Evaluation of Nd isotope data for the Grenville Province of the Laurentian shield using a geographic information system

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ABSTRACT

The Grenville Province of eastern North America contains a record of continental growth on the southeast margin of Laurentia through much of the Proterozoic Eon, and this growth history can be charted using Nd model age mapping. This paper describes the first use of a geographic information system (GIS) to evaluate such data. The Grenville Province of Ontario and western Quebec, Canada, was chosen for study because there is a lack of agreement on the location of major geological boundaries, whereas the high density of Nd isotope sampling allows precise solutions to be proposed. Two different contouring algorithms, triangulated irregular networks (TIN) and inverse distance weighting (IDW), were first evaluated to select the best geospatial analysis method and parameters for visualizing and evaluating Nd model age distributions. The method chosen (IDW at a power of 6), was then used to test the location of two major boundaries that separate rocks of different crustal formation age, the Grenville-age Allochthon Boundary thrust and the pre-Grenvillian Archean-Proterozoic boundary. GIS analysis was initially performed using published data, after which further sampling was performed to improve coverage of problem areas. The GIS analysis was then repeated, incorporating Nd data for over 80 new localities. The result is a more reliable and accurate map of terrane boundaries in the southwest Grenville Province, which is a critical step in reconstructing the Proterozoic evolution of the southeast margin of Laurentia.

INTRODUCTION

The Laurentian shield (Canada) consists of a mosaic of lithotectonic domains and terranes, separated by boundaries that may be the locus of major or minor displacement during the numerous orogenic events that make up its geological development. Therefore, the detailed mapping of terrane boundaries plays an important role in interpreting and reconstructing the growth history of the shield. However, the complexity of this history may obscure its own early development.

One region where mapping of terrane boundaries is particularly problematic is the Grenville Province on the southeast margin of the Laurentian shield, where episodic continental collisions, culminating in the Grenville collisional orogeny, resulted in the addition of external terranes, geological reworking of earlier crust, and exhumation of high-grade gneisses from deep within the crust. These processes have partly obscured the geological evidence normally used to map terrane boundaries in less complex orogenic belts, requiring the development of new geological tools to reconstruct the history of this region.

One tool that has proved useful for understanding the Grenville Province is Nd isotope mapping. However, data from different studies have not yet been fully integrated in order to achieve an overview of their geographical distribution. Therefore the objective of this paper is to achieve a better understanding of the spatial significance of published and new Nd isotopic data through the application of a geographic information system (GIS). The GIS approach has only recently been applied to radiogenic isotope data (e.g., Mamani et al., 2005), and has not previously been used to analyze Nd model age distributions.

HISTORY OF GEOLOGICAL MAPPING IN THE GRENVILLE PROVINCE

Ever since the definition of the Grenville Province by Gill (1948), geologists have attempted to map the various geological boundaries of the province in order to understand its history. For example, the northwest boundary of the province, first referred to by Derry (1950) as the Grenville Front, has been a structure of intense interest over many years. Several other boundaries within the province were also identified by early geological mapping, culminating in the subdivision of the province into major regional segments by Wynne-Edwards (1972), based on differences in structural and metamorphic style. Within the southwestern part of the province, distinct geological features led to the recognition of the Grenville Front Tectonic Zone and the Central Metasedimentary Belt (Fig. 1). However, between these recognized units, the high-grade gneisses referred to as the Central Gneiss Belt presented a major barrier to geological understanding.

During this period, detailed geological mapping of the "sea of gneisses" (Davidson, 1986, p. 61) in Ontario was carried out in a series of map sheets by Lumbers (1971, 1975, 1976). These maps focused principally on the boundaries of mappable plutonic rocks, interpreting the banded structure of the intervening high-grade gneisses as sedimentary layering. However, this interpretation was challenged by Davidson (1985), who argued that the banding of gneisses in the Grenville Province was largely due to tectonic shearing and metamorphic segregation, thus implying that the undifferentiated gneisses might be largely plutonic in origin. With a mixed supracrustal and plutonic origin, the Gneiss Belt was later intruded by additional plutons, which then were further migmatized and deformed (Davidson and Morgan, 1981; Davidson et al., 1982).

Coupled with reconnaissance field mapping, air photographs were used by Davidson and Morgan (1981) to assist in the delineation of distinct lithotectonic domains within the Central Gneiss Belt. Zones of strongly banded gneisses between the less deformed domains were interpreted as ductile shear zones, where deep crustal blocks and slices were displaced relative to one another. In the following years, reconnaissance mapping was continued by Davidson and coworkers, who used structural geology, metamorphic petrology, and geochronology to subdivide the southwestern part of the gneiss belt in Ontario into well-defined lithotectonic domains (Davidson, 1985, 1986).

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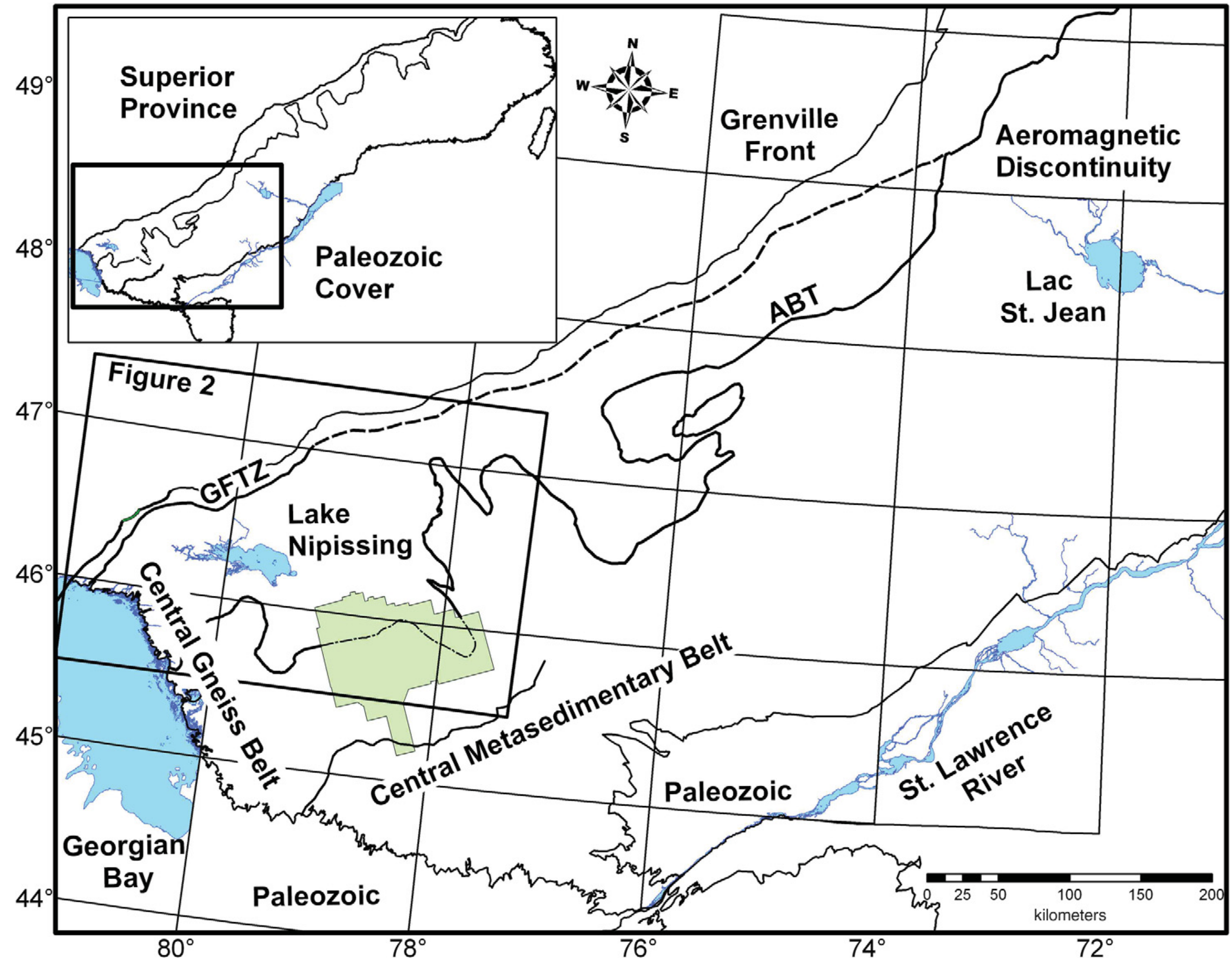


Figure 1. Map showing major geological features of the southwest Grenville Province (inset map shows its relationship to the province as a whole). GFTZ—Grenville Front Tectonic Zone, which is well defined in Ontario (solid boundary), but poorly defined in Quebec (dashed boundary); ABT—Allochthon Boundary thrust. Green shaded block—Algonquin Provincial Park.

Based on Wynne-Edwards' (1972) interpretation of crustal thickening and thrusting within the Grenville Front Tectonic Zone, Frith and Doig (1975) argued that outcrops within this region must be from deep crustal levels. To verify the extent of this exposed basement within the Quebec gneiss segment of the Grenville Province, they carried out aeromagnetic and Rb-Sr isotope analysis in the region northwest of Lac St Jean, Quebec (Fig. 1).

