Paper 71

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

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ABSTRACT

On-going detailed radiogenic dating of rock samples is providing information regarding the trajectory of terrane boundaries within the Grenville Province. In the western Grenville Province the Allochthon Boundary Thrust (ABT) and Parautochthonous Belt Suture (PBS) separate regions have disparate radiogenic signatures. Currently available radiometric information is sparse and spatially poorly constrained. Both the ABT and PBS are continuous bounding surfaces and therefore like any other continuous geological surface they must exhibit a systematic relationship to topography. In this study we combine information derived from SRTM Space Shuttle topographic, Landsat and aeromagnetic imagery over the western Grenville Province of Canada to derive an estimate of the three-dimensional geometry of these bounding surfaces. 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 studies. Testing this relationship provides information about the thrust mechanics and the distribution of post-thrust deformation. The resulting model suggests that the boundary surfaces are not simple planar surfaces.

INTRODUCTION

The Grenville Province is located on the southeast limit of the Canadian Shield and is the youngest tectonic domain (Figure 1). Ongoing degradation and subsequent exhumation of the Grenvillian 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, and many details of the distribution of individual tectonic elements within the Grenville Province remain to be defined. Critical in the solution of the problem is having objective information that will permit precise delineation of the terrane boundaries. Early works relied on field mapping of what was considered to be diagnostic geological rock units. An example of this is the work by Ketchum and Davidson (2000), which identified terrane boundaries on the basis of coronitic olivine diabases. Other 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, a number of studies have attempted to discriminate terranes in the northern Grenville Province by means of using an objective radiogenic approach (mostly Nd-Sm model ages; 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. Detailed radiogenic studies have been performed 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 any other geological structure, 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 the morphology of that surface. In this study we used 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).

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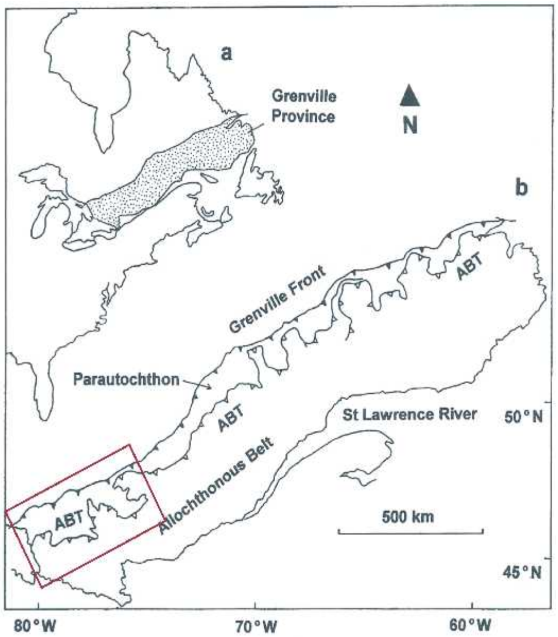

Figure 1: The major tectonic belt division of the Grenville Province according to Rivers et al. (1989). a) The location of the Province within North America; b) The location of the ABT within the Grenville Province. The location of the ABT has been modified by Dickin and McNutt (2003). The study area is indicated by the red box.

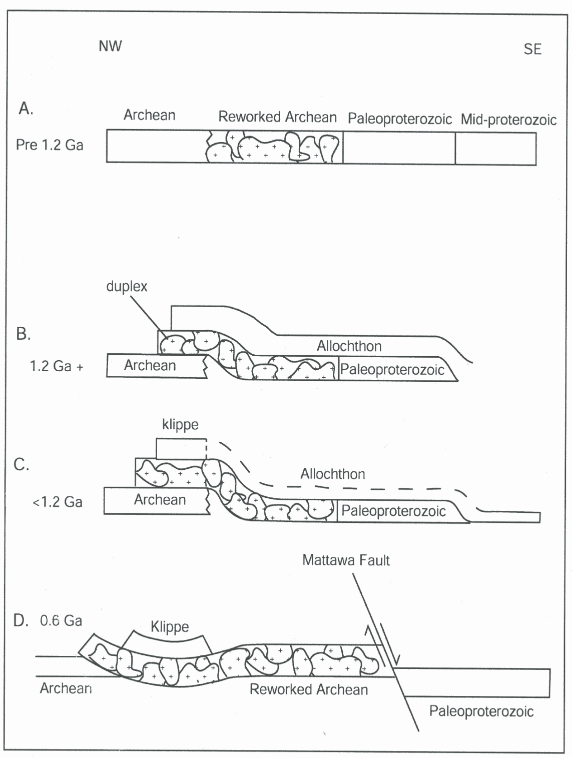

Figure 2: Example of the three-dimensional geometry of the Grenville Province through geologic time within the Mattawa region of Ontario by Herrell et al. (2004). A) The initial position of the different terranes, including the Archean, reworked Archean, Paleoproterozoic and Mesoproterozoic terranes; 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.

