Paper 124

3D Modelling of Basement Structures in Southern Ontario: A compilation of Drillhole, Magnetic and Digital Elevation Data

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ABSTRACT

With increased urbanization of Southern Ontario, there is more demand to understand the relationship between Precambrian faults and subsequent Palaeozoic sedimentary strata and intra-plate seismicity in order to complete detailed seismic hazard assessment. This study, conducted over a selected portion of Southern Ontario, processed and interpreted a variety of different datasets (airborne magnetics, gravity, topography and borehole lithological logs) in order to develop a comprehensive geological framework of the Precambrian basement. The aeromagnetic data was thoroughly investigated and interpreted using a variety of different image enhancement methods. All subsequent datasets, which included lithology, gravity, and a digital elevation model, were comparatively analyzed with the magnetic data results. In the end, a detailed basement framework was established in order to create a 3D model that could be used for future studies. The different structures mapped individually on every lithological segment indicate subsequent reactivation events of basement structures.

INTRODUCTION

Over the past thirty-five years there have been many efforts focused on revaluating Precambrian basement fault zones in order to further understand basement fault reactivation as a critical mechanism in intraplate seismicity. Furthermore, basement faulting controls water reservoir formation, which is critical for urban water resource management. This article discusses modelling of the subsurface distribution of Precambrian and Palaeozoic strata through the integration of different information sources including lithological boundaries defined by oil well logs, regional scale seismic profiles, and inversion of magnetic data over an area located in Southern Ontario; a region covering the greater Toronto area and the Niagara Peninsula (Figure 1). Ultimately, we derive a comprehensive 3D model which will provide insight into the relationships of basement structure and fault system re-activity in Southern Ontario.

The data compiled on this project is common with any mineral exploration project: borehole lithology, magnetic and gravity data, and topography. However, we present a different approach for data analysis that allowed us to infer structural data and end up with a detailed 3D geological model of the area of study.

Southern Ontario's basement is composed of mid-Proterozoic (1.2 Ga) crystalline and metasedimentary rocks with 1500 m of subsequent Palaeozoic (241 Ma to 551 Ma) sedimentary strata (Boyce, 2002). In recent years, there has been significant focus on evaluating deeply seated basement fault zones of Grenville-age (Boyce et al., 2002; Dineva et al., 2004). Many of these studies were prompted by a request to re-evaluate seismic hazard because of an increasing concern over safe operation of strategic facilities, such as the Pickering Nuclear Power Plant, as well as proximity to a highly urbanized area such as metropolitan Toronto (Boyce et al., 2002; Mohajer et al., 1992). Through a study conducted by Mohajer et al. (1992), a series of normal faults were discovered near Lake Ontario in the metropolitan Toronto region that offset bedrock, as well as Quaternary sediments, by over a metre. It was determined that these faults were caused by reactivation stresses, more specifically a series of east-west oriented fractures. Unfortunately, their origins were undetermined; it has since been assumed that this series of fractures may have resulted from horizontal compressive stresses.

The link between seismic activity and the presence of basement propagated faulting has long been controversial (Boyce et al., 2002). The sense of motion and focal centre of a recent faulting event can be determined by first motion studies. But, often the spatial resolution of this approach is insufficient to associate the event with any specific fault. Further definition of the fault plane is commonly based on the interpretation of discontinuities, or lineaments in aeromagnetic data. Prior to 2000, aeromagnetic data available in southern Ontario was insufficiently detailed (nominal 800 to 1000m flight line spacing) to allow comparison of near-surface faults and Precambrian basement structures (Boyce et al., 2002). Further magnetic analysis within the Great Lakes region demonstrated

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that short-wavelength magnetic anomalies detected in the area were associated with basement structures (Dineva et al., 2004). These basement structures are assumed to have originated during the Precambrian Grenville orogeny (Boyce et al., 2002; Dineva et al., 2004). Dineva et al. (2004) showed a direct correlation between the focal center locations of over 100 earthquakes within the Great Lakes region through magnetic and statistical analysis. Through seismicity delineation, several tectonic clusters were determined near Lake Ontario, more specifically the Niagara peninsula, as well as a region near the south shores of Lake Erie. This proximity of earthquake clustering to large bodies of water allowed Dineva et al. to develop the theory that intraplate seismicity within the southern Ontario Great Lake region is greatly attributed to a relationship between pre-existing basement structures coupled with surface waters.

