THE SUDBURY STRUCTURE AND ENVIRONS:
GEOPHYSICAL ANALYSIS OF POTENTIAL FIELDS AND PALEOMAGNETISM

THE SUDBURY STRUCTURE AND ENVIRONS: GEOPHYSICAL ANALYSIS OF POTENTIAL FIELDS AND PALEOMAGNETISM

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Abstract

High - resolution seismic reflection data obtained along the Sudbury Structure Lithoprobe Transect have provided a geometrical and lithologic framework for the evaluation, modelling and interpretation of geophysical potential field and paleomagnetic data covering the Sudbury Structure and environs. Through the evaluation of new high resolution aeromagnetic and radiometric data accompanied by increased gravimetric, paleomagnetic, and rock physical property surveys, the structure of the Sudbury Igneous Complex and environs have provided new insights into the development of the Sudbury Structure. Analysis of the potential field and paleomagnetic data has determined that: 1) a broad regional magnetic anomaly can be ascribed to the Levack Gneiss Complex subjacent to the Sudbury Igneous Complex (SIC); 2) a zone of hydrothermal alteration associated with the southern contact between the Onwatin and Onaping formations which appears to be spatially related to a deep gravity high; 3) a magnetic high associated with the South Range contact of the SIC produced by the juxtaposition of rocks related to northward directed thrust faulting; 4) the North Range contact of the SIC is a simple layered contact which has undergone strike slip faulting; 5) the Cartier Granite Complex is composed of three distinct fault separated plutons (Birch Lake Granite, Cartier Granite, and Venetian Lake Granite) forming an arc around the SIC; 6) arcuate structures mimicking the North Range of the SIC and the Grenville Front are visible within the granite terrain to the north of the SIC; 7) the regional gravimetric setting of the SIC is heavily influenced by the presence of deep

crust, upper mantle related fault and density structures; and 8) the main gravimetric signature associated with the SIC is derived from within 5 km of surface.

Acknowledgments

Financial support for this project was provided by NSERC Lithoprobe and Falconbridge research grants to Dr. W. A. Morris. Paleomagnetic facilities at McMaster University were provided through a McMaster Science and Engineering Research Board startup grant to new faculty. Falconbridge generously provided a high resolution aeromagnetic data set of the Sudbury Structure for use in the study. The use of GM-SYS gravity and magnetic modelling system and the GIPSI line of potential field UNIX based processing and presentation software was provided by Paterson, Grant and Watson Limited, Geophysical Consultants, of Toronto. Additional GEOSOFT software was made available by Guaniamo Mining Company Limited of Georgetown, British West Indies.

The successful completion of this project would never have been accomplished if not for the support and assistance of a large number of fellow students and industry associates. In the early days assistance with magnetic surveying, gravimetric surveying, and rock property sample collection could not have been completed without the involvement and friendship of Michael Clarke, George LeBlanc, Susanne Manning and Ken Versteeg. Stimulating discussions with Dr. Vinod Gupta of the OGS, Drs. John Broome and Peter McGrath of the GSC, Dr. Norman Paterson of PGW, Tony Watts of Falconbridge, and Eberhard Bauer of INCO through the years of research have helped greatly. Pauline Lawrence, Chief Draftsperson at PGW has proven time and again to have been of invaluable service in drafting many of the figures for the published papers and for preparation of slide materials for the many presentations given on the topic and related topics of this thesis.

Help with the editing of the many presentations and manuscripts which this research has produced was very gratefully received from Edna Mueller, Dr. Dominic Channer, Patrick Anderson, and Manuel Aragon-Aerrola.

None of this research would have possible if not for a chance meeting with Dr. W. A. Morris in the board room of PGW in Toronto one hot August day in 1990. During this meeting, held to evaluate the quality of data recorded using a down hole magnetic susceptibility meter used by Falconbridge in the Sudbury Basin, the topic of how ripe Sudbury was for a reexamination of the available geophysical data was discussed. The result was this research project. Dr. W. A. Morris has been the commensurate supervisor. His full support for tackling the problems of the Sudbury Basin, even when the ideas challenged established views, was unflagging. His encouragement to complete and present as much of the research as possible; always being there to review yet another rewrite of work I was unhappy with; and constant friendship provided the impetus to complete this research.

Finally, absolutely none of this work would have been possible without the help, love, support, and companionship of my wife, Elizabeth, and children, Jason, Chantal and Keith. They have had to endure many long separations due to fieldwork and research through the years in addition to many long evenings of my being a captive of the computer.

Table of Contents

List of Illustrations

-Chapter 1-

-Chapter 2-

-Chapter 3-

-Chapter 4-

-Chapter 5-

List of Tables

Preface

Each of the chapters in this thesis, with the exception of the **Introduction** and **Conclusions,** have been prepared for publication in various industry, governmental and academic publications. As per McMaster University regulations, the following section outlines what work was performed by the author and the contributions of the co-authors.

Chapter 2, **Magnetic Interpretation along the Sudbury Structure Lithoprobe Transect**, has been published as chapter 4 in *Proceedings of the Sudbury - Noril'sk Symposium,* Ontario Geological Survey, Special Volume 5, Ministry of Northern Development and Mines, 1994. A condensed version of this chapter has been published in *Geophysical Research Letters, Vol. 21, No. 10, pages 951-954, May 15, 1994.* The primary author was responsible for the acquisition and selection of the aeromagnetic data used in the study, all modelling, interpretation, data processing and writing. Co-author M. D. Thomas provided in-situ susceptibility measurements from long the Lithoprobe Transect, contributions to the section *Magnetic Anomalies and Geologic Relationships,* and critical editing. Dr. W. A. Morris provided the paleomagnetic and rock property data for the portion of the traverse from the North Range Norite through to the Chelmsford formation, Whitewater Group in addition to critical editing of the manuscript. Financial support for the field work and data processing was obtained through NSERC Lithoprobe and Falconbridge research grants to Dr. W. A. Morris. Additional funding for the paleomagnetic sample measurement was provided through a McMaster Science and

Engineering Research Board startup grant to new faculty. This chapter was presented in 1993 at the *63rd Annual International Meeting, Society of Exploration Geophysicists.*

Chapter 3, **The North Range Contact of the Sudbury Intrusive Complex: An Integrated Interpretation,** has been prepared for submission to *Geophysics,* the journal of the Society of Exploration Geophysicists (SEG). This paper was presented in 1994 at the *64th Annual Meeting, Society of Exploration Geophysicists.* Co-author W. A. Morris contributed the paleomagnetic data used in the chapter in addition to critical editing of the text and financial support through NSERC Lithoprobe grants. The interpretation, modelling, data processing, and presentation were completed by the principle author.

Chapter 4, **Geophysics of the Levack Gneiss - Cartier Batholith Complex,** has been prepared for submission to *Geophysics.* Co-author Dr. W. A. Morris provided funding, critical editing and guidance in the role of an M.Sc. thesis supervisor.

Chapter 5, **Regional Gravity Setting of the Sudbury Structure,** has been prepared for submission to *Geophysics.* Co-author Dr. W. A. Morris provided funding, critical editing and guidance in the role of an M.Sc. thesis supervisor.

Chapter 1: Introduction

The origin of the Sudbury Structure and its relationship both geophysically and geologically to the surrounding rocks of the Superior, Southern and Grenville Provinces of the Canadian Shield has been the subject of scientific interest and debate since its discovery by a government land survey party in 1856 (Pye et al., 1984; Grieve et al., 1991; Lowman, 1992; and Lightfoot et al., 1994). To uncover new insights into the origin of the Sudbury Structure, the Sudbury corridor of the Abitibi - Grenville Lithoprobe Transect was established. This resulted in the acquisition of several lines of regional deep crustal seismic reflection data (Milkereit et al. 1992, 1994). When combined these seismic lines provide a complete but somewhat discontinuous cross-section of the Sudbury Structure extending from the Huronian Supergroup metasediments and metavolcanics in the south, to the simple layered contact between the Levack Gneiss - Cartier Batholith Complex to the north. A significant feature of the seismic survey was the absence of any clear indication of deep seated dense bodies underlying the Sudbury Structure.

The availability from Falconbridge of recently (late 1980's) acquired high resolution helicopter magnetic survey data, an expanded gravity database from the Ontario Geological Survey and Geological Survey of Canada, paleomagnetic sampling along the Lithoprobe transect coupled with the seismic model provide the opportunity to model the Sudbury Structure and its environs utilizing information not previously available. This thesis seeks to reconcile the above data sets with the purpose of evaluating existing models of the Sudbury Structure and developing new insights into the formation of the Sudbury Structure and environs, particularly the Levack Gneiss and Cartier Granite Complex.

Previous attempts at the geophysical modelling of the Sudbury Structure (Gupta et al, 1984; McGrath and Broome, 1994) have concentrated primarily on the gravitational fields and not the magnetic field. In the example of Gupta et al. (1984), the model arrived at required the presence of discrete deep seated, dense bodies underlying both the central section and the North Range of the Sudbury Structure. This same model required the presence of a discrete magnetic body separate from the gravity models, at depth underlying the North Range. In the example of McGrath and Broome (1994), the requirement for the deep dense bodies has been removed, primarily accomplished through the selection of an arbitrary base level and background density. In order to resolve the discrepancies between the previous potential models and reconcile the potential field data with the Lithoprobe seismic transect interpretation, we shall examine relationships between the observed magnetic field and the observed gravity field to the mapped geology and seismic interpretation. This examination is divided into four major sections. In the first section we interpret the observed magnetic field to the geologic structure as defined by surface mapping, bore hole logging results and the Lithoprobe seismic interpretation along a profile coincident with the Lithoprobe transect. Specifically we examine the effect that remanent magnetization has on the model of the Sudbury Structure. The second section examines the geophysical relationship between the North Range Contact of the Sudbury Intrusive Complex through the analysis of paleomagnetic and aeromagnetic data. The Lithoprobe seismic interpretation (Grieve, 1991; Milkeriet et al., 1994) has suggested that the North Range contact of the Sudbury Structure is in general terms a simple layered contact. The third section expands into the Levack Gneiss - Cartier Batholith Complex to investigate the geophysical signatures and relationship of the Complex to the Sudbury Structure. An objective of this section is to examine the available geophysical data sets (gravity, aeromagnetic, airborne spectrometer, and airborne VLF-EM) to characterize the geophysical signatures of the components of the Complex and how the formation and metamorphism of the Complex is related to the Sudbury Structure through geophysical analysis, obtaining insights into the origins of both the Complex and the Sudbury Structure. The final section examines the effect of numerical filtering on the Bouguer gravity field for a region extending from Elliot Lake to Englehart and from the Grenville Front to north of the Archean Benny Greenstone Belt. The objective is to examine the problem of the separation of the regional and residual Bouguer anomaly fields in the vicinity of the Sudbury Structure. This includes the identification of deep seated gravity structures which may have influenced the development of the Sudbury Structure.

In order to assist the reader who is unfamiliar with the geologic nomenclature and feature names used in the Sudbury Structure and environs, a suite of geologic maps (Figures 1, 2, and 3) are provided. The terms Sudbury Structure and Sudbury Igneous Complex are used liberally throughout the literature on the Sudbury area. In the example of this thesis the terms are used interchangably, with no specific orogenic meaning for the Sudbury area implied.

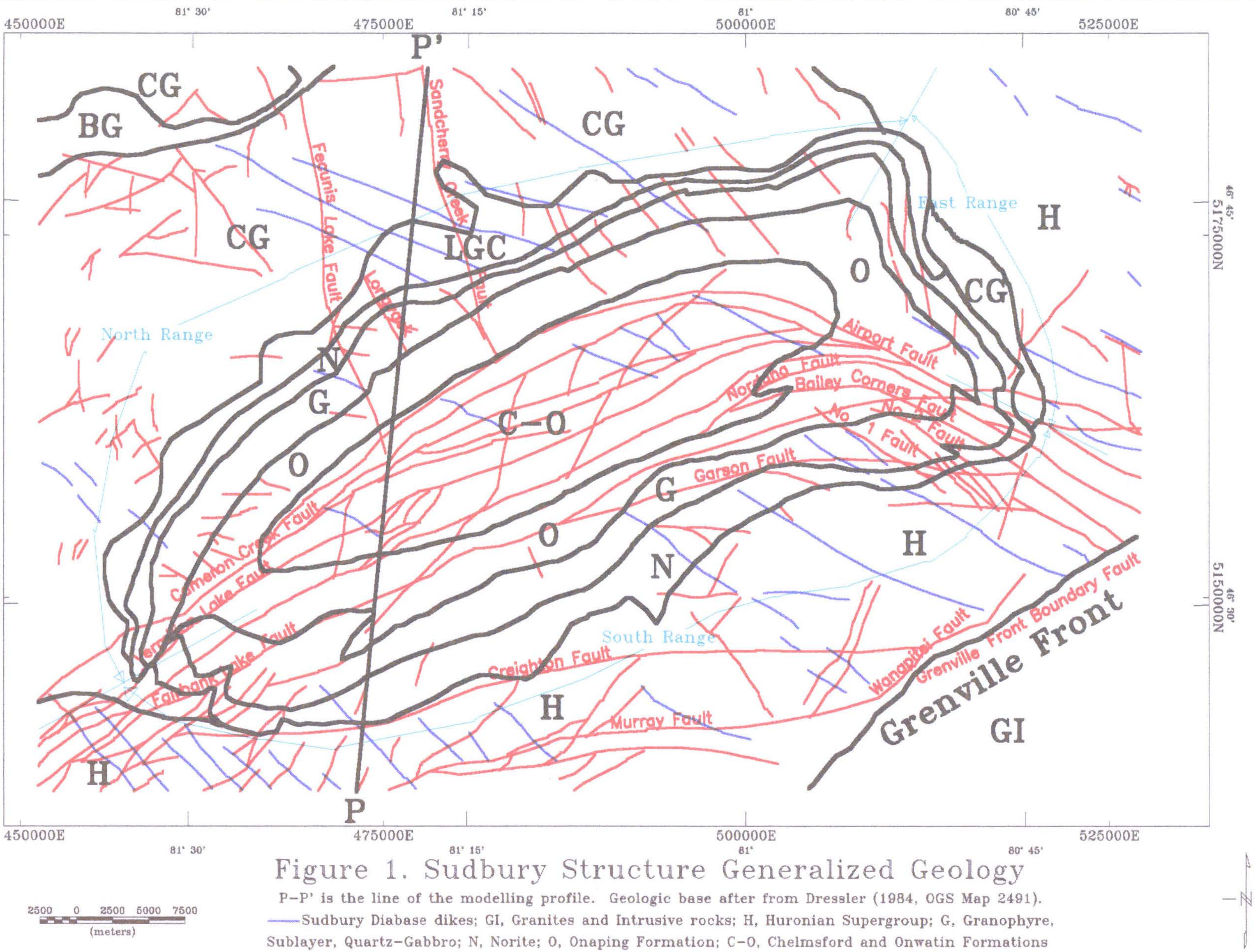


Figure 1. Sudbury Structure Generalized Geology

P–P' is the line of the modelling profile. Geologic base after from Dressler (1984, OGS Map 2491). ——Sudbury Diabase dikes; GI, Granites and Intrusive rocks; H, Huronian Supergroup; G, Granophyre, Sublayer, Quartz-Gabbro; N, Norite; O, Onaping Formation; C-O, Chelmsford and Onwatin Formations (Whitewater Group); BG, Benny Greenstone Belt; CG, Cartier Granite Complex and Gneisses; ——Faults.

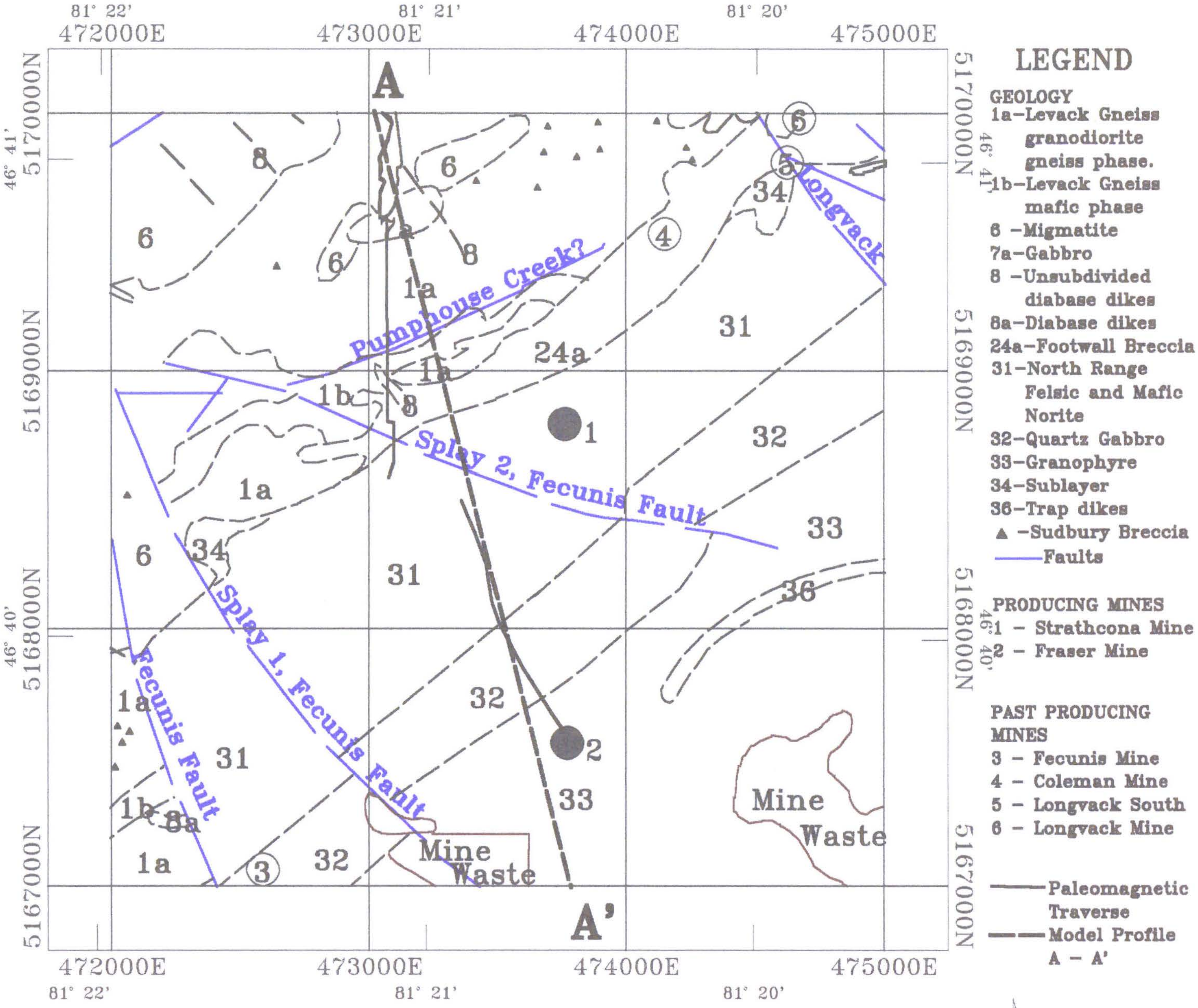


Figure 2. Generalized Geology
Fraser Mine - Strathcona Mine Area
(after Dressler, 1984, OGS Map 2491)

250 0 250 500 750
(meters)

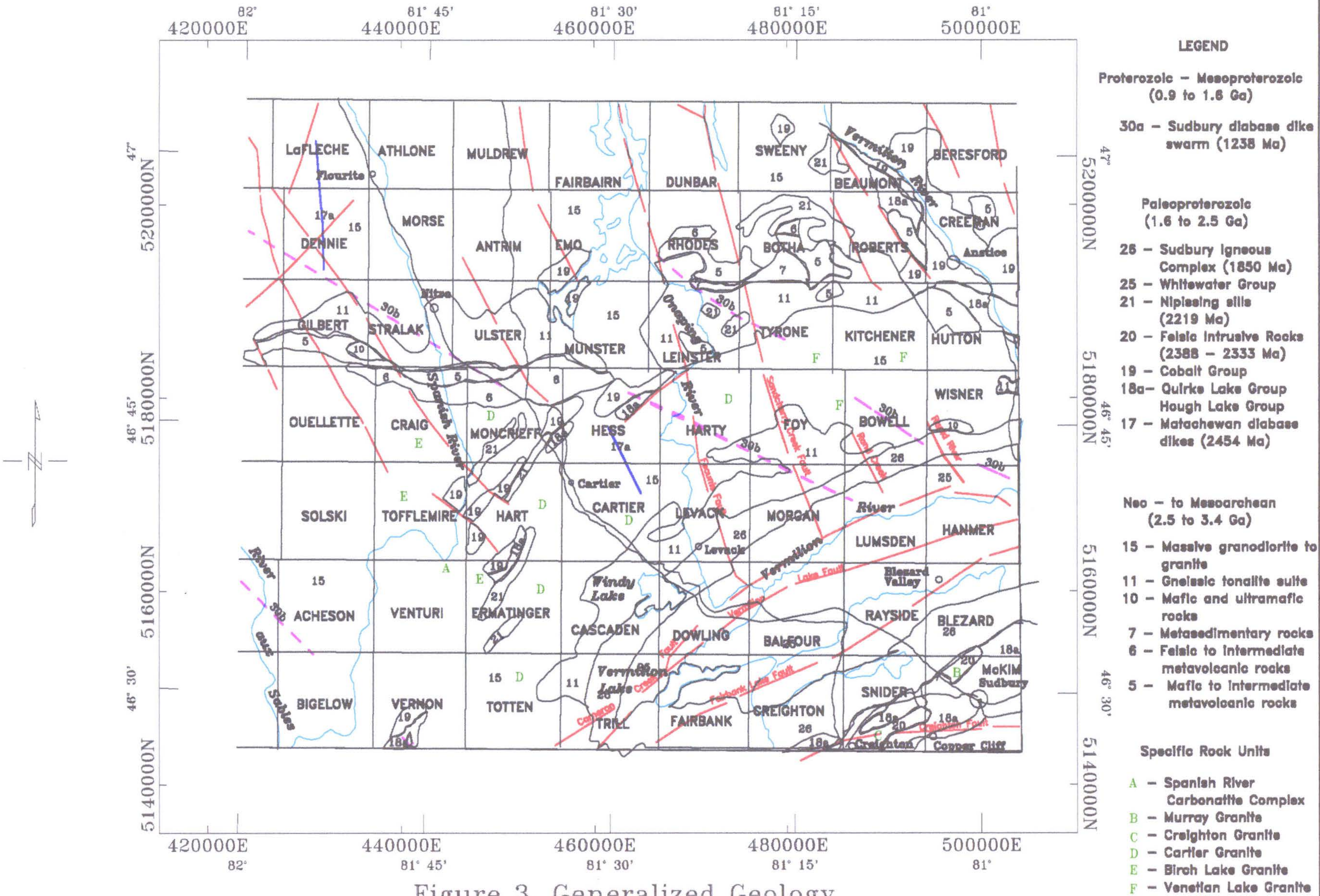
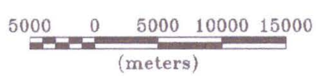


Figure 3. Generalized Geology

Levack Gneiss – Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.



Chapter 2: Magnetic Interpretation along the Sudbury Structure Lithoprobe Transect

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Abstract

High - resolution seismic reflection data along the Sudbury Structure Lithoprobe Transect have provided a geometrical and lithologic framework for the development of a magnetic model. Adoption of this initial constraint was necessary because of the complexity of the magnetic properties exhibited by the rocks composing the Sudbury Structure. In many locales, remanent magnetization dominates over the induced magnetization, and the orientation and amplitude of the remanence vector can vary significantly both between and within the individual rock units. Measured magnetic susceptibility and natural remanent magnetization values from rock samples (*in situ* and laboratory) and borecores, obtained along the Lithoprobe Transect and across the

North Range near Strathcona Mine, have afforded an important constraint on the modelling process, providing a valuable insight into the genesis of the various magnetic anomalies.

The magnetic anomaly profile along the Lithoprobe Transect across the Sudbury Structure appears to arise from 3 main sources: 1) a broad regional magnetic anomaly ascribed to a more magnetic layer of the Levack Gneiss Complex subjacent to the base of the Sudbury Igneous Complex (SIC); 2) a prominent magnetic high associated with the southern contact between the Onwatin and Onaping Formations, believed to reflect a zone of hydrothermal mineralization; and 3) a magnetic high associated with the South Range contact of the SIC produced by the juxtaposition of rock units produced by northward - directed thrusting and an enhanced remanence signature in the basal unit of the South Range Norite.

Introduction

The interpretation of high -resolution seismic reflection data along the Lithoprobe Transect across the Sudbury Structure (SS) (Milkereit et al. 1992) has provided new geometrical constraints for the modelling of magnetic and gravity data. Previous interpretations of these potential field data by Popelar (1972) and Gupta et al. (1984) had been governed essentially by surface geology and by rock property measurements of samples from surface exposures and a limited number of bore holes.

Preliminary modelling using the new seismic data to limit the subsurface position of lithologic boundaries indicates that the seismic model (Milkereit et al. 1992) was conditionally consistent with the gravity data (McGrath and Broome, 1994). Initial magnetic modelling based on rigid adherence to the geometry defined by the seismic data together with the use of the then available measured magnetic parameters could not produce a satisfactory match to the observed magnetic data (Hearst et al. 1992). This incompatibility between the seismic model and an equivalent magnetic model could result from: 1) the significant variations of the magnetic properties within individual rock units; 2) the use of magnetic rock property data collected from off - transect locations; and 3) the fact that the magnetic data set is sensitive to structures that are possibly transparent on the regional scale of the seismic and gravity data. A new magnetic model presented here incorporates the results of the new *in situ* susceptibility and remanent magnetization measurements together with detailed magnetic structures within the broad geometric framework of the seismic and gravity models.

Magnetic Data

The present study utilizes regional magnetic data provided by the Geophysical Data Centre of the Geological Survey of Canada (GSC) and the Ontario Geological Survey (OGS). This data set is presented in gridded, planimetric form calculated using the minimum curvature algorithm of Briggs (1974) as implemented by Swain (1976). The magnetic data, gridded using a grid cell interval of 150 m, were enhanced through leveling with respect to the GSC 812.8 m national grid using the procedure described by Gupta et al. (1989). The magnetic images of the SS are presented in the form of a total magnetic field anomaly map (Figure 1.) and a calculated vertical gradient of the total magnetic field anomaly (Figure 2.).

Regional magnetic susceptibility and natural magnetic remanence values as determined by Morris (1984), and Tanczyk (1991), were used as an initial guide to the magnetic parameters to be used in modelling (Table 1). The magnetic anomaly maps (Figures 1 and 2) indicate that there are rapid changes in magnetic properties both between and within the rock units composing the SS. It is also apparent that the Lithoprobe Transect crosses the SS in a magnetically complex section. Therefore, it was necessary to augment this regional rock property data set by collecting new data along the Lithoprobe Transect. *In situ* susceptibility measurements were completed at approximately 1 km intervals along the transect, using an Exploranium model KT-5 susceptibility bridge. In addition, up to 6 oriented cores were collected at various sites along Lithoprobe Transect Line 40 and across the North Range contact of the SIC near Strathcona Mine. The remanence of these samples was measured on a Molspin spinner magnetometer, the susceptibility measured on a Bartington Instruments MS-2 susceptibility bridge. The induced magnetic field (Figure 3, *in situ* - induced B, specimens - induced A; Figure 4, induced) at each locality was calculated by multiplying the geometric mean susceptibility for the site by the Present Earth's Field (PEF) strength (0.586 Oersteds). The orientation and magnitude of the remanent field vector at each locality was found through calculating the vector sum of each specimen remanence vector, weighting each specimen by the logarithm of remanence intensity. The total magnetic field (Figures 3 and 4) is the vector summation of the remanent and the induced magnetic field

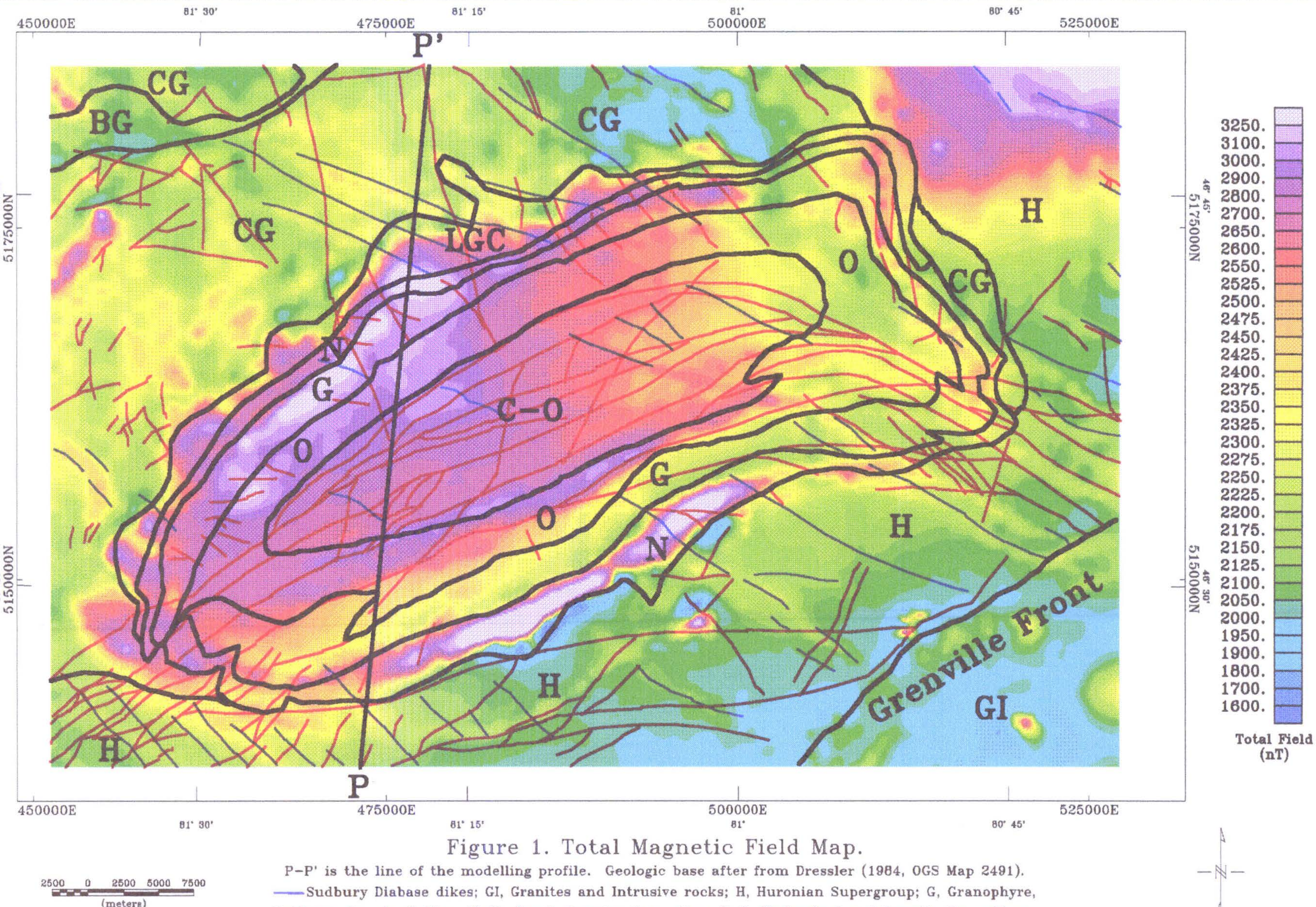


Figure 1. Total Magnetic Field Map.