Allochthon Boundary Thrust (ABT)

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, 2001, 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 we use to define the terrane boundaries is based on the Nd-Sm model ages obtained in the area. 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 histogram with minimum values at ~2.55 Ga, ~2.15 Ga and ~1.80 Ga: all of which correspond to the end of orogenic events in the neighbouring Southern Province (Figure 3).

DATA INTEGRATION

Each of the datasets used in this study has some limitation. Most critical is establishing the elevation of a terrane contact. It is hoped that this can be partially overcome by a) assuming a relatively simple geometry for the thrust surfaces, and b) determining enough points from the imagery to overcome some of the individual errors.

Topographic Imagery

Two sources of topographic data have been used in this study. First, CDED (Canadian Digital Elevation Database) originally derived from stereoscopic interpretation of aerial photographic surveys provide a broad overview of regional scale topographic changes (Figure 4). A DEM was generated from this data source by using a minimum curvature gridding algorithm with a 250m grid cell size. No attempt was made to apply any corrections for stream channel effects. Second, Space Shuttle SRTM data was acquired using a radar interferometry approach with two detectors acquiring information simultaneously. For Canada, this data source provides a topographic surface with 90m spacing. Correction to a local reference frame is easily achieved by referencing to the previous CDED data.

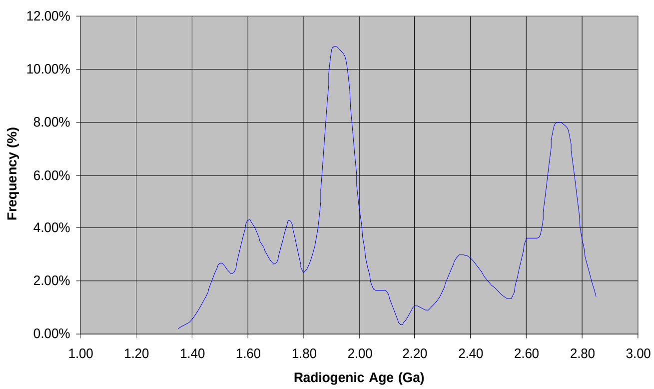

Figure 3: Frequency plot of the Nd isotope dates for the compiled radiogenic studies within the study area. The multimodal histogram was used to determine the age classes for further radiogenic modelling of the terranes of interest within the study area. Three minimums can be seen to occur at ~2.55 Ga,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

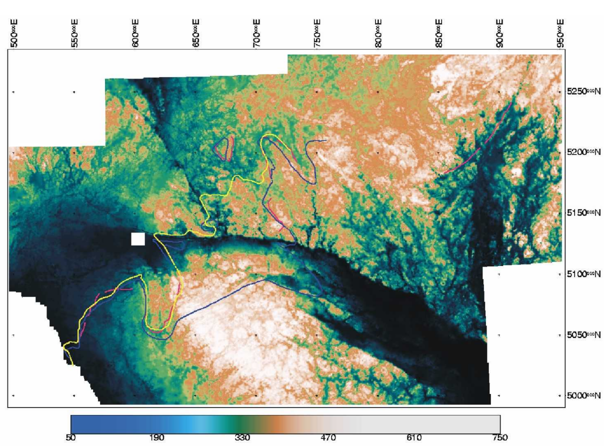

Figure 4: Topography of the study area demonstrating the influence on the geological surface expression of the terrane boundaries. Boundaries: Yellow = Ketchum and Davidson (2000); Blue = Herrell et al. (2004); Red = present study.

Landsat Imagery

Ideally for areas of limited vegetation coverage, Landsat imagery could potentially be used to help discriminate between adjacent rock types. The Landsat mosaic spans UTM zones 17 and 18 with some distortion introduced when the data was projected into zone 17. The Landsat mosaic prepared for this study was derived from the freely available dataset provided by the CanImage data base. However, the eight scenes incorporated into this mosaic were not all acquired at the same time; some were acquired under ideal "leaf-off conditions", while others were collected mid-summer. This results in strong vegetation contrasts between adjacent images. The panchromatic Band 8 of Landsat proved to be the most useful for this study. With a ground resolution of 15m, Band 8 provides additional information on fine topographic texture that is not apparent in the much coarser topographic data sets. When integrated with the aeromagnetic data this textural information accentuates the bounds between continuous lithologic domains (Figure 5).

Airborne Magnetic Data

The magnetic data used in this investigation was provided by the Ontario Geological Survey Province-wide data compilation. While the original data might have been collected at much finer line spacing, the data set as presented has been degraded to a uniform 800m grid cell size. No attempt has been made to apply any noise correction routines to the regional data. As with all other magnetic surveys the signal represents the summation of all magnetic sources under the observation point. No attempt was made to emphasize any near surface boundaries through the application of filtering techniques. Even with this very limited processing, the boundaries between contrasting tectonic domains are readily apparent in the total field data set (Figure 5).