Aeromagnetic data for this region generally displayed east-west trends within 50 km of the Grenville Front, but these were abruptly truncated to the southeast by a zone with more north-south trends (Frith and Doig, 1975). A strong aeromagnetic discontinuity separating these two areas coincided with a change in Rb-Sr isochron age. Thus, Frith and Doig (1975) showed that Archean crust was present within the Grenville Province and argued that the aeromagnetic discontinuity was the northwestern limit of the 1.75 Ga Hudsonian deformation event. At the time, the full potential of aeromagnetics was overlooked; the boundary that Frith and Doig (1975) discovered would later be recognized as one of the most important in the Grenville Province and termed the Allochthon Boundary thrust.

The usefulness of aeromagnetic data was recognized by Rivers and Nunn (1985) and Rivers and Chown (1986), and was used to redefine tectonic boundaries in the northeastern Grenville Province. In eastern Quebec and Labrador, Rivers and Chown (1986) distinguished three separate zones that they named the "autochthon" (consisting of in situ Superior Province crust), the "parautochthon" (consisting of crust that is equivalent to the Superior Province but has been tectonically uplifted), as well as horizontally displaced "allochthonous" crustal units with different metamorphic histories. It was found that regions defined as allochthonous contained highly erratic or noisy magnetic signatures, compared to the parautochthon, where quiet magnetic signatures reflected uniformly metamorphosed gneiss, with the exception of iron formations and basic intrusions. The boundary between these two belts was an aeromagnetic straight zone or discontinuity, which was later defined by Rivers et al. (1989) as the Allochthon Boundary thrust (ABT).

Rivers et al. (1989) combined modern mapping techniques with a comprehensive 1:1,000,000 scale aeromagnetic data set from the Geological Survey of Canada (1985) to extend the nomenclature of Rivers and Chown (1986) to the entire Grenville Province. However, although aeromagnetics proved to be a useful technique in defining the boundary between parautochthonous and allochthonous belts within the central and eastern Grenville Province, this proved more difficult in the southwestern part of the province, where Rivers et al. (1989) acknowledged that the magnetic data were less clear and did not effectively define the ABT. This difficulty can be attributed to the intensity of younger plutonism, which contributes to noisy magnetic signatures on both sides of the ABT. In addition, the deeply exhumed nature of the crust in this area provides few features that allow field mapping of the boundary.

Another problem that hampers mapping of the ABT in the southwest part of the province is the occurrence of late Grenvillian extensional movement, which often overprints the original thrust boundary. This was recognized by Culshaw et al. (1994) during their mapping of the northeast Georgian Bay shoreline (Fig. 1). They sought to define the position of the ABT, locally termed the Shawanaga shear zone (Fig. 2), based on distinct crustal histories of the terranes on either side. Indications of the location of the original boundary were (1) older protolith ages within the parautochthonous rocks north of the boundary, (2) a pre-Grenvillian metamorphic event only seen north of the boundary, (3) a suite of 1.35 Ga plutons only found south of the boundary, and (4) distinctive suites of metabasic rock on opposite sides of boundary.

Ketchum (1994) used the occurrence of metabasic rock types within the southwestern Grenville Province as the primary method of defining the location of the ABT, and proposed that metabasic rocks similar to the 1.24 Ga Sudbury diabase dikes only occurred within the parautochthon, while 1.16 Ga coronitic metagabbro only occurred within the allochthon; therefore the ABT would be between these two rock types. In addition, the location of the boundary was further narrowed by the occurrence of retrogressed eclogite, which was only found within the thrust zone or within the hanging wall of the allochthon.

This method was applied by Ketchum and Davidson (2000) to determine a new location for the ABT in eastern Ontario and western Quebec. However, in the northeastern part of their study area (Fig. 2) the outcrops of mafic rocks became very sparse, requiring extrapolation across gaps as large as 50 km. As an alterative to a continuous thrust boundary extending between these isolated outcrops, it was proposed (Dickin and McNutt, 2003) that some of the outcrops represented structural outliers of the allochthonous belt that had been isolated by erosion (klippen), as shown in Figure 2. Hence, this implied that the main trace of the ABT would be located much farther to the southeast.

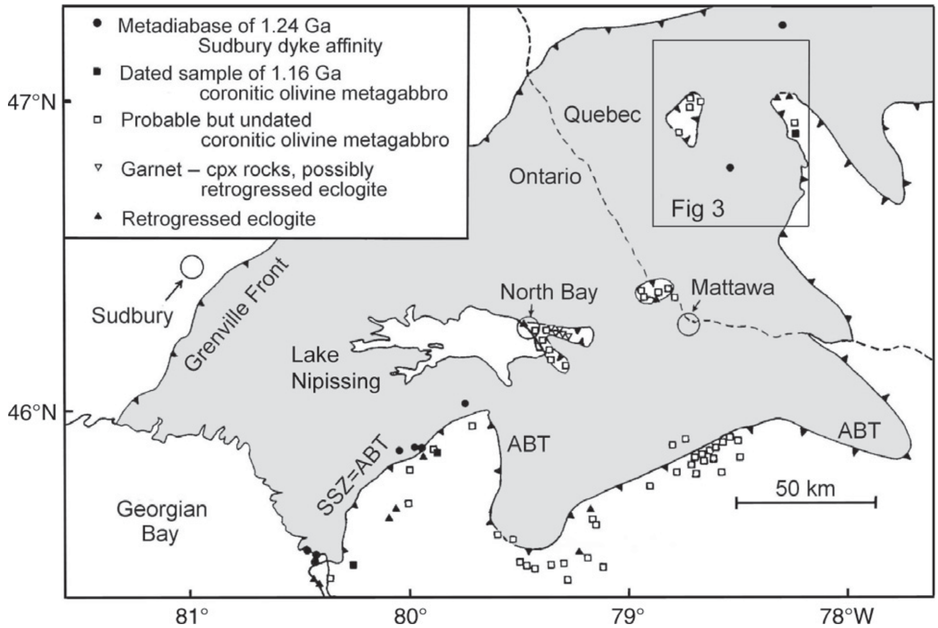


Figure 2. Map showing the location of the Allochthon Boundary thrust (ABT) in the southwest Grenville Province, as proposed by Dickin and McNutt (2003) and compared with the distribution of different metabasic rock types (Ketchum and Davidson, 2000). SSZ—Shawanaga shear zone; cpx—clinopyroxene.

DETAILED MAPPING OF THE ABT: WESTERN QUEBEC CASE STUDY

One part of the southwest Grenville Province where shallower crustal levels crop out is the area north of Mattawa in western Quebec (see Fig. 2). In this region the preservation of supracrustal units, including quartzites and iron formations, has allowed conventional geological mapping of thrust boundaries. This has led to several studies being focused in this area, briefly reviewed here to illustrate the challenges in trying to map thrust boundaries with confidence.

Kellett et al. (1994) integrated various data sets, including aeromagnetic mapping, new deep seismic reflection data from Lithoprobe line 15, and geological mapping based on the 1:250,000 compilation maps of Rive (1981), to study the geometry of crustal boundaries, including the Grenville Front and the northern extent of the allochthonous belt. In addition to the main body of the allochthonous belt, a tectonic klippe was identified to the north of Lac Booth (Fig. 3). However, subsequent work has suggested that the tectonic unit that they mapped as a klippe is joined by a narrow neck to a larger thrust sheet south of Lac Booth, so that the tectonic unit identified by Kellett et al. (1994) is not a klippe. In addition, the lithological boundary that they defined as the ABT (red line in Fig. 3) was based on incorrect labeling of some units on the compilation map of Rive (1981; as explained in Herrell et al., 2006). Therefore, this casts doubt on the location of the ABT proposed by Kellett et al. (1994).

A revised interpretation of the geological structure of the region was given by Currie and van Breemen (1996), who proposed the existence of two major thrusts in the study area, rather than one. The upper thrust largely corresponded to the ABT of Kellett et al. (1994), except that Currie and van Breemen (1996) defined a smaller extent for the tectonic unit north of Lac Booth, which was now recognized as a true klippe (black line in Fig. 3). A lower thrust was placed northwest of (structurally beneath) a laterally extensive quartzite-bearing supracrustal unit, but not consistently. Therefore, this boundary is not shown in Figure 3.