P-P' is the line of the modelling profile. Geologic base after from Dressler (1984, OGS Map 2491). —— Sudbury Diabase dikes; GI, Granites and Intrusive rocks; H, Huronian Supergroup; G, Granophyre, Sublayer, Quartz-Gabbro; N, Norite; O, Onaping Formation; C-O, Chelmsford and Onwatin Formations (Whitewater Group); BG, Benny Greenstone Belt; CG, Cartier Granite Complex and Gneisses; —— Faults.

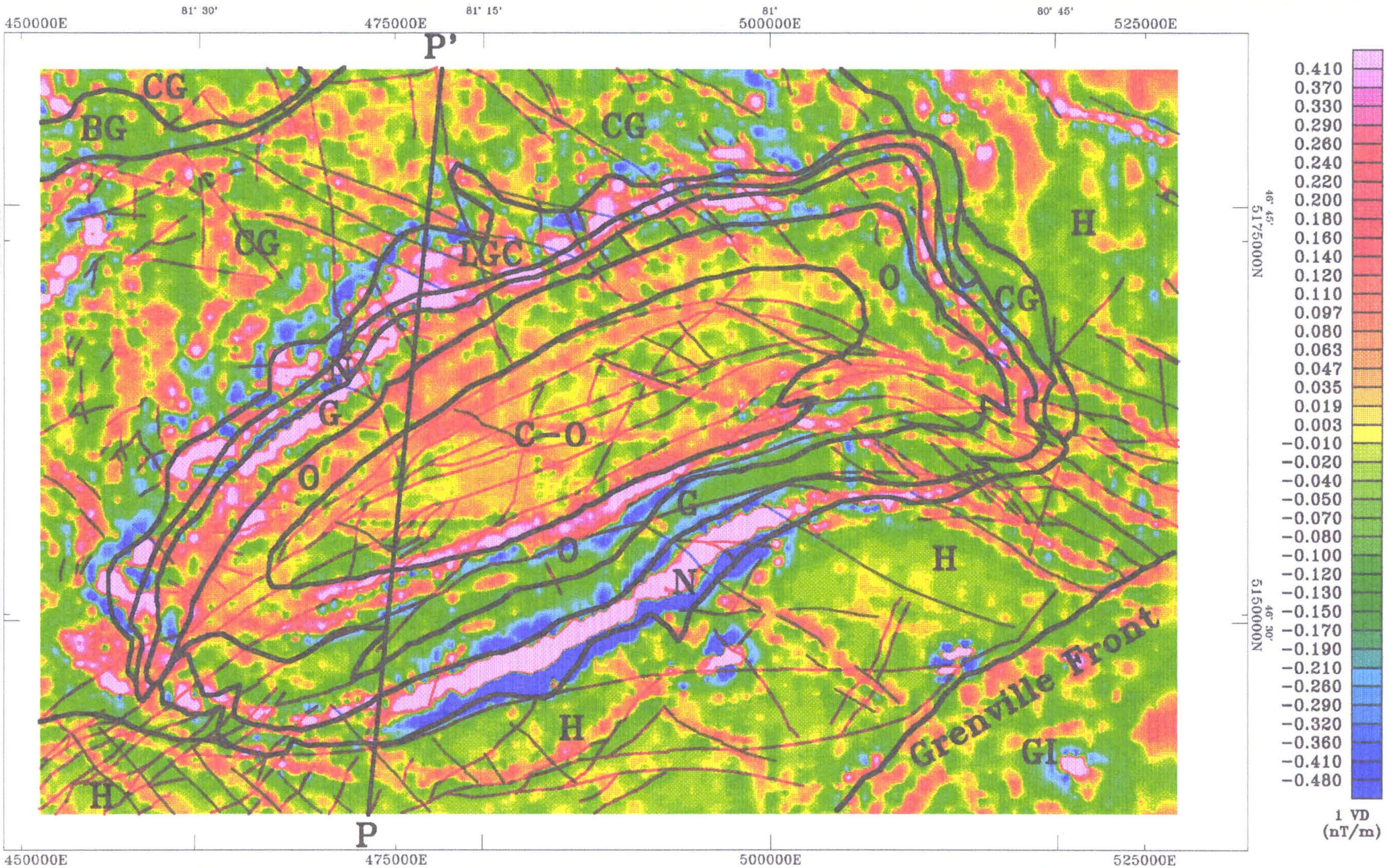
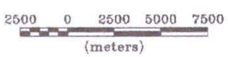


Figure 2. Pole Reduced First Vertical Derivative of the Total Magnetic Field

P–P' is the line of the modelling profile. Geologic base after from Dressler (1984, OGS Map 2491). —— Sudbury Diabase dikes; GI, Granites and Intrusive rocks; H, Huronian Supergroup; G, Granophyre, Sublayer, Quartz-Gabbro; N, Norite; O, Onaping Formation; C–O, Chelmsford and Onwatin Formations (Whitewater Group); BG, Benny Greenstone Belt; CG, Cartier Granite Complex and Gneisses; —— Faults.



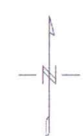


Figure 3. Variations of: a) total magnetic field inclination; b) total magnetic field declination; and c) induced field A and total magnetic field A calculated from laboratory measurement of specimens and induced field B derived from *in situ* magnetic susceptibility measurements along the Lithoprobe Transect across the South Range of the Sudbury Structure. PEF denotes the Present orientation of the Earth's magnetic field. Distances are along the actual route of the Lithoprobe Transect, 0 marks the southern contact of the SIC. CHELM - Chelmsford Formation; GRAN - Granophyre; ONW - Onwatin Formation.

Figure 4. Variation of: a) total magnetic field declination; b) total magnetic inclination; and c) induced and total field calculated from laboratory measurement of specimen susceptibility and remanence along a traverse across the North Range of the Sudbury Structure near Strathcona Mine. PEF denotes the orientation of the Present Earth's magnetic field. Zero (0) marks the northern contact of the SIC. TZ - transition zone.

components. The importance of having remanent magnetization data is obvious considering: 1) the significant differences between the remanent magnetization (Table 1) and the induced magnetization (inclination = 74°, declination = 351°) vector especially for the South Range Norite; and 2) the magnitude of the remanent magnetization in most geologic units.

The lower part of the Norite on the transect across the South Range is characterized by remanent magnetization that is significantly stronger than the induced component (Figure 3), and, hence, the total magnetic field vector for this part of the transect (inclination = 75°, declination = 210°) is quite different from the induced field direction. In the upper part of the Norite, all of the Granophyre and lower section of the South Range Onaping Formation, the induced magnetic field predominates. Consequently, the total magnetic field vector is oriented parallel to the PEF. Within both the upper Norite and the Granophyre, the susceptibility exhibits variations on the order of several magnitudes (Figure 3). The upper part of the South Range Onaping Formation consists of 3 zones that exhibit enhanced induced and remanent field components separated by 2 areas in which the susceptibility is reduced and the remanence is almost nonexistent. Individual specimens from this section of the Onaping do not exhibit a coherent, consistent remanence direction that is systematically divergent from the PEF direction. Demagnetization of these specimens reveals that the characteristic remanence vector is directed at moderate inclination to the east. This direction is similar to the typical Grenville Front overprint direction reported by Palmer et al. (1977).

Table 1. Average rock magnetic properties.

Unit	Susceptibility		Natural Remanent Magnetization		
	Observed (x 10^{-4} SI)	Interpreted (x 10^{-4} SI)	Interpreted (x 10^{-4} SI)	Declination (degrees)	Inclination (degrees)
Huronian:					
Sedimentary Rocks	10	3	N/A	350	65
Mafic Rocks	20	10	N/A	N/A	N/A
South Range:					
Norite	60	45	7.5	189	64
Norite (enriched)	63	150	7.5	189	64
Granophyre (enriched)	150	150	7.5	116	84
Granophyre	25	87.5	10	116	84
Onaping A	10	50	56	130	21
Onaping B	150	100	56	130	21
Onaping C	30	75	56	130	21
Chelmsford	10	100	N/A	N/A	N/A
Glacial Valley:	N/A	250	N/A	N/A	N/A
North Range:					
Onaping D	8.4	250	56	130	21
Granophyre A	78	275	75	329	68
Granophyre B	78	250	75	329	68
Norite	7.5	350	75	316	69
Levack Gneiss:					
Dense	N/A	550	25	330	60
Magnetic Dense	N/A	850	25	330	60
Less Dense	N/A	470	50	320	45
Depleted Les Dense	N/A	200	50	320	45
Cartier Granite:	N/A	375	N/A	N/A	N/A
Dikes:					
Dike (Sudbury type 1)	N/A	1750	550	260	60
Dike (Sudbury type 2)	N/A	300	300	260	60
Benny Greenstone:	N/A	325	N/A	N/A	N/A

The lower part of the Norite on the North Range, the Felsic Norite, is composed of 2 magnetically distinct units: a lower, more magnetic unit; and an upper, weakly magnetic unit. In both phases, but especially in the lower, more magnetic phase, remanence again dominates over the induced magnetization. The resulting total magnetic field vector is divergent from the PEF's direction and from the orientation of the remanence - dominated total field vector found in the Norite of the South Range. The difference in the orientation of the remanence vector in the North and South Range Norites reflects post remanence acquisition deformation of the SS (Morris 1984). The Middle Zone (oxide - rich Gabbro) of the SIC in the North and East ranges has an anomalously high total magnetic field that is dominated by the induced magnetic field as expected from a unit that is characterized by the presence of coarse - grained magnetite.

The Granophyre is represented by a magnetic low relative to other units of the SIC. Samples of the Levack Gneiss from within the thermal aureole of the SIC have magnetic intensities similar to those found in the oxide - rich Gabbro. With increasing distance from the contact, the magnetic intensity shows a broad - scale reduction with a number of localized moderate highs and lows. From the limited extent of this profile line, it is not possible to define a background magnetic level for the Levack Gneiss. The observed variations of magnetization within the Gneiss may correspond to compositional variations.

Magnetic Anomalies and Geologic Relationships

The SS, as outlined on Figure 1, is an elongate elliptical structure with the major axis striking in a northeast direction. The total magnetic field anomaly map is dominated by a prominent, broad magnetic high, which lies mostly within and immediately northwest of the SS. This anomaly extends over a region that on surface encompasses outcrops of the Whitewater Group, the Onaping Formation, all the North Range units of the Sudbury Igneous Complex (SIC) and the Levack Gneiss Complex (LGC). The general increase of the background level over the same region in the vertical derivative plot (Figure 2) suggests this magnetic anomaly could originate from a deep - seated source underlying the SS. A clue to the possible source of this large magnetic anomaly is provided by the association of the steep northern flank of this anomaly with the contact between the LGC and the Cartier Granite. Rock property measurements from the Strathcona Mine - Webfoot Lake section across the North Range contact document the presence of a strongly magnetic phase of the Levack Gneiss close to the contact with SS.

The interior of the SS is marked by a distinct linear positive anomaly straddling the southern contact between the Onaping and Onwatin Formations. This anomaly is more or less bounded by the Fairbank Lake Fault to the south and an unnamed sub parallel fault to the north. The source of this anomaly is not readily apparent. Gupta et al. (1984) have suggested gabbroic intrusions within the Onwatin Formation as a possible source. Limited diamond drilling in this region has not substantiated this explanation. Magnetic susceptibilities determined along the Lithoprobe Transect suggest that much of this anomaly could come from locally mineralized zones in the Onaping Formation (Figure 3). Within at least some of these zones of enhanced magnetization, remanence signatures of Grenvillian age are found residing in the mineral pyrrhotite, suggesting that mineralization may have occurred as a result of fluid pulses related to the developing Grenville Orogen to the south. Having supported several past - producing mines, particularly in the Vermilion Lake area, this zone is of economic interest (Rousell 1984).

A correlation exists between the Norite member of the SIC and an elliptical ring of high amplitude anomalies. Over the South and East ranges of the SS where this correlation is best developed, the anomaly lies predominately along the upper contact, between the mapped Norite and Granophyre units and, therefore, as shown in Figure 5, is probably associated with the magnetite - rich, oxide - rich Gabbro unit. The amplitude of the anomaly is significantly higher along the central South Range (greater than 2000 nT) than along the North Range (approximately 1000 nT maximum) reflecting primary compositional differences between the North and South Range Norite (Naldrett et al. 1970) and more extensive secondary alteration of the South Range Norite (Morris 1984). Dressler et al. (1991), following Naldrett et al. (1970), describe the standard geologic section through the SIC on the South Range with a gradational transition zone between the Norite and the overlying Quartz Gabbro, which in turn is overlain by the Granophyre. Along the Lithoprobe Transect across the South Range, there are no mapped outcrops of the Quartz Gabbro, suggesting that the exposed contact between the Norite and the Granophyre is actually a south dipping thrust and/or that the Quartz Gabbro pinches and swells along the strike of the contact . Magnetic rock property results from samples obtained along this stretch of the

Lithoprobe Transect confirm the presence of a zone of enhanced magnetization at the base of the Granophyre (Figure 3). The Norite in this location appears to be more magnetic in the lower part of the section corresponding to the "black" as opposed to the "green" Norite varieties, in apparent conflict with the observed magnetic anomaly profile data. A plausible explanation for this apparent contradiction is that the observed magnetic high may actually be originating from the more magnetic "black" Norite phase, which is present at shallow depth below the thrust surface.

The South Range Granophyre is, for the most part, coincident with a magnetic low, while the Granophyre of the North and East Ranges is locally associated with magnetic highs. This pattern is replicated in the vertical derivative map (Figure 2). Since the Granophyre from all parts of the SIC is assumed to be lithologically equivalent, the magnetic anomaly differences within the Granophyre are probably related to secondary process(es) that have preferentially reduced the magnetite content on the South Range. The Granophyre from the South Range (Figure 3) has significantly lower total magnetic field than the equivalent North Range unit (Figure 4).

A series of linear northwest to west - northwest striking anomalies, clearly evident on the vertical gradient map (Figure 2), are best developed in the eastern half of the Sudbury Region. In this area, these anomalies extend from the Grenville Front in the southeast, passing through the SS into the Archean to the northwest. Mapped Diabase dikes of the 1238 Ma. Sudbury dike swarm correlate with these anomalies. These dikes, which are predominately olivine tholeiites containing 5% to 10% magnetite - ilmenite, have been mapped with widths of generally 15 m to 30 m, although some have been mapped with widths of up to 100 m (Osmani 1991). Towards the western end of the SS, similar northwest - trending dikes are continuous and well defined around the southern perimeter; however, within the SS, there are only sporadic indications of these dikes. The regional geology map (Dressler 1984, OGS Map 2491) indicates that these dikes are present in this region; however, they are not obvious on the total magnetic field map (Figure 1) and only marginally enhanced on the vertical derivative map (Figure 2). On more recent, unpublished high - resolution airborne and ground magnetic surveys, northwest - trending dike anomalies are also found in the southwest part of SS. The general lack of definition of these anomalies in the magnetic data set presented in Figure 1 can be attributed to a low rate of sampling in the original survey, in combination with a large grid cell size with respect to anomaly width.

Magnetic Model of the Sudbury Structure

The total magnetic field profile of Figure 5 has been extracted from the 150 m minimum curvature gridded data set along a profile (P-P' in Figures 1 and 2) coincident with the gravity model profile of Broome and McGrath (1994; Figure 6) and approximately parallel to the seismic transect.

The following criteria were used for the modelling: 1) the orientation of the representative remanence vector within each unit was fixed, but the amplitude of the remanence contribution was allowed to vary (Table 1); and 2) lithologic units of the seismic - gravity model were subdivided

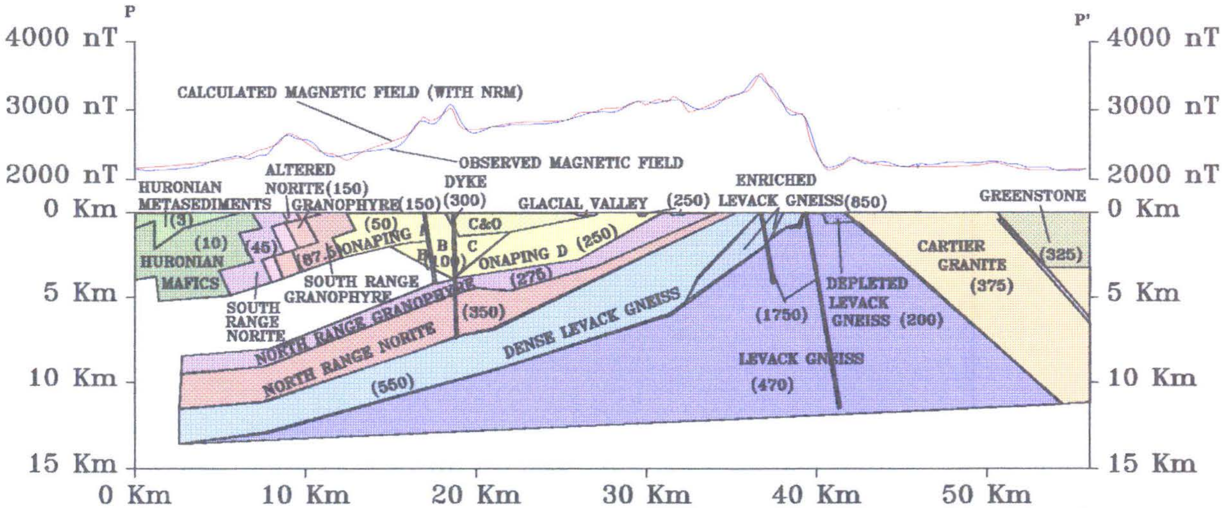


Figure 5. Magnetic Model of the Sudbury Structure.

Magnetic susceptibility and remanence values are from Table 1. Interpreted susceptibilities are indicated on the plot using parenthesis (S.I. x 10E−4). C&O − Chelmsford and Onwatin Formation NRM − natural remanent magnetization.

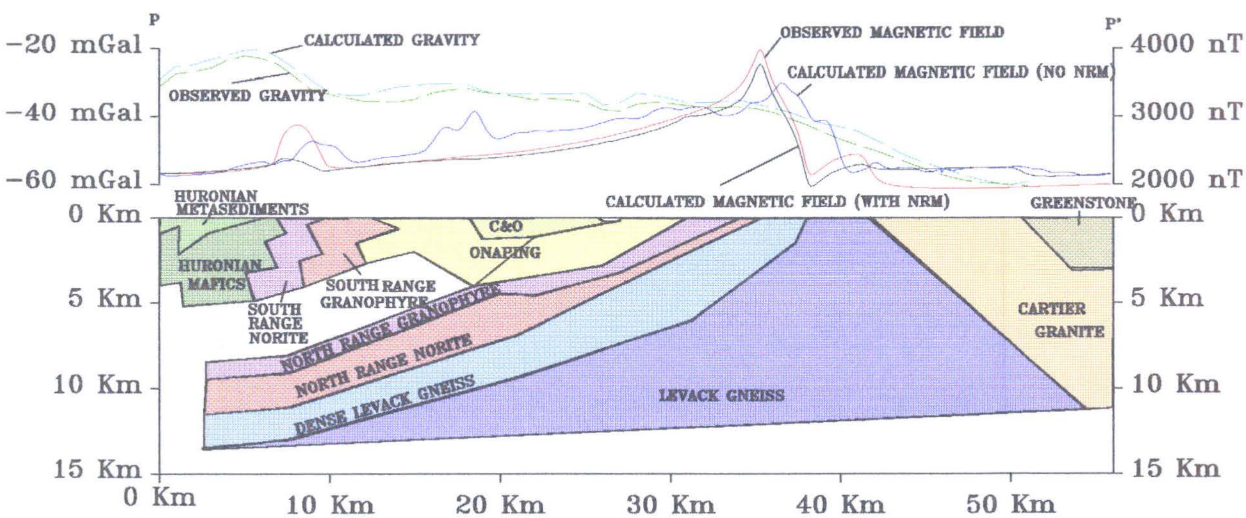


Figure 6. Gravity Model of the Sudbury Structure

Gravity model of the Sudbury Structure along profile line P–P' (after Broome and McGrath, 1984) into more elements with contrasting rock magnetic properties, and a number of magnetic dikes were introduced into the model. These changes are consistent with the locally enhanced response resulting from the greater sampling detail of the magnetic data set and with the observed surface geology as outlined in OGS Map 2491 (Dressler 1984). The resulting 2.5D magnetic model of Figure 5 gives a good match between the observed data and the calculated magnetic field profiles.

The progressive northward increase in the magnetic field along the magnetic profile can be explained in large part by assigning a slightly enhanced magnetic susceptibility (relative to the main mass of the LGC) to a northward thickening wedge of Levack Gneiss that underlies the base of the SIC. By suggesting that it is more dense than other phases of the Levack Gneiss Complex, McGrath and Broome (1994) attribute much of the regional Bouguer gravity anomaly over the SS to this same wedge - like feature (Figure 6). While this interpretation satisfies the computational aspects of the gravity and magnetic models, it produces some geologic problems. Limited rock property sampling on a surface traverse across the North Range contact (Figure 4) shows that the zone of enhanced magnetization is much narrower than the thick dense zone required by McGrath and Broome (1994) for their gravity model.

An acceptable match between the observed and calculated magnetic fields for the North Range contact between the Levack Gneiss and the Cartier Granite cannot be achieved using only the northward thickening wedge. Interpretation of the detail in the magnetic data suggests the LGC may comprise as many as 4 magnetically distinct units (Figure 5). For example, to model the shoulder on the northern edge of the regional anomaly requires the introduction of an even more magnetic phase along the northern margin of the south dipping wedge of more dense LGC.

In addition, to reproduce the localized magnetic low close to the contact with the Cartier Granite, a small zone of reduced magnetic susceptibility has been included in the less dense phase of the Levack Gneiss. Evidence for the regional significance of these features is provided by broad scale zoning in the vertical derivative map (Figure 2)., which may be related to differentiation in the LGC. Correlation of the vertical derivative anomalies to the regional geology as currently mapped is low. Further resolution of this feature will be developed as more rock property information and detailed mapping of the Levack Gneiss and Cartier Granite becomes available (F. Feuten and R. Seabright, Brock University, personal communication, 1993).

Sharp peaked anomalies, found at 36,750 m and 39,500 m on the profile, correlate with mapped outcrops of Sudbury diabase dikes (Figure 4). The vertical derivative map clearly defines these dikes, which are magnetic highs in the Cartier Granite but predominately magnetic lows in the LGC, illustrating the potential for a highly magnetic near surface phase of the LGC.

The total magnetic field map (Figure 1) shows a pronounced magnetic high, superposed on the broad regional magnetic high, near the southern contact between the Onaping and Onwatin Formations. Lying mainly within the Onaping, this anomaly is terminated where northwest trending structures cross the eastern end of the SS. The vertical derivative map shows this feature as separating into 2 sub parallel west - southwest trending anomalies in the vicinity of the Lithoprobe Transect (Figure 2). The amplitude and width of the 2 peak anomalies suggest a structure that is of regional significance. Locally, these anomaly peaks may be enhanced by the presence of Sudbury dikes, one of which crosses the transect near the more northerly peak. Gupta et al. (1984) modelled this anomaly by introducing a gabbroic intrusive into the Onwatin

Formation. Geologic evidence for the existence of such a unit can be found on OGS Map 2491 (Dressler 1984) where gabbroic rocks (map unit 35) form a west - southwest trend of isolated outcrops. However, these rocks outcrop to the north of the locus of the magnetic high and cannot contribute to this anomaly. To explain a residual gravity high along the same boundary, McGrath and Broome (1994) appeal to a slice of tectonically emplaced noritic rocks. Limited diamond drilling in this region, however, has not substantiated these explanations. Our preferred model proposes that the broad magnetic high (Figure 5, Onaping B) represents a zone of enhanced magnetization within the Onaping Formation. Such a region of enhanced magnetization could be produced by the hydrothermal introduction of sulphide rich fluids (which could deposit pyrrhotite) along a regional fracture zone. Geologic logging, together with preliminary magnetic property measurements of drill cores, confirms that enhanced concentrations of pyrrhotite are present in this region of the Onaping - Onwatin Formations, both in sulphide veins (fracture infilling) and disseminated throughout the rocks. Profiles of rock magnetic properties from the Lithoprobe Transect illustrate 2 (or more) distinct zones of magnetization enhancement (Figure 3). Further evidence for the hydrothermal genesis of this anomaly can be found in the Errington and Vermilion copper - lead - zinc mineral deposits, which are located within this feature (Rousell 1984).

The South Range Norite anomaly is a magnetic high that straddles the boundary between the Norite and the overlying Granophyre. As noted above, the standard section through the SIC on the South Range usually contains a Quartz Gabbro unit between the Norite and the overlying Granophyre; however, no Quartz Gabbro crops out along the Lithoprobe Transect. The exposed contact between the Norite and the Granophyre could therefore delineate a south dipping thrust.

Modelling this anomaly, while at the same time maintaining the geometry of the seismic - gravity model, requires the introduction of subsidiary magnetic units with higher magnetic intensity at the top of the Norite and the base of the Granophyre. Magnetic property results from the Lithoprobe section (Figure 3) confirm the presence of a zone of locally enhanced magnetization at the base of the Granophyre. Conversely, the most magnetic part of the Norite appears to be lower part of the section in apparent conflict with the observed magnetic anomaly data. The adopted explanation for this apparent contradiction is that the observed magnetic high is originating from the more magnetic phase of the Norite, which is present at shallow depth below the thrust surface.

The location of this proposed thrust surface is broadly coincident with the southern margin of the South Range Shear Zone mapped by Shanks and Schwerdtner (1991). This whole zone is characterized by an anomalously low magnetic signature. Rock property measurements on samples from this zone describe a region of reduced magnetic mineral content.

Conclusions

Modelling of the observed magnetic anomaly requires a more complex geologic section than that provided by the seismic - gravity model developed by Milkereit et al. (1992) and McGrath and Broome (1994). The observed magnetic field profile can be matched closely when: 1) the magnitude, not the orientation, of the observed remanent magnetic parameters are varied;

2) the geometry of the seismic - gravity model is subdivided to include discrete magnetization units; and 3) the model is modified to include discrete localized sources that are not apparent in the currently available seismic and gravity data sets. The magnetic data, as illustrated by Figures 1 and 2, have the advantage of containing more geologic information than either the regional gravity data set or the presently available seismic images. The increased detail is the result of a more complex, spatially variable relationship between magnetic properties and local geology (Figures 3 and 4). Such detail arises from factors that include: magnetic mineral content and composition variations that may reflect primary mineralogy or local secondary alteration products in addition to induced and variably oriented remanence magnetization; small - scale geologic features (i.e., dikes) that are magnetically distinct but seismically and gravitationally transparent; and increased data sampling as opposed to the regional nature of the gravity and seismic data sets.

In this model of the SS, we attribute the major part of the magnetic anomaly profile across the Lithoprobe Transect to 3 sources: 1) the Levack Gneiss Complex anomaly, 2) the Onwatin - Onaping contact anomaly and 3) the South Range Norite anomaly. The broad regional magnetic high of the SS is attributed to a wedge of enhanced magnetization in the Levack Gneiss Complex, which parallels the Norite contact of the SIC. The genesis of this more magnetic wedge could represent the thermal aureole of the SIC as shown in Figure 4. This scenario requires the contact aureole effect to be much narrower than the thick dense zone required by McGrath and Broome (1994) to satisfy their gravity model. Unfortunately, the geometry of this feature within the Levack Gneiss north of the North Range was not imaged by the currently available seismic data. Gupta et al. (1984), without the benefit of the recently acquired seismic data, interpreted this same broad anomaly in terms of a large south dipping dense magnetic body underlying the North

Range, which they consider represented a hidden layered phase of the SIC. Geologically, the wedge model is problematical: 1) it requires an alternative source be found for these Sublayer xenoliths; and 2) the limited rock property measurements suggest the zone of more dense, more magnetic material that parallels the base of the SIC is much narrower than required by the current gravity model, suggesting more dense material must be located elsewhere in the section. The gravity and magnetic potential field data do not provide a unique solution; either of the hidden layer or wedge models equally satisfy the mathematical aspects of matching the anomalies.

The elongate magnetic high that is spatially associated with the southern contact between the Onwatin and Onaping Formations cannot be explained by the presence of a hidden intrusive body as previously suggested by Gupta et al. (1984). To generate this broad magnetic high, it is necessary to invoke some mechanism that can locally produce enhanced magnetization. Our model to explain this anomaly requires that the region between the Fairbank Lake Fault and a sub parallel fault to the north was at some time preferentially magnetized through the introduction of pyrrhotite. Evidence for such a pyrrhotite - residing magnetization has been found in both surface and core samples from this area. The problem with this interpretation is that we require 3 alteration (magnetization) events: 1) hydrothermal emplacement of pyrrhotite in the region north of the Fairbank Lake Fault to enhance magnetization; 2) alteration of the Granophyre south of the Fairbank Lake Fault to decrease magnetization by the oxidation of magnetite to a nonmagnetic phase; and 3) enhancement of the remanence signature in the South Range Norite through the exsolution of magnetite. Formation of the enhanced magnetite was probably produced as a result of early fluid rock interaction. During the second event, which was probably contemporaneous with the development of the South Range Shear Zone of Shanks and Schwerdtner (1991), fluids generated during the mylonitization and shearing possibly produced the oxidation. During the third event, the sulphide mineralization was preferentially emplaced in a zone bounded by the 2 parallel faults. The relative (and absolute) timing of these events is uncertain. The prevalence of the typical SIC remanence direction in the South Range Granophyre suggests that the second event was of Penokean age. In a paleomagnetic study of the SS, Morris (1984) conclusively showed that, synchronous with the intrusion of the SIC, the SS was being progressively deformed. The first alteration event may represent the culmination of the syntectonic intrusion of the SIC, the SS was being progressively deformed. The first alteration event may represent the culmination of the syntectonic intrusion of the SIC. Any estimate of the timing of the third alteration event must be treated as speculative. One possible model could involve fluid expulsion produced during Grenville age (ca. 900 Ma) thrusting along the Grenville Front.

