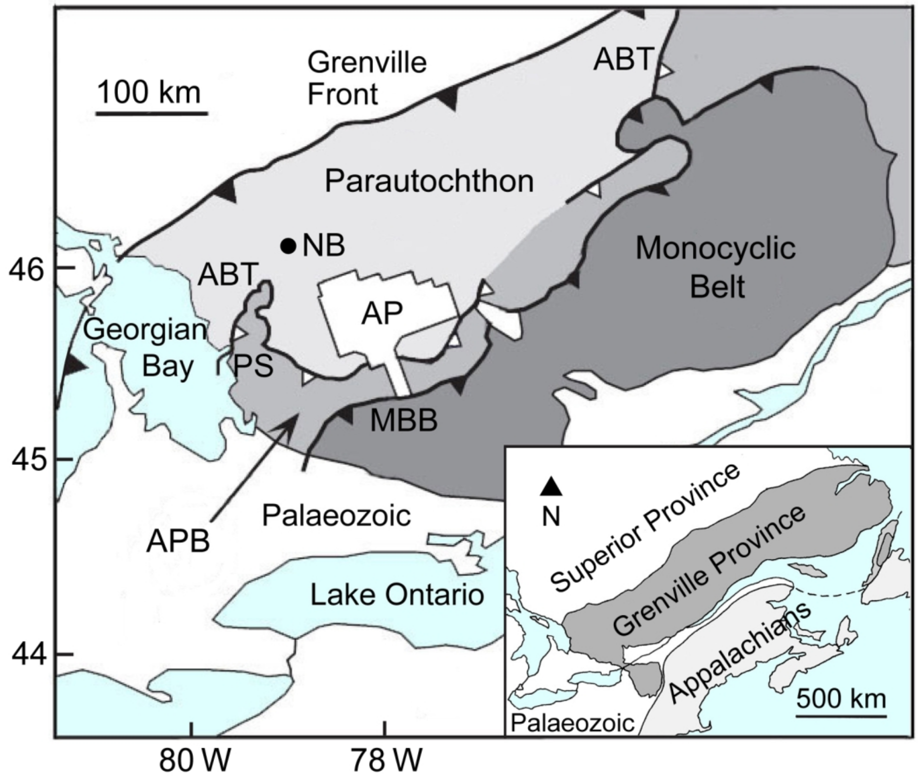

Fig1

152x123mm (300 x 300 DPI)