Further work was carried out by Indares and Dunning (1997) using published geological maps, U-Pb geochronology, and lithological

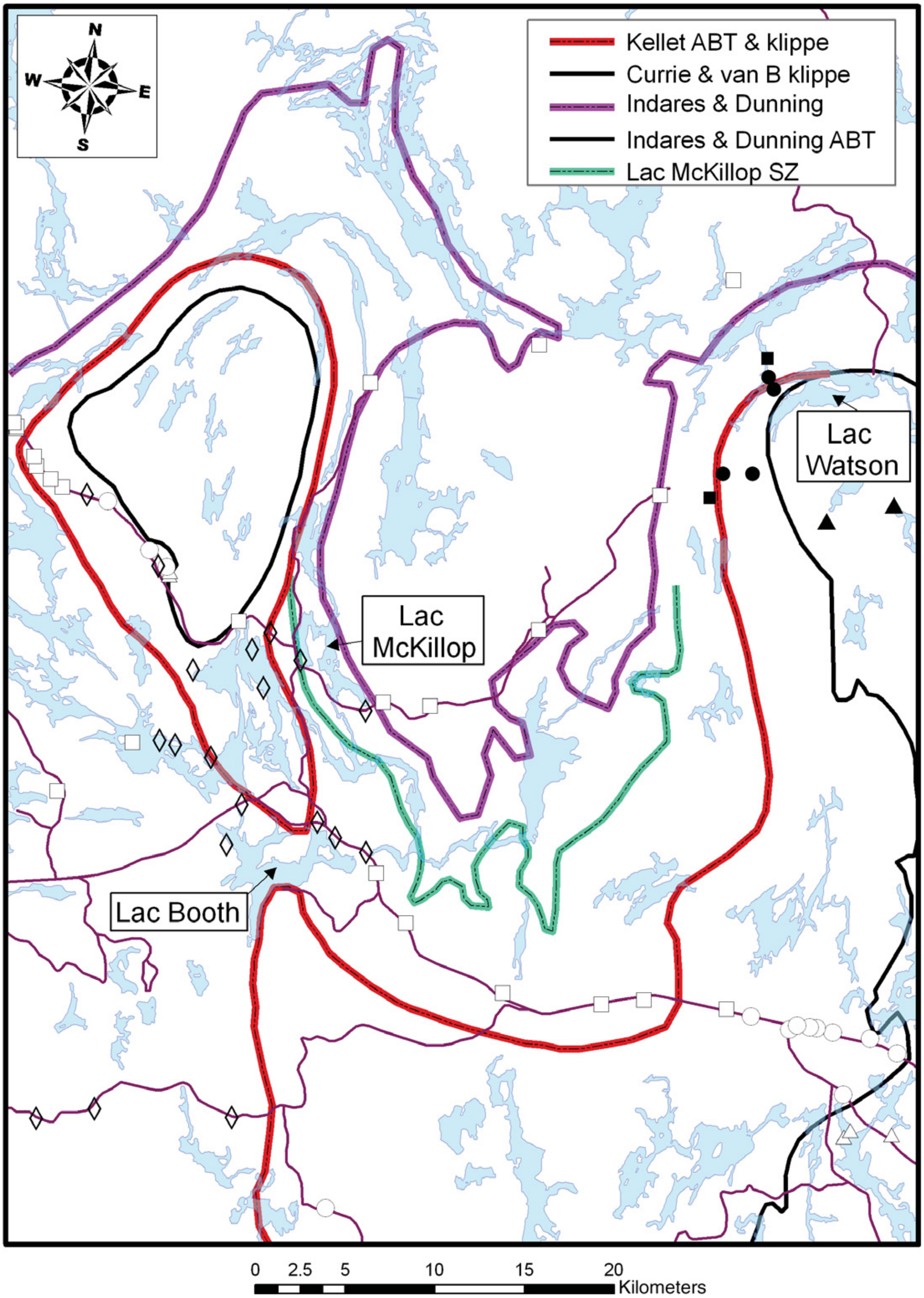


Figure 3. Map showing alternative thrust boundaries in western Quebec in the vicinity of Lac Booth and Lac Watson (location shown in Fig. 2). ABT—Allochthon Boundary thrust; SZ—shear zone.

observations such as textural overprints of igneous relics; they accepted the boundary of the klippe proposed by Currie and van Breemen (1996), but proposed a higher structural level for the ABT in the eastern part of the study area, based on the observation of a major shear zone at Lac Watson (black line in Fig. 3). In addition, Indares and Dunning (1997) proposed a lower shear zone similar to that of Currie and van Breemen (1996), but placed it more consistently below the quartzite-bearing supracrustal unit (purple line in Fig. 3).

The problem was revisited by van Breemen and Currie (2004), who proposed that the lower thrust zone was located above (southeast of) the supracrustal unit, which they termed the Lac McKillop Group. Hence we refer to this boundary as the Lac McKillop shear zone (green line in Fig. 3). This latter interpretation implies that the supracrustals may be in unconformable contact with the basement, but are overthrust by another basement slice. However, it is simplistic to assume that the thrust zone must always follow the southeast side of the Lac McKillop Group, since the outcrop extent of this unit may simply reflect the effects of folding and erosion of this unconformable unit. Therefore, mapping of the basement-cover boundary alone is not sufficient to constrain the ABT.

To summarize, geological mapping of structural domains with distinct lithologies can yield useful information about the location of thrust zones in the southwest Grenville Province. In addition, the nonoverlapping extents of different mafic suites on either side of the ABT show that it separates terranes that have undergone large-scale relative horizontal motion. However, both methods lose their reliability when thrust boundaries juxtapose terranes composed of high-grade gray gneisses, since these cannot be reliably distinguished in the field. This problem led one of us (Dickin, 2000) to propose an alternative method of mapping the ABT, based on differences in the Nd model ages of terranes juxtaposed across the ABT, attributed to distinct ages of crustal formation. This technique can be applied to any orthogneiss outcrop, allowing for much higher spatial resolution in mapping the ABT.

Nd ISOTOPE MAPPING IN THE SOUTHWEST GRENVILLE PROVINCE

Nd model ages were used to separate the southwest part of the Grenville Province into four geographically distinct crustal belts (Dickin, 2000), each with a distinct range of Nd model ages, which we refer to here as age suites (Fig. 4). The first age suite represents relatively pristine Archean crust with Nd model ages older than 2.5 Ga that can be found several tens of kilometers southeast of the Grenville Front, representing the metamorphosed equivalents of Superior Province basement within the Grenville Province.

During the Mesoproterozoic, the Laurentian foreland was subjected to massive plutonism and migmatization, some of which was emplaced into Archean crust and led to mixing of Archean and Mesoproterozoic Nd age signatures. This created a second suite of model ages within the parautochthon, with much more variable signatures, typically from 2.0 to 2.5 Ga, which was referred to in Dickin and Guo (2001) as reworked Archean crust. The boundary between pristine and reworked Archean crustal zones may originally have been very diffuse, but Grenvillian thrusting telescoped the crust, so that in western Quebec (Fig. 3) the zone of convergence is now mappable based on Nd model ages, and corresponds in its type locality to the Lac McKillop shear zone. However, Nd data suggest that southeast of the type locality the thrust boundary trends farther south than the position proposed by van Breemen and Currie (2004), as shown by Herrell et al. (2006).

A third suite of T_{DM} (depleted mantle model) ages with a much tighter clustering between 1.8 and 2.0 Ga was recognized in the southern part of the parautochthon, in a strip extending west to east on either side of Lake Nipissing. This was attributed (in Dickin and McNutt, 1989) to the accretion of a juvenile arc terrane onto the southeastern margin of the Superior craton during the 1.85 Ga Penokean orogeny, creating a suture zone between these two crustal blocks. The evidence that these Nd model ages represent the actual crustal formation age of a juvenile Paleoproterozoic terrane was discussed in detail in Dickin et al. (2008). This terrane was also reworked during the Mesoproterozoic, but due to the closer similarly in the ages of the mixing materials, this reworking had relatively little effect on measured Nd model age signatures.

The location of the Archean-Proterozoic suture (marking the Archean-Proterozoic boundary)