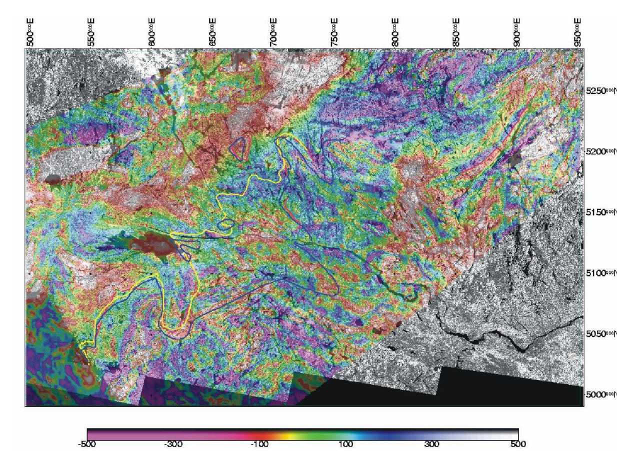

Figure 5: OGS 800m grid cell aeromagnetic data overlain on Landsat panchromatic Band 8. Ottawa – Bonnechere graben complex is identified by black lines. Thrust boundaries as presented in Figure 4.

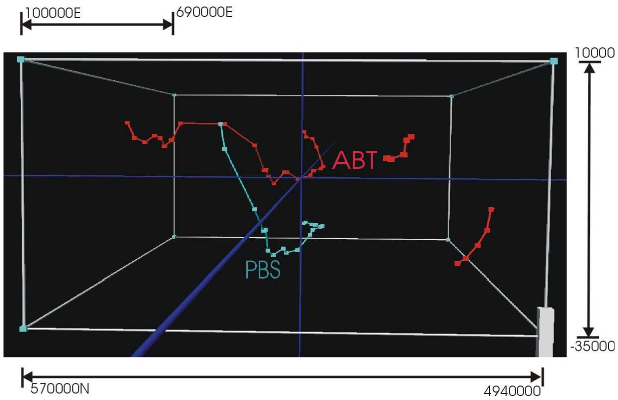

Figure 6: Three-dimensional representation of ABT (red) and PBS (green) bounding surfaces as imaged by Lithoprobe seismic reflection profiles.

Regional Scale Seismic Data

Any attempt to construct three-dimensional models based on only surficial information is limited by the amount of direct information regarding the geometry of the model in the vertical dimension. Commonly, Precambrian terranes have been extensively denuded and reduced to the form of a broad peneplane. In this situation the limited topographic relief provides only limited constraints on the subsurface geometry.

The Canadian Lithoprobe program produced four crustal scale seismic reflection surveys for this study area. Compiling these surveys into a single simple model provides some information regarding the position of the ABT and PBS thrust surfaces (Figure 6).

RESULTS

Terrane Boundary Location

The near surface geometry of the ABT and PBS thrust surfaces was derived from the distribution of the radiogenic isotope data. The thrust surface is to be placed at some point between regions having contrasting radiogenic signatures. Many of the original radiogenic sample sites were identified by reference regional scale topographic maps (+100m), with high resolution GPS data (+10m) only available for more recent studies. Usually there is no sufficient density of observation points to geographically constrain the location of a bounding surface to better than 500m. To attempt to construct a 3D model of these thrust surfaces, we obviously need to be able to estimate the thrust locus to a higher level of accuracy. We achieved this goal by using the Band 8 panchromatic Landsat imagery and aeromagnetic data to optimize the interpreted trajectory for the thrust.

We used previous estimates of the locus of these surfaces by Ketchum and Davidson (2000) and Herrell et al (2004) as the initial constraint in developing our preferred bounding surfaces. A consequence of the non-systematic distribution of the radiogenic mapping method is that the locus of the thrusts is better constrained in some areas than others.

3D Model Development

Locating the trajectory of the proposed thrust surfaces on the topographic surface provided two X,Y,Z point data sets (ABT, PBS). In keeping with most thrust models, the descriptive model (Figure 2) proposed by Harrell et al., (2004) incorporates near flat-lying thrusts, which become more steeply inclined adjacent to the thrust front. This simple geometry can be approximated by a regional scale polynomial surface. Even a simple model computed using Surfer with a coarse 10 km grid cell size gives a crude approximation to the anticipated thrust surface geometry. This represents a crude first approximation since it ignores the seismic data and does not account for any displacements associated with the much younger Ottawa valley fault graben system, which cross-cuts the study area. These elements will be incorporated into a more complete 3D Geomodeller based model.

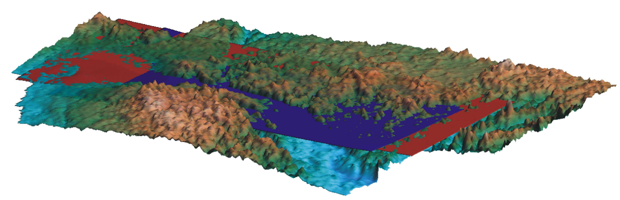

Figure 7: Simplified three-dimensional representation of relationship between topographic surface and ABT and PBS thrust surfaces.

CONCLUSIONS

The radiogenic dating approach provides a clear, objective subdivision of spatially adjacent and lithologically similar tectonic terranes. A simple dot pattern map shows that the three age classes have distinct spatial distributions. The radiogenic sampling density is rarely sufficient to locate the entire 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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