Our preferred model for the SS is broadly similar to Model A (profiles D-D' and E-E') of Gupta et al. (1984). Both models require remanently magnetized narrow bodies of less than 5 km depth extent to model the South Range magnetic anomaly; both models incorporate a more magnetic body in the Onaping Formation close to the southern Onaping - Onwatin contact; and the dense and magnetically enriched Levack Gneiss units of our model have some similarities with the large south dipping magnetic body underlying the North Range as proposed by Gupta et al. (1984). The difference between this new model and that of Gupta et al.'s Model A lies in the geologic interpretation of the processes that have resulted in these zones of enhanced magnetic response.

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Chapter 3: The North Range Contact of the Sudbury Intrusive Complex: An Integrated Interpretation

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Abstract

High resolution seismic reflection data from the Abitibi-Grenville LITHOPROBE transect across the Sudbury Structure suggests a simple intrusive contact for the boundary between the Levack Gneiss and the Sudbury Igneous Complex. The same profile also suggests that the constituent members of the Sudbury Igneous Complex (Norite, Oxide Rich Gabbro and Granophyre) form a simple layered sequence in geophysical terms. Models based on regional gravity and aeromagnetic coverage tend to support this interpretation. Further support for a mainly simple contact is provided through the image analysis of the high resolution aeromagnetic

data set utilising techniques of vertical derivative calculation, Euler deconvolution, and analytic signal analysis.

A paleomagnetic survey completed on a surface traverse across the contact aureole with the North Range of the Sudbury Igneous Complex in the vicinity of the Strathcona Mine defines a zone of remagnetization that is coincident with the distribution of thermally reset plagioclase recrystallisation. Continuation of the surface traverse to the south in rocks of the Sudbury Igneous Complex between the Strathcona and Fraser Mines in conjunction with sampling from the underground workings at the Strathcona Mine reveal the localised development of two divergent remanent magnetisation directions. This suggests that the contact between the Levack Gneiss and the Sudbury Igneous Complex has been modified by at least two post-Sudbury Intrusive Complex remagnetisation events. Paleomagnetic and rock magnetic property studies also define a zonation within the Felsic Norite thought to have developed as a result of deuteric alteration.

Introduction

The Sudbury Structure is located near the junction of the Archean and Proterozoic rocks of the Superior, Southern, and Grenville Provinces of the Canadian Shield in north central Ontario, Canada. This structure is host to one of the world's most significant base metal concentrations. Genesis of the Sudbury Structure, in particular the Sudbury Igneous Complex (SIC) and associated sulphide ores has been the topic of considerable debate in the literature (Guy-Bray, 1972; Card et al., 1984; etc.) alternating from a meteorite impact to explosive magmatism.

Previous paleomagnetic investigations in the Sudbury Region have indicated that the SIC and its associated ore deposits represent the end-product of a number of separate intrusive and tectonic events (Morris, 1984). It is possible to illustrate that elements of the SIC (Norite and Granophyre) are related to an identifiable remanent magnetic signature. The differences in orientation of any one signature between the constituent limbs of the Sudbury Structure (SS) are related to tectonic rotations separating the individual intrusive pulses (Table 1; Morris, 1984). Seven distinct types (periods) of remanence acquisition related to separate geologic events have been defined. Type 1 remanence correlates to the intrusion of the Norite. Type 2 was associated with the initial post-tectonic intrusion of the Granophyre. A later, second intrusive pulse of Granophyre material is manifest as type 8 magnetic remanence. Late stage Quartz Diorite intrusions (locally referred to as SIC Offsets) are associated with type 6 magnetic remanence. Detailed geologic examination of the ore-bearing occurrences suggests that three episodes of ore genesis can be recognised; two of which significantly post-date the emplacement of the SIC, represent local remobilisation or hydrothermal effects (Naldrett, 1984; Coats and Snadjr, 1984). Late stage hydrothermal alteration events are paleomagnetically associated with type 3 and 4 magnetic remanence directions. The thermal overprinting in the Sudbury region resulting from the Grenville Orogeny is recognised as type 7 remanent magnetisation. On the basis of these broad scale investigations it has been assumed that the North Range Contact of the SIC with the Levack Gneiss is a simple intrusive contact which has not been significantly altered or deformed since the initial intrusion is supported.

Currently available results from the LITHOPROBE high resolution seismic profile across the Sudbury Structure (SS) do not actually cross the North Range - Levack Gneiss contact (Figure 1.). Preliminary interpretation of the seismic profiles which do extend into the North Range suggest that the individual members of the SIC form a simple layered sequence (Milkereit et al., 1992). This interpretation is predicated on the coincidence of seismic reflectors with identifiable boundaries in borehole logs. Projecting this layering to the north across the contact with the Sudbury Igneous Complex (SIC) and the Levack Gneiss supports the assumption of a simple intrusive contact. Further support for this assumption is the reported thermally reset plagioclase recrystallisation observed in the migmatitic gneiss along the North Range contact (Dressler, 1984).

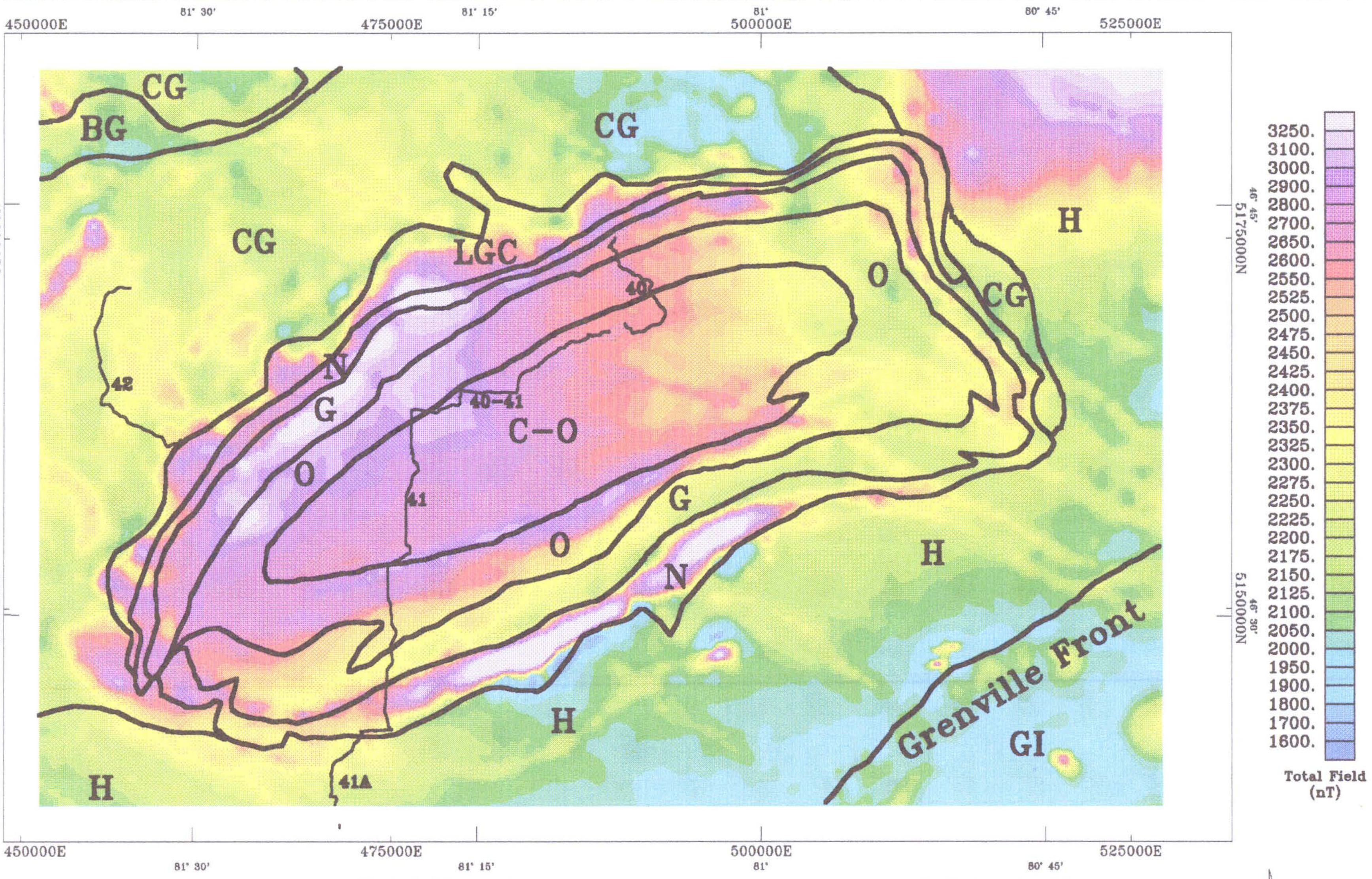
Detailed studies of the North Range contact in the proximity of Strathcona Mine suggest that this contact may be more complex. Geological evidence suggests that the Contact Sublayer unit of the SIC, which is sandwiched between the Main Mass Norite (Felsic and Mafic Norite) and the footwall Gneiss Complex may either pre-date, post-date, or be synchronous with the intrusion of the Main Mass Norite (Naldrett et al., 1984). Recent Rb-Sr isotope studies on this same contact have returned ages ranging from 1.67 Ga to 1.43 Ga; these have been interpreted as being the product of "metasomatic processes in the Footwall Breccia during the declining Penokean metamorphism" (Deutsch et al., 1989), postdating the intrusion of the SIC at 1.85 Ga (Peredery, 1991). Recent structural mapping has suggested that locally this contact may form part of a more pervasive reverse ductile shear zone identified by Card (1994) as the Pumphouse Creek Deformation Zone. When all these additional features are considered the simple looking intrusive contact begins to acquire a more complex character. To investigate this possibility the results of a paleo-magnetic survey along a surface profile extending from the Levack Gneiss in the vicinity of Webfoot Lake south across the North Range contact to the Fraser Mine in the Granophyre of the SIC (Figure 2.) are integrated with high resolution helicopter magnetic data. Additionally rock samples from underground workings at Strathcona Mine were studied to determine the magnetic signature of the Contact Sublayer of the SIC. The paleomagnetic samples also provided physical property information (Table 1) to establish initial constraints on the magnetic anomaly model.

Table 1: Summary of paleomagnetic traverse rock properties.

Sample #	Sudbury Paleomagnetic Phase	Inclination (Primary Phase Only)	Declination
1	1	308	77
2	2,4,7	284	74
3	1	306	67
4	1	310	54
6	4	292	16
7	1?	314	57
8	1?	322	69
9	2?	297	64
10	6	33	48
11	6	15	71
12	4	294	45
13	2?,7	294	74
14	2?,6,7	303	70
15	2?	306	78
16	1,2	329	62
17	1	315	50
18	1,4	343	64
19	?	184	72
20	7	177	62
21	?	198	-44

Table 1: Summary of paleomagnetic traverse rock properties.

Sample #	Sudbury Paleomagnetic Phase	Inclination (Primary Phase Only)	Declination
22	?	198	-53
23	2?	290	62
24	1?,2,6	334	60
25	1,4,6	356	59
26	6,4	23	62
27	3	17	-53
28	3,?	27	-54
29	2,7	257	77
30	6	8	73
31	1,2,?	320	66
33	6,7	67	71
35	1,4	328	69
36	1	338	75
37	Dike	210	77
38	1, Dike	327	54
39	Dike,7	225	76
40	Dike	219	66
42	6	55	72
44	2	277	68
45	2,4	275	69
46	4,3	314	21
47	1,4	323	69
48	1,3,7	306	73
49	3	184	44



2500 0 2500 5000 7500
(meters)

Figure 1. Total Magnetic Field, Generalized Geology and Seismic Lines

Geologic base after from Dressler (1984, OGS Map 2491). Lines 40 & 41, 120 fold seismic line; lines 41A, 40-41, & 42, 60 fold seismic line; GI, Granites and Intrusive rocks; H, Huronian Supergroup; G, Granophyre, Sublayer, Quartz-Gabbro; N, Norite; O, Onaping Formation; C-O, Chelmsford and Onwatin Formations (Whitewater Group); BG, Benny Greenstone Belt; CG, Cartier Granite Complex and Gneisses.

Figure 2: Paleomagnetic Sampling Sites.

Preparation of Geophysical Data Sets

PALEOMAGNETIC DATA

Paleomagnetism is a useful tool for unravelling the geologic and potentially the tectonic history of an area due to the unique ability of some rock types being able to record specific magnetic vector orientations which can be correlated to specific geologic events. The recognition of multi - component remanence residing within a specimen and the separation of these components through analytical methods is a common paleomagnetic procedure Halls, 1977; Zijderveld, 1967; Roy and Park, 1974; and Hoffman and Day, 1977; Morris, 1984). Differences in the orientation of the remanence vector between successive events records the sense, magnitude and potentially the timing of relative rotations between rock units in a given study area. If the age of remanence acquisition is known and a reference polar wander/continental drift path has been established, then the time dependence in the shift of the magnetic vectors present within a given rock unit and locality can be established. Similarly, defining the sequence and spatial extent of magnetic overprints present in rock units can provide insight into the thermal and chemical history of the region. At each stage of the heating and cooling cycle related to the emplacement of a younger igneous intrusion or metamorphic event, the remanence record of the host rock is either totally or partially reset dependent on the proximity of the individual element of the rock to the event and the initial remanence characteristics of the host rock. It is therefore possible that a locality which initially appears to be simple can contain a paleomagnetic record of a series of magmatic, metamorphic, and tectonic events history.

At each of the profile sample locations illustrated in Figure 2, up to six oriented borecores were obtained. Local inhomogeneties at a particular outcrop present as epidote veining, local shearing, or intense jointing were avoided during the collection of borecores as these features can give rise to spurious magnetic components (Morris, 1980). Orientation of the borecores was accomplished using a combination of magnetic compass and sun compass techniques. As many of the collected borecores were of highly magnetic rocks, the sun bearing estimate was preferred, particularly when estimates of sample orientation varied by greater than 10°. Underground samples obtained from Strathcona Mine were oriented by referencing a flashlight pointer beam to a known underground survey point.

All borecores were divided into two specimens, one specimen undergoing alternating field demagnetisation, the second specimen undergoing complimentary thermal demagnetisation. Thermal demagnetisation was accomplished through the use of a Schonstedt TSD instrument in a null magnetic field, utilising thermal intervals ranging from 10°C to 100°C. The actual step size used was specimen dependent and related to the remanent magnetisation characteristics of the specimen under study. Alternating field demagnetisation was applied up to a maximum field strength of 100 mT to the second specimen of each collected borecore. Independent of the demagnetisation step used, all borecores underwent a minimum of 10 demagnetisation steps. Principal Component Analysis was applied to all data collected utilising a Maximum Angular

Divergence criteria of 10° in order to determine the orientation of the characteristic remanent magnetisation vector.

Specimen specific remanence directions were obtained through the analysis of the demagnetisation trajectory using both Kirschvink and Stereo analysis. Kirschvink analysis involves the analysis of all linear segments of the demagnetisation trajectory to obtain an estimate of vector direction and angular variability through least squares line fitting. Stereo analysis involves the calculation of a series of magnetic vector subtractions on the demagnetisation trajectory data string. The subtracted vectors are contoured on a standard Schmidt stereo net initially using equal weight and a 1% contour interval. The vectors are also contoured weighted for vector magnitude. The Stere method allows for the isolation of significant linear sections of demagnetisation trajectory in addition to isolating components that correlate to large intensity decay situations (short trajectory).

All site mean directions were then calculated following standard Fishers (1953) statistical methods. Individual site mean directions were compared to results previously reported for the North Range (Morris, 1984).

AEROMAGNETIC DATA

Magnetically the Sudbury Basin and environs are recognised as exhibiting a high degree of variable remanent magnetisation (Morris, 1984). Past attempts at constructing a magnetic model profile across the Sudbury Basin (Hearst et al., 1992; 1994a; 1994b) which honours the LITHOPROBE seismic model (Milkereit et al., 1992) and gravity model (McGrath and Broome,

1994) have proven to be less than satisfactory. The shape of a magnetic anomaly is dependent upon the geometry of the source body, the orientation of the source body within the Earth's magnetic field and the possible presence of internal remanent magnetic effects. Generally, when magnetic modelling is undertaken, the source body shape and orientation are unknown and the contribution to the anomaly shape and amplitude by magnetic remanence is thought to be negligible. Initial modelling attempts were undertaken using only the geometrical constraints provided from the layered sequence seismic interpretation predicated on the coincidence of seismic reflectors with identifiable boundaries in borehole logs (Milkereit et al., 1992) and to simplified mine sections (Coats and Snajdr, 1984). Projecting the seismic layering north across the contact with the SIC and the Levack Gneiss leads to the assumption of a simple intrusive contact. The addition of the simplified geologic sections illustrates the possibility of locally complex geologic features along this contact. The unsatisfactory fit of the magnetic data to the seismic model highlighted the magnetic complexity of the Sudbury Structure in general, and the North Range SIC - Levack Gneiss contact in particular (Hearst et al., 1992). It was hypothesised that the magnetic complexity is primarily the result of : (1) significant variations in the magnetic properties within the individual rock units (variable remanent magnetisation); (2) sensitivity of the magnetic data set to structures that are transparent to the seismic and gravity data; and (3) the greater sampling frequency of local variations in the Earth's magnetic field due to high resolution aeromagnetic survey techniques.

Inherent difficulties associated with specific feature modelling can be overcome by utilising image processing techniques to outline the source body geometry. Two of the image processing techniques employed in this study: 3-D analytic signal; and Euler deconvolution are relatively insensitive to magnetic inclination, declination and remanence effects at high magnetic latitudes (Reid et al, 1990; Roest et al., 1992; McLeod et al., 1993a, 1993b) and hence can be used to help define body geometry. The final image processing technique utilised was calculation of the first vertical derivative of the pole reduced total magnetic field. The pole reduction operator results in the simplification of anomaly shapes, placing the maximum or minimum response directly over the causative body (assuming induced magnetisation). Calculation of the first vertical derivative results in maximum and minimum anomalies occurring over the points of inflection of the total magnetic field, effectively highlighting body edges and linear structural features such as fault structures.

High-resolution total field helicopter borne aeromagnetic data was originally provided by Falconbridge Inc. for this study (Figure 3). The magnetic field observations were acquired along northwest - southeast flight lines. Flight line separation was nominally 100 m, the down line nominal data sample interval equates to an on ground sample interval of 3 to 4 m. To reduce the possibility of between flight line signal aliasing resulting from a high density of data points down line versus a large line separation, the data set was grided using the minimum curvature method (Briggs, 1974) to a grid cell size of 10 m.

Results

Geologic mapping along the ground paleomagnetic profile from Webfoot Lake in the north to Fraser Mine in the south has identified several geologic units. Archean Levack Gneiss

(Granodiorite Gneiss phase and Mafic phase) hosts intrusives of Gabbro and Diabase dikes in addition to zones of Migmatization. The contact of the Levack Gneiss with the SIC is marked by the presence of Footwall Breccia containing fragments of the Levack Gneiss in a granoblastic and in places granophyric matrix. The hanging wall consists of the basal unit of the SIC, the North Range Norite (Felsic and Mafic phases). This is in turn overlaid by the Quartz Gabbro and finally the Granophyre in the vicinity of Fraser Mine which comprise in part the Transition Zone units.

Aeromagnetic Data

Examination of the aeromagnetic data and processed products suggests that there is considerable zonation within the Levack Gneiss. Brecciated zones within the Levack Gneiss tend to correlate to, or are adjacent to, magnetic lows, suggesting destruction of magnetite and low magnetic susceptibility. This is supported by coincident analytic signal lows. Some geologic units hosted by the Levack Gneiss, in particular the Migmatite tend to be poorly defined by the aeromagnetic data. Similarly the contact between different phases of the Levack Gneiss is not always obvious. The granodiorite phase is the most magnetically distinct component in the Levack Gneiss, where it tends to be associated with magnetic highs of high frequency. Although in both the west and east of the study area this phase is coincident with magnetic lows, suggesting some magnetic inhomogeneity. The mafic phase is less abundant and is more closely correlated to magnetic highs. Diabase dikes appear to be magnetically homogeneous but of low to moderate susceptibility. In Migmatitic regions (northwest) the dikes are discernible as magnetic highs and/or saddle points striking northwest on the total magnetic field, first vertical derivative and analytic signal plots (Figures 3,4 and 5).

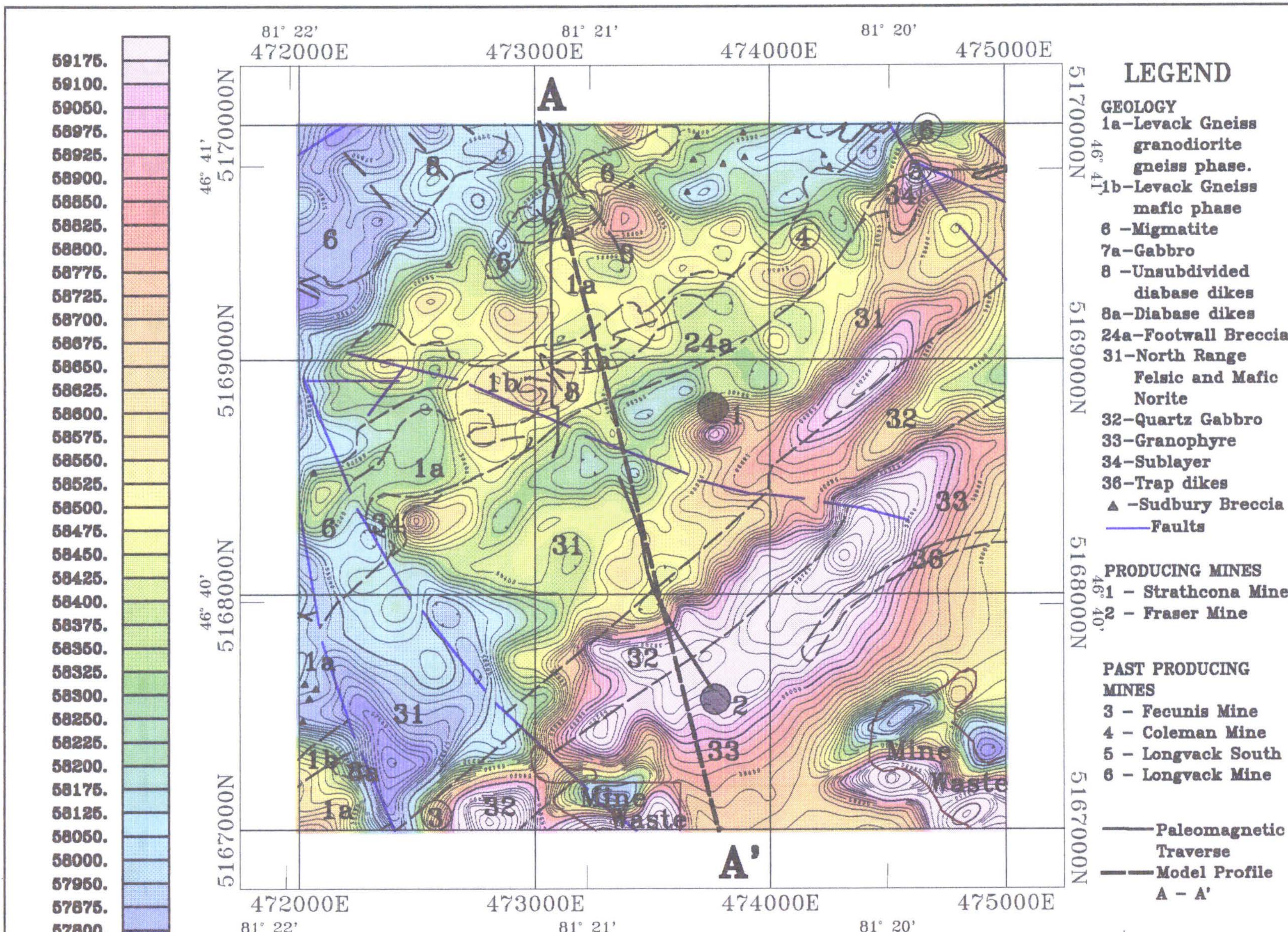


Figure 3. Total Magnetic Field Map

Fraser Mine - Strathcona Mine Area with geological overlay (after Dressler, 1984, OGS Map 2491).

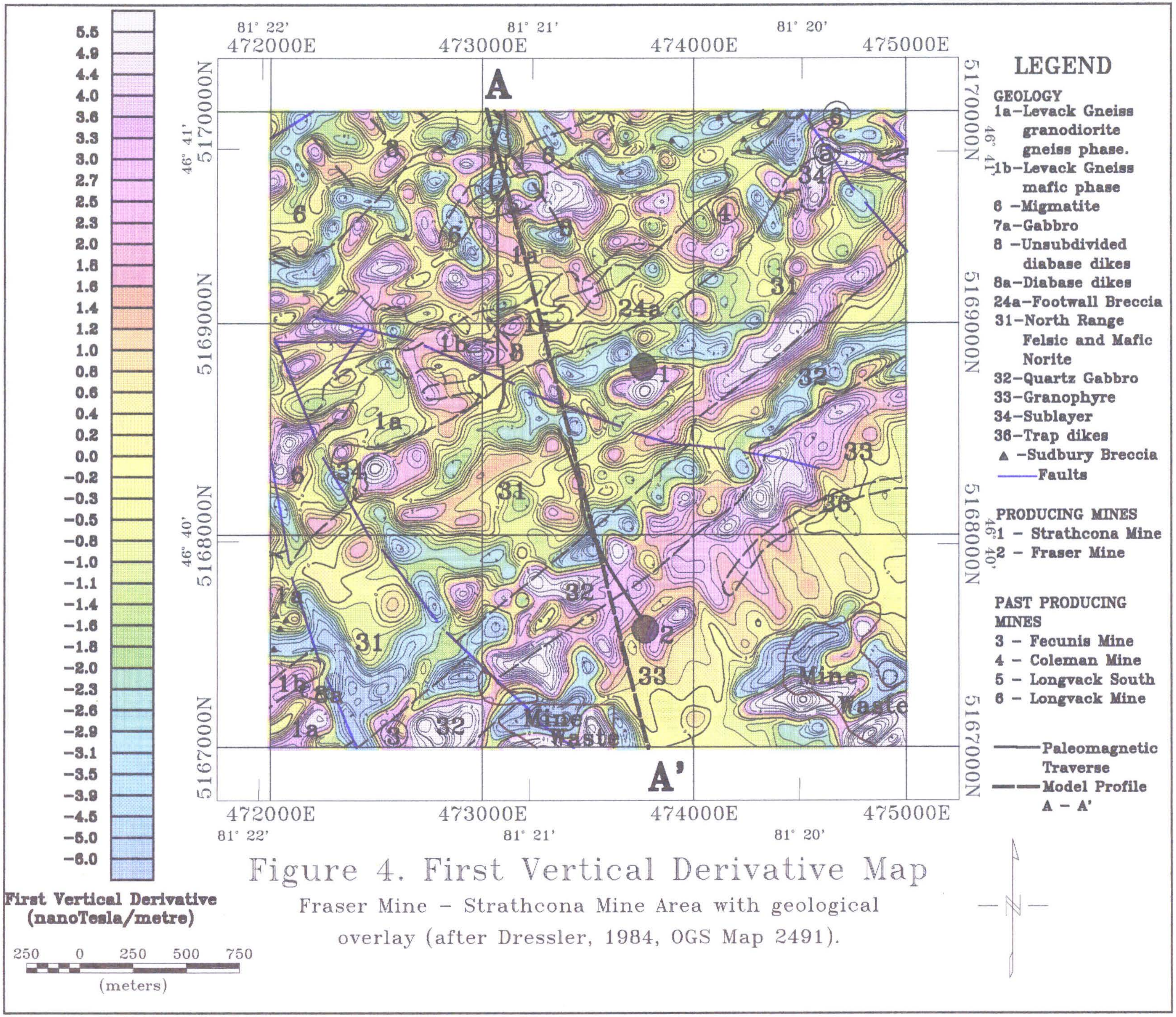


Figure 4. First Vertical Derivative Map

Fraser Mine - Strathcona Mine Area with geological overlay (after Dressler, 1984, OGS Map 2491).