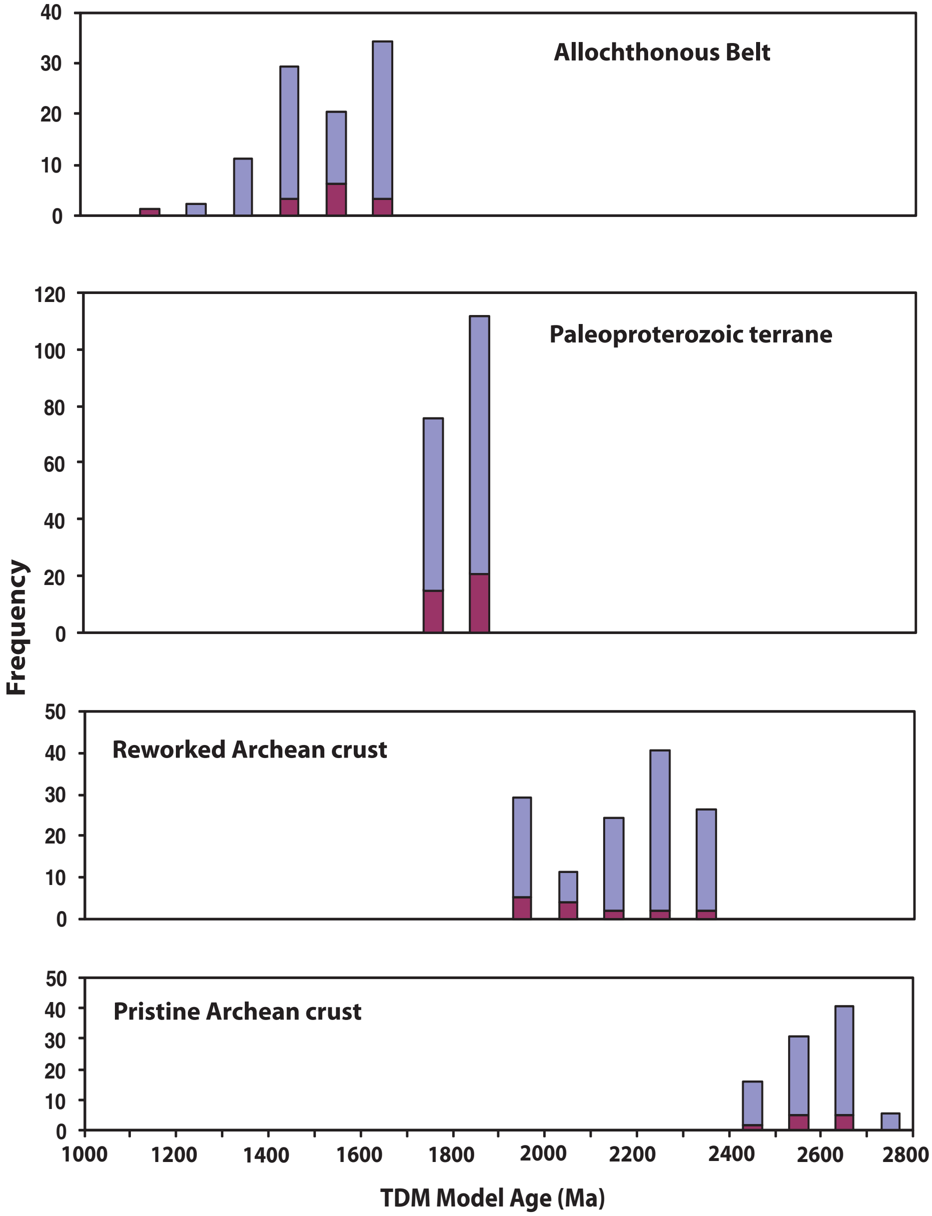


Figure 4. Distribution of Nd model ages in the four geographically defined age suites used to categorize Nd data from the southwest Grenville Province. Blue shading—published data; red shading—new data in Table 1.

first recognized in Dickin and McNutt (1989) has been refined in the North Bay, French River, and Mattawa areas (Fig. 5) by further detailed Nd isotope mapping (Holmden and Dickin, 1995; Dickin, 1998, 2000; Dickin and Guo, 2001; Dickin and McNutt, 2003; Herrell et al., 2006). However, difficulty of access has previously limited sampling in the Lake Nipissing area, so that the suture location is undefined within the lake (e.g., Dickin, 2000).

A fourth suite of model ages, with a range from 1.4 to 1.8 Ga, was recognized farther to the south within the allochthonous polycyclic belt of Rivers et al. (1989). This crustal belt is attributed to crustal formation in a long-lived continental margin arc located on the edge of the Laurentian craton during the Mesoproterozoic (Dickin et al., 2008).

The effectiveness of Nd isotope mapping to locate the ABT was demonstrated by detailed studies in the Lac Booth, Mattawa, North Bay, and Burk's Falls areas (Fig. 5; Dickin and Guo, 2001; Dickin and McNutt, 2003; Herrell et al., 2006; Dickin et al., 2008). In all cases, the distribution of Nd model ages was consistent with evidence from the distribution of metabasic rock types. However, these studies indicated that unlike the single klippe previously known from north of Lac Booth, two more erosional outliers of the allochthonous belt were located near North Bay and Mattawa, as shown in Figure 2.

COMPARISON WITH THE GEOLOGICAL SURVEY OF CANADA COMPILATION MAP

Davidson (1998a) wrote *An Overview of Grenville Province Geology, Canadian Shield*, and presented a map showing the lithology of the Grenville Province as a whole (Davidson, 1998b; published by the Geological Survey of Canada, referred to herein as the GSC map). This was a compilation of previous maps at various scales (1:1,000,000 in Ontario and 1:250,000 in Quebec). This map is the most recent compilation map for the Grenville Province, and was therefore chosen as a base map for comparison with Nd model age data within our study. The GSC map essentially follows the location of the ABT proposed by Ketchum and Davidson (2000), indicated by a dashed blue line in Figure 5. In contrast, the evidence from Nd isotope mapping leads to a location for the ABT much farther to the southeast (solid black line in Fig. 5), accompanied by the existence of three allochthonous klippen (black perimeters in Fig. 5).

Although the evidence from Nd isotope mapping is consistent with lithological mapping, as described here, others have not found the ABT location proposed in Dickin (2000) and in subsequent more detailed studies to be convincing. For example, Jamieson et al. (2007), Rivers (2008), and Slagstad et al. (2009) followed the trajectory of Ketchum and Davidson (2000). Hence, this suggests that additional sampling, coupled with

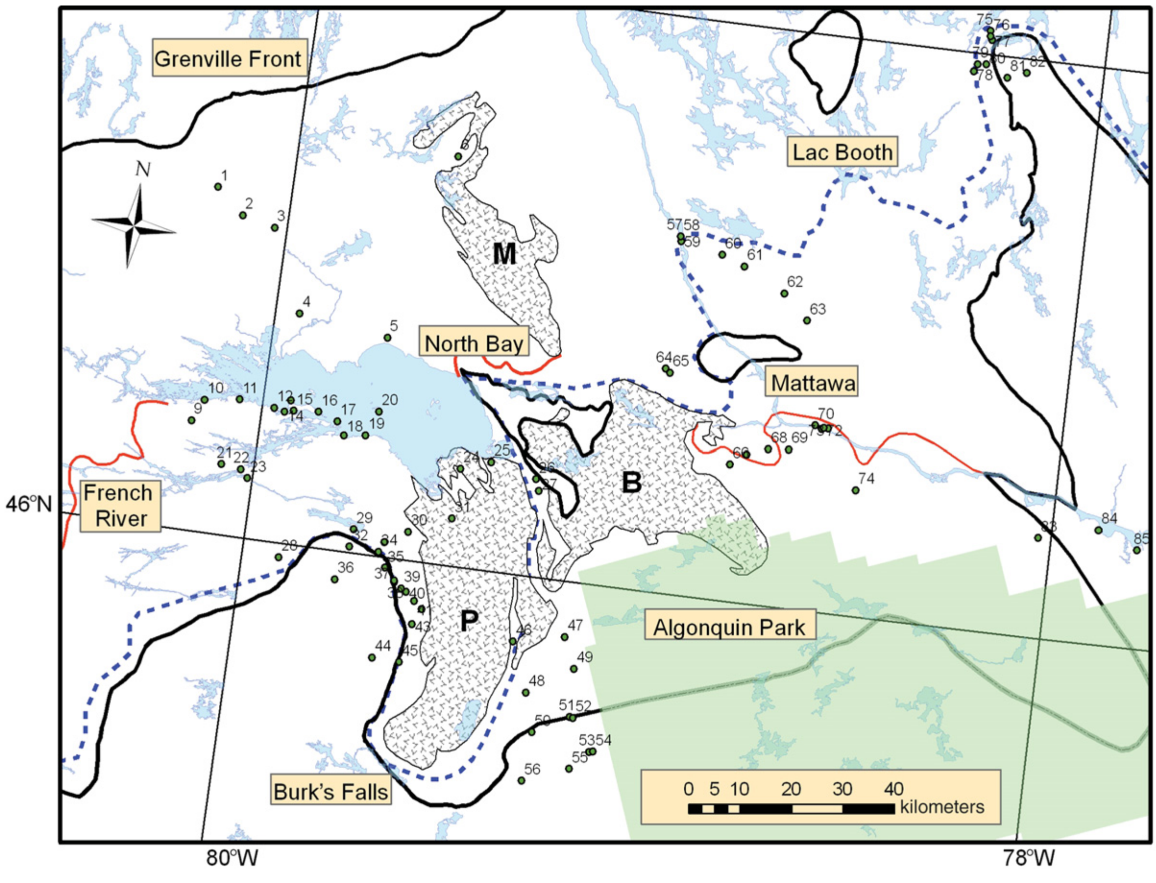


Figure 5. Map of the study area, corresponding to the eastern part of Figure 2 tilted to optimize the coverage of geological boundaries. Red line—Archean-Proterozoic suture (Dickin, 2000); dashed blue line—trend of Allochthon Boundary thrust proposed by Ketchum and Davidson (2000); black line—trend of ABT proposed by Dickin and McNutt (2003). Stippled areas are granitic batholiths (P—Powassan, B—Bonfield, M—Mulock). Numbered points are new sample localities listed in Table 1.

more thorough geographical analysis, is necessary in order to convince other workers of the reliability of the Nd isotopic evidence.

GIS ANALYSIS METHODS

Our objective for this study was to create an interpolation map of the southwestern Grenville Province that better defines the age boundaries present within the region. To achieve this, an age contour map was created by digitally interpolating (contouring) the spatial distribution of crustal formation ages calculated from sampled orthogneiss within the southwest Grenville Province.

The initial phase of the project was based on results collected from the Grenville Province over the past 20 yr (references cited here and in Dickin, 2000). Two principal techniques, using triangulated irregular networks (TIN) and inverse distance weighting (IDW) were tested to assess their effectiveness in creating a contoured surface that embodied both global and localized trends. These analysis methods attempt to interpolate the age of unknown points between sampled localities, assuming spatially continuous data (see details in following).