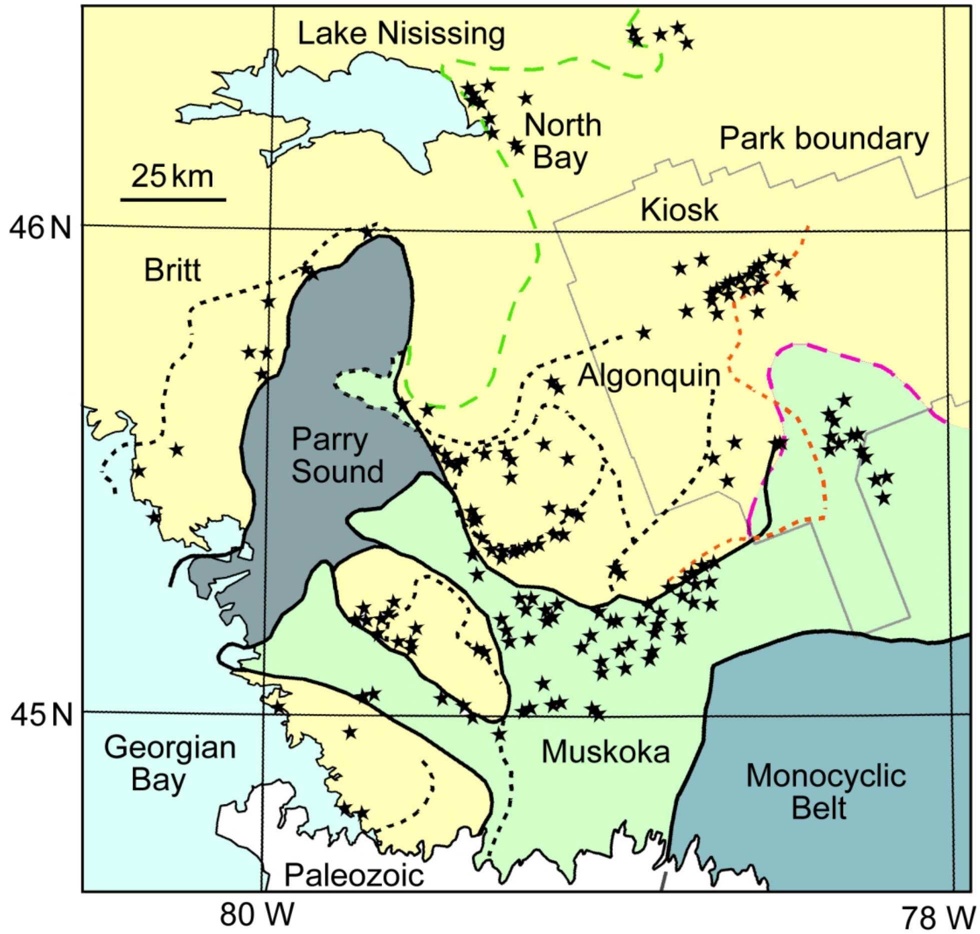

Fig2

152x147mm (300 x 300 DPI)

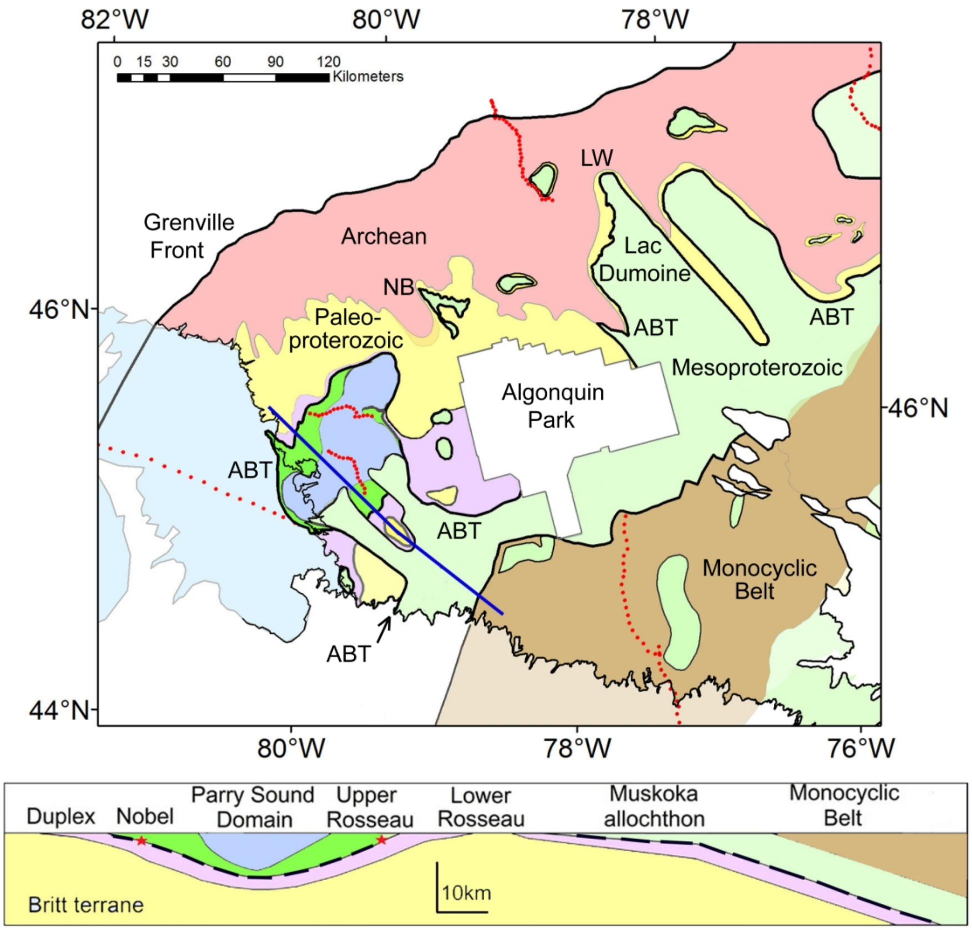

Fig 3

228x220mm (300 x 300 DPI)