Other recent studies which have included new high-resolution magnetic (50m line spacing) and detailed seismic surveys have allowed a direct relationship to be inferred. Based on previous studies which identified faulting in lake sediments, Boyce et al. (2002) completed high-resolution magnetic and seismic surveys over western Lake Ontario and Lake Simcoe. In both instances it was possible to outline the presence of fault displacements in thick sequences of recent lacustrine sediments coincident with magnetically defined basement discontinuities (Boyce et al., 2002).

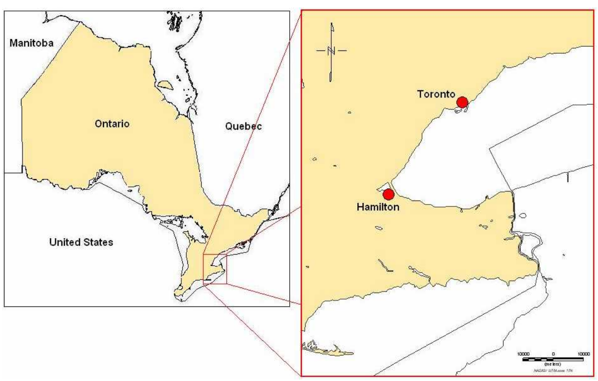

Figure 1: Area of study. The cities of Toronto and Hamilton are given for reference.

From these previous studies it has become apparent that the aeromagnetic data contains a wealth of information concerning the geometry and disposition of lithological units in the Precambrian basement. The most comprehensive study to date was a collaborative study between the National Research Council (NRC) and the Ontario Power Generation (OPG), completed in 2006 (Leblanc, 2006). The NRC and OPG conducted a series of aeromagnetic surveys over a selected portion of southern Ontario and northern New York, covering north-eastern Lake Erie and south-western Lake Ontario. These aeromagnetic surveys were of higher resolution and accuracy than those completed in previous decades by various Canadian and U.S. Federal agencies. These aeromagnetic survey datasets, in association with previously collected gravity, seismic, and water well data sets, were analyzed in order to identify many Precambrian structural relationships like dip direction of rock units; distinction between successive rock units; interpreted boundaries; and the location of inter-sedimentary features. These Precambrian structural relationships helped in a two-dimensional interpretation of the tectonic setting of southern Ontario and northern New York. Ultimately, a three-dimensional model of the basement geological framework was constructed by integrating all the data into 3D Geomodeller.

REGIONAL GEOLOGY

The study area is located within the southern portion of the Grenville orogen, which dips to the southeast and is composed of Palaeozoic bedrock that primarily consists of marine sediments from the Cambrian to Mississippian age, due North America's proximity to tropical latitudes during the Palaeozoic Era (Armstrong and Carter, 2006). It lies on the interior platform between the Appalachian Basin to the west and the Michigan Basin to the east (Armstrong and Carter, 2006). The region is underlain by a basement arch, which is comprised of the Algonquin and Findlay Arches. These arches trend northeast and divide the Appalachian and Michigan basins (Dineva, 2004). The region is underlain by Precambrian rocks of the Grenville Province of the Canadian Shield. Tectonic processes resulting from the convergent continental margin of Laurentia during 1.3-1.0 Ga were recorded in these rocks (Dineva, 2004). These tectonic processes resulted in vertical, and occasional lateral movement of structural features, siliclastic sedimentation, and eutectic changes in sea level (Armstrong and Carter, 2006).

Sedimentary thickness varies across the study area with an average of 1500 m of Palaeozoic sedimentary strata that have been preserved in Southern Ontario (Boyce, 2002; Armstrong and Carter, 2006). The sedimentary cover exhibits the Precambrian dip direction (Leblanc, 2006), where the bedrock strata display a dip of 5.5 m/km near the Algonquin Arch into the Michigan basin to 8.5 m/km into the Appalachian Basin (Armstrong and Carter, 2006). The regional bedrock dipping can be seen in Southern Ontario, where older units outcrop east and north away from the Michigan and Appalachian basins. In the case of the study area, Palaeozoic bedrock geology is comprised of Middle and Lower Silurian, and Upper Ordovician lithologies (Armstrong and Carter, 2006).