Once the variability of the interpolation maps was assessed, areas where the contouring revealed poorly constrained or discrepant Nd model ages were revisited and additional samples were collected where possible. After completing Sm-Nd isotopic analysis, model ages for these additional samples were calculated and included in the geospatial analysis. The new interpolation maps were assessed relative to the predefined geological mapping within the area, as summarized on the GSC map (Davidson, 1998b).

Visualization

The main program used for this project was the ESRI ArcMap 9.2. Extensions including Spatial Analyst, 3D Analyst, Geostatistical Analyst, and Georeferencing helped with processing the data to create the final map. A digitized version of the GSC map (including proposed ABT boundary location) was loaded into ArcMap, where it was georectified with grid points acquired from the National Topographic Database (2006). Other shapefiles, such as waterbodies and major and minor roads, were acquired to help determine accessibility for resampling.

Based on the Nd model ages collected by one of us (Dickin) and colleagues, a shapefile of the location of the ABT proposed in Dickin et al. (2008) was also digitally created using the GSC map as a base map. Therefore there would not be any discrepancies between the two proposed boundaries due to mapping or scale error. All shapefiles were saved under the common projection datum of NAD83 (1983 North American Datum geodetic network).

For both interpolation methods, contours were separated into intervals of 100 m.y., from 1000 Ma to 3000 Ma. This bin size was used with an extended color spectrum in order to precisely depict the location of important boundaries. After initial visualization on the computer monitor, it was later found that some color bins were not adequately distinct on printed copies. Therefore, the shades of some contour intervals were slightly edited to improve color contrasts (e.g., across the 1800 Ma boundary, corresponding to the location of the ABT).

Geostatistical Analysis

In order to apply the most appropriate geostatistical analysis technique, it is important to establish whether the data being analyzed are deterministic or stochastic. Deterministic data would imply that the variable being studied provides completely predictable results, while stochastic data would imply that the variable is subjected to random error and therefore contains a degree of unpredictability.

The present data set contains two different forms of uncertainty. First, analytical errors in mass spectrometry contribute a stochastic element to individual Nd model ages, with an estimated uncertainty of ±20 m.y. However, this error is relatively small when compared to the spread of the data.

The second form of uncertainty associated with this method is due to geological processes. When using Nd model age analysis, the assumption is that samples collected and analyzed represent melts of metaigneous sources that accurately reflect the crustal formation age of the particular terrane. However geological processes such as melting of sediments, mixing with more recent juvenile mantle-derived magmas, or initial crustal derivation from a non-normal mantle source can cause calculated Nd model ages to yield older or younger ages. However, these samples cannot always be excluded using geological screening methods, and therefore they remain within the data set and contribute to the interpolation.

If a sample is found to yield a locally anomalous Nd model age, it must be tested by the collection of additional samples in the same vicinity. A stochastic analysis method can then use the surrounding samples to reduce the amount of weight the anomalous sample has on interpolated age contours. However, if additional sampling confirms the previously anomalous value, this indicates that the model age distribution is more complex than was previously recognized, which may require a modification to the geological model. Either way, the end result is a more accurate location of geological age boundaries.

TIN Analysis

Tessellation (tiling) using a TIN was used first to examine the age variation (assuming deterministic data). The collected sample points were used as vertices to make triangles, which then ultimately created the interpolated ages across the surface of the Grenville Province. The X and Y axes were set as the sample Northing and Easting coordinates, respectively, and the Z axis was set to the T_{DM} model age of the individual samples.

The tessellation routine breaks the irregular (essentially stochastic) spatial distribution of sample points into a set of triangles, based on the rule that the sides of each triangle should be as nearly of equal length as possible. Having divided the map into triangles, the value of the Z axis (model age) is determined by linear interpolation between the vertices along each side of the triangle to determine the predicted value for all unsampled sites between them. Isolines are then drawn within each triangle to connect equal values along each side.

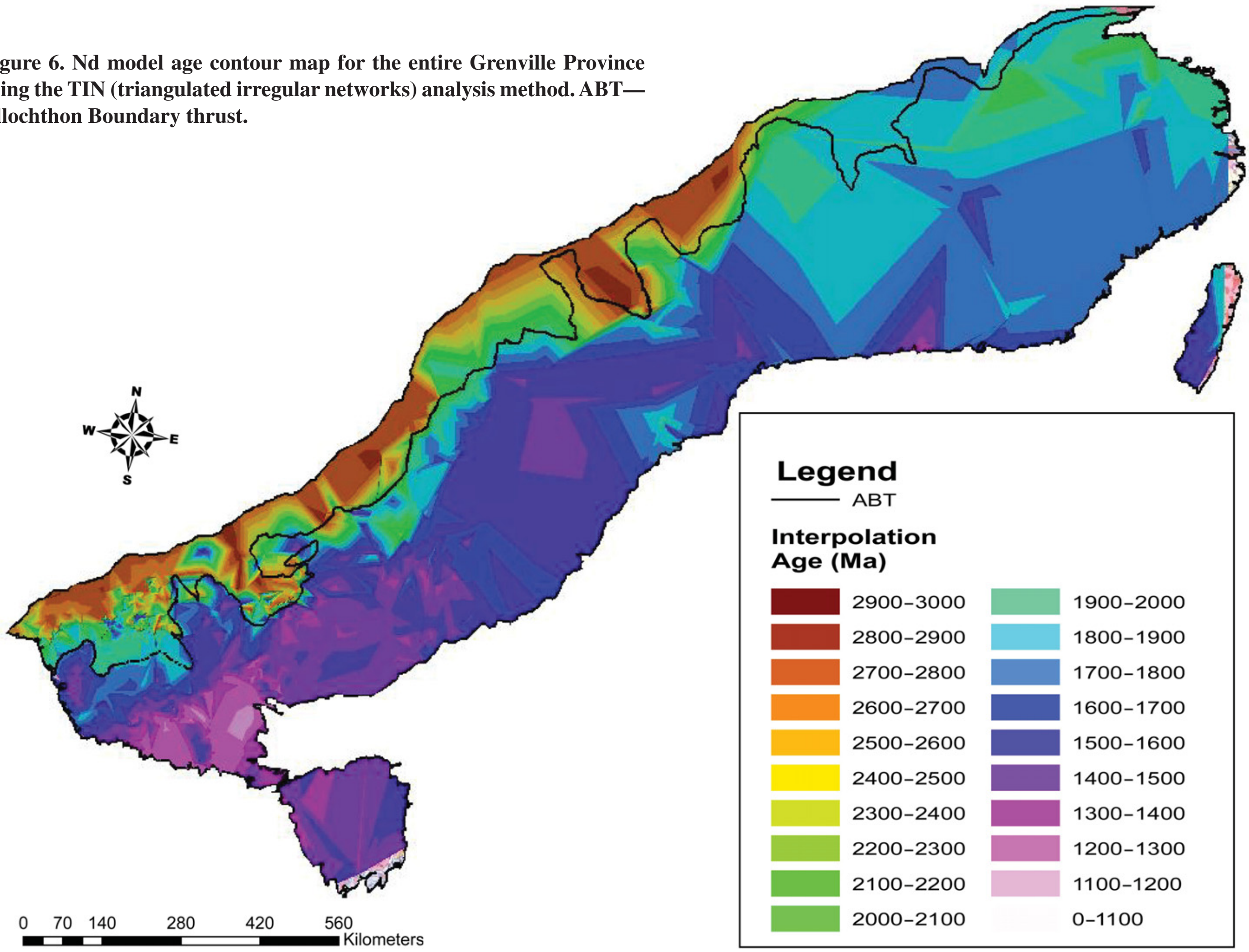
The TIN interpolation creates contour planes that are not smooth. This is illustrated in a TIN interpolation of model ages for the entire Grenville Province in Figure 6. The abrupt nature of this method has both advantages and disadvantages as an interpolation method. The sharp contour lines draw attention to the location of age boundaries, which is advantageous to our objective. However, the angular nature of the contours is not geologically realistic. In addition, since the TIN interpolation is deterministic, the method is not capable of reducing the effect of geological noise caused by a few abnormal samples, even when these are shown to be geologically aberrant by other sampling. This tendency to noise can obscure real geological age boundaries. Therefore, this is not the preferred method for interpolating our data.

IDW

Unlike the TIN method, the IDW method interpolates the Z axis value (Nd model age) as smooth contours. Although termed a deterministic interpolation, the IDW method can be used to contour data with a stochastic component, because it effectively averages local values of the Z axis variable.

Using the Spatial Analysis tool in ArcMap 9.2, the degree of smoothing within an interpolation can be changed by modifying the power parameter within the distance decay model. By using a low power at which the interpolation is

Figure 6. Nd model age contour map for the entire Grenville Province using the TIN (triangulated irregular networks) analysis method. ABT—Allochthon Boundary thrust.



calculated (such as a power of 2), samples within close proximity to an unsampled location have only slightly more influence on the estimated age than those that are farther away. As the power is increased, samples located close to the unsampled location will have a much stronger influence on the predicted age of the unsampled region than those farther away. Since the most common power chosen for an IDW interpolations has been set to the exponent of two (Isaaks and Srivastava, 1989), the first interpolation of our data set was calculated at a power of two. This gives us a basis for comparison with interpolations calculated at a higher power.

