3D Structural Geometry of a Thrust Duplex within the Grenville Province, Ontario: Integration of Radiogenic Isotope, Magnetics, and SRTM topography data

School of Geography and Earth Sciences

H.A. Slavinski, W.A. Morris, A.P. Dickin & Ugalde H.
McMaster Applied Geophysics and Geological Imaging Consortium
School of Geography & Earth Sciences, McMaster University, Hamilton, Ontario

McMaster University

ABSTRACT

In this study we present detailed topographic, Landsat and aeromagnetic imagery for the Grenville Province within Ontario and western Quebec. Detailed radiogenic dating of gneissic samples has been interpreted in terms of three distinct terranes separated by respectively the Allochthon Boundary Thrust and Parautochthonous Belt Suture. As more radiogenic data became available the loci of the proposed terrane boundary surfaces has been radically revised. The thrust surfaces, like all geological boundaries, must exhibit some systematic relationship to topography Therefore by examining the spatial distribution of known isotopic dates in relation to the observed topography it should be possible to critically assess the viability of previously proposed loci for the thrusts. Three distinct populations of radiometric age are separated using a simple histogram approach. Topographic information was provided by the 90m Space Shuttle SRTM data. Additional evidence for geological discontinuities was provided by the Provincial aeromagnetic data base, and a Landsat composite. Using these remote sensing data sources a location of the thrust and suture can be determined even without the presence of outcrop exposure for isotopic study. Combining these sources of information it is possible to derive an estimate of the three-dimensional geometry of these boundary surfaces. Testing this relationship provides information about the thrust mechanics and the distribution of post-thrust deformation. Currently available radiometric information is sparse and spatially poorly constrained. The resulting model suggests the boundary surfaces are not simple planar surfaces.

GRENVILLE PROVINCE BACKGROUND AND STUDY AREA

The Grenville Province is located on the southeast limit of the Canadian Shield and is the youngest tectonic domain (Figure 1). Ongoing degradation and consequent exhumation of the Genvillian mountain belt has exposed a region which has experienced a long and complex history of igneous intrusion, metamorphism and deformation. The boundaries between individual terrane elements are difficult to identify because of the high grade metamorphic overprint imposed by the terminal Grenvillian Orogeny.

Many details of the distribution of individual tectonic elements within the Grenville Province remain to be defined. A key aspect of the problem is having objective information that will permit precise delineation of the terrane boundaries. Some of the earliest work relied on field mapping of what was considered to be diagnostic geological rock units. Ketchum and Davidson (2000), for example, identified terrane boundaries on the basis of coronitic olivine diabases. More regional assessments have been made using various types of remote sensing techniques with limited resolution, including aerial photography, lineament analysis of Landsat imagery, SEASAT-radar data and both aeromagnetic and gravity surveys.

More recently Dickin and his colleagues have reported a number of studies that use an objective radiogenic approach (mostly Nd-Sm model ages) to discriminate terranes in the northern Grenville Province (Dickin and Guo, 2000; Dickin, 1998a; Dickin, 1998b, Herrell *et al*., 2001; Drielsma, 2001; Slavinski, 2004). This method has the capability of precisely locating terrane boundaries and is limited only by the accuracy of the GPS measurements used to locate the sample points. Samples have been collected at a number of spots along the northern Grenville Province Allochthon Boundary Thrust. It is, however, impractical to apply the radiogenic methodology to the entire Grenville Province. Even if one could process large numbers of samples this method is limited to areas with geological outcrop exposure.

Like all other geological structures, a terrane boundary represents a continuous three-dimensional surface. This surface must conform to a common geological mapping principle; that is, there is a genetic relationship between the local dip of the terrane boundary and the local topographic surface. The terrane boundary is continuous unless it is interrupted by a fault, which produces a relative displacement of the surface. Hence if one has a number of observations of the location and elevation of a terrane boundary it should be possible to construct a morphology of that surface. In this study we use SURFER and ER Mapper to examine two terrane boundary surfaces (the Allochthon Boundary Thrust and the Parautochthon Belt Suture). Herrell *et al*. (2004) have suggested that these two surfaces are linked by a thrust duplex (Figure 2).