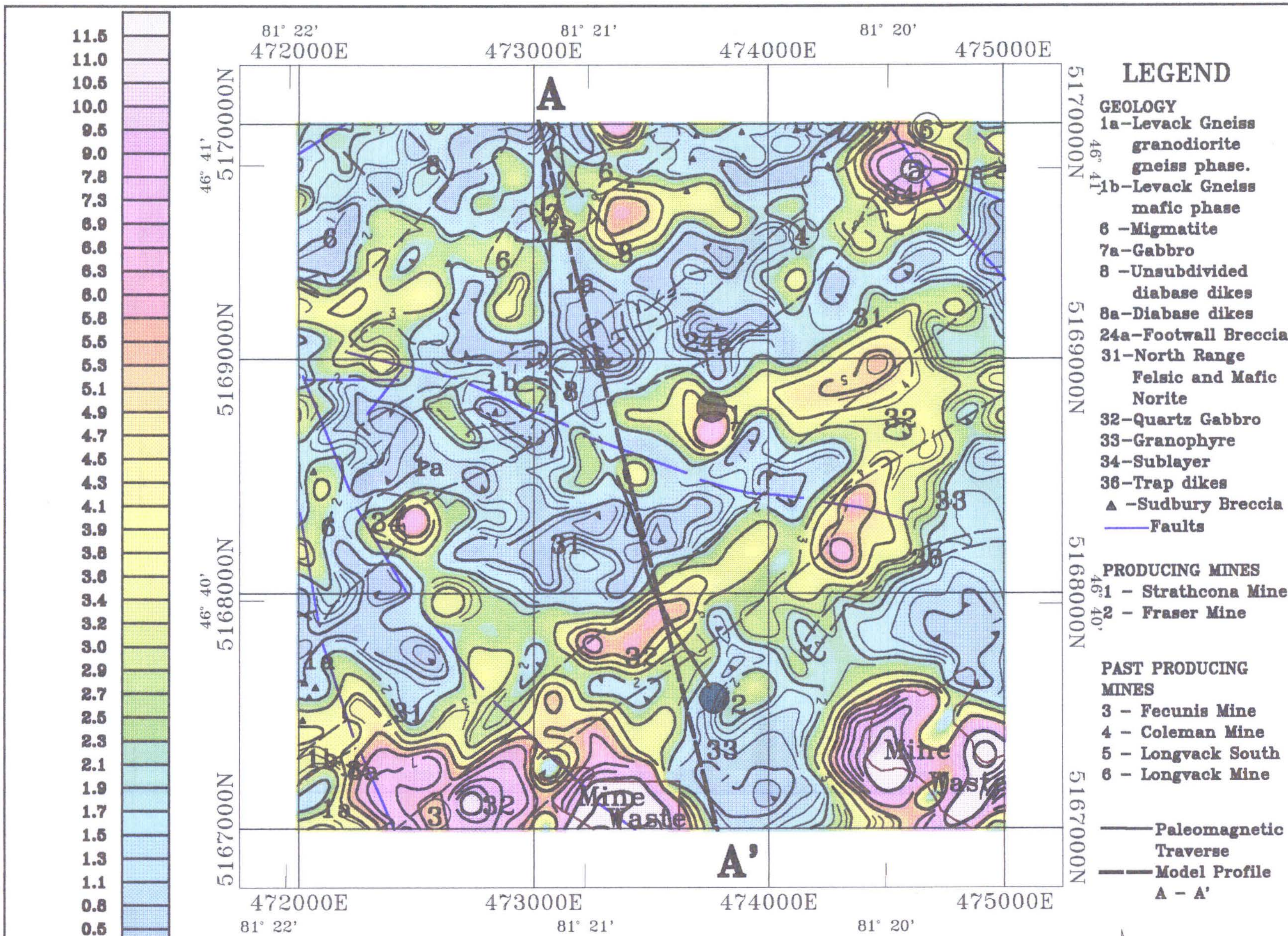


Figure 5. Analytical Signal Map

Fraser Mine – Strathcona Mine Area with geological overlay (after Dressler, 1984, OGS Map 2491).

250 0 250 500 750
(meters)

The North Range Norite exhibits a variable magnetic signature, but this may be in part a reflection of the zonation of the Norite into Felsic and Mafic components. Zonation within the Norite is visible on all magnetic products. The Norite appears to be more magnetically homogeneous than the Levack Gneiss and consists of longer wavelength (km vs. 100's m) components. The Felsic phase appears to correlate to magnetic lows and the Mafic phase correlating to magnetic highs. Magnetically, the contact between the Norite and the Quartz Gabbro is sharply defined, with the Quartz Gabbro tending to be considerably more magnetic than the Norite. This is also confirmed by the analytic signal, particularly in the vicinity of Fraser Mine. To the east of Strathcona Mine the magnetic relationship between the Quartz Gabbro and the Norite appears to be reversed. Examination of the first vertical derivative suggests that the Quartz Gabbro may be non-magnetic in this area and that the Mafic Norite phase is dominant and responsible for the anomaly. This may be related to movement along a east-southeast splay of the Fecunis Lake Fault resulting in a reorientation of blocks of Quartz Gabbro without resetting the magnetic characteristics of the rock. This would give the appearance of a remanently magnetised rock unit. A consistent magnetic relationship exists along the contact between the Quartz Gabbro and the Granophyre. The contact zone within the Granophyre is significantly more magnetic than within the main body of the Granophyre 300m south of the contact. This is visible on both the total magnetic field and the first vertical derivative. The analytic signal and Euler deconvolution maps suggest however that the source of the magnetic signal is not in the near surface, but from depth, possibly from the Quartz Gabbro which is thought to underlie the Granophyre.

Major and minor structural lineaments are readily discernible from the aeromagnetic data sets. Major lineaments tend to parallel the SIC (semi-arcuate form, striking northeast) and are orthogonal to the SIC (northwest strike). The Fecunis Lake Fault in the extreme west corner of the study area is a good example of an anomaly related to a major structural trend. This appears as a total magnetic field low but is well defined by the first vertical derivative. The analytic signal and Euler deconvolution (Figure 6.) both suggest that the fault zone is magnetic at depth and dipping steeply to the northeast. The higher order processed products (first vertical derivative, analytic signal, and Euler deconvolution) suggest that many of the mapped dikes extend at depth along strike (northwest) into the SIC and are more extensive than currently mapped.

Paleo and Rock Magnetism

Travelling along the surface paleomagnetic profile from north to south reveals a complex history of magnetic remanence acquisition. Sites sampled around the shore of Webfoot Lake outside the metamorphic aureole of the SIC exhibit magnetic poorly constrained remanence directions: there seems to be no preferred direction and the intensity of the remanence is low. The remanence acquisition processes leading to these features must therefore have originated from local shearing or hydrothermal activity.

The south end of Webfoot Lake is marked by type 6 remanence directions which are observed to be associated with a distinct Mafic phase within the Levack Gneiss. The mafic phase correlates to a magnetic gradient on the total magnetic field and returns shallow Euler deconvolution solutions, suggesting a shallow contact at depth. Other researchers have mapped this unit as a small Gabbro pluton (Unit 7a, Figure 3; Dressler, 1984). This is compatible with the predominance of the type 6 vector in similar mafic zones of the Foy Offset (Morris, 1984).

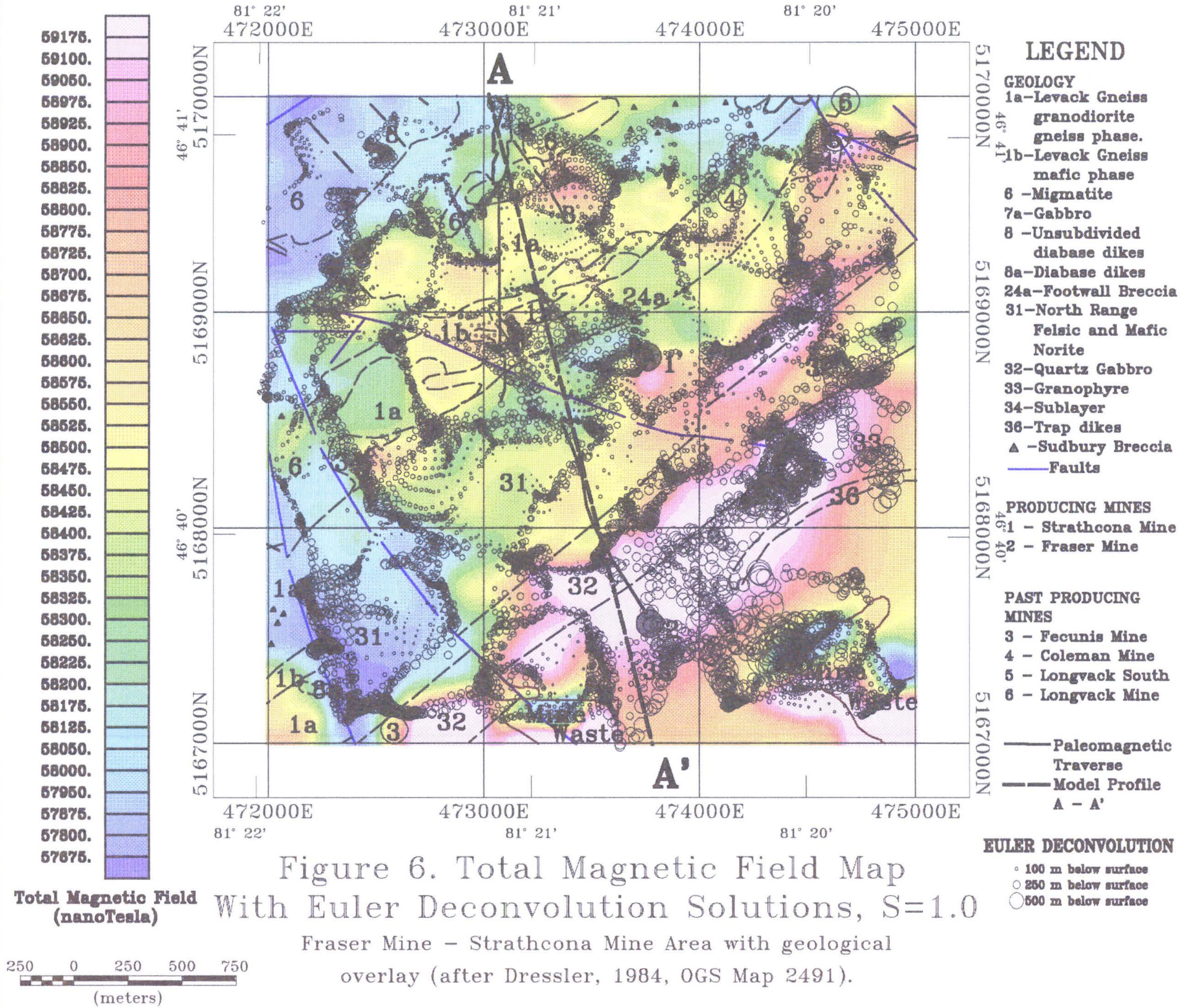


Figure 6. Total Magnetic Field Map With Euler Deconvolution Solutions, S=1.0

Fraser Mine - Strathcona Mine Area with geological overlay (after Dressler, 1984, OGS Map 2491).

A belt of high frequency total magnetic field anomalies extending from south of Coleman Mine to the west appears to correlate to the Pumphouse Creek Structural Zone proposed by Card (1993). The structural zone, although striking westward, is visibly offset by a series of northwest striking Diabase dikes and magnetic faults (Figures 3, 4 and 5). If the high frequency anomalies are indeed defining the trace of the Pumphouse Creek zone, then this indicates that the genesis of the structural zone predated the dikes (Sudbury type, 1.28 Ga) and faulting of the SIC (age unknown) must be post 1.85 Ga). The north boundary of the zone is visible on the Euler deconvolution solution map as a series of linear solution segments striking west-southwest. The zone is less visible on the first vertical derivative, which is dominated by lineations in a northwest direction. These lineations have two possible sources: (1) levelling error or line noise from the survey and survey line direction and/or gridding errors; (2) related to the diabase dikes which tend to strike parallel to the flight lines in this locality. The relationship to the Diabase dikes is of interest as coincident parallel flight line and anomalous magnetic responses are observed to the northwest of Strathcona Mine, suggesting that the dikes, if they are magnetic, may be significantly longer than currently mapped and may extend into the SIC.

A broad zone of type 1 remanence reflecting the intrusion of the North Range Norite is present over much of the remainder of the distance to Strathcona Mine. This zone correlates to an ellipsoidal region of total field magnetic highs and is devoid of analytic signal or Euler deconvolution anomalies. These observations combine to suggest that the zone is magnetically homogeneous. The paleomagnetic, rock magnetic and aeromagnetic uniformity does not reflect observed lithological variations in the Levack Gneiss; the uniformity probably represents the thermal overprinting of the SIC. Remanence directions obtained from samples within Strathcona Mine mineralisation zones are commonly of type 1 suggesting a possible Norite related genesis. In contrast the Strathcona Mine Deep Copper Zone sulphides also contain evidence of the type 4 mineralisation direction in addition to the type 6 dike intrusion - middle zone Quartz Diorite related remanence direction. This evidence suggests a possible younger genesis for this ore. The total magnetic field data places Strathcona Mine on the north flank of a dipolar magnetic feature, slightly ellipsoid in shape, striking west - southwest. The first vertical derivative and analytic signal maps also confirm the presence of a discrete anomaly, however, contributions from mine buildings in the area may be having a considerable influence on the overall signature; for example there is a strong positive anomaly associated with the location of Strathcona Mine.

Continuing south from Strathcona Mine to Fraser Mine the profile crosses sequentially units of the SIC; Felsic Norite; Oxide Rich Gabbro; Transition Zone material; and the lowermost portion of the Granophyre. Two distinct zones are identifiable within the Felsic Norite. The lower zone has higher intensity magnetic remanence and susceptibility relative to the upper zone. The remanence direction is similar in both zones of the Norite and the contact aureole. Visible on the total magnetic field map is a broad magnetic low in the north partially correlating to the lower zone of the Felsic Norite. The upper zone of the Felsic Norite appears to correlate to a moderate magnetic high. This same contact between the upper and lower zones of the Felsic Norite is clearly defined on the Euler deconvolution map (Figure 6.). This boundary does not seem to be present on similar sections further to the northwest.

The contact between the Felsic Norite and the Oxide Rich Gabbro is sharply defined magnetically, chemically and petrographically. Magnetically the Oxide Rich Gabbro is locally up to two orders of magnitude higher in susceptibility. Chemically the amount of total Fe present has doubled within the gabbro resulting in an increase in coarse grained magnetite relative to the underlying Felsic Norite. In plan view on the aeromagnetic maps, the contact between the Felsic Norite and the Oxide Rich Gabbro is sharply defined. The Oxide Rich Gabbro exhibiting a significantly higher amplitude signal. The analytic signal defines the unit over much of the study area as a discrete southwest striking high. Euler deconvolution results strongly suggest a steep southward dipping contact between the Felsic Norite and the Oxide Rich Gabbro, suggesting that the actual contact may be located further to the north (approximately 200 metres) than indicated.

On this traverse the Transition Zone is problematical. Along strike Dressler (1984) noted the presence of a "trap dike" (Figure 3). Paleomagnetic surveys along both this and a traverse 60 km to the east (Wisner traverse; Morris, 1984) have found the type 6 direction associated with this transition zone. There is no obvious evidence to support a dike visible in the aeromagnetic data or any of the derivative products. If there is a "trap dike" in this area it is magnetically transparent and the similarity between the Strathcona and Wisner traverse suggest an evolution related to the SIC rather than a local dike feature.

On this traverse only the base of the Granophyre was sampled and this did not define any coherent remanent signal. Unlike the sharp magnetic contrasts defined by the Felsic Norite/Footwall and the Oxide Rich Gabbro/Felsic Norite contacts, the upper parts of the SIC do not contain any strong magnetic contrasts. From the aeromagnetic data it is apparent that the Granophyre is either zoned or that the contact is shallow dipping to the south with respect to the both the Transition Zone and the Oxide Rich Gabbro. The Euler solutions are less focused and maintain an ever increasing depth to the south, coupled with the lack of a distinct analytic signal anomaly, this suggests that the Granophyre in this area is primarily magnetically transparent, a conclusion that agrees with the albeit limited paleomagnetic evidence.

Magnetic Modelling

Magnetic modelling of a profile sub parallel to the paleomagnetic surface traverse was undertaken. The input model was based heavily on the geologic section as published by Coats and Snadjr (1984) in conjunction with the plan geology map of Dressler (1984). This section was compiled from diamond drill, surface geology and subsurface geology data in the vicinity of Strathcona, Fraser and Coleman Mines. Forward modelling of the total magnetic field assuming only induced magnetisation resulted in a general fit to the observed field profile. Difficulties were encountered in the modelling with the strong magnetic low observed in the centre of the profile at 1500 m (Figure 7). Upon examination of the mapped geology, it was apparent that this feature was related to a sub parallel diabase dike that may cross the profile at an oblique angle. Bodies striking at an oblique angle to the profile are not handled by the multi-body modelling program used (GM-SYS by NWGA). It was therefore necessary to model the dike response separately (Figure 8) and then remove the effect from the model profile line prior to commencement of the modelling of the North Range contact (Figure 7). Initial susceptibilities used were determined from the current and previous studies of the SIC and environs (Hearst et al., 1992; Morris, 1984). Discrepancies between the observed and calculated total magnetic field were greatest in the Levack Gneiss and the Quartz Gabbro. Introduction of observed magnetic remanence characteristics to the modelling process resulted in a closer fit between the observed and calculated magnetic responses (Figure 7).

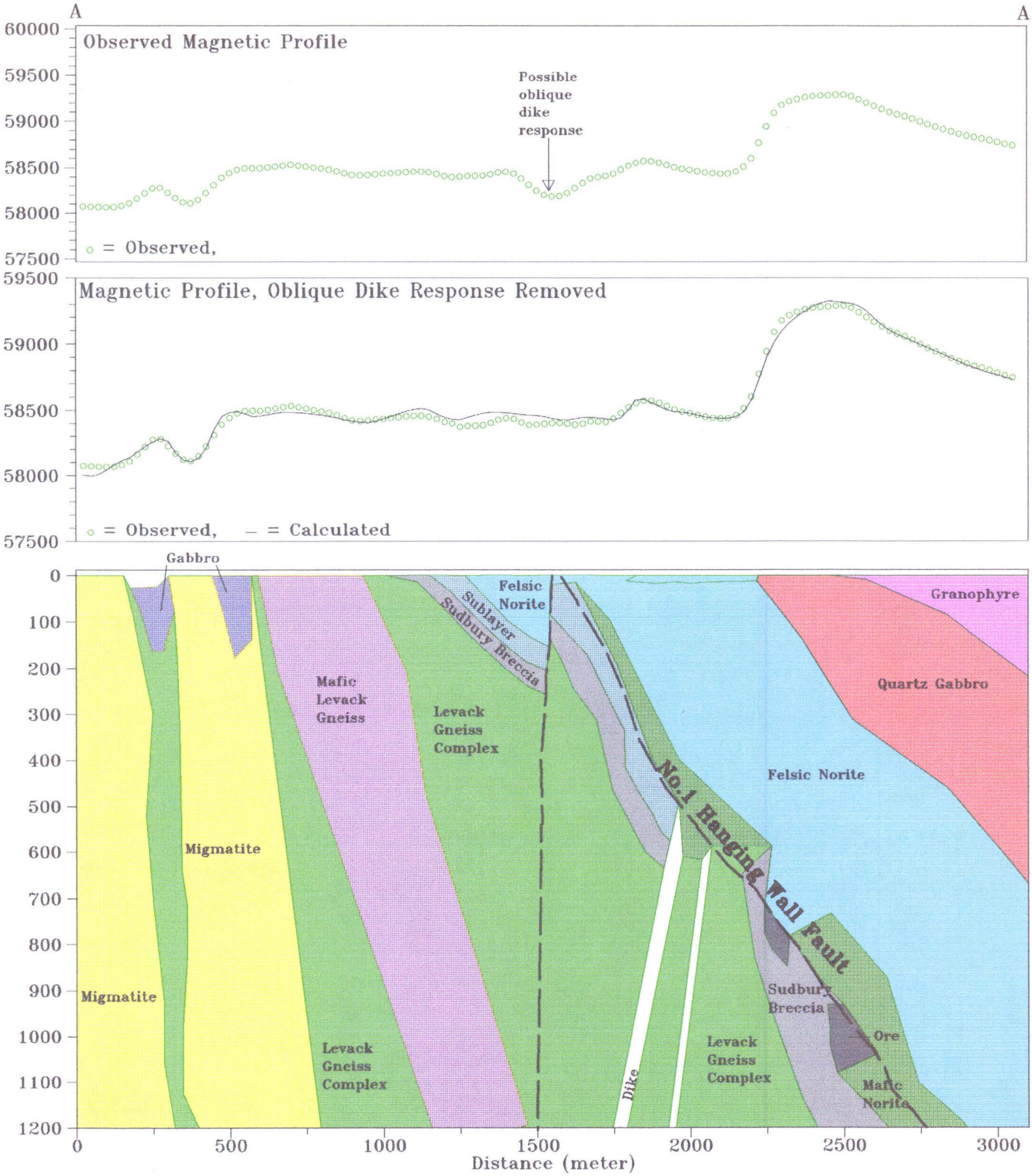
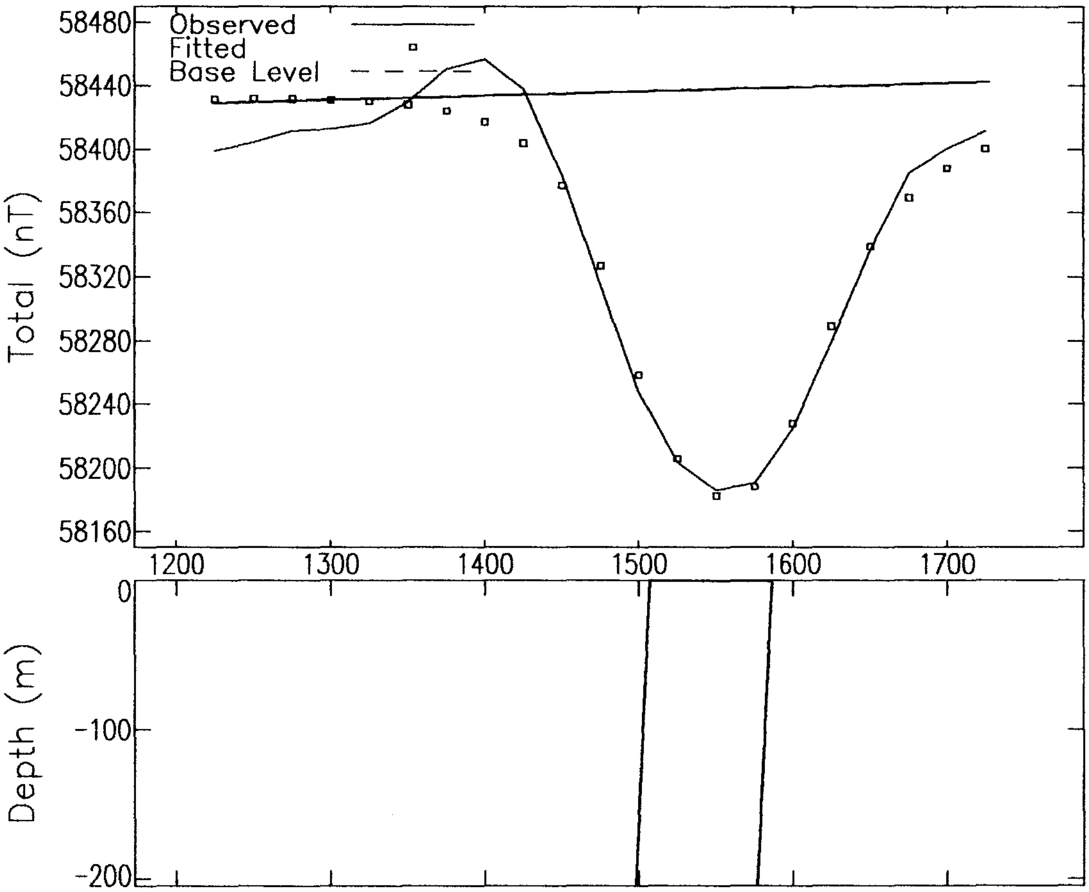


Figure 7. North Range Model Profile
(geology after Snadjr and Coats, 1984; Dressler, 1984)

Figure 8.
Sudbury Dike Model
North Range Profile



MODEL PARAMETERS:

Model Type		Tabular
Depth	L	0.270 m
Half Width	F	40.8 m
Dip	F	87 deg
Susceptibility	F	0.00161 emu
Remnance Ratio	X	1.767092
Remnance Incl	X	-100 deg
Remnance Decl	F	-28 deg
Main Position	F	1546.647 m
Cross Position	X	473373.5 m
Base Level	F	58437.65 nT
Base Slope	X	.0261662 nT/m
Base Curvature	X	0 nT/m2

(F-fitted, X-fixed, L-limit)

GEOMAGNETIC FIELD:

Field Strength	56000 nT
Inclination	75 deg
Declination	350 deg

COORDINATES:

Sensor Height	30 m
Strike Perp	15 deg
Line Direction	145 deg
Main Direction	160 deg
Main Offset	
Cross Direction	70 deg
Cross Offset	

Geosoft MAGMOD-3 Modeling Result 96/08/11

The magnetic modelling suggests at least 4 major phases to the development of the North Range in the area of study. The phases consist of: (1) metamorphism and deformation of the Levack Gneiss resulting in the formation of Migmatite zones and the Pumphouse Creek Structural Zone of Card (1994); (2) emplacement of the Sudbury Igneous Complex; (3) strike-slip faulting of the SIC; (4) reverse faulting of the SIC and Levack Gneiss Complex accompanied by Diabase dike intrusion. The exact sequencing of events can not be entirely determined from the magnetic modelling.

The Levack Gneiss Complex appears to consist of at least 3 different magnetic phases. The major constituents are "typical" Levack Gneiss (average susceptibility, 3.14 x 10-3 S.I.), Migmatite (very low susceptibility, 1.5 x 10-3 S.I.), Mafic Levack Gneiss (slightly higher susceptibility, 3.2 x 10-3 S.I.). The mafic intrusive mapped at the south end of Webfoot Lake as a gabbro or mafic phase of Levack Gneiss appears to be of limited depth extent (< 200 metres), confirming the results of the Euler deconvolution process. The susceptibility used in the modelling of 3.47 x 10-3 S.I. is consistent with Metagabbros sampled along the North Range of the SIC.

The Footwall Breccia is modelled as a thin magnetic unit (3.28 x 10-3 S.I.) in a simple layered relationship to the Levack Gneiss. Immediately adjacent to and of similar thickness, is a thin layer of SIC Sublayer material (2.4 x 10-3 S.I.).

The North Range Norite was modelled as a thin magnetic Mafic phase (3.5 x 10-3 S.I.) overlain by a less magnetic Felsic phase (2.93 x 10-3 S.I.). As with the Sublayer and Sudbury Breccia units, the Norite is down faulted by a splay off of the Fecunis Fault in the vicinity of station 1500. Movement is modelled as down to the north. Remanent magnetisation within the Felsic Norite appears to be localised to near surface zones, particularly to the north of the contact with the Quartz Gabbro.

The Quartz Gabbro exhibits the highest magnetic susceptibility (7.1x10-3 S.I.) of all constituents of the North Range of the SIC. It is apparent from the modelling that the Quartz Gabbro is responsible for the magnetic anomaly associated with the North Range of the SIC in this area. The shallow dip to the south of the Quartz Gabbro is consistent with Euler deconvolution results. The Granophyre, as suggested from the processing of the airborne survey data, is magnetically transparent when compared to the Quartz Gabbro.

CONCLUSIONS

Paleomagnetic results, image processing of the airborne magnetic data, and magnetic anomaly modelling along a traverse across the North Range of the Sudbury Structure from the Levack Gneiss and into the SIC provides confirmation that the North Range contact of the SIC is in broad terms is a simple intrusive contact as suggested from the LITHOPROBE high resolution seismic survey (Milkereit et al., 1992). Detailed rock property and potential field analysis indicate that this contact has a considerable geological history which appears to post-date the intrusion of the SIC. Paleomagnetically, a probable sequence of events for the development of the North Range in this area is (1) metamorphism of the Levack Gneiss with localised zones of remagnetisation possibly related to Migmatization; (2) emplacement of the SIC and accompanying late stage metasomatism resulting in the footwall mineralisation of the Copper and Deep Zones of the Strathcona Mine; (3) strike-slip faulting (No. 1 Hanging Wall Fault) of the SIC within the Norite, resulting in enhanced magnetisation within the Mafic Norite; (4) reverse faulting of the SIC and the Levack Gneiss Complex. Similar zones of remagnetisation are observed within the Levack Gneiss immediately to the north of the contact aureole of the SIC. Magnetic zoning within the Norite (both Mafic and Felsic components) and the implied lack of coherency of magnetic properties within the Granophyre as indicated from the potential field processing are suggestive of a more complex history than originally suggested by the simplicity of the seismic interpretation. There is evidence for the intrusion of north northwest striking Diabase dikes postdating the intrusion of the SIC but predating the development of the Pumphouse Creek Structural Zone of Card (1994). One such dike appears to be offset by an east southeast splay of the Fecunis Lake Fault within the North Range Norite immediately west of Strathcona Mine. The implication of the aeromagnetic data is that the North Range contact of the SIC with the Levack Gneiss was initially a simple layered intrusive contact. However this contact has undergone both strike slip faulting (No. 1 Hanging Wall Fault), reverse faulting (splay of the Fecunis Lake Fault) and late stage intrusion of dikes.

Chapter 4: Geophysics of the Levack Gneiss - Cartier Batholith Complex

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Abstract

Recent geologic mapping along a transect across the Levack Gneiss and Cartier Granite has revealed previously unmapped ductile shear zones and evidence that the current contact between the Levack Gneiss and Cartier Granite has been located several kilometres too far south of the actual location. Regional potential field data sets encompassing an area larger than the currently mapped extent of the Levack Gneiss - Cartier Batholith Complex have been analysed for (1) evidence supporting the revision of the geologic contact of the Levack Gneiss and Cartier Granite and (2) geophysical evidence of major shear zones.

Examination of the processed images derived from gravity, aeromagnetics, airborne gamma-ray spectrometry, and airborne VLF-EM datasets suggests that the Archean Gneisses and/or greenstones of the Superior Province to the immediate north and west of the Sudbury Structure, specifically the Levack Gneiss - Cartier Batholith Complex are dipping towards the south and under the Sudbury Basin. Good correlation exists between the aeromagnetic, gravity and spectrometer data sets with respect to the ability to map out the contact between the Levack Gneiss and Cartier Granite.

Introduction

The origin of the Sudbury Structure and its relationship both geophysically and geologically to the surrounding rocks of the Superior, Southern and Grenville Provinces of the Canadian Shield has been the subject of scientific interest and debate since its discovery by a government land survey party in 1856 (Pye et al., 1984; Grieve et al., 1991; Lowman, 1992; Lightfoot et al., 1994). Economically, the Sudbury Structure and environs are of interest for hosting world-class mineral deposits including nickel, copper, cobalt, and platinum group elements. To uncover new insights into the origin of the Sudbury Structure, the Sudbury corridor of the Abitibi-Grenville LITHOPROBE Transect was established. This resulted in the acquisition of several lines of regional deep crustal seismic reflection data and high resolution deep crustal seismic reflection data (Milkereit, et al. 1992, 1994). When combined these seismic lines provide a complete but somewhat discontinuous cross-section of the Sudbury Structure extending from the Huronian Supergroup metasediments and metavolcanics in the south, to the contact between the Levack Gneiss - Cartier Batholith complex to the north. Seismic data from the lines extending across the North Range of the Sudbury Structure (Figure 1, Line 40) and the Levack Gneiss (Figure 1, Line 42) suggest a relatively simple layered structure dipping to the south (Milkereit et al., 1992). To connect the package of simple southerly dipping reflectors with outcrops of potentially equivalent lithologic boundaries in the Levack Gneiss, it is necessary to invoke an interpretation where the reflective layers must be compressed and the dip steepened. While this steepening of the dip is compatible with the magnetic and gravimetric potential field modelling (Hearst et al, 1994; McGrath and Broome, 1994), it suggests a more complex structural history for the North Range of the Sudbury Structure.