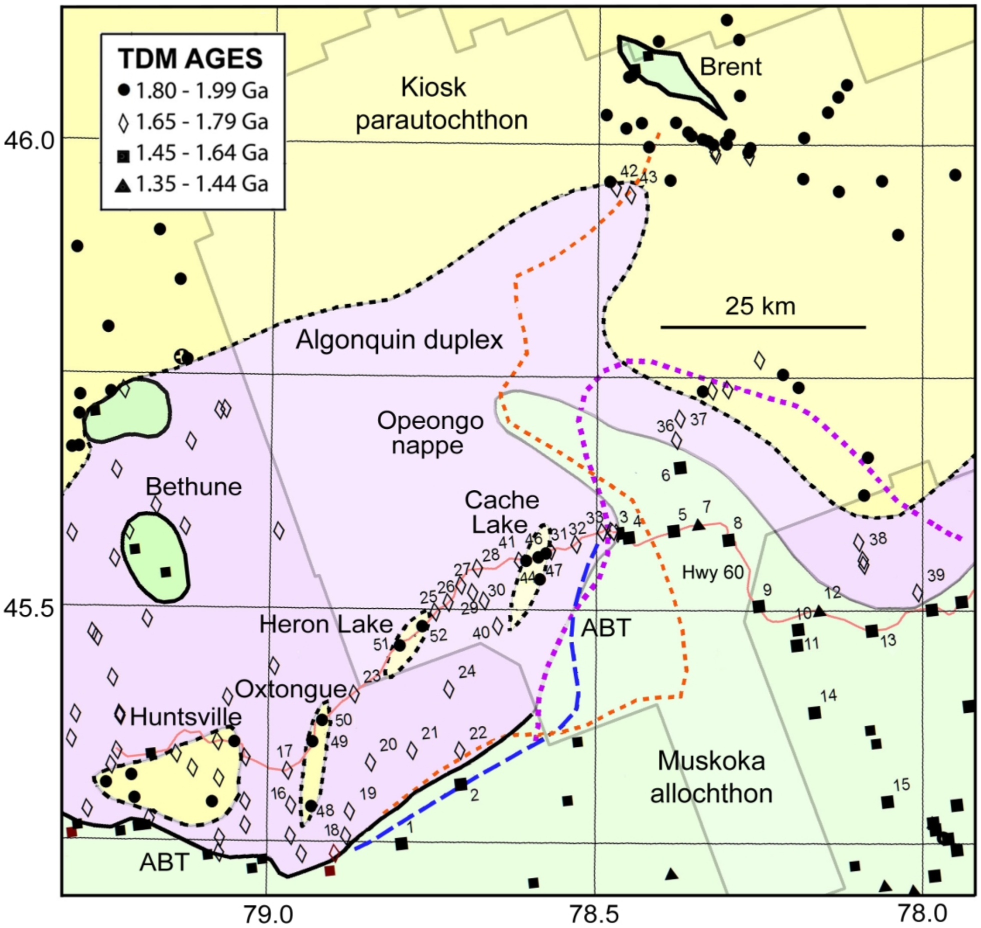

Fig4

168x165mm (300 x 300 DPI)