Allochthon Boundary Thrust (ABT or Baskatong-Désert Lineament)

The ABT represents a major thrust fault running northeast along the Grenville Province in the study area that formed around 1.2 Ga. At that time a large thrust sheet (an Allochthon) was pushed northward over the Parautochthonous belt forming the ABT (Dickin and Guo, 2000, Slavinski, 2004). The ABT, a primary tectonic boundary, separates the Allochthonous Belt transported from the southeast from the underlying Parautochthonous Belt that has remained more or less in place.

Parautochthonous Belt Suture (PBS)

The PBS, which formed earlier than the ABT (~1.4-1.77 Ga), was produced when young Paleoproterozoic crustal terranes were forced into and became fused to the larger and older Archean section of the shield (Dickin and Guo, 2000; Dickin, 1998a, Dickin, 1998b, Slavinski, 2004). Within the study area the PBS is situated between the Grenville Front to the north and the ABT to the south. The ABT surface overrides the PBS and is treated as a truncation surface.

INTERPRETATION TECHNIQUE USING HISTOGRAM ANALYSIS

The primary constraint that we use to define the terrane boundaries is based on the Nd-Sm model ages obtained by Dickin and his colleagues. The age divisions for the terrain classifications were based on a frequency distribution plot of all the radiogenic ages that were collected from the various studies of this area of the Grenville Province (Dickin, 1998a; Dickin, 1998b; Dickin, 2000; Dickin and Guo, 2001; Dickin and McNutt, 1989; Dickin and McNutt, 2003; Drielsma, 2001; Guo and Dickin, 1996; Guo, 1995; Herrell *et al*., 2004; Holmden and Dickin, 1995; Slavinski, 2004; Zelek, 2006). This produced a multimodal frequency histogram with multiple minimum values (Figure 3), which when examined, were determined to be gaps in the ages (at ~2.55 Ga, ~2.15 Ga and ~1.80 Ga) that represent the different terranes that form the framework of the Grenville Province.

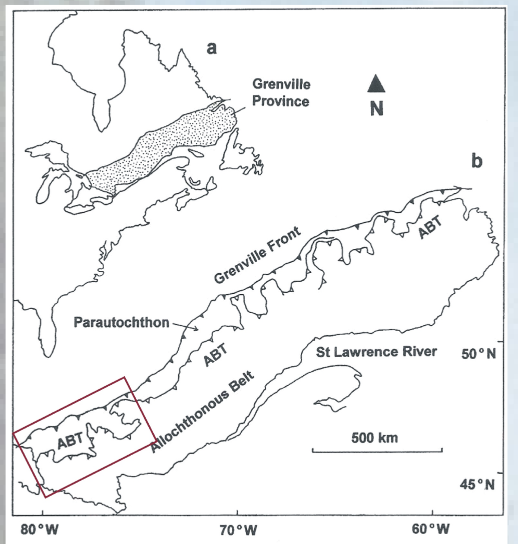

Figure 1: The major tectonic belt division of the Grenville Province according to Rivers *et al*. (1989).
a) The location of the Province within North America;
b) The location of the ABT within the Grenville Province. The study area is indicated by the red box.

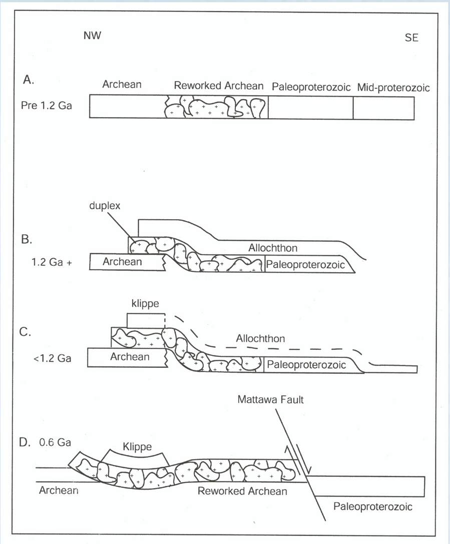

Figure 2: Example of the three-dimensional geometry of the Grenville Province through geologic time within the Mattawa region of Ontario by Herrell *et al*. (2004).
A) The initial position of the different terranes, including the Archean, reworked Archean, Paleoproterozoic and Mesoproterozoic terranes;
B) The reworked Archean and Mesoproterozoic terranes are forced over the parautochthonous Archean terrane, forming a thrust duplex;
C) Surficial expression is altered by exhumation and degradation the crustal terranes;
D) Re-activated faults cause further complexity of the Province.