The Oak Ridges Moraine, which is of particular interest, is present in the northern portion of the study area. The Oak Ridges Moraine is the result of ice-margin depositional material from the late Wisconsin ice age (which occurred 25 000 to 12 000 years ago). It displays upwards of 200 m of Pleistocene material deposited on top of Palaeozoic shales and carbonates. (Leblanc, 2006)

Other large scale geological features can be seen within the study area, which include the Central Gneissic Belt (CGB), the Central Metasedimentary Belt (CMB) which are separated by the Central Metasedimentary Belt Boundary Zone (CMBBZ). All rocks found in the Central Gneissic Belt are older than the Grenville orogeny and are unique in the sense that they cannot be related to any other rocks outside of the Grenville Province. The Central Gneissic Belt displays detailed lithologic boundaries and thrust induced folding. The Central Metasedimentary Belt has been highly investigated, as its origin has been highly debated. It has been determined that it is an amalgamation of a series of different terranes from different metamorphosed volcanic and platformal sedimentary rock members. The Central Metasedimentary Belt Boundary Zone separates the Central Gneissic Belt and the Central Metasedimentary Belt. It is essentially a mid-crustal shear zone located between the footwall of the Central Gneissic Belt and the hanging wall of the Central Metasedimentary Belt. Like the Central Metasedimentary Belt, the CMBBZ's origin is highly debated, however it is widely accepted that the CMBBZ formed at mid-crustal depths due to the Grenville orogeny (Leblanc, 2006).

DATA INTEGRATION

Airborne Magnetic Data

The aeromagnetic survey data used in this study is from a total field aeromagnetic survey conducted in 1998 by collaboration between the Geological Survey of Canada, Ontario Power Generation and the Multi-Disciplinary Center for Earthquake Engineering Research (MCEER, Buffalo, NY). The high resolution survey covered an area of approximately 44 000 km^2. The western half of the survey had a line spacing of 400 m while the eastern half had a line spacing of 800 m, all flown east-west. Tie lines were flown north-south with a separation distance of 5000 m. The average terrain clearance was 150 m with a minimum of clearance of 300 m in urbanized regions. Regular levelling and microlevelling routines were applied in order to remove any undesired signal contamination prior to the structural interpretation.

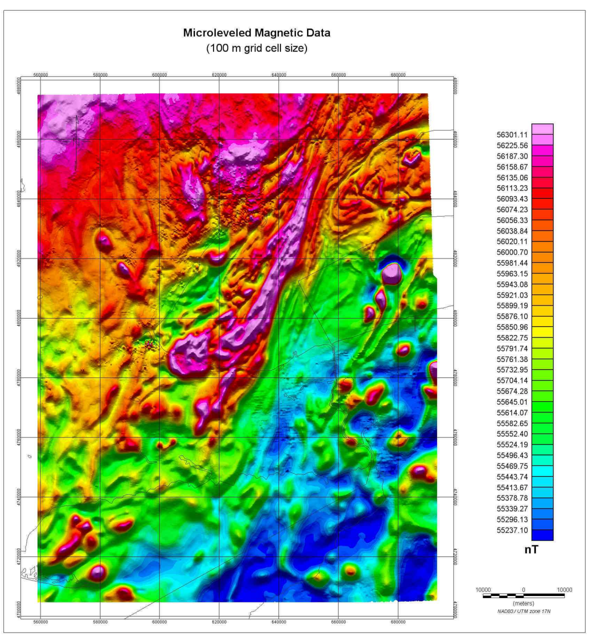

Figure 2: Airborne magnetic data.

Magnetic data interpretation was accomplished by means of using different sub-products of the total magnetic field grid that enhance geological contacts and structures (e.g. first vertical derivative of the TMI; amplitude of the analytic signal of the TMI; and wavelet based edge detection algorithms). Euler deconvolution was applied in order to get an estimation of depth and dip of the different geological features mapped before.

Borehole Stratigraphy

The geophysical logs and drill cores referenced in this study are stored at the Oil, Gas and Salt Resources Library, which is a public resource center dedicated to the further investigations of the subsurface Palaeozoic bedrock geology of Ontario. Wells selected for this study were ones that were located within the region of study. Subsequently, datasets were separated according to Devonian, Silurian, Ordovician, Cambrian, and Precambrian Units. The subsurface elevation of each unit was gridded using minimum curvature interpolation at a grid cell spacing of 1000 m and 2000 m based on average separation distance of well locations. Regional-residual separation was accomplished by gridding each dataset with a large cell size (e.g. 20 km) in order to obtain the longer wavelengths (regional trends), which were subsequently subtracted from the original grid. This approach removes any bias in the data caused by irregular sampling, and avoids the subsequent propagation of that "noise" by regular FFT based regional-residual separation methods. A structural interpretation of each lithological segment allowed the identification of faults that could have been reactivated through time (Figure 3).