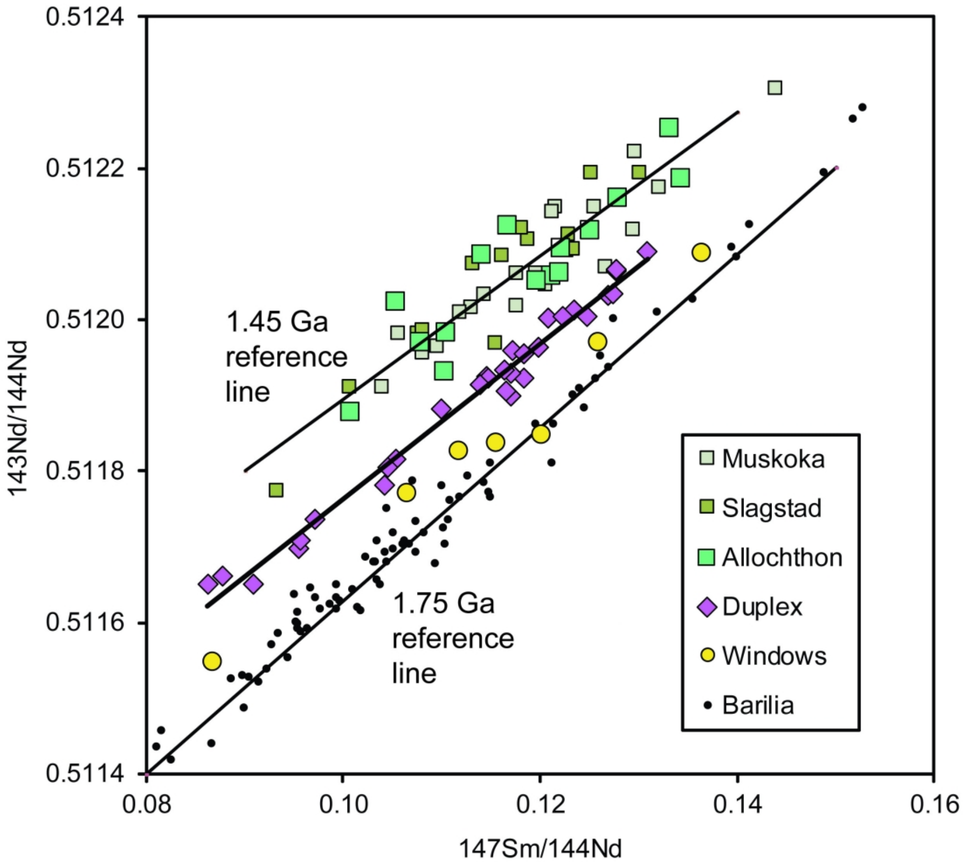

Fig5

217x203mm (300 x 300 DPI)

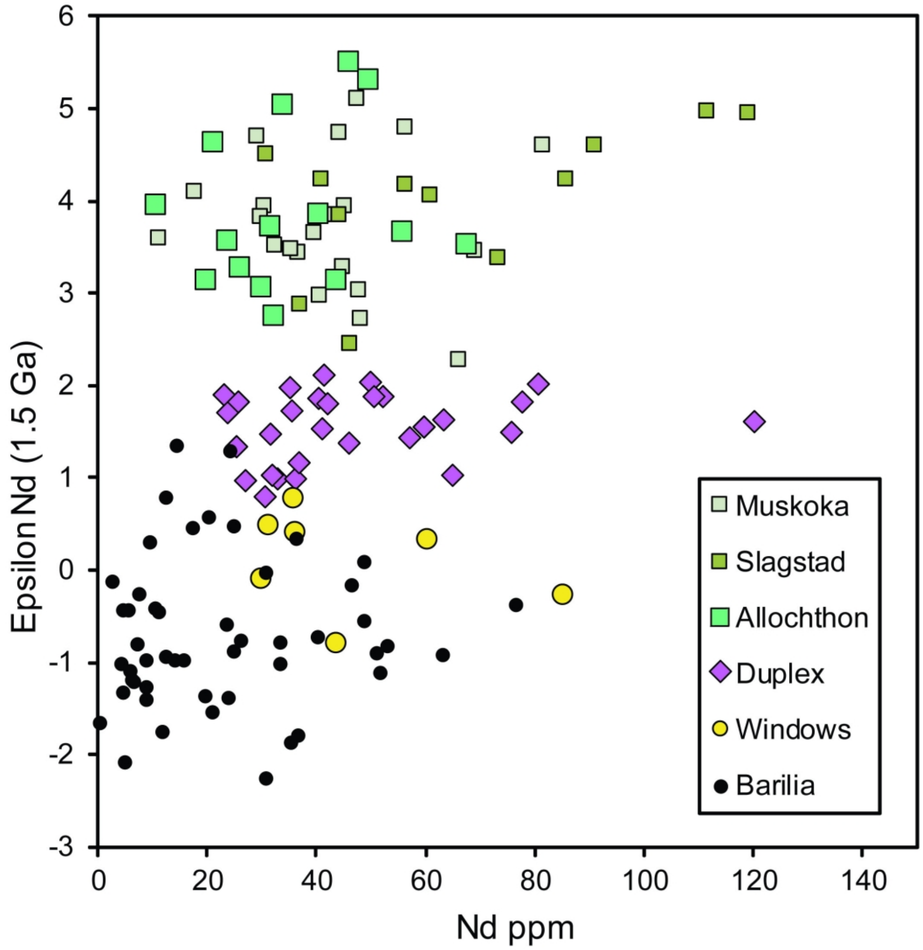

Fig6

197x203mm (300 x 300 DPI)