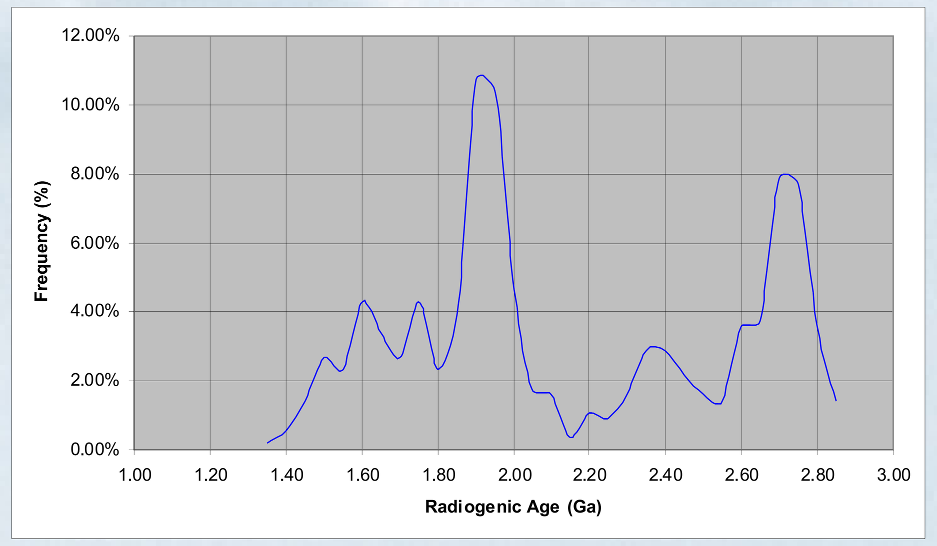

Figure 3: Frequency plot of the Nd isotope dates for the compiled radiogenic studies within the study area. The multimodal histogram was used to determine the age classes for further radiogenic modeling of the terranes of interest within the study area. Three minimums can be seen to occur at ~2.55 Ga, ~2.15 Ga and ~1.80 Ga, separating the different terranes of the area.

RESULTS

Terrane Boundary Location

In order to derive a three-dimensional representation of the ABT and PBS it is necessary to obtain location and elevation estimates for the boundaries. The primary constraint on the loci of the boundaries was provided by the radiogenic data. That is the radiogenic data should exhibit the same grouping spatially as it is does in the histogram. The presence of spatially isolated clusters of anomalous data points immediately requires the presence of klippe as recognised by previous authors. Previous estimates of the locus of these surfaces by Ketchum and Davidson (2000) and Herrell et al (2004) are respectively shown in orange and blue (Figure 4). Initially revised estimates for the boundaries were based on constraints provided by the aeromagnetic and Landsat Band8 Panchromatic data compilation (Figure 5). A Landsat RGB composite of Bands 3,2 and 1 30m imagery, overlain on the 15m panchromatic Band 8 intensity layer proved especially informative. Combining the optical imagery with the detail provided by Band 8 locally permitted the recognition of geological continuities and discontinuities. This is especially relevant to the Ottawa Valley - Bonnechere graben which crosscuts the study area, and must displace the boundaries.

Previous Lithoprobe crustal seismic studies have been performed a number of profiles across the Grenville. Four profiles have been reported from the study area. Rendering the limited seismic data in a simple 3D image (Figure 6) shows that both the ABT and PBS are characterized by a number of sub-horizontal sections as originally proposed in the hypothetical models (Figure 2). Steeper slopes in the seismic data correspond to the displacement associated with te hOttawa Valley graben and proximity to the thrust ramp front. Since the thrusts approximate sub-horizontal surfaces a preliminary estimate of their geometry is given by selecting a contour level. As demonstrated by figures 7 and 8 even this simple approach provides a very rapid close approximation of the currently available radiogenic data. The presence of klippe are easily explained in terms of topographic outliers. Some areas are better constrained than others as a consequence of the large time requirements of the radiogenic mapping method.

Each of these datasets has some limitation. The Landsat images used in the mosaic (eight separate scenes) were not acquired at the same time; some were acquired under ideal "leaf-off conditions", while others were collected mid-summer. The Landsat mosaic also spans UTM zones 17 and 18 with some distortion introduced when the data was projected into zone 17. The topographic data was gridded at a 250m grid cell with some details of topographic significance lost. The magnetic data were derived from a national database compilation with an 800m grid cell size limiting the spatial resolution. Finally, many of the radiogenic samples were collected by reference regional scale topographic maps ($\pm$100m), with high resolution GPS data ($\pm$10m) only available for more recent studies.