By defining the size of the calculation window or kernel, the number of samples that will be used for the interpolation will be modified. Based on the distribution of samples throughout the area, the size of the window or kernel on which the calculation is performed will automatically change. The effect of this variable was analyzed by comparing two interpolations, one with the number of nearest neighbors at 6 and the second calculated with 12. However, this was observed to have much more limited effects on the interpolation than changing the power, so it is not discussed further.

GIS ANALYSIS OF PUBLISHED DATA

The objective of this study is to reevaluate the location of two major age boundaries in the southwestern Grenville Province, the ABT and the Archean-Paleoproterozoic suture. This was attempted by interpolating T_{DM} ages of orthogneiss samples. The first step in performing a statistical analysis of the published data was to create a point map, which indicates the location of all published analyses of granitoid orthogneisses from the southwest Grenville Province.

Additional Archean ages (2.75 Ga) were added north of the Grenville Front (Fig. 7) in order to confine the contoured interpolation and restrict contours of local younger T_{DM} ages from distorting the age contouring in the Grenville Front region. Because the Superior craton has been previously dated as Archean (Jackson and Fyon, 1991), these additional data points were inserted without the region being sampled. The area of Algonquin Park has been blanked out on the maps, since poor access and extensive glacial cover in this area have not yet allowed sampling at sufficient density to contour accurately.

As noted here, it is traditional to use a power of 2 for IDW interpolations, creating a smooth contour surface that emphasizes regional trends. For the Nd isotope data, this gives a good representation of the broad-scale variation of model ages over the province. However, geological age boundaries are usually comparatively sharp, at

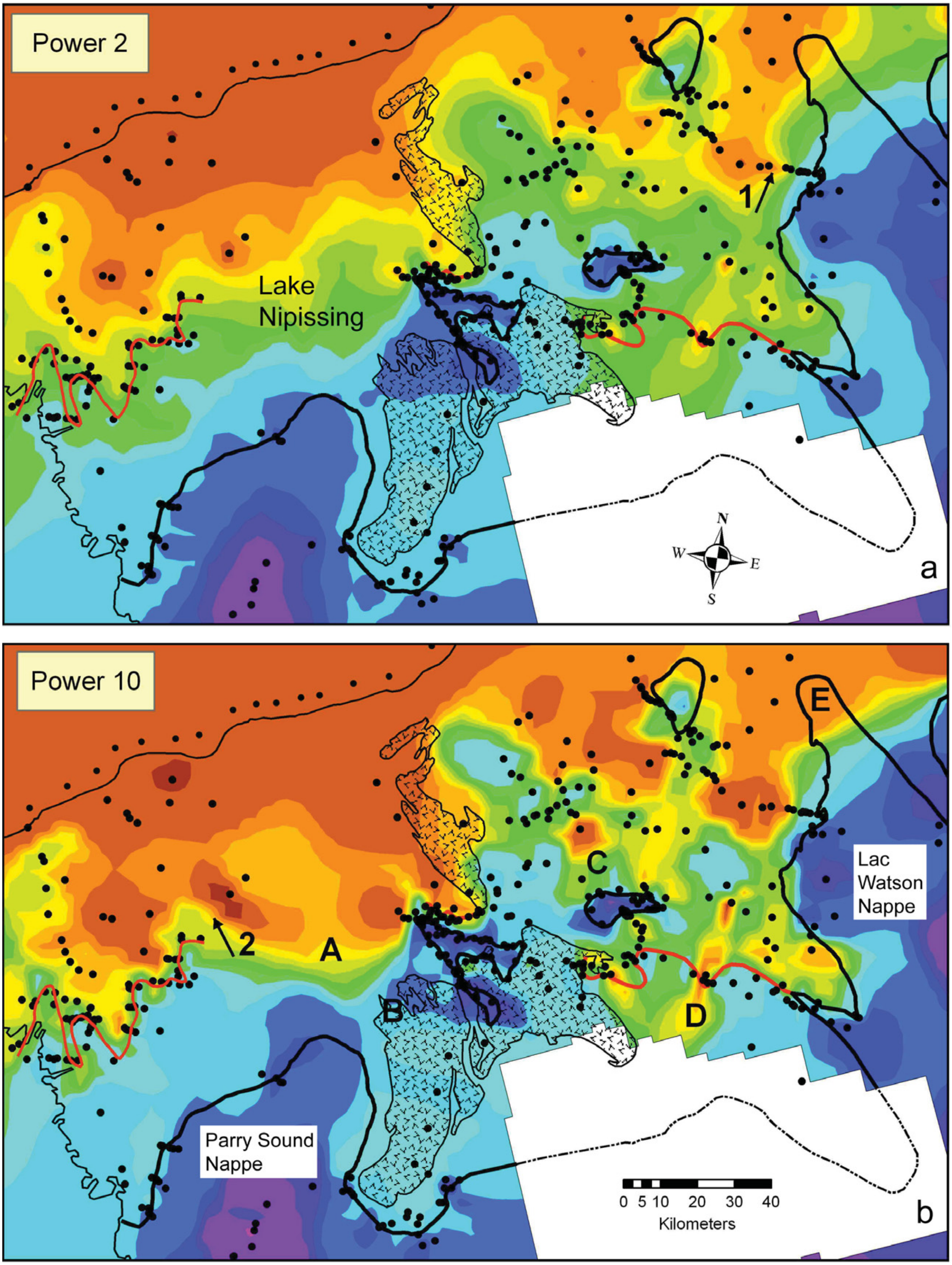


Figure 7. Comparison of contouring intervals for published Nd model age data based on IDW (inverse distance weighting) analysis at powers of 2 and 10. Heavy lines denote location of Allochthon Boundary thrust and klippen proposed by Dickin et al. (2008). Arrows 1 and 2 show features of contouring discussed in the text. Localities A–E are some of the problem areas requiring additional work (see text).

least on scales above 1:1,000,000, so smooth age trends may not be geologically realistic.

To demonstrate the effect of varying the power at which IDW contouring was performed, results at powers of 2 and 10 are compared in Figure 7. Increasing the power emphasizes the consistency of Nd model ages within each terrane and the sharpness of the boundaries between them, which is more geologically realistic. For example, in the eastern part of the study area, the power of 10 fit accommodates a sharp drop in model ages seen on a detailed east-west transect by Herrell et al. (2006). In contrast, the power of 2 contours cannot properly accommodate the sharp 700 m.y. drop in model ages (see arrow 1 in Fig. 7A). However, in the western part of the study area, the power of 10 fit generates sharp contours where the data do not demand it (see arrow 2 in Fig. 7B). This suggests that 10 may be too high a power. Therefore, a power of 6 was chosen as a compromise value for further calculations (see following).

SAMPLING TARGETS

The contour fits in Figure 7 highlight areas where additional sampling is needed. These are discussed in two sections essentially corresponding to the western and eastern halves of the map area in Figure 7. New localities sampled to address these problems are shown in Figure 5.

In the western area there are two major problems. The first is the poor definition of the extent of Archean crust in the region around Lake Nipissing (A in Fig. 7B). For example, the trajectory of the Archean-Proterozoic suture across the lake was unknown (Fig. 5). This is now rectified by detailed sampling along the south shore. The second major problem is the poor definition of the extent of Mesoproterozoic crust, which the computer interpolation suggests might connect across between the Parry Sound nappe and the North Bay klippe in the area southeast of Lake Nipissing (B in Fig. 7). This is in contradiction to the proposed location of the ABT in this area (Fig. 5), and has been rectified by detailed sampling west of the Powassan batholith (P in Fig. 5). The results of the new sampling to address these problems are reported in Table 1 (1–45).

In the eastern area there are three major problems. The first is the need for additional data immediately to the west of Algonquin Park to test previous Nd isotope mapping (e.g., Dickin et al., 2008), which defines a southern location for the ABT, as opposed to the northern trajectory of Ketchum and Davidson (2000). The second problem is the poor definition of the extent of Archean crust, both to the northwest and southeast of Mattawa (Fig. 5). To the northwest, the problem is to determine if a single Archean outlier is indicative of a wider extent of Archean crust in this area (C in Fig. 7B). To the southeast of Mattawa, Archean outliers have been confirmed, but their possible continuation to the south is very poorly constrained (D in Fig. 7B). The third major problem in the eastern part of the study area is