The Levack Gneiss - Cartier Batholith Complex (Langford, 1960; Dressler, 1984; Peredery, 1991; Fueten et al., 1992; Card, 1994) comprises felsic banded gneisses of granodiorite, tonalitic to quartz dioritic compositions with local concentrations of gabbroic, anorthositic and ultrabasic rocks. Further complicating the geology are pockets of metasedimentary - metavolcanic assemblages (Card and Innes, 1981). All of the rocks have undergone migmitization to various stages, implying complex tectonic and high grade metamorphic histories. Mineral assemblages within the gneisses typically lie within the granulite and amphibolite facies, metasedimentary rocks generally exhibiting sillimanite - cordierite - orthopyroxene assemblages. Massive felsic plutons ranging in modal composition from granite to granodiorite or tonalite intrude into the gneisses and greenstone assemblages throughout the study area. Geologic mapping by Fueten et al. (1992) has indicated the presence of at least two east-west striking south dipping ductile zones within the Cartier Granite. The first of these shear zones is the near the Benny Greenstone - Cartier Granite contact, the second near the Cartier

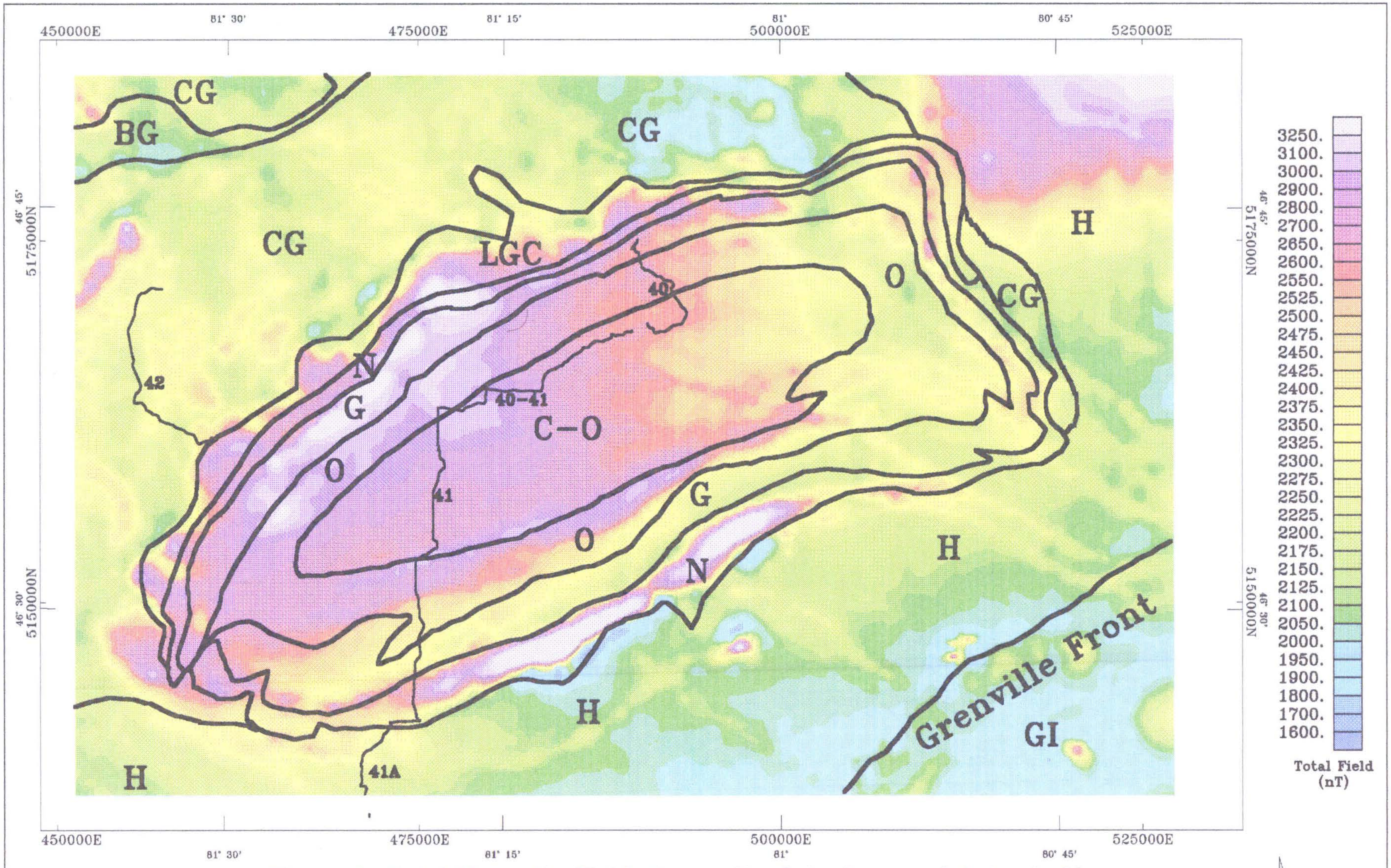


Figure 1. Total Magnetic Field, Generalized Geology and Seismic Lines

Geologic base after from Dressler (1984, OGS Map 2491). Lines 40 & 41, 120 fold seismic line; lines 41A, 40-41, & 42, 60 fold seismic line; GI, Granites and Intrusive rocks; H, Huronian Supergroup; G, Granophyre, Sublayer, Quartz-Gabbro; N, Norite; O, Onaping Formation; C-O, Chelmsford and Onwatin Formations (Whitewater Group); BG, Benny Greenstone Belt; CG, Cartier Granite Complex and Gneisses.

2500 0 2500 5000 7500
(meters)

Granite - Levack Gneiss contact independently confirmed by Card (1994). Additional mapping by Card (1994) has confirmed an eastwest striking shear zone extending from Levack Township westward, cutting both the Levack Gneiss and Cartier Granite subparallel to Pumphouse Creek. Recent interpretation of LITHOPROBE seismic line 42 (Windy Lake Traverse) indicates a south dipping shear zone within the Cartier Granite near the contact with Levack Gneiss (Milkereit et al., 1993). Matachewan and Sudbury swarm diabase dikes intrude the Archean felsic plutonic and gneissic rocks. Intrusions of the Sudbury Igneous Complex Sublayer/Offset dikes are common in the south-eastern portion of the study area.

Through the integration of the gravity, aeromagnetic, airborne spectrometer, and airborne VLF-EM data sets a more detailed picture than was previously available can be developed for the Levack Gneiss - Cartier Batholith Complex, particularly in areas where ground access is difficult and hence outcrops are limited. Zones of migmatization and the location of igneous intrusions within the Cartier Granite can be mapped geophysically.

Utility and Preparation of Potential Field Data Sets

Gravity Data

The gravity method of exploration is predicated on the assumption that different rock units have different densities and masses. The gravity effect of a body is dependent upon it's geometry, the distance from the body to the observation point, and the contrast between the body density and that of the host rock. A small density contrast may render the body undetectable. The variability or non-uniqueness of gravity solutions for a given model is well documented (Dobrin, 1976; Telford et al., 1990).

The frequency of gravity observations effectively limits the usefulness and resolving power of a gravity survey. If the stations are spread over a large area (1 observation per several kilometres) then shallow bodies of limited size (< several kilometres) will not be resolved. If a uniform sample frequency resulting in significantly more observations per kilometre is available, then smaller features can be resolved in addition to deeper seated, larger features. In this study, gravity essentially provides an indication of deeper geologic structure and density variation primarily as a result of the sample frequency of observations.

The gravity measurements used in this study were acquired by the Earth Physics Branch of the Geological Survey of Canada (GSC) and the Ontario Geological Survey (OGS) between 1947 and the present (Gupta and Hearst, 1991). The data has been referenced to the International Gravity Standardisation Net 1971 (ISGN71) and the Geodetic Reference System 1967 (GRS67). The Bouguer anomaly values were calculated utilising a vertical gradient of 0.3086 mGal/m and a crustal density of 2.67 g/cm^3. Gravity observation station density is highly variable, ranging from 100 m intervals along short sections of road traverses within parts of the Sudbury Basin to a density of 1 observation for every 10 to 15 km over much of the Levack Gneiss - Cartier Batholith Complex. A total of 1654 observation points were gridded using the minimum curvature algorithm of (Briggs, 1974) to a grid cell interval of 250 m. The final grid cell size of 250 m is a compromise between the areas of high and low observation density, producing a detailed, but low aliasing Bouguer anomaly grid.

Through the calculation of the 3-D analytic signal of the Bouguer anomaly, zones of significant density contrast are identified (Hansen et al., 1987; Roest et al., 1992). Anomalous amplitudes may result from large mylonitization zones and associated metamorphism along faults leading to the lowering of the apparent density of the rocks within and/or adjacent to the fault; increased contrast due to juxtaposition of lower density units against units of higher density; hydrothermal metamorphism; and/or compaction/tensional settling of sedimentary units. The ability to resolve these features is heavily dependent on the number of gravity observations obtained. In combination with the aeromagnetic data, the gravity provides the interpreter with a picture complimentary to that of the surface mapping techniques of VLF-EM and gamma-ray spectrometer.

Aeromagnetic Data

Magnetically the Sudbury Basin and environs are recognised as exhibiting a high degree of variable remanent magnetisation (Morris, 1984). Attempts at constructing a magnetic model profile across the Sudbury Basin (Hearst et al., 1992; 1994a; 1994b) which honours the available seismic (Milkereit et al., 1992) and gravity (McGrath and Broome, 1994) models have proven to be less than satisfactory. The shape of a magnetic anomaly is dependent upon the geometry of the source body, the orientation of the source body within the Earth's magnetic field and the possible presence of internal remanent magnetic contributions. Usually both source body shape and orientation are unknown. The modelling attempts were undertaken using constraints derived from the seismic interpretation. The unsatisfactory fit of the magnetic data to the seismic model highlighted the magnetic complexity of the Sudbury Structure in particular, and the Levack Gneiss - Cartier Complex in general (Hearst et al., 1992). It was hypothesised that the magnetic complexity is primarily the result of : (1) significant variations in the magnetic properties within individual rock units (variable remanent magnetisation); (2) greater sensitivity of the magnetic data set to structures that are transparent to the seismic and gravity data; and (3) the greater sampling frequency of observations of the local variations in the Earth's magnetic field. The inherent difficulties associated with feature modelling can be overcome by using image processing techniques which will outline the source body geometry irrespective of the orientation of the magnetic vector. The two image processing techniques, 3-D analytic signal and Euler deconvolution used in this study are relatively insensitive to magnetic inclination, declination and remanence effects at high magnetic latitudes (Reid et al, 1990; Roest et al., 1992) and hence can be used to define body geometry.

Aeromagnetic data was obtained from the Geophysical Data Centre of the GSC and the OGS. The data was acquired along north-south oriented flight lines at a line spacing of approximately 500 m and a mean terrain clearance of 300 m. In this study, the magnetic data set is arguably the most detailed data set available by virtue of the high sampling frequency employed in the data acquisition. The data set was gridded using the minimum curvature method utilising a grid cell size of 150 m. The gridded total magnetic field was levelled to the GSC's 812.8 m national grid using the levelling procedure described by Gupta et al. (1988).

Airborne Gamma-ray Spectrometer and VLF-EM Data

Airborne gamma-ray spectrometer data is especially useful in delineating granite bodies from those composed of basic intrusives and/or sedimentary sequences. The method is predicated on the assumption that individual rock units can be categorised on the basis of measurable anomalous concentrations of radioactive mineral elements (Darnley, 1972). Typically the gamma ray flux is measured over a series of energy windows covering the radioactive decay series of potassium (1.46 MeV, ^{40}K), uranium (1.76 MeV, ^{214}Bi) and thorium (2.62 MeV, ^{208}Tl). Geochemical sampling of various rock units and ore deposits (Darnley, 1972; Telford et al., 1990) suggests that with the exception of potassium rich granite, sedimentary and metamorphosed sediments generally exhibit more gamma ray activity than igneous and other metamorphic rocks. Spatial variations between the radiometric signatures of the principal rock units in the study area as a result of observable differences in the concentrations of ^{40}K, ^{214}Bi, and ^{202}Tl allow for the location of contacts and some metamorphic features to within the survey sampling density and line separation (nominally 100 m downline, 1000 m between line). However, the usefulness of spectrometer data is restricted by: (1) the limited depth of investigation; (2) the gamma-ray spectrum contrast between adjacent rock units; (3) the presence of thick (> 1 m) blankets of surface materials which may not be representative of the host rock; (4) detector crystal size (in general larger crystals can detect smaller concentrations) and (5) sparse sampling resulting from detector integration time, aircraft speed, and survey height. Darnley (1972) estimates that 90% of the total gamma ray radiation is produced from the upper 15 to 23 cm for a rock of density 2.7. This effectively limits the gamma ray method to representing a planar or 2-D surface as opposed to the 3-D mapping potential of magnetic and gravity methods. The shallow depth of investigation also highlights the assumption that all material in the upper metre is representative of and derived from the underlying rock. This implies that the concentration of potassium, and the decay products for uranium and thorium for both outcrops and overburden have the same relative distribution and have not been significantly altered by weathering. This is often not the case in areas of extensive glacial, alluvial, fluvial, and/or aeolian activity, where the near surface is often composed of drift material derived from distant sources. The effect of this is to mask the desired signal. Signal masking can also occur in areas of dense vegetation coverage, where the canopy can absorb significant amounts of signal. The overall effectiveness of the gamma-ray method is restricted by the sampling rate of the instrument and the aircraft speed. Most modern systems sample at 1 second intervals, in a fixed wing aircraft this typically results in 1 sample for every 80 to 120 m flown and may not allow for sufficient or detailed enough measurements to be obtained.

Major fault zones and intrusive dike features which crop out or are present in the near surface can be readily identified from the VLF-EM data. Detectability of these features is based on the assumption that the world-wide network of marine navigation VLF stations propagate an EM signal that is perpendicular to or near perpendicular to relatively conductive geologic structures of interest and that the resulting secondary EM field signal is measurable (Telford et al., 1990). Depending on the VLF transmitting stations selected a directional bias is introduced into the data set, only those conductive geologic features orthogonal to the transmitter signal direction will be detected. Depth penetration of the VLF-EM method is limited by the high frequency of the broadcast signal and therefore is heavily biased by near surface conductors of natural and man-made varieties. A further complication to the interpretation of VLF-EM data is introduced by the presence of enhanced surface features (topography, conductive overburden, groundwater concentration, etc.).

The gamma-ray spectrometer and VLF-EM data were acquired concurrently by the GSC along north-south flight lines spaced at 1 km with a nominal ground clearance of 110 m during the summer of 1989. All data corrections and levelling were completed by the GSC. Traditional gamma-ray spectrometer windows centred on 1.46 MeV (K, potassium), 1.76 MeV (U, uranium), and 2.62 MeV (Th, thorium) were employed as were corrections for atmospheric temperature and pressure, background radiation, spectral scattering, and deviation of terrain clearance (Singh et al., 1994). Grids using a grid cell resolution of 100 m were created for K (%), eTh (ppm), eU (ppm), eU/eTh, eU/K, and eTh/K. A colour ternary plot utilising yellow for U, magenta for K, and cyan for Th was prepared (Figure 7.) along with colour maps of each of the spectrometer ratio grids. The VLF-EM data was prepared as total field response and quadrature response grids using a grid cell resolution of 100 m. The data is presented in Figures 11 and 12 as colour maps.

Analytical Methods and Procedures

3-D Analytic Signal

The theoretical foundation of the 3-D analytic signal method of processing has been covered in detail by Nabighian (1972), Marson and Klingele (1993) and MacLeod et al. (1994).

The method is based on the premise that the corners and edges of a 3-D body are well defined in the horizontal plane and related to the maxima of the signal amplitude (magnetic and gravimetric). The maxima of the signal amplitude occurring directly over the edges of the source body. It has been demonstrated by Roest et al. (1992) that the analytic signal amplitude for a magnetic source is related to the amplitude of magnetisation and not to the direction of magnetisation; hence the method is not influenced by the presence of remanent magnetisation. The analytic signal of gravity or magnetic data can be calculated in one of two fashions, dependent upon the quality of the data and the interpreter's preference. The traditional calculation is derived from the three orthogonal gradients of the total magnetic field or Bouguer gravity using the expression

$$|A(x,y)| = \sqrt{\left(\frac{\partial N}{\partial x}\right)^2 + \left(\frac{\partial N}{\partial y}\right)^2 + \left(\frac{\partial N}{\partial z}\right)^2} \quad , \text{(1a)}$$

where N is either the Bouguer gravity anomaly or the total magnetic field. The result of this equation when applied to the Bouguer gravity anomaly is to locate the maxima of the analytic signal within the causative body (Marson and Klingele, 1993). When applied to the total magnetic field, the effect is locate the maxima of the analytic signal over the edges of the causative body (Roest et al., 1992; MacLeod et al., 1994).

An equally effective variation of the analytic signal calculation (Marson and Klingele, 1993) is to use the vertical gradient (either measured or calculated) of the Bouguer gravity (g) in an analogous expression given by

$$|A(x,y)| = \sqrt{\left(\frac{\partial^2 g}{\partial x \partial z}\right)^2 + \left(\frac{\partial^2 g}{\partial y \partial z}\right)^2 + \left(\frac{\partial^2 g}{\partial z^2}\right)^2} \quad . \text{(1b)}$$

The effect of this expression is to localise the maxima of the analytic signal in extremely close proximity to the edges of the causative body.

For the interpreter who prefers to have analytic signal maxima of the total magnetic field located directly over the causative body, the vertical integral of the total field is used in equation (1a) for the calculation of the horizontal gradients, the total field being used in place of the vertical derivative term (MacLeod et al, 1994).

All calculations are performed on gridded data sets, the solutions are presented as (x,y) plane colour maps.

Euler Deconvolution

The application of Euler's homogeneity relation through the process of deconvolution has been demonstrated to be an effective method for rapid delineation of potential field boundaries and for obtaining estimates to the top of the source (Reid et al., 1990; Paterson et al., 1991; Marson and Klingele, 1993). The method of solving Euler's homogeneity relation is based on the 3-D implementation of the EULDPH algorithm (Thompson, 1982 and Reid et al., 1990). This methodology utilises the total potential field and its related gradients (X, Y, and Z components) to derive the rate of change of the potential field with respect to distance from the source location and depth. The degree of homogeneity of the rate of change of the three gradient components is directly related to the geometry of the source body. This factor is frequently referred to as the structural index or SI (Thompson, 1982). Euler deconvolution does not assume any particular geologic model. The process can be applied to individual datasets to search for many different types of source bodies ranging from contacts through to buried prisms. If the source geometry is known, or can be approximated, a specific SI or range of SI's can be pre-selected in the Euler deconvolution process. This approach generally results in an increased reliability in source location and depth estimation. When a specific SI is used, ideal sources of different SI are either eliminated or produce solutions with unfocused locations, and/or depth estimates with a large associated error function. This allows for some degree of screening out of inappropriate responses. Further screening can be provided by careful analysis and selection of the window size over which the Euler deconvolution operator is applied. In all cases a window size of 20 grid cells in X and Y was used (5 km X 5 km for the Bouguer gravity and 3 km X 3 km for the total magnetic field).

Source geometry's for which the degree of homogeneity has been defined by direct solution of Euler's equation are based on the assumption of the use of magnetic potential field data sets (Reid et al., 1991) and are listed in Table 1. For these SI's to be used with gravity potential field data sets it is recommended that the first vertical derivative of the gravity field be utilised as the primary dataset. It has been demonstrated by Marson and Klingele (1993) that this results in more realistic location and depth estimates being obtained.

Table 1. Euler deconvolution structural indices and type models

Structural Index (SI)	**Magnetic**	**Gravity**
0	contact	contact
1	sill	pipe
2	pipe	sphere
3	sphere	N/A

All Euler deconvolution calculations were performed on gridded data sets. The solutions are plotted as discrete points using proportional circles to indicate depth. The solution location is the centre point of the proportional circle.

Results

Gravity Data

Prominent features of the Bouguer anomaly gravity map (Figures 2 and 3.) are: (1) the positive amplitude anomalies associated with the Benny Greenstone Belt in Gilbert, Stralak, Craig, Moncrieff, and Hess Townships, suggesting as might be expected that the density of the basaltic rocks of the Benny Greenstone Belt are of a higher density than the adjacent Cartier Granite; (2) the lack of a similar anomaly coincident with rock units of the same type as the Benny Greenstone Belt in the north-east quadrant of the study area (Leinster, Rhodes, Botha, Tyrone, Roberts, Kitchener, Hutton, and Creelman Townships) suggesting no significant variation in density between the basalt and granite; (3) the pronounced gradient paralleling the north-west margin of the Sudbury Structure coincident to the contact of the Levack Gneiss and Cartier Granite indicating a significant regional scale density contrast; (4) the negative Bouguer anomaly coincident with the possibly less dense Venetian Lake Granite Pluton; (5) the negative Bouguer anomaly coincident with the central Cartier Granite suggesting a lighter intrusive centre, or banded intrusive; (6) the negative Bouguer anomaly coincident with the possibly less dense

Birch Lake Granite; and (7) the positive Bouguer anomaly associated with the Sudbury Structure as a result of the denser geologic units comprising this structure.

Aeromagnetic Data

Prominent features of the aeromagnetic data are: (1) linear north-west and west-northwest striking anomalies correlating to the Sudbury and Matachewan dike swarms respectively; (2) a linear arc of magnetic highs correlating to the Felsic Norite and Quartz Gabbro of the North Range of the Sudbury Igneous Complex and the immediately adjacent Levack Gneiss; (3) a pronounced magnetic low correlating to the Geneva Lake metavolcanic and metasedimentary assemblage of the Benny Greenstone Belt; (4) a magnetic high coincident with the Spanish River Carbonatite Complex in Venturi Township; (5) a pronounced magnetic high coincident with the mapped Nipissing sill in eastern Moncrieff and northern Hart Townships; (6) coincident magnetic high with the Gowganda Formation of the Huronian Supergroup in Beaumont, Creelman and Hutton Townships; and (7) increased magnetic susceptibility in the granite terranes to the west of the Spanish River Carbonatite Complex and north of the Benny Greenstone Belt.

Airborne Gamma-ray Spectrometer Data

The ternary plot of K, eU, and eTh is particularly useful in conjunction with the element ratio maps. Dominant trends emerging from the spectrometer data (Figures 7,8,9 and 10.) are: (1) the pronounced Th concentration in the Cartier, Venetian Lake, and Birch Lake Granite

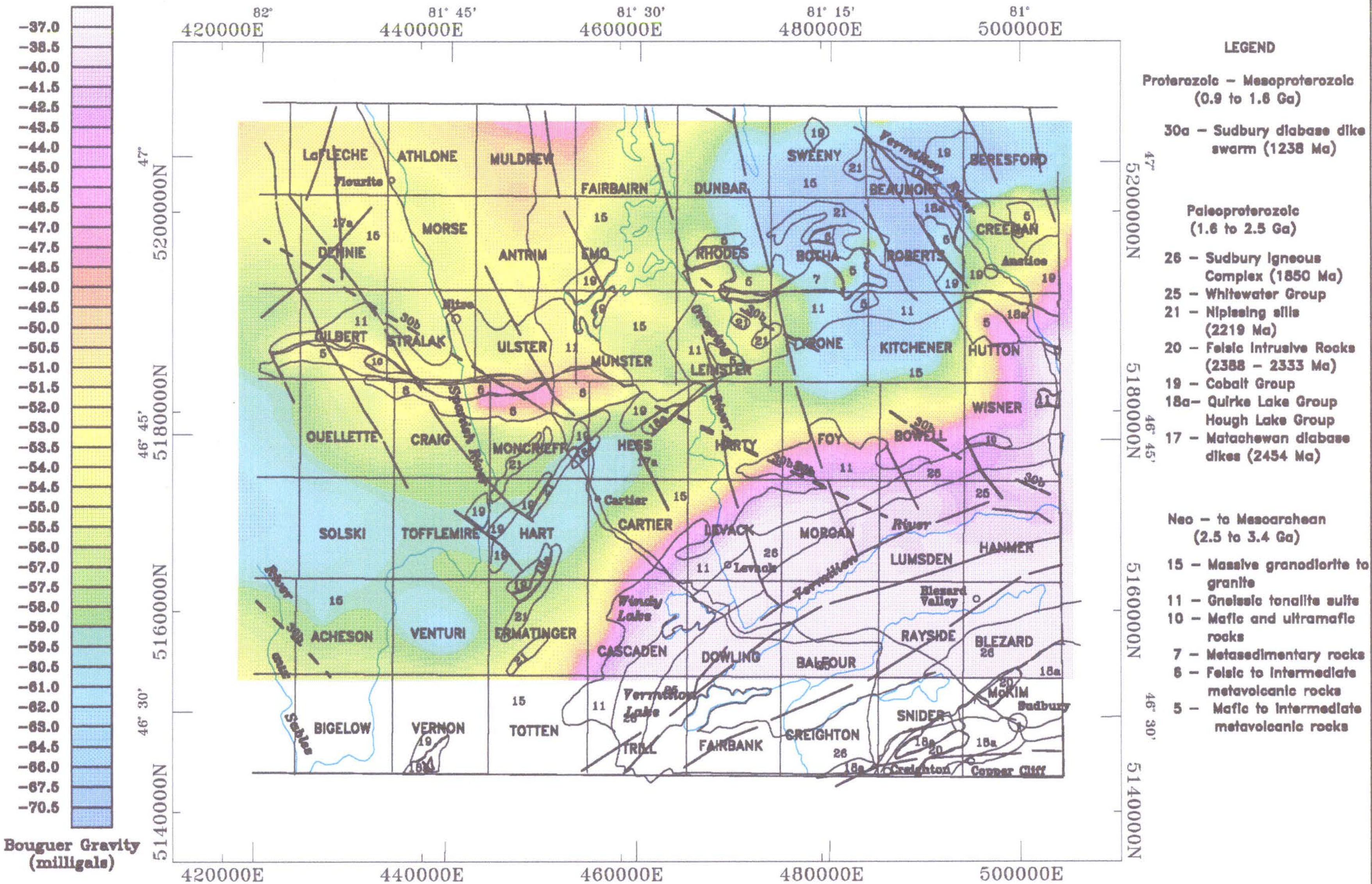


Figure 2. Bouguer Gravity Map

Levack Gneiss – Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

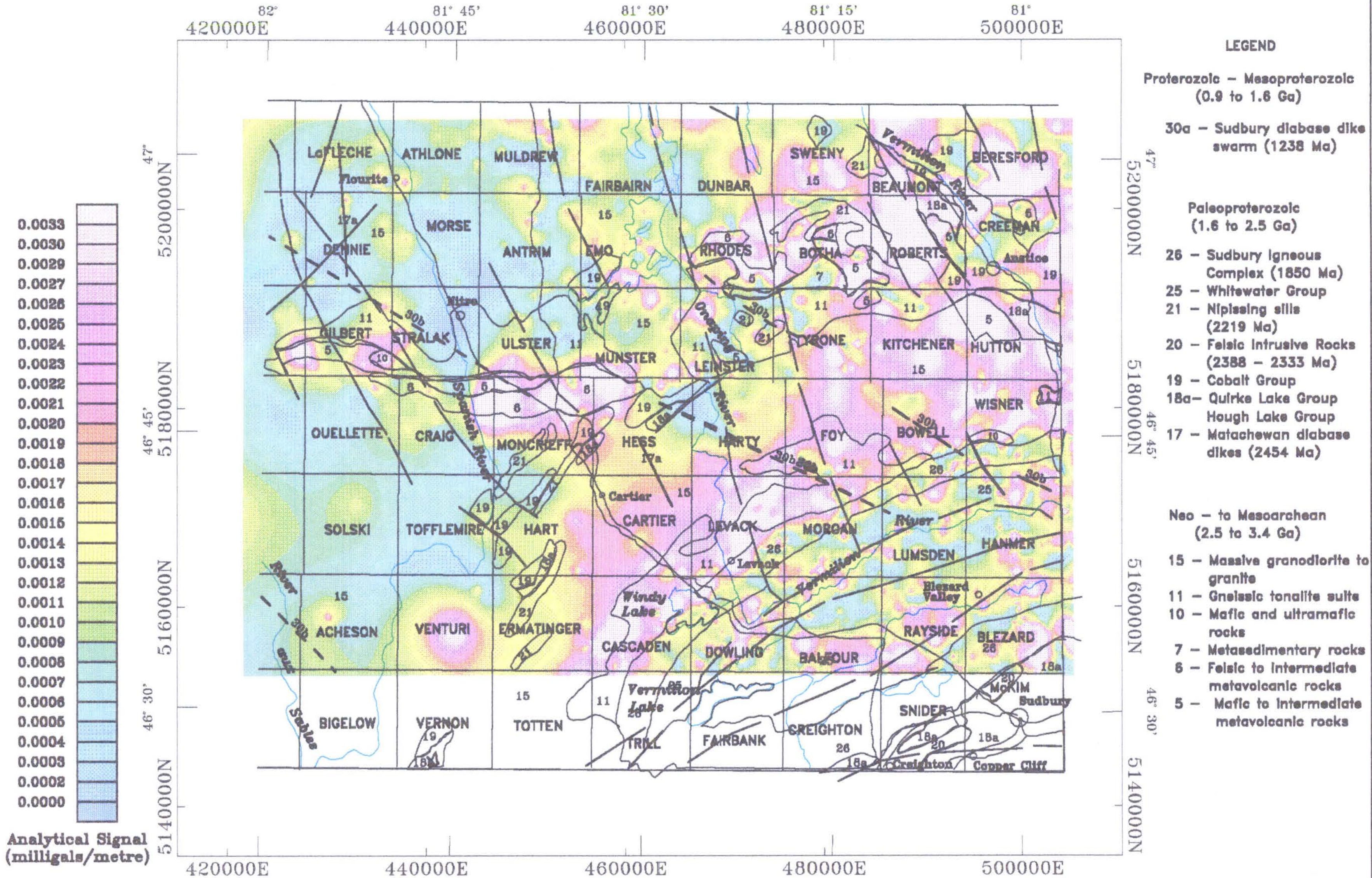
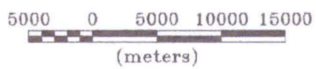
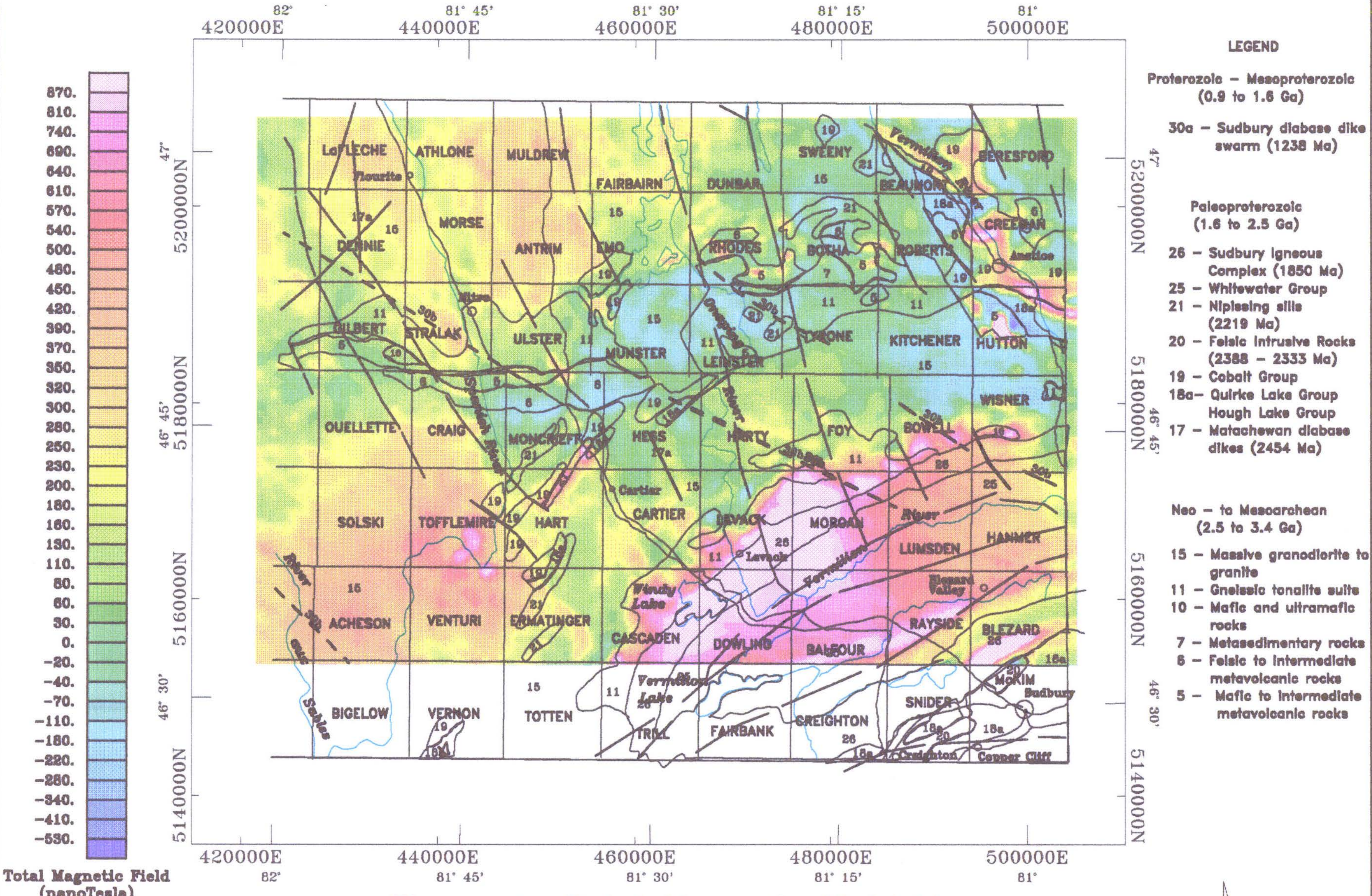


Figure 3. Bouguer Gravity Analytical Signal Map

Levack Gneiss – Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.