3D Model Development

Two point sets (ABT, PBS) were created from the radiogenic data and the imagery. In stratigraphic terms the ABT truncates, or onlaps, onto the underlying PBS. The two surfaces have no genetic relationship and therefore must be modelled as separate entities. The geometry of the bounding surfaces was computed using a minimum-curvature gridding approach in SURFER. To overcome local topographic artefacts a coarse grid-cell of 10km was used. This minimizes the effect of any local changes in the bounding surfaces.

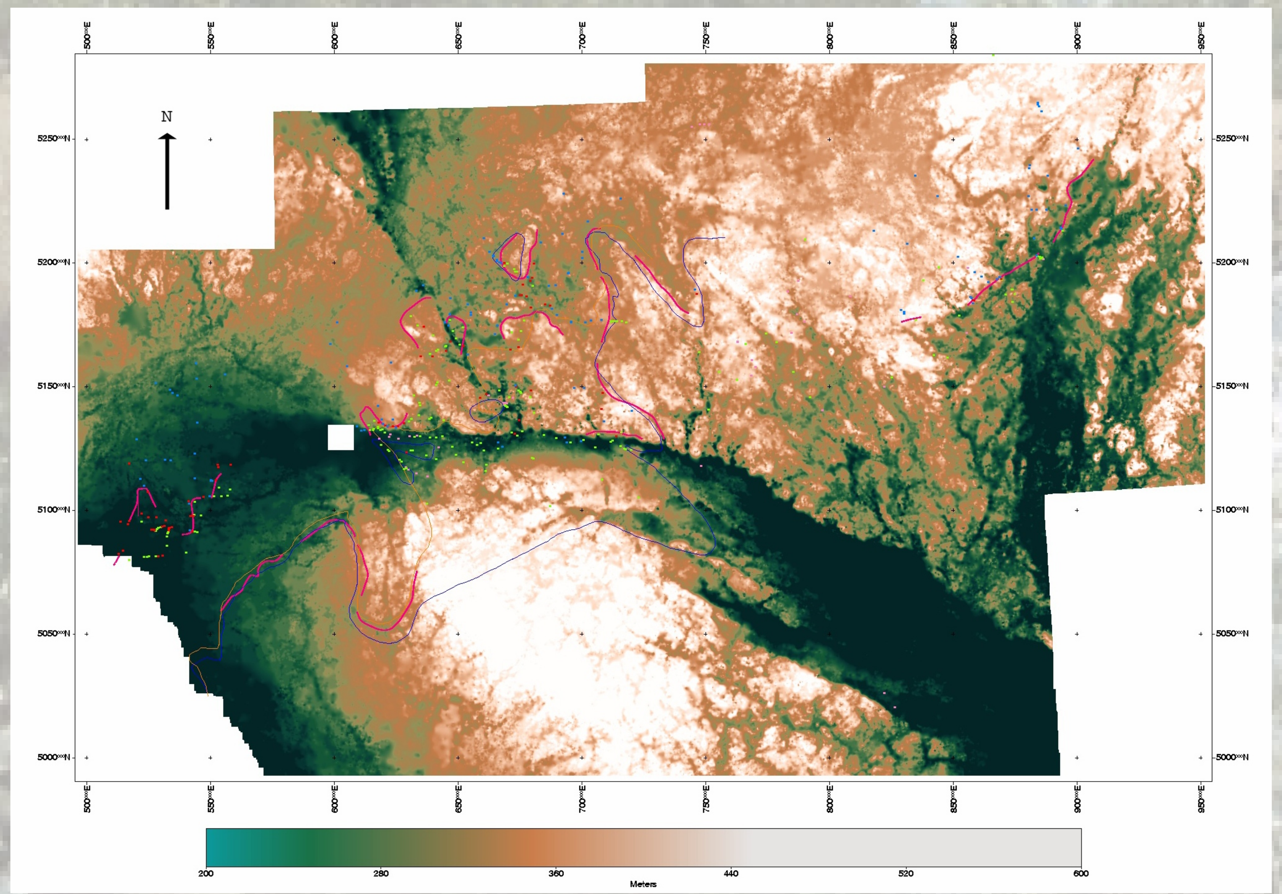

Figure 4: Topography of the study area demonstrating the influence on the geological surface expression of the terrane boundaries. Boundaries: Orange = Ketchum and Davidson (2000); Blue = Herrell *et al*. (2004); Red = present study.