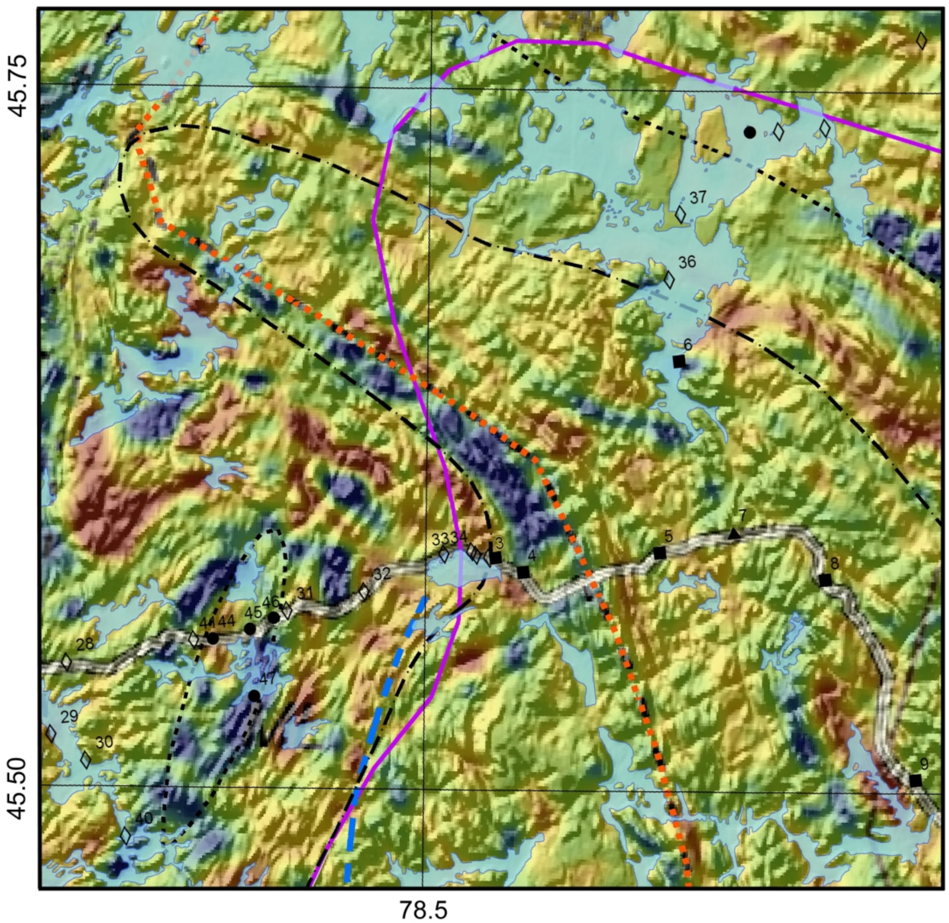

Fig7

167x165mm (300 x 300 DPI)

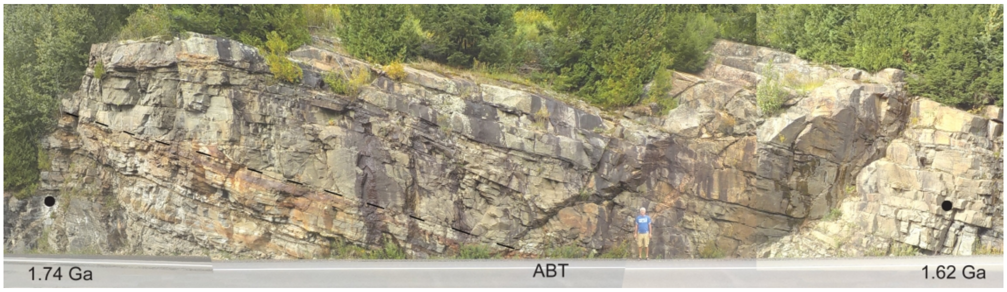

Fig8

266x76mm (300 x 300 DPI)