5000 0 5000 10000 15000
(meters)

Figure 4. Total Magnetic Field Map

Levack Gneiss - Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

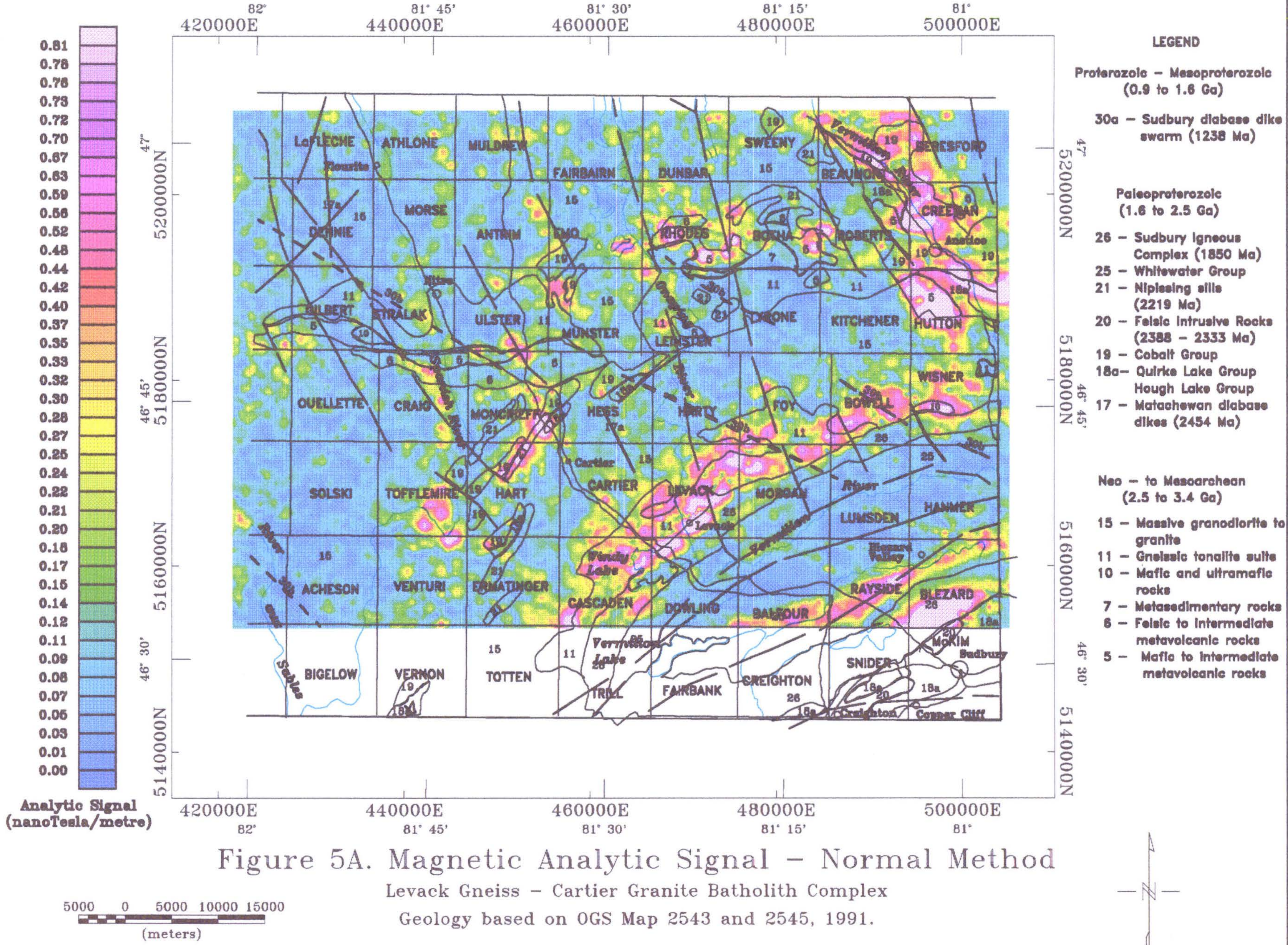


Figure 5A. Magnetic Analytic Signal - Normal Method

Levack Gneiss - Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

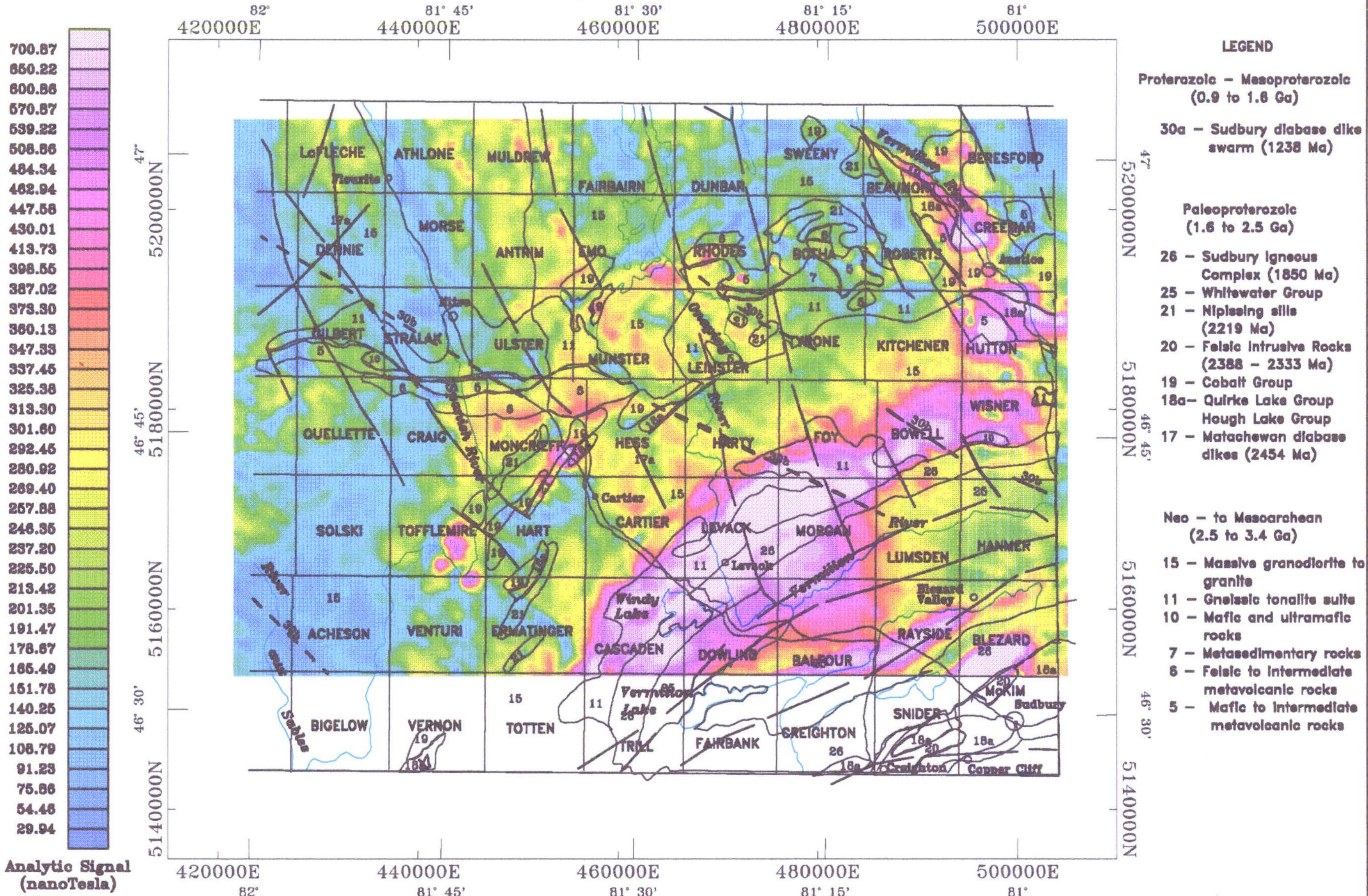


Figure 5B. Magnetic Analytic Signal – Integral Method

Levack Gneiss – Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

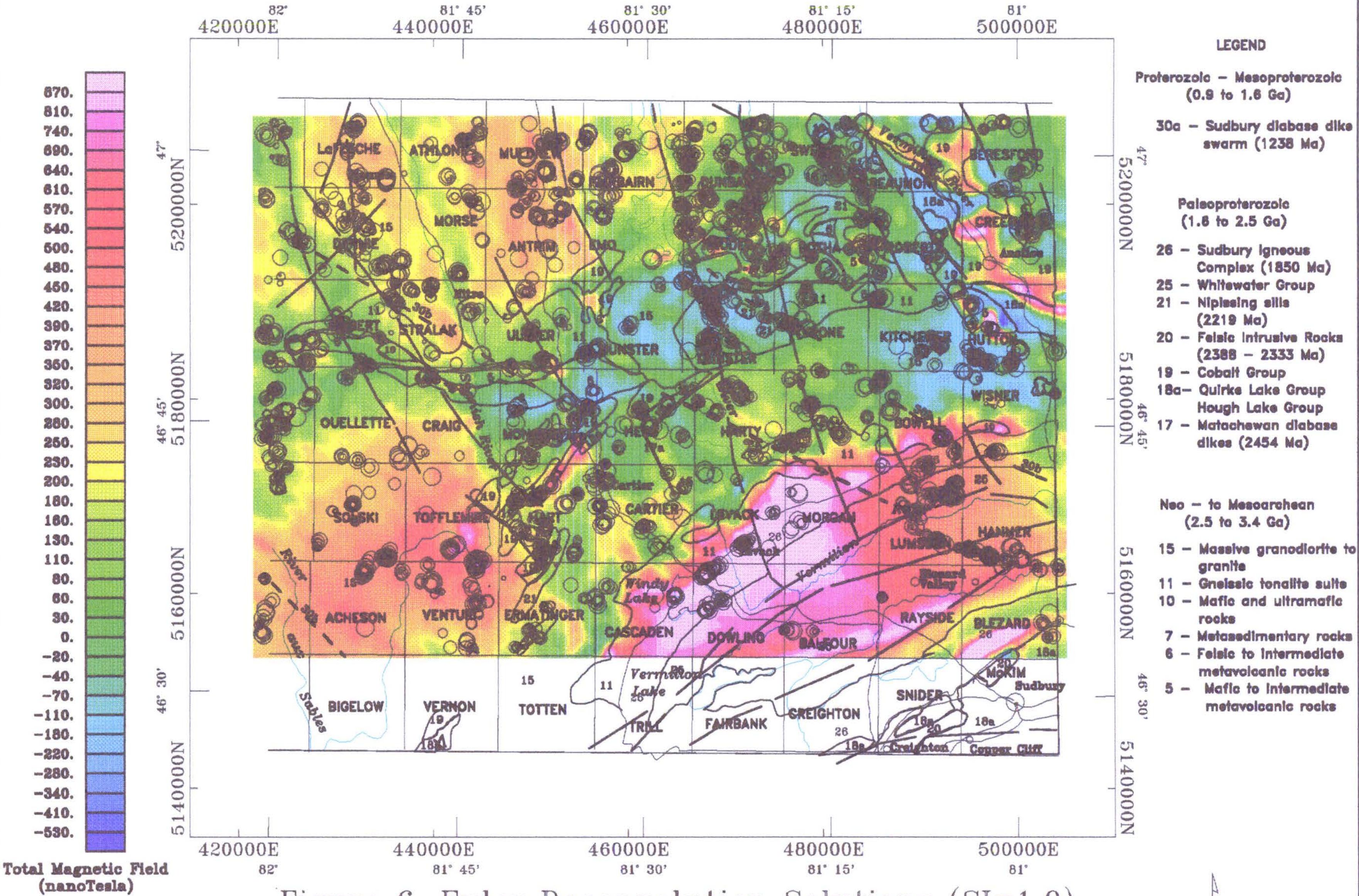


Figure 6. Euler Deconvolution Solutions (SI=1.0)

Levack Gneiss – Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

Batholiths effectively mapping the surficial extent of these units, the migmatites to the north and south of the Benny Greenstone Belt and to the west of the Spanish River; (2) decreased K associated with dikes of the Sudbury swarm consistent with mafic intrusives; (3) elevated K and Th coincident with the Sudbury Igneous Complex/Offset dike in Foy Township; (4) depletion of all elements along faults of the Cameron Creek and Vermilion Lake families within the Sudbury Structure, possibly the result of fluvial processes in conjunction with the formational tectonic processes related to the faults; (5) the suggestion that the lack of radioelement concentration coincident with the Benny Greenstone Belt and extending to the east may be indicative of a previous larger greenstone or mobile belt than currently mapped; and (6) the suggestion of radioelement zonation in arcs mimicking the shape and outline of the Sudbury Structure.

Airborne VLF-EM Data

The dikes of the Sudbury and to a lesser extent Matchewan swarms appear as more continuous features than the current geologic mapping indicates. Features striking north-south in the direction of the flight lines such as the Fecunis and Sandcherry Faults, and most Matchewan dikes are poorly defined in the VLF-EM data set, primarily as a result of flight line direction and spacing. Correlation of VLF-EM anomalies to the Offset dikes of the Sudbury Igneous Complex is also possible. In general, the Levack Gneiss contact with the Cartier Granite does not appear to have a consistent VLF-EM response. Within Levack Township the contact between the lower members of the North Range of the Sudbury Igneous Complex and the contact

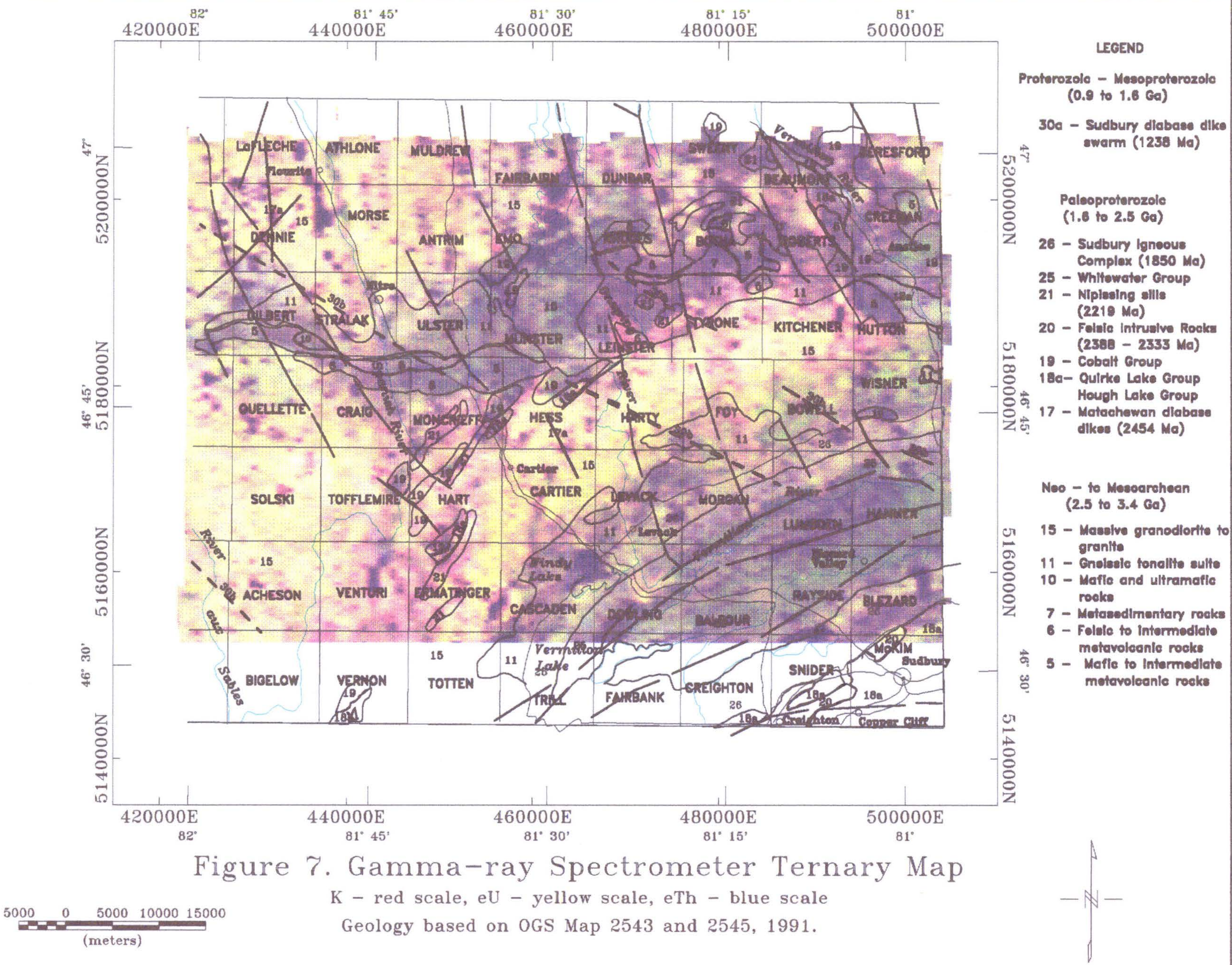


Figure 7. Gamma-ray Spectrometer Ternary Map

K – red scale, eU – yellow scale, eTh – blue scale

Geology based on OGS Map 2543 and 2545, 1991.

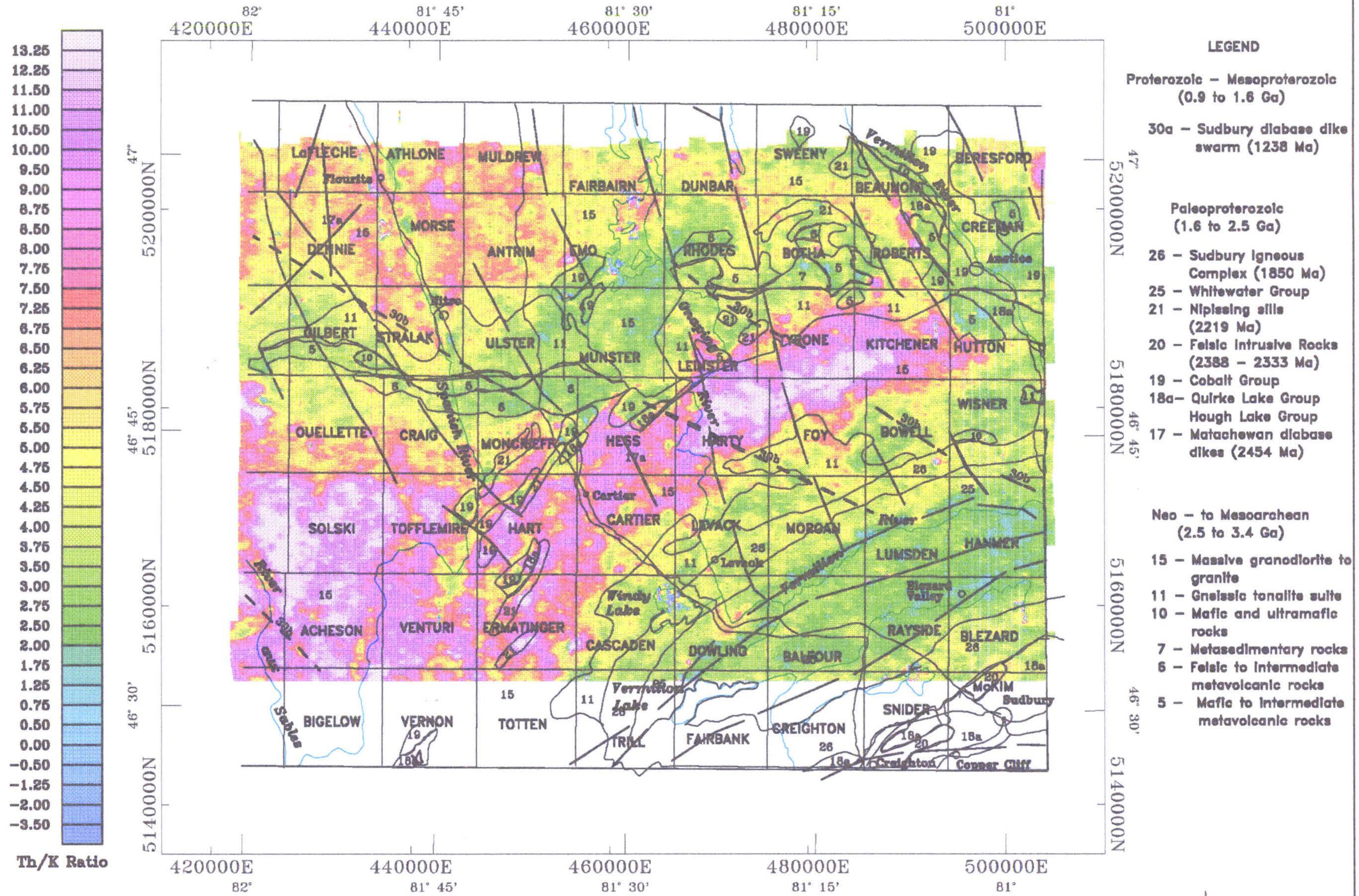


Figure 8. Gamma-ray Spectrometer eTh/K Ratio Map

Levack Gneiss - Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

5000 0 5000 10000 15000

(meters)

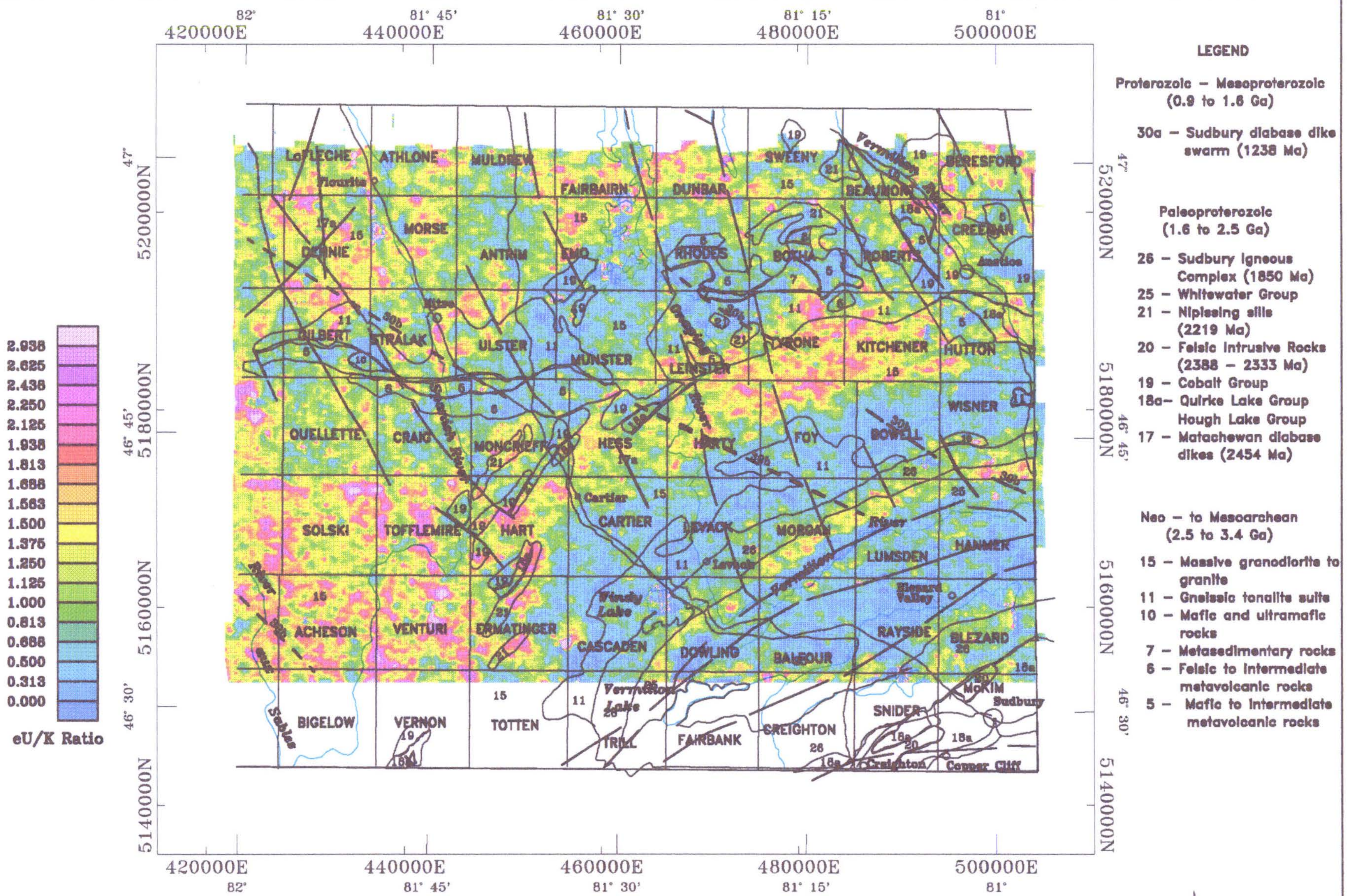


Figure 9. Gamma-ray Spectrometer eU/K Ratio Map

Levack Gneiss - Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

5000 0 5000 10000 15000
(meters)

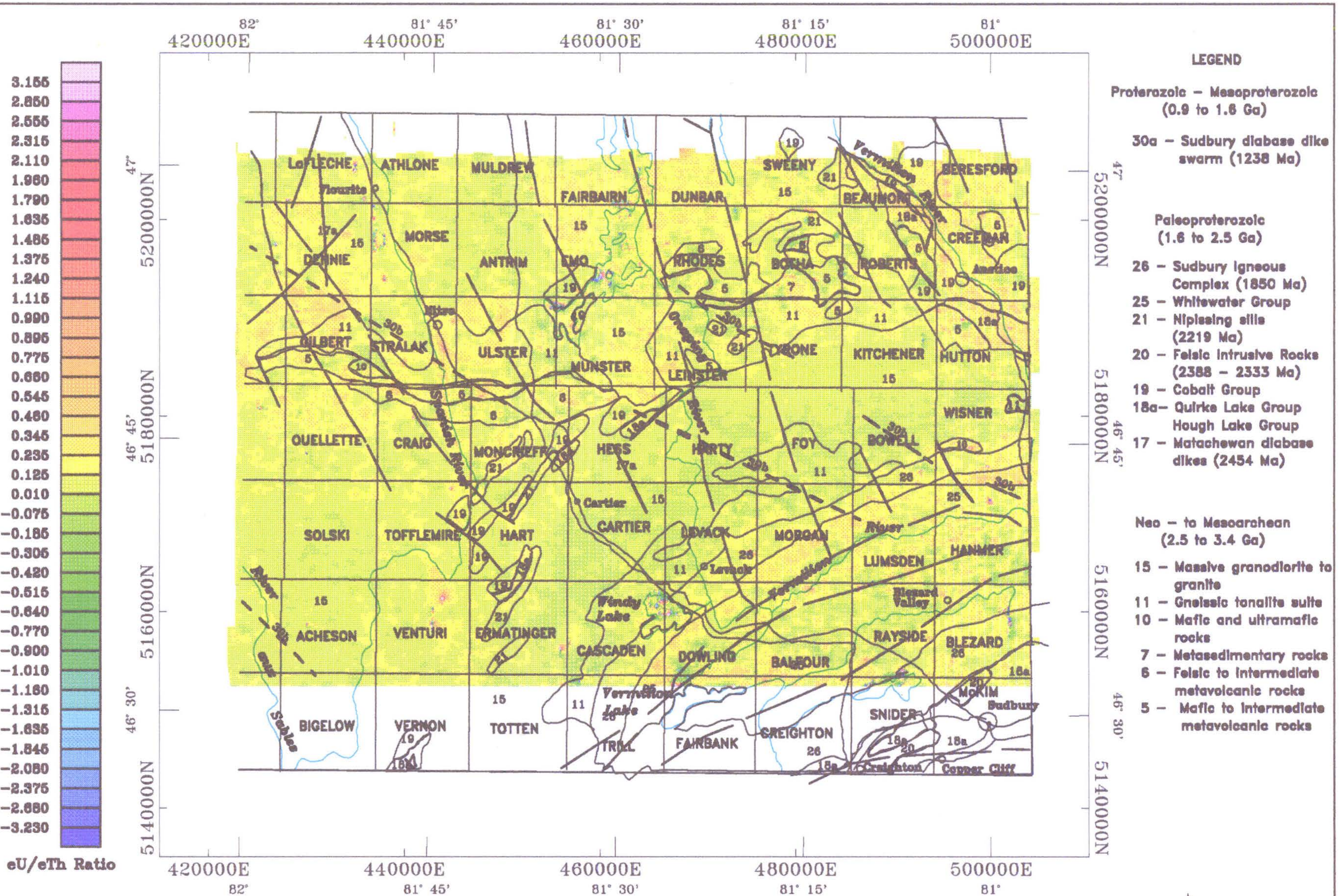


Figure 10. Gamma-ray Spectrometer eU/eTh Ratio Map

Levack Gneiss - Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

5000 0 5000 10000 15000

(meters)

with the Levack Gneiss are coincident with total field VLF-EM highs and quadrature highs (Figures 11 and 12).