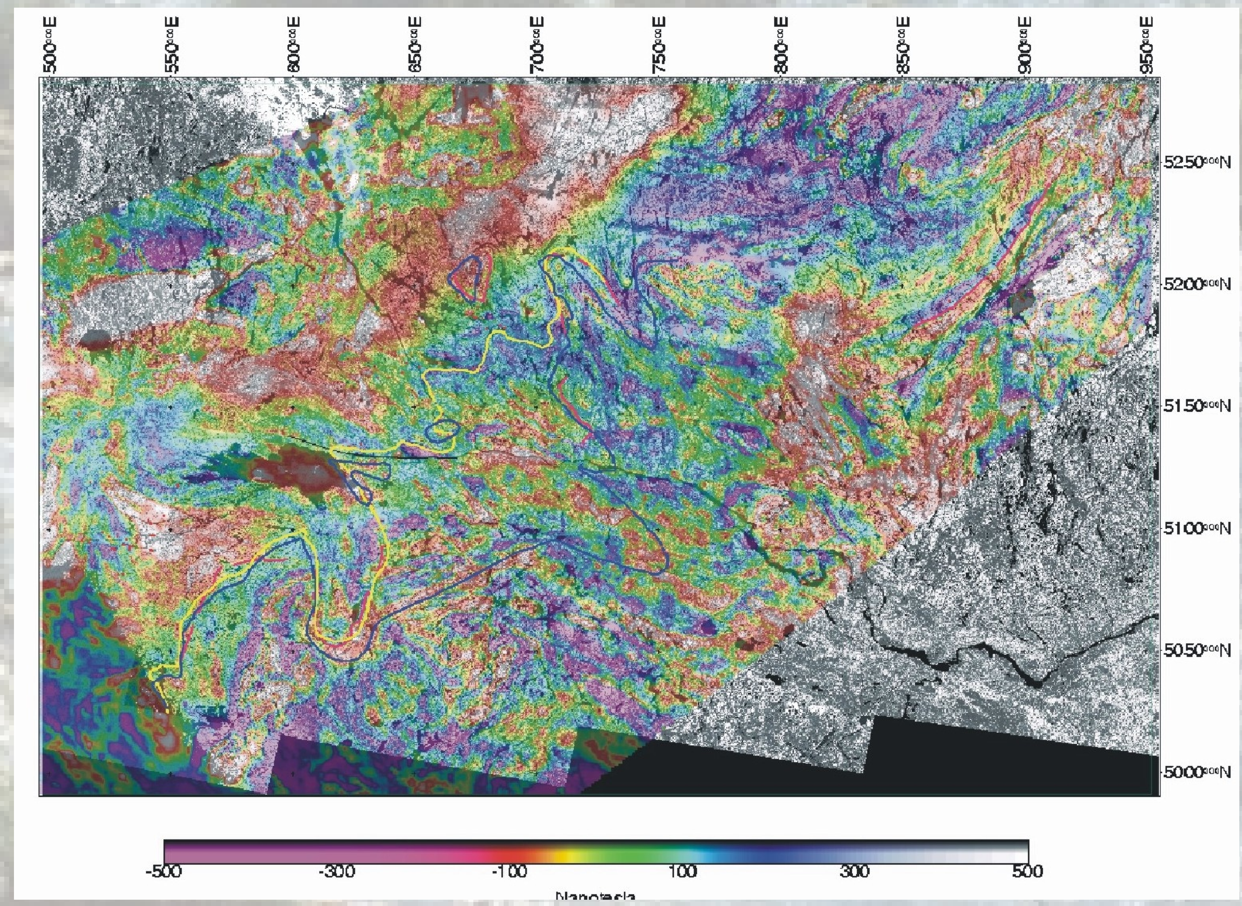

Figure 5: 15m panchromatic mosaic of Band 8 (0.52-0.90μm) displayed as an intensity layer from Landsat images for the study area. The regional total magnetic intensity has been displayed on the image. Boundaries: Orange = Ketchum and Davidson (2000); Blue = Herrell *et al*. (2004); Red = present study.