TABLE 1. Nd ISOTOPE DATA

Sample number	Sample identification	Northing	Easting	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	TDM (Ga)
1	SF 40	5160700	562200	35.0	6.24	0.1078	0.511169	2.72
2	SF 30	5156000	567800	6.1	1.10	0.1095	0.511192	2.73
3	SF 24	5154550	574200	10.1	1.92	0.1147	0.511295	2.71
4	SF 3	5138930	581530	15.4	2.21	0.0866	0.510819	2.68
5	SF 9	5136900	599000	69.8	10.39	0.0899	0.510884	2.67
6	EM 9	5173576	607185	41.1	7.81	0.1148	0.511228	2.82
7	KE 7	5083000	540800	53.3	10.20	0.1157	0.511747	2.02
8	KE 9	5083000	542800	57.4	9.93	0.1045	0.511749	1.80
9	NV 17	5115400	564000	12.9	2.71	0.1272	0.511919	1.98
10	WB 3	5119700	565900			0.0915	0.511519	1.90
11	WB 5	5120800	572600			0.1049	0.511383	2.33
12	NP 9	5120200	579450	66.2	11.51	0.1051	0.511717	1.86
13	NP 8b	5122100	582350	18.4	2.86	0.0937	0.510956	2.67
14	NP 7	5119700	581450	37.0	6.51	0.1062	0.511596	2.05
15	NP 6	5120200	583200	43.6	6.91	0.0958	0.511587	1.88
16	NP 5	5120700	588000	42.1	6.95	0.0998	0.511497	2.07
17	NP 4	5119450	591850	51.0	10.20	0.1207	0.511793	2.05
18	NP 3	5117000	593550	28.4	4.96	0.1055	0.511560	2.09
19	NP 2	5117600	597600	38.6	6.31	0.0988	0.511622	1.88
20	NP 1b	5122550	599550	45.7	6.84	0.0904	0.511329	2.12
21	NV 3	5108000	570950			0.0968	0.511645	1.82
22	NV 4	5107600	574800			0.1045	0.511679	1.90
23	NV 6	5106100	576300			0.1033	0.511679	1.88
24	PO 7	5114120	616700	20.7	3.61	0.1054	0.511515	2.15
25	PO 9	5116270	622410	38.2	7.30	0.1157	0.511635	2.19
26	PO 13	5114330	631480	52.0	8.84	0.1029	0.511688	1.86
27	PO 12	5112160	632250	14.0	2.54	0.1095	0.511692	1.98
28	EM 35	5091885	584550	28.6	4.62	0.0978	0.511616	1.88
29	EM 32	5099406	598129	35.4	7.94	0.1356	0.512026	1.98
30	PO 5	5100550	608600	54.6	10.71	0.1127	0.511793	1.88
31	EM 6	5104327	616553	59.6	11.96	0.1213	0.511809	2.04
32	EM 29	5095979	597762	48.1	7.44	0.0935	0.511585	1.85
33	EM 5	5097813	604376	107.8	14.26	0.0799	0.511443	1.82
34	RE 034	5095850	603500	57.8	14.60	0.1529	0.512278	1.92
35	EM 3	5093086	605210	29.6	5.83	0.1191	0.512050	1.60
36	EM 33	5089307	595924	27.8	6.80	0.1480	0.512382	1.53
37	EM 2	5090834	607281	28.4	5.90	0.1258	0.511921	1.94
38	PO 3	5090550	607300	60.9	12.86	0.1275	0.512000	1.84
39	EM 1	5089507	608848	47.3	7.38	0.0943	0.511701	1.71
40	EM 28	5088964	609890	29.5	4.86	0.0995	0.511617	1.90
41	EM 27	5087465	611667	30.6	6.32	0.1248	0.511991	1.80
42	EM 26	5086159	613351	51.9	9.12	0.1062	0.511701	1.90
43	EM 25	5083001	612001	25.4	5.04	0.1197	0.511861	1.92

(*continued*)

the poor definition of the Lac Watson nappe at its northern end, where the existence of Mesoproterozoic needs to be confirmed (E in Fig. 7B). Results of new sampling in these areas are reported in Table 1 (46–86).

ANALYTICAL METHODS

Sm-Nd analysis followed our established procedures. After dissolution using HF and HNO_3, samples were split and one aliquot treated 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 normalized to an ^{146}Nd/^{144}Nd ratio of 0.7219. Average within-run precision on the samples was ±0.000013 (2 sigma), and an average value of 0.51185 ± 2 (2 sigma population) was determined for the La Jolla standard during this work. The reproducibility of ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd is estimated as 0.1% and 0.002% (1 sigma), respectively, leading to an average uncertainty on each model age of 20 m.y. (2 sigma), based on empirical experience over several years of analyzing duplicate dissolutions. All model ages are calculated using the depleted mantle model of DePaolo (1981). A few samples have no concentration data due to the loss of weighing information for these samples.

GIS ANALYSIS INCLUDING NEW DATA

New Nd model age data are presented in Table 1, and are compared with published Nd model age suites in Figure 4. Although the new samples only contribute a fraction of the total Nd model ages within the sampled region, the age distributions of both data sets are very similar. The sharpest peak within the data is ca. 1.8 Ga to 2.0 Ga, representing the Paleoproterozoic arc terrane Barilia (defined in Dickin, 2000). A second peak from 2.5 to 2.8 Ga represents crust generated during the Kenoran orogeny. The broad peak from 1.5 Ga to 1.8 Ga characterizes the allochthonous crustal terranes. The long tail of ages from 2.0 to 2.5 Ga represents the extent of reworked Archean crust within the parautochthon.

The four age suites are denoted by different symbol shapes in Figure 8 (see legend), and distinguished by solid and open symbols for new and published data, respectively. The contour map for the combined data set was then calculated by IDW interpolation at a power of 6. The new sampling (localities in Fig. 5) provides improvements in most of the problem areas identified above, although the complexity of the geology prevents a perfect solution.

Beginning with the extent of Archean crust, the new sampling in the northern part of the study area solidifies the extent of relatively

TABLE 1. Nd ISOTOPE DATA (*continued*)

Sample number	Sample identification	Northing	Easting	Nd (ppm)	Sm (ppm)	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	TDM (Ga)
44	EM 23	5075479	605324	26.1	5.22	0.1210	0.512012	1.69
45	EM 20	5075364	610566	40.0	6.60	0.0998	0.511627	1.89
46	KW 1	5082600	631700	62.4	12.86	0.1246	0.511883	1.98
47	KW 3	5085000	641500	47.7	9.06	0.1148	0.511770	1.96
48	AP 17	5073240	635740	4.5	0.70	0.0945	0.511551	1.90
49	AP 15	5079160	644170	47.7	9.07	0.1150	0.511765	1.97
50	AP 12	5065850	638000	15.1	3.67	0.1467	0.512314	1.65
51	AP 11	5069900	644700	28.8	5.25	0.1095	0.511677	2.00
52	AP 14	5069760	645380	18.3	2.87	0.0951	0.511635	1.81
53	AP 8	5063760	649460	30.8	4.86	0.0953	0.511685	1.75
54	AP 9	5063910	650220	74.9	15.36	0.1241	0.512000	1.77
55	AP 7	5059930	646180	11.7	2.32	0.1195	0.511933	1.79
56	AP10	5056270	637460	40.0	7.52	0.1137	0.511918	1.71
57	TG 8	5164874	651903	59.9	9.63	0.0971	0.511394	2.16
58	TG 10	5164793	651894	61.7	10.18	0.0996	0.511381	2.22
59	TG 9	5163928	652143	20.9	3.24	0.0933	0.511017	2.58
60	TG 3	5162512	660457	25.1	4.90	0.1182	0.511331	2.75
61	TG 4	5160976	665023	33.9	4.35	0.0776	0.510669	2.67
62	TG 6	5157000	673375	41.9	6.57	0.0948	0.511240	2.32
63	TG 7	5152452	678567	16.3	2.57	0.0950	0.511165	2.42
64	TG 11	5139111	652992	69.6	12.61	0.1095	0.511397	2.42
65	TG 12	5138483	653850	26.3	5.25	0.1206	0.511421	2.68
66	TG 17	5122757	667988	29.0	6.50	0.1354	0.512025	1.98
67	TG 16	5125091	670883	1.2	0.19	0.0964	0.511268	2.31
68	TG 15	5126754	674901	15.5	1.87	0.0731	0.510635	2.62
69	TG 14	5127330	678812	31.1	5.93	0.1153	0.511818	1.90
70	OR 14	5132650	683200	100.3	16.86	0.1016	0.511586	1.98
71	OR 10	5132200	684500	44.4	8.28	0.1127	0.511753	1.95
72	OR 12	5132450	684900	95.6	17.31	0.1095	0.511595	2.12
73	OR 11	5132450	685750	119.7	18.32	0.0925	0.511536	1.89
74	TG 13	5121531	692799	54.1	9.78	0.1091	0.511734	1.91
75	LW 11	5213234	705066	15.9	2.71	0.1030	0.511080	2.72
76	LW 13	5212227	705282	70.9	11.95	0.1019	0.511649	1.90
77	LW 12	5211586	705669	75.9	14.30	0.1139	0.511758	1.96
78	LW 3	5205094	703077	9.5	1.53	0.0969	0.511102	2.55
79	LW 4	5206556	703599	51.3	9.11	0.1074	0.511697	1.93
80	LW 7	5206791	705213	49.5	7.53	0.0920	0.511559	1.86
81	LW 9	5204831	709680	37.0	6.62	0.1080	0.512164	1.28
82	LW 10	5206279	713216	56.3	9.31	0.1000	0.511782	1.69
83	AQ 24	5117700	729100	39.2	6.51	0.1003	0.511650	1.87
84	MT 10	5120300	277550	45.8	8.67	0.1144	0.511990	1.61
85	MT 11	5116950	285200	43.8	7.38	0.1018	0.511940	1.50
86	ZC 6	5134300	298000	46.3	10.46	0.1367	0.512265	1.54

Note: TDM—depleted mantle model age.