The contact between the Cartier Batholith complex and the gneissic tonalite suite in Leinster, Tyrone and Kitchener Townships is coincident with a east northeast - west southwest trending anomaly visible on both the total field and quadrature responses. This feature appears to cross the entire study area subparallel to the North Range of the Sudbury Structure.

3-D Analytic Signal and Euler Deconvolution

Calculation of the magnetic 3-D analytic signal as defined by equation 1a results in a product (Figure 5a.) which compliments the total magnetic field by providing increased resolution in the North Range of the Sudbury Basin and the adjacent Levack Gneiss in addition to defining the dikes comprising the Sudbury and Matachewan dike swarms. Several faults are accentuated. The 3-D analytic signal of the Bouguer gravity is of little use in areas of low gravity observation station density (10 to 15 km spacing between observation locations). Most maxima tend to coincide with the location of the gravity observations suggesting that the gravity field is grossly under sampled compared to the other potential field data sets. Calculating the analytic signal of the Bouguer gravity using equation 1b yielded results that were similar in texture and detail to the magnetic analytic signal of Figure 5b.

For both the gravity and aeromagnetic data sets the number of solutions increased as the structural index was increased from SI = 0 through to SI = 3. As predicted by Reid et al. (1990)

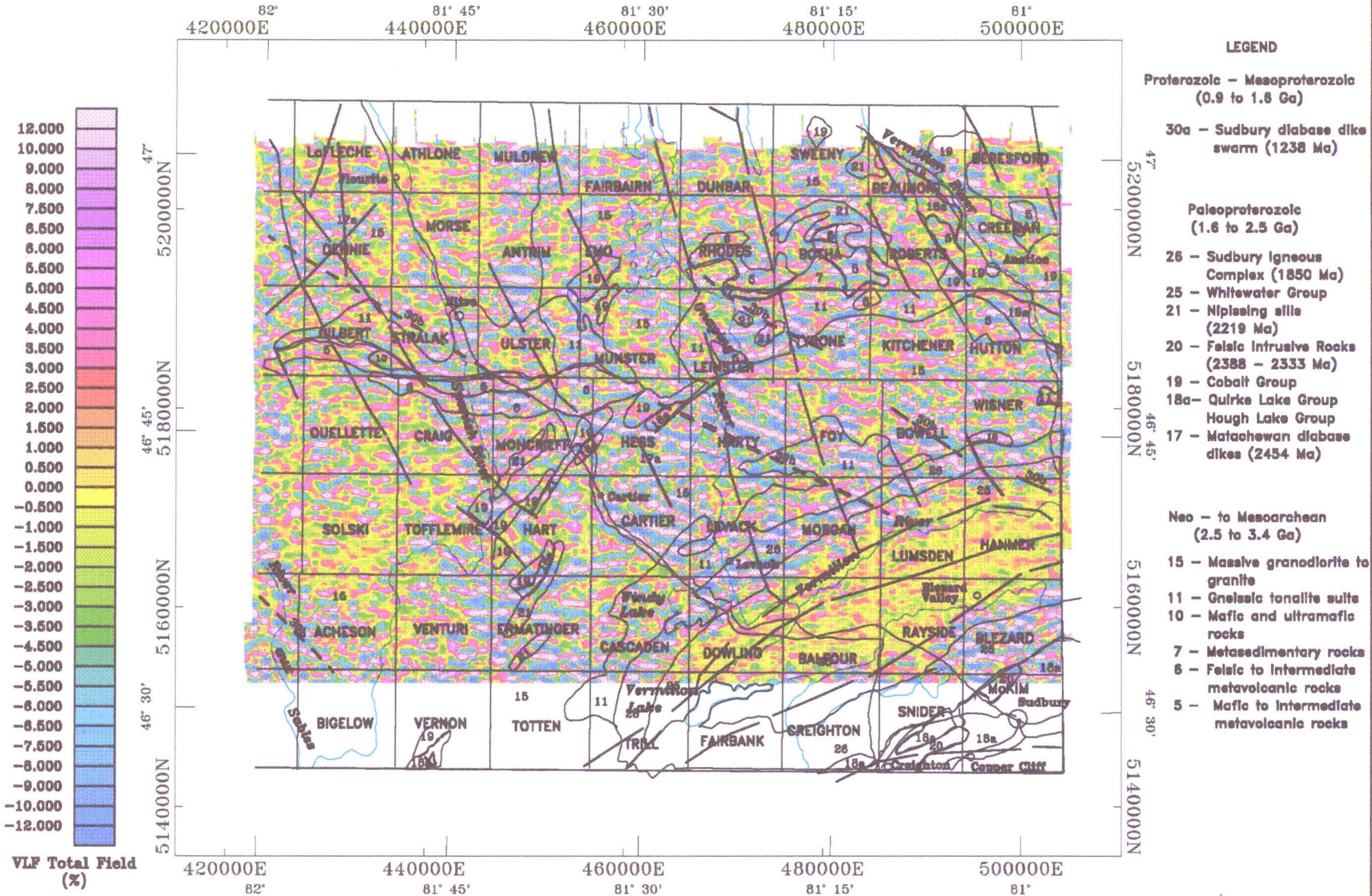


Figure 11. VLF–EM Total Field Map.

Levack Gneiss – Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

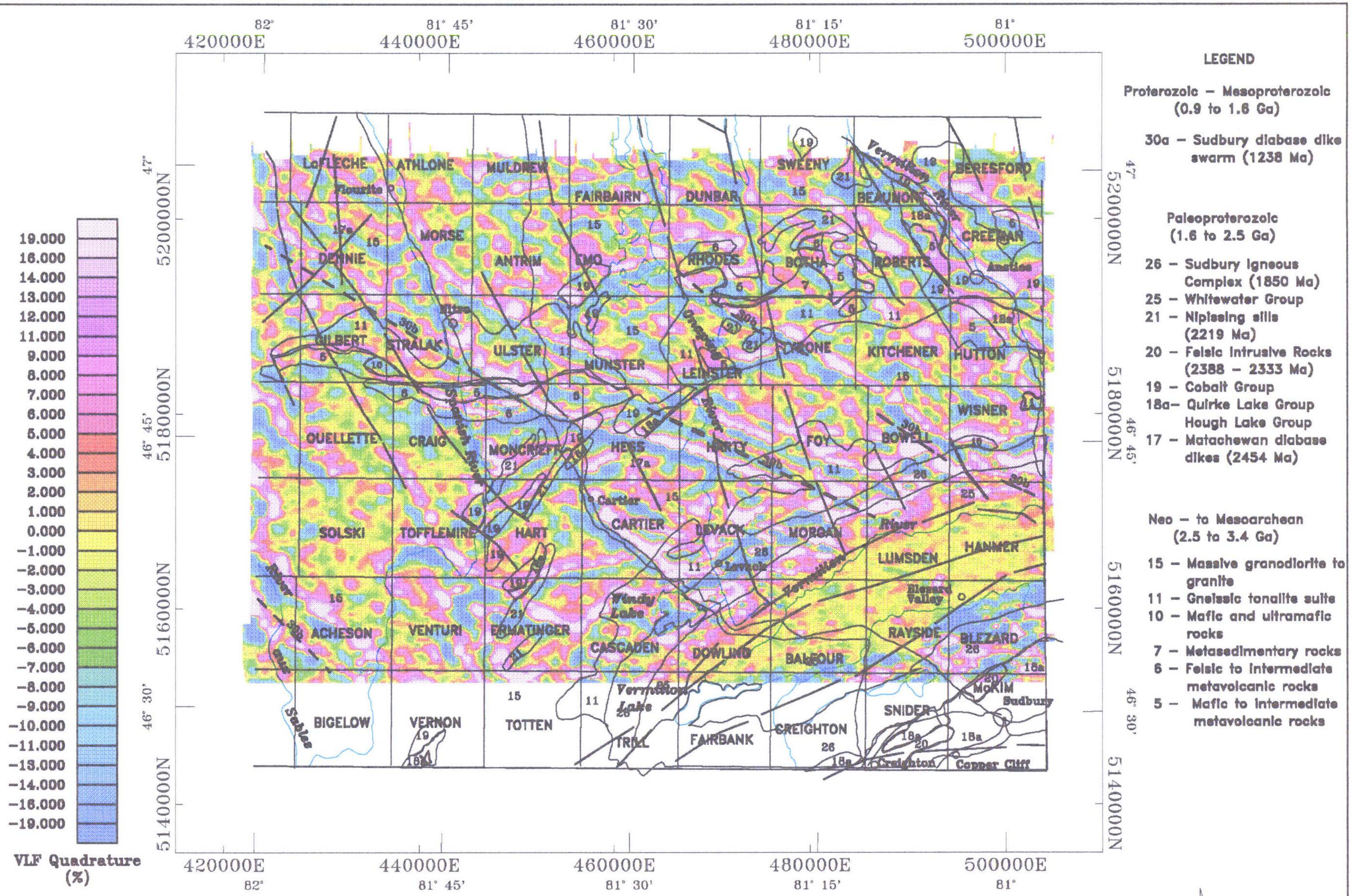


Figure 12. VLF–EM Quadrature Component Map.

Levack Gneiss – Cartier Granite Batholith Complex

Geology based on OGS Map 2543 and 2545, 1991.

and Paterson et al. (1991), when the SI used was 0 or 0.5, the solutions tended to be scattered. At higher values for SI (SI = 2 or 3), the number of solutions increased dramatically, resulting in a distinct lack of focus in the location and depth of the solutions. For both the gravity and aeromagnetic data sets a SI of 1 provided an acceptable compromise between the number of solutions, and focused versus unfocused solutions.

Both analytic signal and Euler deconvolution are highly successful methods for locating igneous intrusive features such as the Spanish River Carbonatite Complex (Venturi Township), Sudbury and Matachewan family dikes, and possible zones of hydrothermal activity within the Cartier Granite and neighbouring migmatites (Figure 3, 5a, 5b, and 6).

Conclusions

Through the analysis of the available geophysical datasets it is possible to define a signature for the major rock types and zones within the Levack Gneiss - Cartier Batholith Complex as indicated in Figure 13 and Table 2. The Cartier Granite can be subdivided geophysically into three fault separated plutons forming an arc from west to east around the Sudbury Structure; the Birch Lake Granite, the Cartier Granite and the Venetian Lake Granite. The Sudbury swarm dikes and faults of the Onaping Set restrict the three granite plutons in east-west extent. The northern extent of the Cartier and related granite batholiths is restricted by an arcuate geophysical feature that appears to mimic the North Range of the Sudbury Structure. This feature may correlate to the more northerly shear zone mapped by Fueten et al. (1993).

It is strongly suggested that on the basis of the spectrometer, gravity, aeromagnetic, and recently completed geologic mapping that the boundary of the Levack Gneiss and Cartier Granite is in fact several kilometres further north than indicated on current geological maps, but only in the vicinity of Highway 144 in Cartier Township. The shear zone mapped by Fueten et al. (1993) in this area may be related to an observed east-west trending VLF-EM anomaly. In other areas the geological and geophysical contacts appear to be coincident within the resolution of the data sets.

Major structural trends possibly related to the origin of the Sudbury Structure have been identified. These consist primarily of the arcuate ring structures mimicking the North Range of the Sudbury Structure and visible in the spectrometry, VLF-EM, analytic signal and Euler deconvolution products of the gravity and aeromagnetic data. Dressler (1984a) has hypothesised that these ring like features represent an artefact of the meteorite impact that purportedly created the Sudbury Structure (Lowman, 1991, 1992; Grieve, 1991). However it is important to note that the these ring structures not only appear to mimic the North Range of the Sudbury Structure, but also the Grenville Front contact to the south of the Sudbury Basin. This raises the question as to whether the structures (1) predate the development of the Sudbury Structure and acted as a plane of weakness along which the North Range of the Sudbury Structure was emplaced; (2) are related to the possible meteorite impact thought to have been the catalyst for the development of the Sudbury Structure, or (3) are related to the overthrusting which occurred during the Grenville Orogeny and subsequent events responsible for the current location of the Grenville Front. This problem can be addressed by examining dikes crossing the Cartier Granite. Dikes of the Sudbury and Matachewan swarms as identified from the current data sets appear to cut these arcuate structures with no appreciable offset. The implication of this is that if the Matachewan dikes are not offset by the arcuate features, then the arcuate zones must be Archean in age suggesting a pre Sudbury event origin. This can be tested by conducting a paleomagnetic contact test. Thermobarometry studies completed by James et al. (1992) provide support for both a tectonic and meteorite induced uplift for the Levack Gneiss, tectonism occurring at pre Huronian Supergroup time (> 2150 Ma), uplift post-dating the 1850 Ma Sudbury Event. The tectonism necessary would then be similar to a Kapuskasing type event (Percival and Card, 1985; and James et al, 1992); however, if the arcuate structures are real and tectonically related to the Grenville the age would be approximately 900 Ma. The current density of sample points for the regional data used in this study does not permit the resolution of this question.

Acknowledgements

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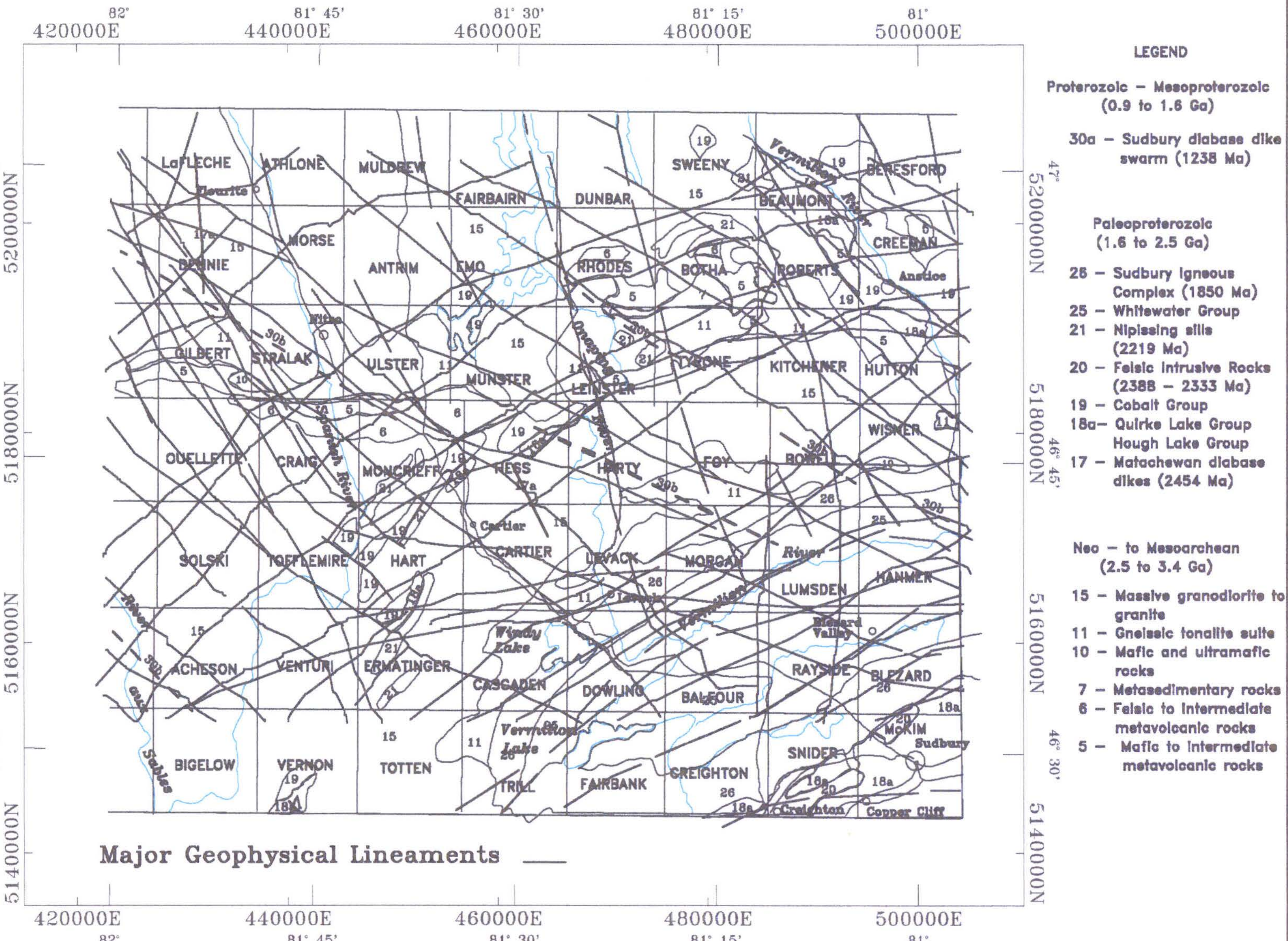

Figure 13: Geophysical Interpretation

Table 2. Summary of geophysical signatures of geologic units.

Geologic Unit Late PreCambrian	**Magnetic Signature**	**Gravity Signature**	**Gamma-Ray Spectrometer Signature**	**VLF-EM Signature**
Alkalic Rock - Carbonatite Complexes, Spanish River Carbonatite Complex	Magnetic "Bull's Eye" of high amplitude in Venturi Twp.	Indication of local gravity high, however based on 1 point. Data is under sampled.	Apparent depletion in all elements. Th>K>U. Virtually no U signature at all.	TF and Quad "Bulls Eye" anomaly.
Geologic Unit Proterozoic-Mesoproterozoic (0.9 - 1.6 Ga)	**Magnetic Signature**	**Gravity Signature**	**Gamma-Ray Spectrometer Signature**	**VLF-EM Signature**
Sudbury Swarm diabase dikes (1238 Ma)	Northwest striking narrow linear magnetic anomalies. Normally polarised of moderate amplitude (100+ nT), appear as negative linear anomalies where they cross the North Range of the SIC	Gravity data is under-sampled to allow for a definite correlation; some indication in Harty Twp. that there may be a positive 2 mgal. anomaly associated with these dikes.	No discernible signature.	Very strong (38%+) linear Quad. response coincident with these dikes and possibly the Onaping Fault family. TF response is also strong, but less obvious.
Geologic Unit Paleo-Proterozoic (1.6 - 2.5 Ga)	**Magnetic Signature**	**Gravity Signature**	**Gamma-Ray Spectrometer Signature**	**VLF-EM Signature**
Sudbury Igneous Complex (SIC), Sublayer/Offset	Very thin, moderate amplitude (100nT), usually not discernible except in Foy Twp.	No discernible signature due to insufficient observations.	Possible Th enriched anomaly associated with Foy Twp. Offset dike. Very low U, low K. TH>>K>U.	Moderate TF and Quad. anomalies (12%) apparently coincident in Foy Twp. Some indication that the TF anomaly may be negative

Geologic Unit Paleo-Proterozoic (1.6 - 2.5 Ga)	**Magnetic Signature**	**Gravity Signature**	**Gamma-Ray Spectrometer Signature**	**VLF-EM Signature**
Sudbury Igneous Complex, Upper Zone Granophyre	Non-magnetic	Moderate 1-2 mgal. anomaly along North Range except in vicinity of the Venetian Lake Granite Pluton, where signature is masked. South Range is moderate to 3 mgal. anomaly.	Th depletion. K>U>Th. Not possible to separate from the Onaping Fm. of the Whitewater Gp.	Weak TF and Quad. anomalies along contact with Onaping Fm. Northwest and east striking features most likely related Sudbury dikes and Onaping family faults.
Sudbury Igneous Complex, Middle Zone Quartz Gabbro and Lower Zone Norite	Quartz Gabbro appears to be non-magnetic. Norite is very magnetic (up to 3000nT+ anomalies) and magnetically homogeneous.	South Range component is a gravity low in Blezard Twp. North Range is a gravity high, largest high within the SIC.	Indiscernible from the Upper Zone Granophyre above.	Indiscernible from the Upper Zone Granophyre above.
Whitewater Gp. Chelmsford and Onwatin Fms.	No discernible magnetics, Masked by underlying rock units.	No discernible gravity, masked by under lying units.	Generally depleted in all elements, high K wrt U and Th, U > Th.	Apparent weak TF (5%) and Quad. (5%) anomalies coincident with Chelmsford Fm. and Onwatin Fm. contact. Stronger anomalies along contact with Onaping Fm.

Geologic Unit Paleo-Proterozoic (1.6 - 2.5 Ga)	**Magnetic Signature**	**Gravity Signature**	**Gamma-Ray Spectrometer Signature**	**VLF-EM Signature**
Whitewater Gp. Onaping Fm.	Moderately magnetic (100nT) along contact with North Range SIC. Strongly magnetic (300nT) along contact with the South Range SIC, possibly related to faulting and mineralization along the Fairbank Lake Fault family.	Moderate gravity anomaly (3 mgals) near South Range contact. No discernible anomaly along North Range.	Th depletion with K>U>Th. K enriched along contact with Onwatin Fm.	Strong conductors indicated as the contact with the SIC is approached. Anomalies associated with the South Range are stronger than the those associated with the North Range (dynamic range > 20%).
Nipissing Sills and Dikes. Gabbro, Diabase and/or Granophyre (2219 Ma)	Mostly non-magnetic to slightly magnetic with the exception of one sill in eastern Hart and Moncrieff Twps. which is strongly magnetic (1000nT).	No discernible signature due to under sampling of the gravity field.	Generally depleted in K, locally in U, relatively Th enriched. Th>U>K.	Generally associated with arcuate features mimicking the Sudbury Structure.
Murray Granite (2388 Ma.) (Partially within Study Area)	Strong magnetic low response heavily influenced by adjacent South Range Norite.	No discernible signature due to insufficient observations.	Enriched in all three elements. Relative concentrations are Th>U=K.	No discernible signature.
Huronian Supergroup (2.2Ga-2250Ma) Cobalt Gp. Lorraine Fm.	Non-magnetic	No discernible signature due insufficient observations.	General and equal depletion of all elements.	No discernible signature.

Geologic Unit Paleo-Proterozoic (1.6 - 2.5 Ga)	Magnetic Signature	Gravity Signature	Gamma-Ray Spectrometer Signature	VLF-EM Signature
Huronian Supergroup (2.2Ga-2450Ma) Cobalt Gp. Gowganda Fm.	Moderate magnetic anomaly in Twps. to the west of the Onaping River. Extremely magnetic (2000 nT+) in northeastern Twps straddling the Vermilion River.	No discernible anomaly, however there is the possibility of a residual anomaly.	Lack of all elements in units to the east of the Onaping River. Units to the west of the Onaping appear to be slightly Th enriched wrt the other elements.	Generally strong positive Quad. anomaly. TF anomalies cross cut the fm. in all instances.
Huronian Supergroup (2.2Ga-2450Ma) Quirke Lake Gp, Hough Lake Gp, and Elliot Lake Gp.	Non magnetic, generally occupying mag lows with exception of the Serpent Fm, Quirke Lake Gp. in Hutton Twp. where it appears to be very magnetic, however response is probably that of the underlying Gowganda Fm., dipping south?	No discernible signature.	Generally enriched in U wrt to the other elements. U>Th>K.	Generally conductive along the contact with older Archean mafic massive and pillowed lava flows as in Hutton Twp.
Matachewan Diabase Dikes (2454 Ma)	Moderate 100 to 200 nT thin linear anomalies striking north-northwest usually following faults.	No discernible signature.	No discernible signature.	Not in optimal direction for coupling with the VLF-EM transmitter signals. Possible unrecognised dikes in Tofflemire, Craig, Gilbert Ouellette, and Twps. are very conductive and well defined.
Geologic Unit Neo- to Mesoarchean (2.5 - 2.9 Ga)	**Magnetic Signature**	**Gravity Signature**	**Gamma-Ray Spectrometer Signature**	**VLF-EM Signature**

Geologic Unit Neo- to Mesoarchean (2.5 - 2.9 Ga)	Magnetic Signature	Gravity Signature	Gamma-Ray Spectrometer Signature	VLF-EM Signature
Massive Granite to Granodiorite Includes the Cartier Granite, Birch Lake Granite, and the Venetian Lake Granite.	Cartier, Birch Lake and Venetian Lake Granites are magnetically low. Granite and migmatite to the north of Benny Greenstone Belt and to the west of the Spanish River is strongly magnetic.	All granite terrain with the exception of north of the Benny Greenstone Belt are gravity lows.	Th enrichment in all granite terranes, some K depletion in the granites north of the Benny Greenstone Belt and in Venturi Twp.	Arcuate features cut through the granites as do anomalies related to dike swarms and the Onaping family of faults.
Gneissic Tonalite Suite (Levack Gneiss)	Magnetically extremely active along contact with SIC, gradient dropping off towards contact with adjacent granites.	Coincident with a steep gravity gradient of over 2 mgal/km decreasing towards the Cartier and associated granites.	General depletion in all elements. U>Th>K .	Levack Gneiss in Foy Twp. is arcuate east-west in form for both TF and Quad.
Foliated Tonalite Suite	No discernible mag. anomaly	No discernible gravity anomaly	Slight enrichment in U and Th, depletion in K. U>Th>K.	Coincident TF and Quad anomaly.
Mafic and Ultramafic Rocks	Contact with SIC is extremely magnetic in Wisner Twp. Occurrence in Gilbert and Stralak Twps is not magnetic.	Possible gravity high associated with Gilbert and Stralak Twps. body; residual anomaly in Wisner Twp.	Strong depletion in all elements.	Positive Quad and TF anomaly in Wisner Twp. Anomaly in Gilbert and Stralak Twps. is associated with TF and Quad. low.
Metasedimentary Rocks	No discernible mag. anomaly	No discernible gravity anomaly	Depletion in all elements	No discernible signature.

Geologic Unit Neo- to Mesoarchean (2.5 - 2.9 Ga)	Magnetic Signature	Gravity Signature	Gamma-Ray Spectrometer Signature	VLF-EM Signature
Felsic to Intermediate Metasedimentary Rocks (Geneva Lake Metasedimentary rocks)	Speckled magnetic high and low signature.	Peak gravity response of the entire Benny Greenstone Belt is centred on the Geneva Lake Fm.	Depletion in all elements. Extremely devoid of U. Th>K>U	Contacts with adjacent units are indicated by Quad and TF anomalies.
Mafic to Ultramafic Metavolcanic rocks	Consistent with magnetic lows. Contact with Gneissic tonalites along the Benny Greenstone Belt.	Usually associated with gradients in gravity lows (regional lows) except in Tyrone Twp. where coincident with a residual gravity high.	Generally depleted in all elements with apparent zonation, U depleted in central areas of unit, K and Th depletion along edges.	Conductor indicated within the unit along the contact with the Gneissic Tonalite Suite on the Benny Greenstone trend.

Chapter 5: Regional Gravity Setting of the Sudbury Structure

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Introduction

The Sudbury Structure is located near the junction of three major geological and structural provinces of the Canadian Shield in north central Ontario, Canada. The gneissic and granitic terrain of the Superior Province bounds the Sudbury Structure to the north and west; the south and east extent is bounded by the rocks of the Huronian Supergroup and the Nipissing Gabbro of the Southern Province. The Grenville Front, marking the edge of the Grenville Province mafic and felsic intrusives closes to within 10 km of the south east corner of the Sudbury Structure.

A large arcuate regional gravity high extending for 350 km from west of Elliot Lake, Ontario to east of Englehart, Ontario, broadly correlates to the contact between the Southern and

Superior Provinces. The Sudbury Structure comprises an elliptical 60 km long by 27 km wide positive Bouguer gravity anomaly that is situated astride the broad regional anomaly. The close proximity of the northern margin of the Sudbury Structure to the northern flank of the regional anomaly produces a situation where it is difficult to extract a meaningful regional gravity surface to provide a residual gravity anomaly that is solely related to the Sudbury Structure. A direct consequence of this problem of non-uniqueness in the regional-residual separation of the gravity field has led to the development of totally different geological models for the deep seated portion of the Sudbury Structure.

Previous attempts at modelling the gravity effect of the Sudbury Structure have focused on the removal of a regional which has been tightly constrained by the gravity field in the immediate vicinity of the Sudbury Structure (Gupta et al, 1984; McGrath and Broome, 1994). This has resulted in the residual gravity fields being heavily biased over the immediately adjacent rocks of the Huronian Supergroup and Levack Gneiss. As will be illustrated, the method used in obtaining the residual gravity of the Sudbury Structure directly impacts on the model(s) required for explaining the residual gravity field.