CONCLUSION

The radiogenic dating approach provides a clear, objective subdivision of temporally identical. A simple dot pattern map shows that the four age classes have distinct spatial distribution. Locally sampling density is sufficient to locate the bounding surface. At some locations it is possible to correlate the bounding surface with a discontinuity in the topography, magnetics and/or satellite imagery. In these situations one can stretch the two-dimensional extent of the bounding surface. Extending this to a full three-dimensional model remains a challenge because of limited sampling and poor topographic control. The current model, while having the correct placement of the PBS and ABT does not show the correct truncation sequence between the two surfaces. Future development of the model to address this concern will require the more interactive model approach offered by 3D GeoModeller.

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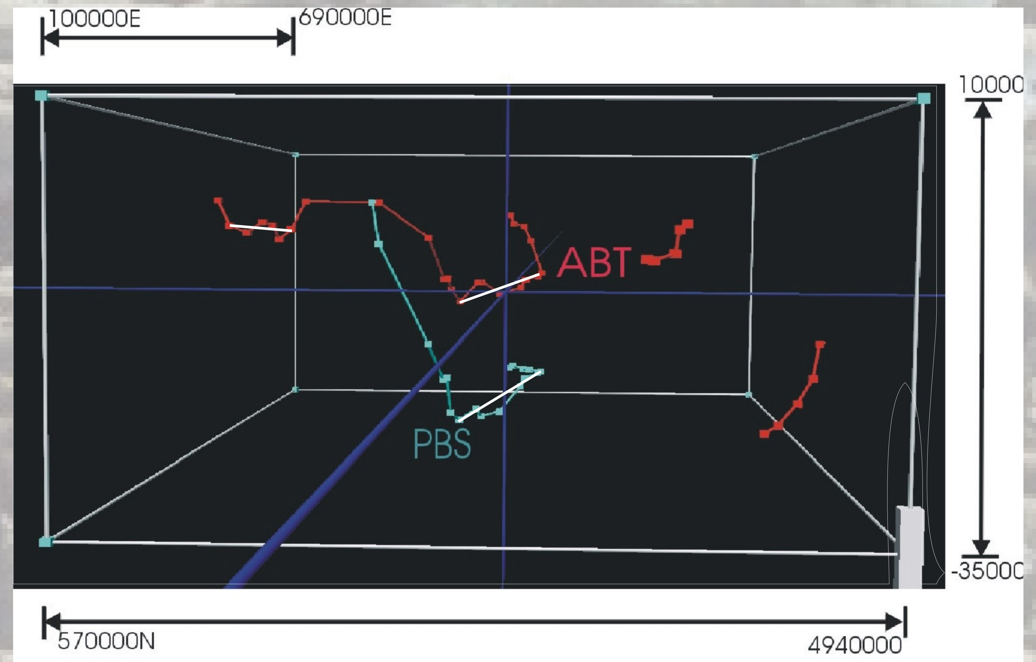

Figure 6 3D representation of ABT and PBS surfaces as mapped by Lithoprobe seismic surveys across Grenville. White lines identify sub-horizontal portions of thrust surfaces.