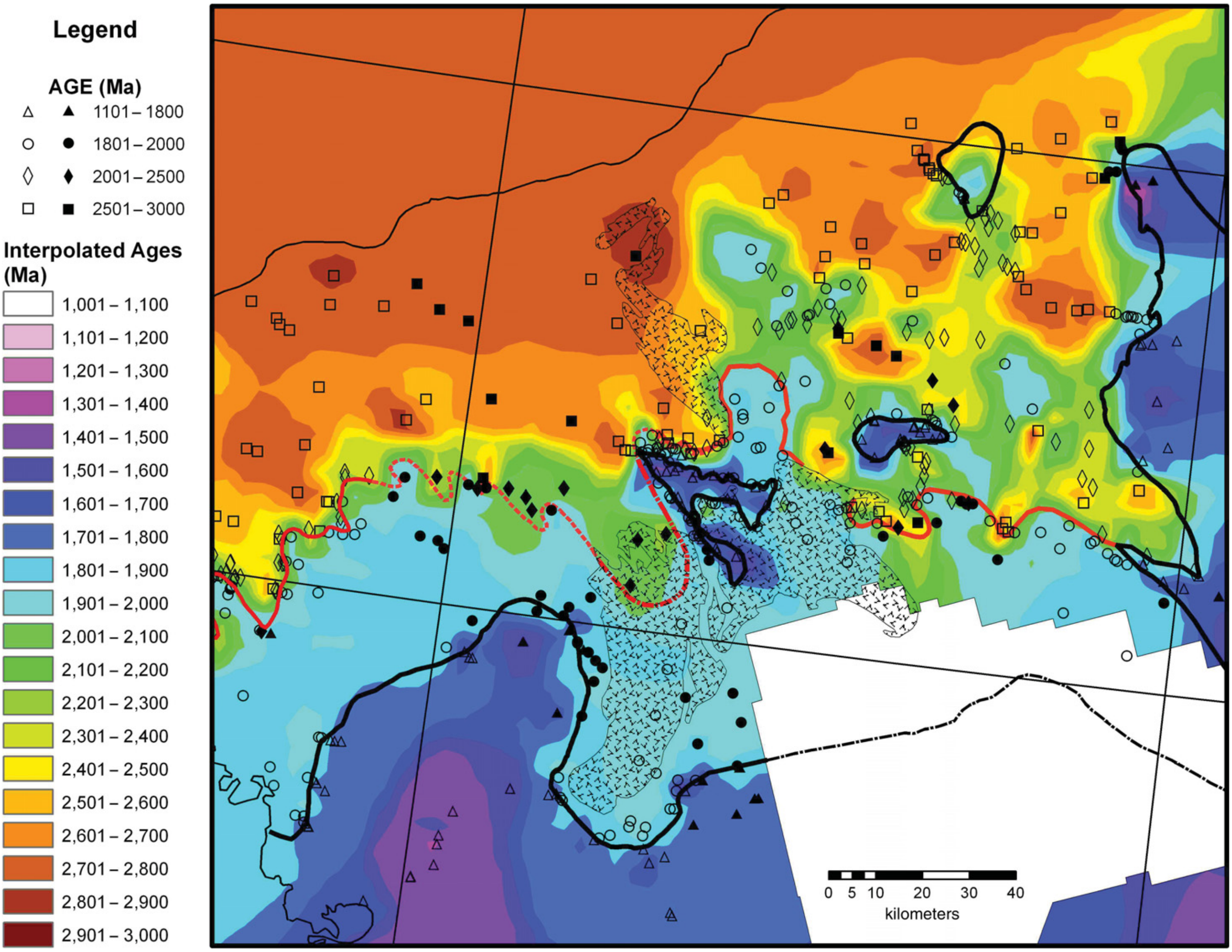


Figure 8. Final Nd model age contour map for the southwest Grenville Province, incorporating both published and new data and using the IDW (inverse distance weighting) method at a power of 6. Open symbols are published data; solid symbols are new sample localities shown in Figure 5. Thin black line—Grenville Front; heavy black line—location of Allochthon Boundary thrust and tectonic klippen proposed by Dickin et al. (2008); solid red lines—previously proposed locations of Archean-Proterozoic suture; dashed red line—new proposed suture location in Lake Nipissing area.

pristine crust with model ages older than 2.5 Ga, equivalent to Superior Province basement. In the west, this is shown to extend as far as the north shore of Lake Nipissing (red-orange contour intervals in Fig. 8). However, the Penokean suture of Dickin and McNutt (1989) is believed to be somewhat farther south, and is separated from pristine Archean crust by a zone with model ages older than 2 Ga (yellow-green contour intervals in Fig. 8) This corresponds to suite 2 model ages defined above, attributed to a Paleoproterozoic–Mesoproterozoic continental margin arc that caused magmatic reworking of the edge of the Archean craton. The boundary between this material and the suite 3 model ages (pale blue–green contour intervals) is a good fit to the proposed suture boundary (red line in Fig. 8), which was drawn following regional foliations on the geological map.

The new sampling of the suture boundary along the south shore of Lake Nipissing suggests that the suture cuts into the northern edge of the Powassan batholith (P in Fig. 5). This relationship is visible because the batholith tends to break up into a series of large sheets at its northern edge, leaving country-rock screens that were selected for analysis. These crosscutting relationships confirm that the suture boundary predates emplacement of the batholith at 1270 Ma (U-Pb age from Davidson and van Breemen, 2001), and the boundary may also have been involved in folding before emplacement of the batholith. This is consistent with the proposed Paleoproterozoic age of the suture, in contrast to the Grenvillian (ca. 1070 Ma) age of the ABT.

In the eastern part of the study area, the new sampling extends the known extent of Archean crust north and west of the Mattawan klippe, showing that it almost completely encircles the allochthonous klippe, as might be expected. However, the new sampling also places tighter limits on the southern extent of Archean crust to the east of Mattawa, showing that it does not extend as far as Algonquin Park.

The new sampling also confirms the location of the ABT more tightly in several areas. First, it severs the bridge of younger contours that previously extended between the Parry Sound nappe and the North Bay klippe. Second, it confirms the location of the ABT mapped in Dickin et al. (2008) around the south side of the Powassan batholith (stipple in Figs. 5 and 8). Third, the extent of the Lac Watson nappe is confirmed at its northern end and in the vicinity the Ottawa River, where it is offset by the Mattawa fault.

By constraining the northern extent of Paleoproterozoic crust against Archean basement, and its southern extent against the allochthon, our work also clarifies the extent of juvenile Paleoproterozoic crust.

CONCLUSIONS

The objective of our project was to reevaluate the location of proposed geological boundaries based on the interpolation of Nd model ages within the southwestern Grenville Province. This was based on the premise that most geological boundaries within the Grenville Province separate terranes with distinct crustal formation ages. Two different forms of geostatistical analysis were applied to the previously published Nd model ages of northeastern Ontario and western Quebec.

Triangulations proved to be beneficial by defining regions of abrupt age difference. However, because of its angular nature, this interpolation method made the contouring difficult to compare with geological boundaries.

A variety of inverse distance weighted interpolations was calculated using different variables. It was established that the best procedure for contouring Nd model ages was the IDW method, calculated at a power of 6. This procedure revealed several areas where the published Nd data set did not provide sufficient constraints for a purely numerical contouring method to adequately test proposed geological boundaries. Therefore, these problem areas were revisited and sampled further if possible, after which a revised contour map was calculated.

The result of this work is an Nd data set with sufficient geographical coverage of a large segment of the Canadian shield to allow GIS analysis to predict the location of geological boundaries based entirely on computed age contouring. The results agree very well with those of other workers concerning the shape of the Parry Sound and Lac Watson nappes (Fig. 8), and confirm that the ABT is situated at the location proposed in Dickin et al. (2008). Tectonic klippen near Mattawa and North Bay are also very well confined by the model age contouring.

Precise mapping of major terrane boundaries in the Grenville Province is important in order to accurately reconstruct the geological evolution of this segment of the Laurentian margin. For example, localization of major boundaries allows their age and tectonic character to be better determined by more detailed mapping.

The Archean-Proterozoic boundary has been interpreted as a Paleoproterozoic collisional suture (Dickin and McNutt, 1989), and detailed mapping is therefore necessary to constrain the timing of the proposed collision and the mechanism by which a hypothesized Paleoproterozoic arc terrane was accreted to the Laurentian craton. This is pertinent to questions about the extent of the Penokean orogeny in North America (Holm et al., 2007). In contrast, the ABT has been interpreted as a crustal-scale ramp developed in response to crustal thickening during the Ottawan phase of the Grenvillian terminal orogeny (Rivers et al., 2002). Hence, accurate delineation of the ABT is important in reconstructing the three-dimensional structure of the Grenville orogen. In both cases, the ability of Nd model age mapping to predict geologically reasonable boundary locations gives increased confidence to our models for crustal growth of Laurentia during the Proterozoic Eon (e.g., Dickin, 2000; Dickin et al., 2010).

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