Digital Elevation Model

Structural patterns of the landscape can be displayed in a digital elevation model (DEM), which was derived from aerial photographic imagery using stereoscopy. Many different highs and lineaments may be interpreted, which represent lithological boundaries mixed with fault locations. Aspects of the topographic sign (hills and valleys) often resonate into the magnetic and gravity datasets. Buried valleys now infilled with glacial sediments will produce magnetic and gravity lows. Dissolutions of the salina salt will produce an increase in magnetics and gravity signal because of the diamagnetic and low density characteristics of the salt horizon.

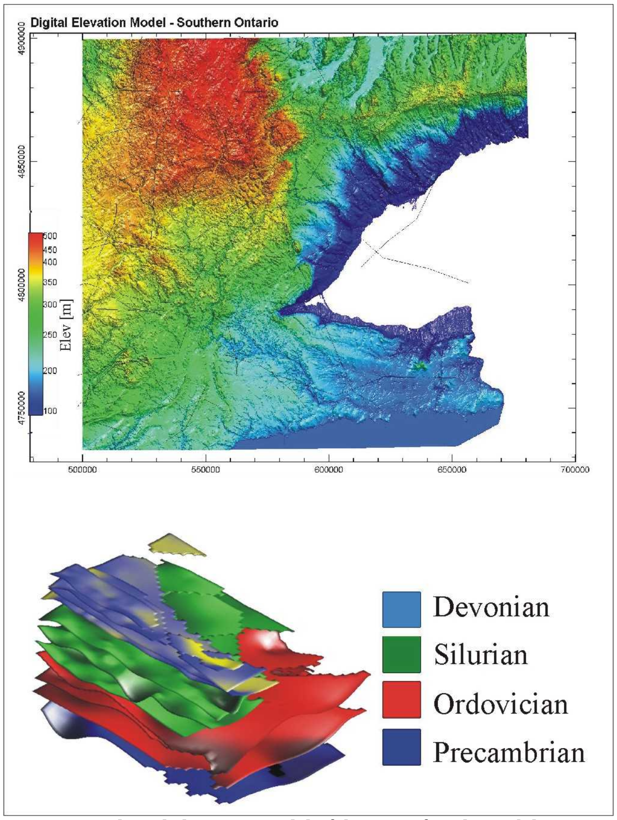

Figure 3: Top, digital elevation model of the area of study, with linear features extracted from the different stratigraphic levels. Bottom, 3D model of the different stratigraphic levels, as mapped from borehole lithological logs. Each 3D surface represents the top of the corresponding geological unit.

CONCLUSIONS

A 3D geological model was produced with all the data and their interpretations. The model was constructed using the 3D Geomodeller package from Intrepid-Geophysics. The model included all the borehole information and the structures identified from both topographic and magnetic data. All the structures identified on the lithological surfaces constructed from the boreholes are located on 3D space, and therefore any reactivation of older structures can be recognized by a spatial correlation of older and newer structures. The model honours the surface and borehole information, and extends the structural mapping done from the analysis done on the magnetic and topographic data on 3D.

Through the analysis of magnetic, gravity, lithological, and topographical datasets, a detailed geological framework was derived for the intended study area in Southern Ontario, intended to demonstrate a correlation between mid-Proterozoic basement structures and Paleozoic sedimentary fault systems. By understanding the link between these two geological structure systems, mapping of the basement faults may be re-evaluated; however, another important contribution of this research will be the assessment of water resources in Southern Ontario, as this is the most populated region in Canada, thus occurrence and accessibility to natural resources is critical.

Finally, of most interest is the approach taken on this project to analyze the borehole data from a structural perspective; that combined with the advantages of 3D visualization allowed as to provide new insights into the regional geology of the area of study. All the data compiled in this project is common with any mineral exploration program, therefore there is no reason for not applying this techniques into at least the early stages of any mineral exploration reconnaissance program.

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