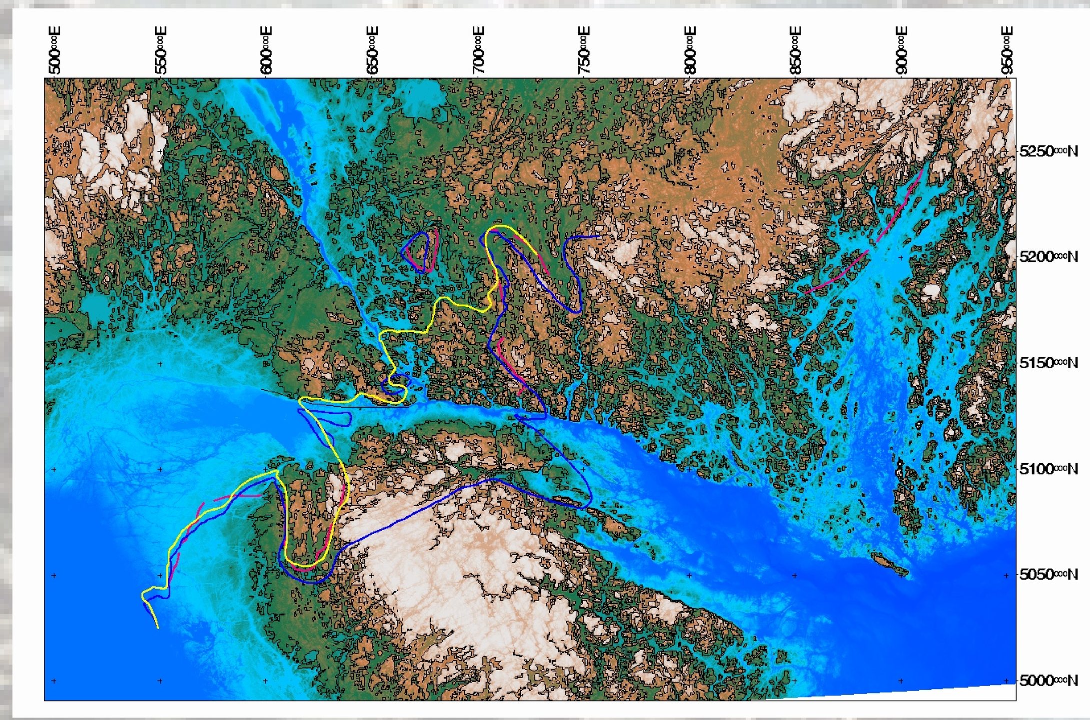

Figure 7: Proposed locus of ABT boundary (red) compared to contoured topographic image. Note that model approach offers a much more detailed estimate of geometry of boundary which could form basis for future radiogenic sampling program.

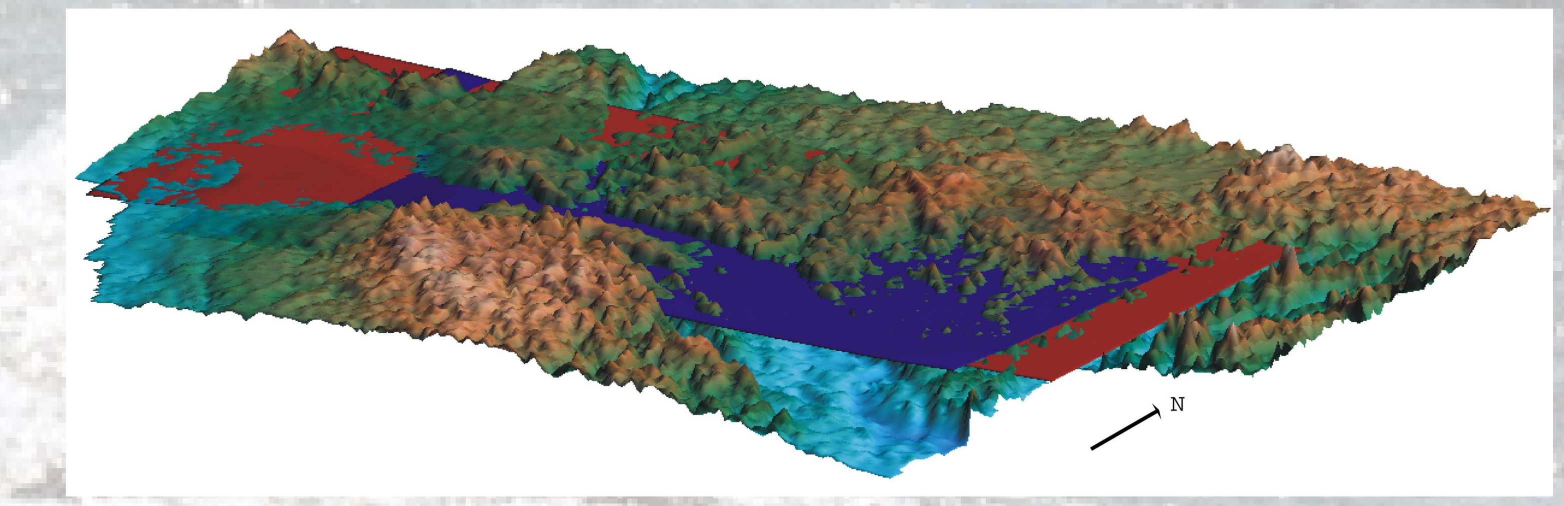

Figure 8: A three-dimensional model of theABT as seen at various angles with topography of the study area. The Allochthonous Belt is represented in blue, with the Parautochthonous Belt illustrated in red.