In their study Gupta et al. (1984) adopted an approach to the regional - residual separation that involved a multiple step (supra-regional, regional, residual) sequence of qualitative and quantitative methodologies. The first step involved the determination of a supra-regional gravity field thought to contain the gravity response from deep crustal and upper mantle sources. This procedure was largely subjective, and the resulting supra-residual or anomalous Bouguer gravity (determined through the subtraction of the supra-regional from the total gravity field) implicitly assumes a uniform upper mantle at depth within the Sudbury region. It was acknowledged by Gupta et al. (1984) that the presence of the Grenville Front and associated rocks to the southwest may not be adequately accommodated by this supra-regional field model. The resulting anomalous Bouguer gravity was then believed to contain only the effects due to density variations within the upper 10 to 15 km of the earth's crust. A series of 9 north-northwest trending profiles were then constructed over anomalous Bouguer gravity field in order to deconvolve the response into shallow and deep residual responses. Again the techniques applied were largely qualitative in nature, involving the smooth fitting of base levels both along the profiles and across the profiles. The derived " "regional" component of anomalous Bouguer gravity" (Gupta et al.; 1984) was then subtracted from the anomalous Bouguer gravity resulting in a residual Bouguer gravity. Quantitative assessment of the validity of this methodology was in part assessed through the downward continuation of the anomalous Bouguer gravity to a depth of 3 km. This resulted in gravity highs over both the North and South Ranges of the Sudbury Structure. The amplitude of the response over the North Range was of higher amplitude than that observed over the South Range, suggesting that the North Range is of shallower origin than the South Range. The result of this highly subjective multi-step regional-residual extraction process was the placement of large, high density bodies at depth (5 to 10 km) beneath the centre of the Sudbury Structure in an effort to adequately model the residual Bouguer gravity. In turn these large high density bodies obtained significance as evidence for a possible "hidden layered series" that could represent the differentiate associated with the higher level Sudbury Intrusive Complex giving support to a magmatic origin for the Sudbury Structure.

The gravity model of McGrath and Broome (1994) handles the regional-residual separation in a different manner. Their solution to the problem of a regional-residual separation was not to attempt one. They chose to constrain the base level for modeling to an arbitrary value with limited range (-41 or -42 milligals). This amounts to the removal of a linear, horizontal surface from the model profile and equating the density of the Levack Gneiss (2.73 gm/cc) as the background density. The implications of this approach are clearly acknowledged by McGrath and Broome (1994) as:

> 1) the calculated gravity anomaly tends to a zero value over model units representing Archean Gneiss and 2) the value of the base level shift required to compare the observed and calculated gravity data is not independent of the selected background density value.

The result of this planar regional is that the deep, high density bodies of Gupta et al. (1984) are no longer required and the gravity model now correlates to the geometric constraints derived from the LITHOPROBE seismic survey across the Sudbury Structure. A major assumption of the McGrath and Broome model is that the Levack Gneiss or similar rock floors the whole of the Sudbury Structure and is of uniform density. The gravity model resulting from this approach to regional-residual separation produces a simple layered structure for the Sudbury Intrusive Complex: a model that is more compatible with meteorite impact origin for the Sudbury Structure.

Both of the above methods result in plausible models for the gravitational field of the Sudbury Structure within the limitations and constraints placed on the model by the methodology used. Geologically, both methods make use of a large database of surface rock and borehole derived density measurements and the current sampling density of the gravity field available in the Sudbury region. On the basis of model fitting to the available gravity and density data it is not possible to differentiate between these two quite different geological interpretations.

In the present study, the problem of what constitutes a reasonable regional - residual model for the greater Sudbury region and the implications of each method on the interpretation of the Sudbury Structure are examined. The methods examined for regional - residual derivation include (a) downward continuation operators; (b) upward continuation operators; (c) wavelength filtering based on spectral analysis; and (d) trend surface removal.

Bouguer Gravity Data

Gravity observation data over the area bounded by 80°30' W to 82°30' W and 46°15' N to 47°15' N were obtained from the National Geophysical Data Centre, Geological Survey of Canada and the Ontario Geological Survey. The data has been referenced to the International Gravity Standardisation Net 1971 (ISGN71) and the Geodetic Reference System 1967 (GRS67). The Bouguer anomaly values were calculated utilising a vertical gradient of 0.3086 mGal/m and a crustal density of 2.67 gm/cc.

As illustrated by Figure 1, the spatial density of the gravity observations varies considerably throughout the study area. The frequency of gravity observations effectively limits the usefulness and resolving power of a gravity survey. If the observation points are spread over a large area (1 observation per several kilometres) then shallow bodies of limited size (< several kilometres) will not be adequately resolved and the possibility of significant bias arising from a single erroneous observation or a local high increases. Gravity observation density within the study is highly variable, ranging from 100 m intervals along short sections of road traverse within parts of the Sudbury Basin to a density of 1 observation for every 10 to 15 km to the north and west of the Sudbury Basin. A total of 3366 observation points were gridded using the minimum curvature algorithm of Briggs (1974) to a grid cell interval of 250 m. The grid cell size of 250 m is a compromise between the areas of high and low observation density and produces a detailed Bouguer anomaly gridded data set exhibiting minimal signal aliasing.

Prominent features visible on the Bouguer anomaly map (Figure 1) include (a) the arcuate gravity high extending from 82°30'W, 46°30'N to 80°30'W, 47°10'N; (b) The Grenville front and associated rocks in the southeast corner; (c) the ellipsoidal Sudbury Structure extending from 81°30'W, 46°30"N to 80°50'W, 46°40'N; (d) the Benny Greenstone Belt striking east-west and centred on 81°38'W, 46°50'N; (e) a large pronounced gravity low associated with the Levack Gneiss and the Cartier Granite Complex and (f) a gravity high at 81°38'W, 47°10'N falling within gneissic terrain.

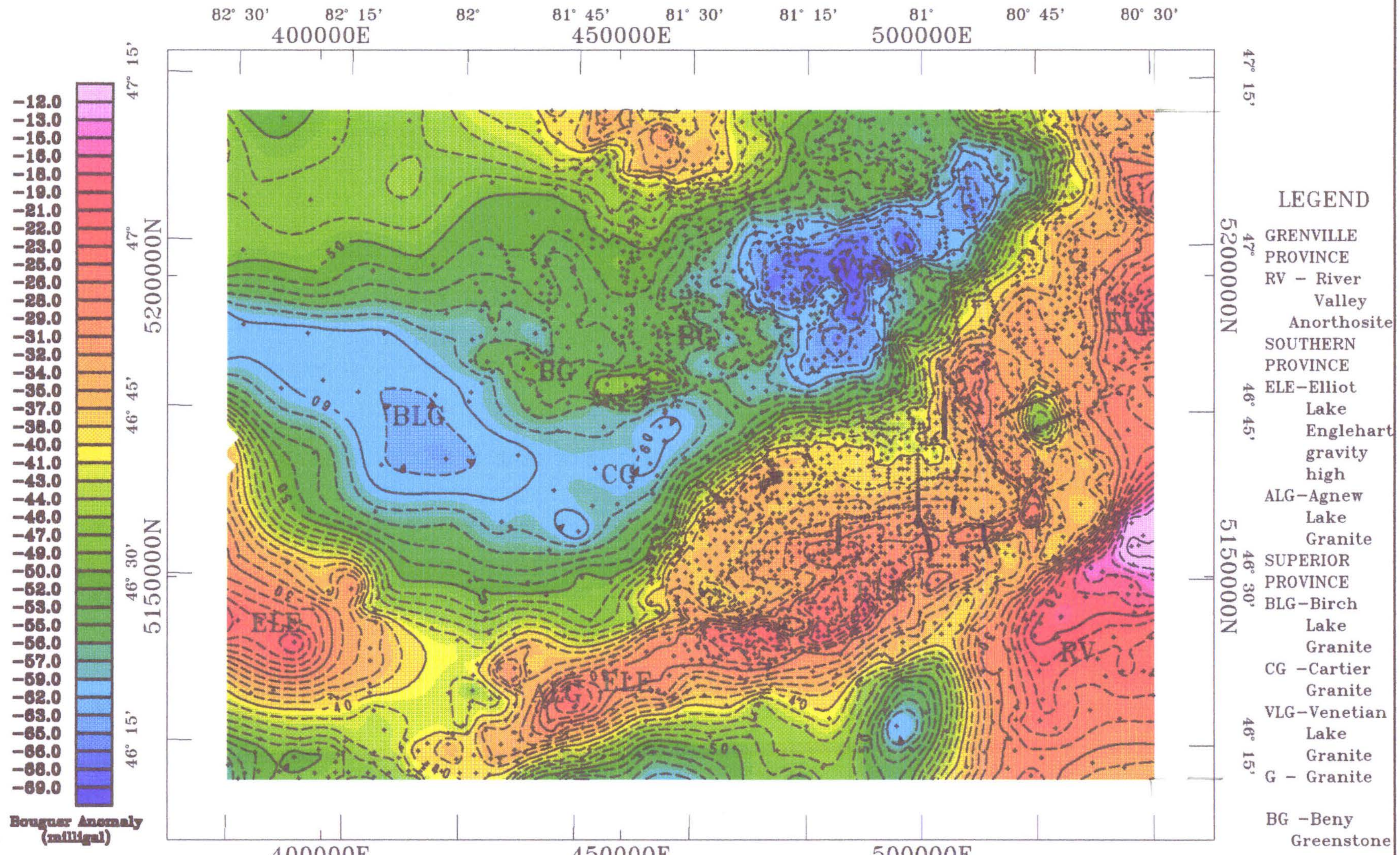
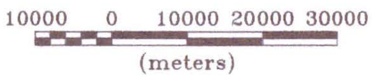


Figure 1: Bouguer Gravity Anomaly Map

Elliot Lake – Englehart Regional Gravity Field

with gravity observation locations



Extraction of Regional - Residual

The methods examined herein for the determination of the regional and residual components of the Sudbury Structure and surrounding area are quantitative. The purpose is to examine and evaluate each method with respect to usefulness and geologic implications of the data produced. The methods examined include upward and downward continuations, wavelength filtering, trend surface removal, and derivative methods.

Downward Continuation

In almost all circumstances the causative body responsible for a gravity anomaly lies below the plain of observation of the gravity field. In such cases it is beneficial to calculate the gravity field that would be observed if the plane of observation were closer to the upper surface of the causative body. The result of this process, known as downward continuation, is to produce a map where the anomaly being investigated becomes sharper, less confused, and of higher amplitude when the upper surface of the causative body is approached. Limitations of the method are that (a) if the plane of calculation is below the top of the causative body, high frequency noise, referred to as "ringing", is produced by the calculation and (b) minor noise present in the original observed gravity field is amplified in the downward continued field and may mask or partially obscure signals of interest. It is therefore important that (a) the initial observed gravity field be as smooth as possible whilst honouring the measured gravity values and devoid of gridding artifacts; and (b) that an optimum Weiner filter is applied in conjunction with the downward continuation operator in order to minimize or eliminate altogether the effects of continuing down through a shallow source body. The downward continuation process can be used to determine, as a first approximation, the effective depth of a causative body.

In the approach of Gupta and Grant (1984), the downward continuation process was applied to the anomalous Bouguer gravity to a depth of 3 km leading to the conclusion that the North Range of the Sudbury Structure has a gravitational source at a shallower depth then the South Range. In the current study, the downward continuation process has been applied to the observed Bouguer gravity over discrete steps of 1, 2, 3, 4, 5, 7.5, and 10 km below the plain of observation (Figure 2).

Examination of the 1 km and 2 km downward continued maps (Figure 2 (a) and (b)) in comparison with the Bougeur anomaly map (Figure 1) strongly suggests that the majority of the high frequency anomalies originate from within the 3 km of the surface. At a continuation depth of 3 km (Figure 2(c)), the North Range of the Sudbury Structure coalesces into a single arcuate anomaly, the South Range is absorbed into the arcuate east - west gravity structure and a structure within the centre of the Sudbury Structure coincident with the surface expression of the Vermilion Lake Fault appears. The Wanapitei Structure, River Valley Anorthosite Complex, and the Benny Greenstone Belt appear as distinctive sharp anomalies until a depth of 5 km. Continuation below 5 km results in diffuse long wavelength anomalies (Figures 2 (e), (f) and (g)) and the disappearance of the Wanapitei and arcuate North Range anomaly. The Cartier Granite Complex associated anomalies appear to exhibit a shallow (4 km) and deep (10 km) sharpening up of shape suggestive of a complex density distribution with depth.

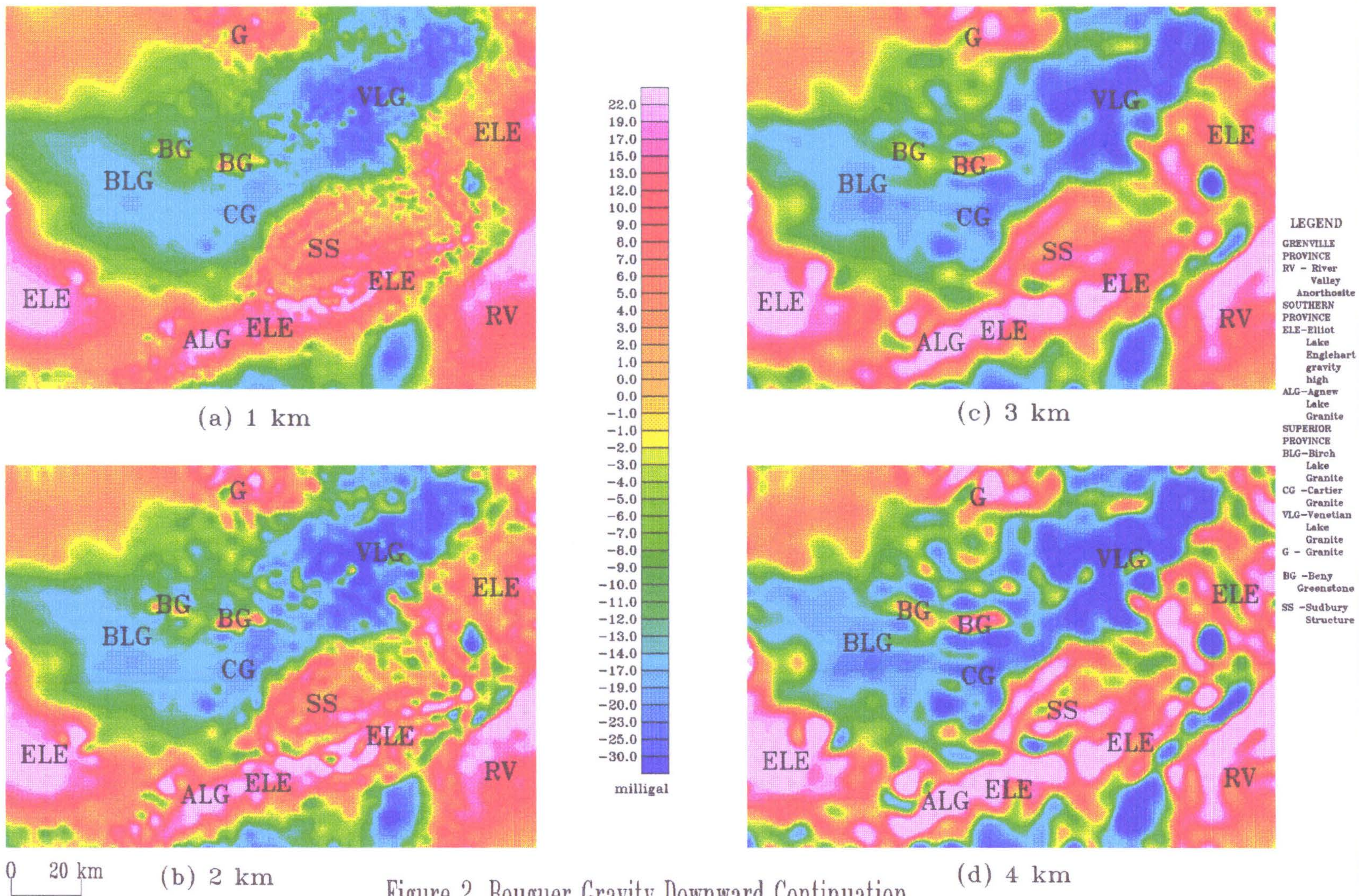


Figure 2. Bouguer Gravity Downward Continuation

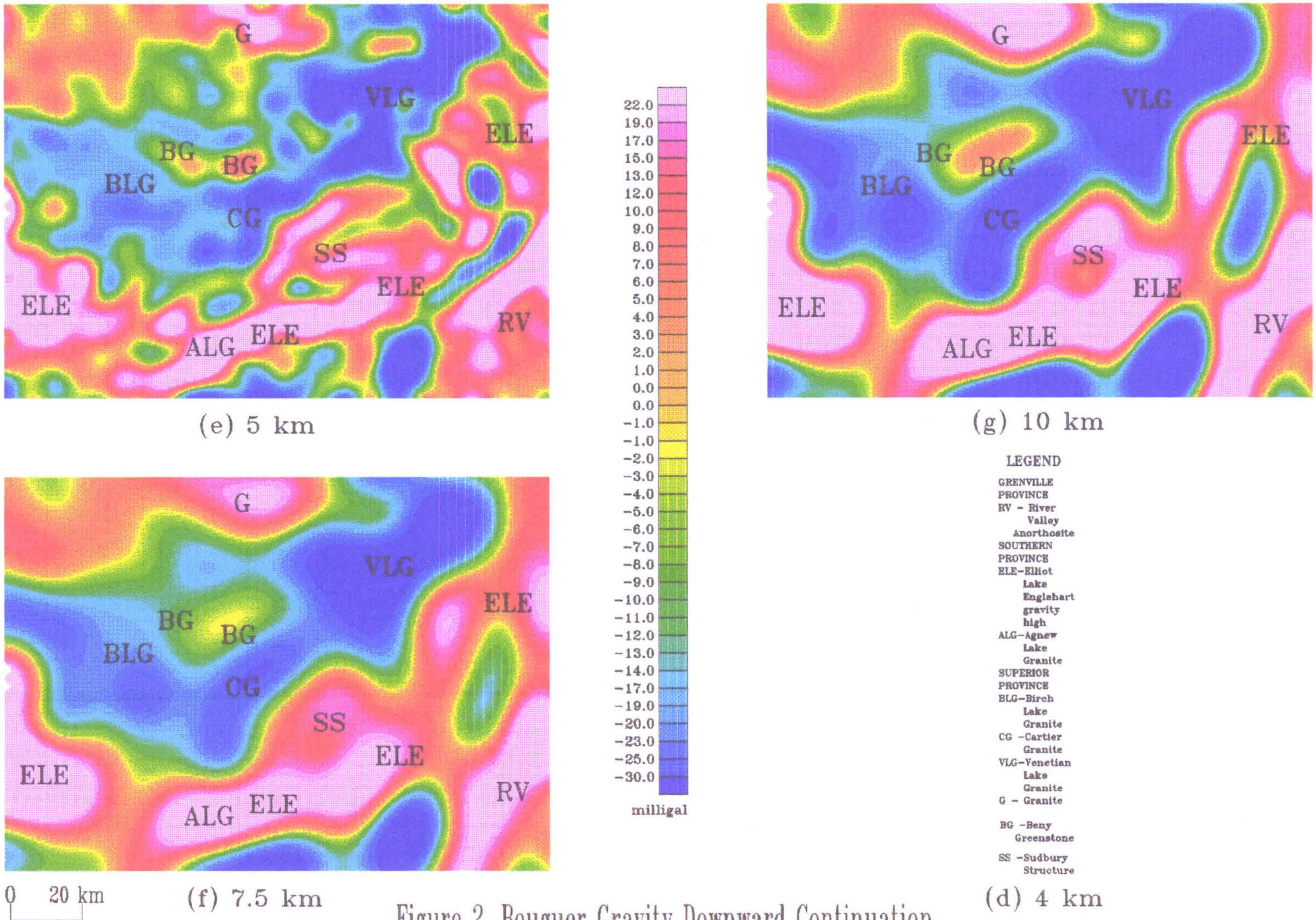


Figure 2. Bouguer Gravity Downward Continuation

Upward Continuation:

When the gravity field is calculated at a surface above the plain of observation, the process is referred to as upward continuation. The effect of the upward continuation process is to effectively remove the contribution of high frequency near surface, shallow causative bodies from the gravity field, resulting in a smooth surface reflecting the deeper causative bodies and or density structures. The effect of the process on individual anomalies is that as the plane of observation increases in distance from the causative source, the anomaly decreases in amplitude proportional to 1/r where r is the distance between the plane of observation and the causative body, and the anomaly becomes broader and more diffuse. A limitation of the method is that closely spaced high frequency anomalies, when upward continued, may merge together to form a single broad low amplitude response not dissimilar to the response from a larger single body. A benefit of the process is that any noise present in the original observed gravity field is minimized as the continuation height is increased. An approximation of depth to the causative can be obtained through the application of the "half width" method of depth estimation (Telford et al, 1990). Deep seated bodies, after upward continuation of the gravity field through several discrete levels, will provide similar depth below surface estimates.

In this study, the upward continuation process was applied to the observed Bouguer anomaly over the range of 2.5 km to 75 km in increments of 2.5 km between calculated surfaces. Selected results of this process are illustrated by Figure 3 . At the first continuation level of 2.5 km, the North Range of the Sudbury Structure is no longer distinct as a separate anomaly, but is merged into a broader, longer wavelength feature forming the central portion of the accurate gravity high extending across the study area. The South Range is indistinguishable from the arcuate high. The Cartier Granite Complex to the north of the Sudbury Structure is visible as chain of three large gravity lows. The Wanapitei, Benny Greenstone Belt, and River Valley Anorthosite anomalies are still visible as discrete positive anomalies. As we progress through to an upward continuation level of 15 km, the Sudbury Structure is effectively absent as a discrete anomaly by 7.5 km; the Wanapitei and Benny Greenstone Belt anomalies are absent by 12.5 km and 15 km respectively; and the Cartier Granite has become a single, large gravity low by 15 km. At 20 km, the arcuate high is beginning to separate into discrete east and west lobes, by 40 km this separation is complete and the map is dominated by the Cartier Granite Complex low. There is no appreciable change in the upward continued gravity after 40 km.

Wavelength Filtering

The derivation of the regional and residual components of gravity field through wavelength filtering is accomplished through time series analysis. For an in depth discussion of the fundamentals of time series analysis the reader is directed to one of the many excellent texts Bouguer gravity field to obtain the residual Bouguer gravity field. The advantage of calculating the regional-residual separation in this manner is that aliasing and noise related to high pass filters is not present in the short awvelength residual data.

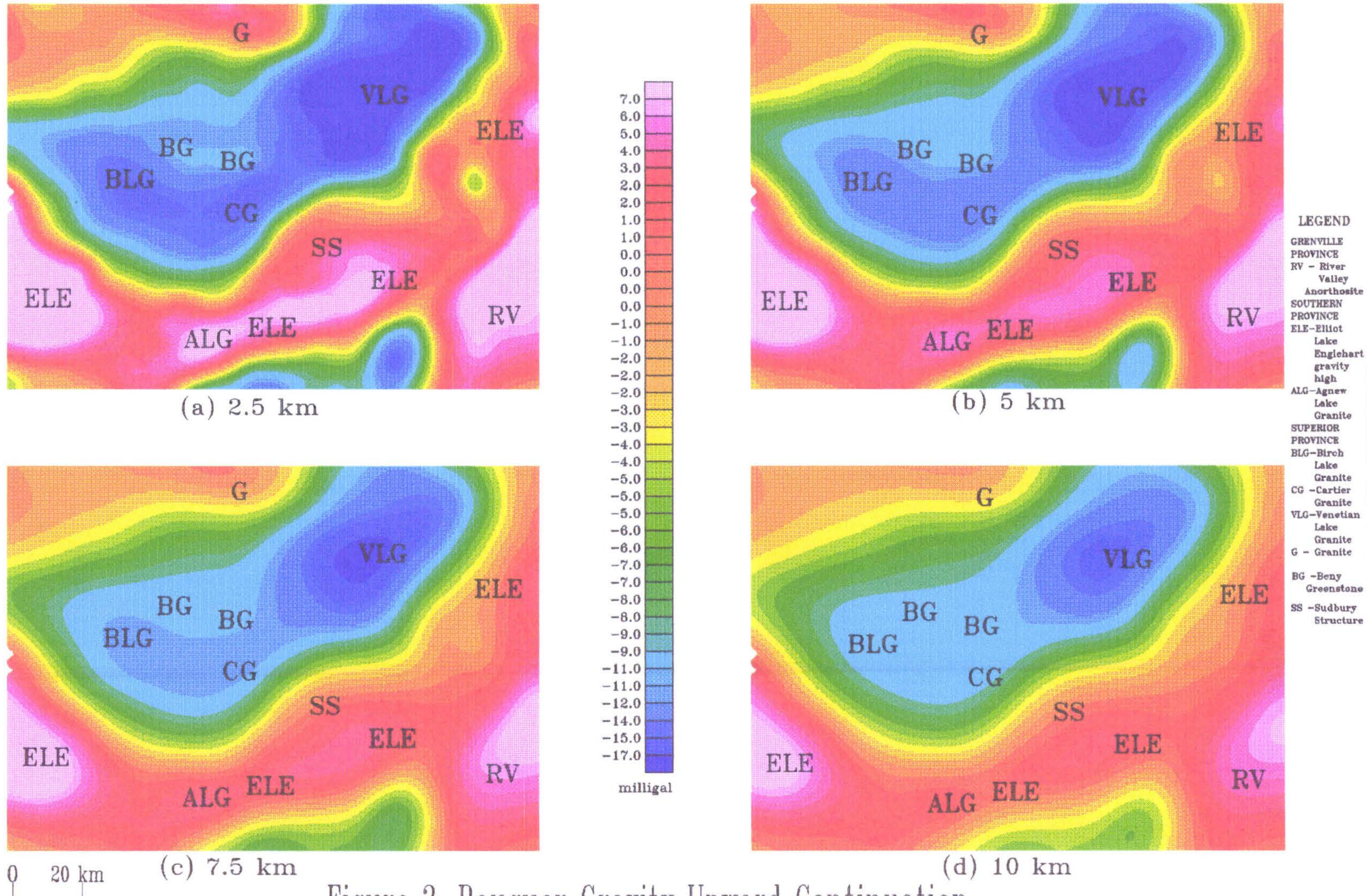


Figure 3. Bouguer Gravity Upward Continuation

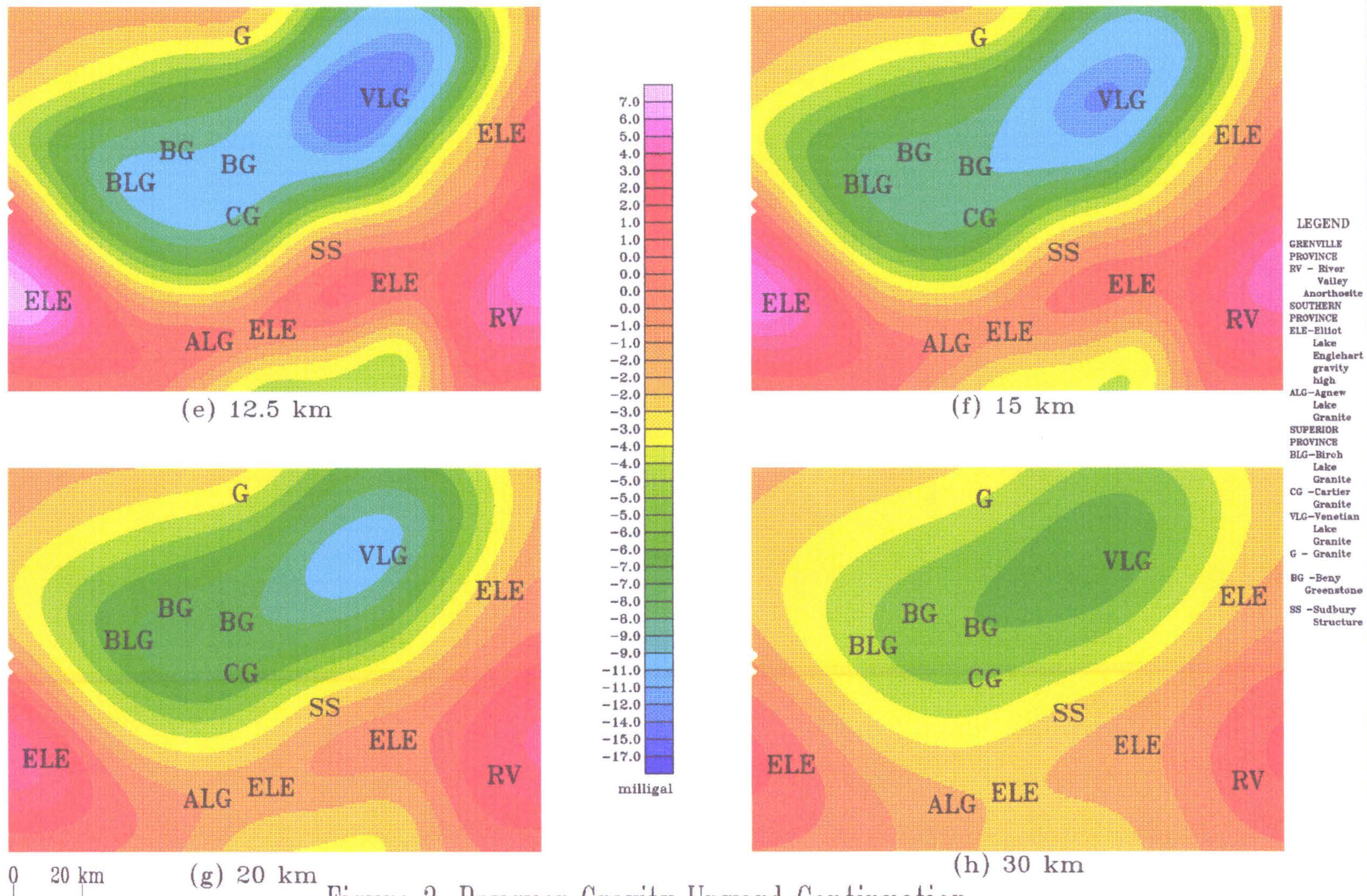


Figure 3. Bouguer Gravity Upward Continuation

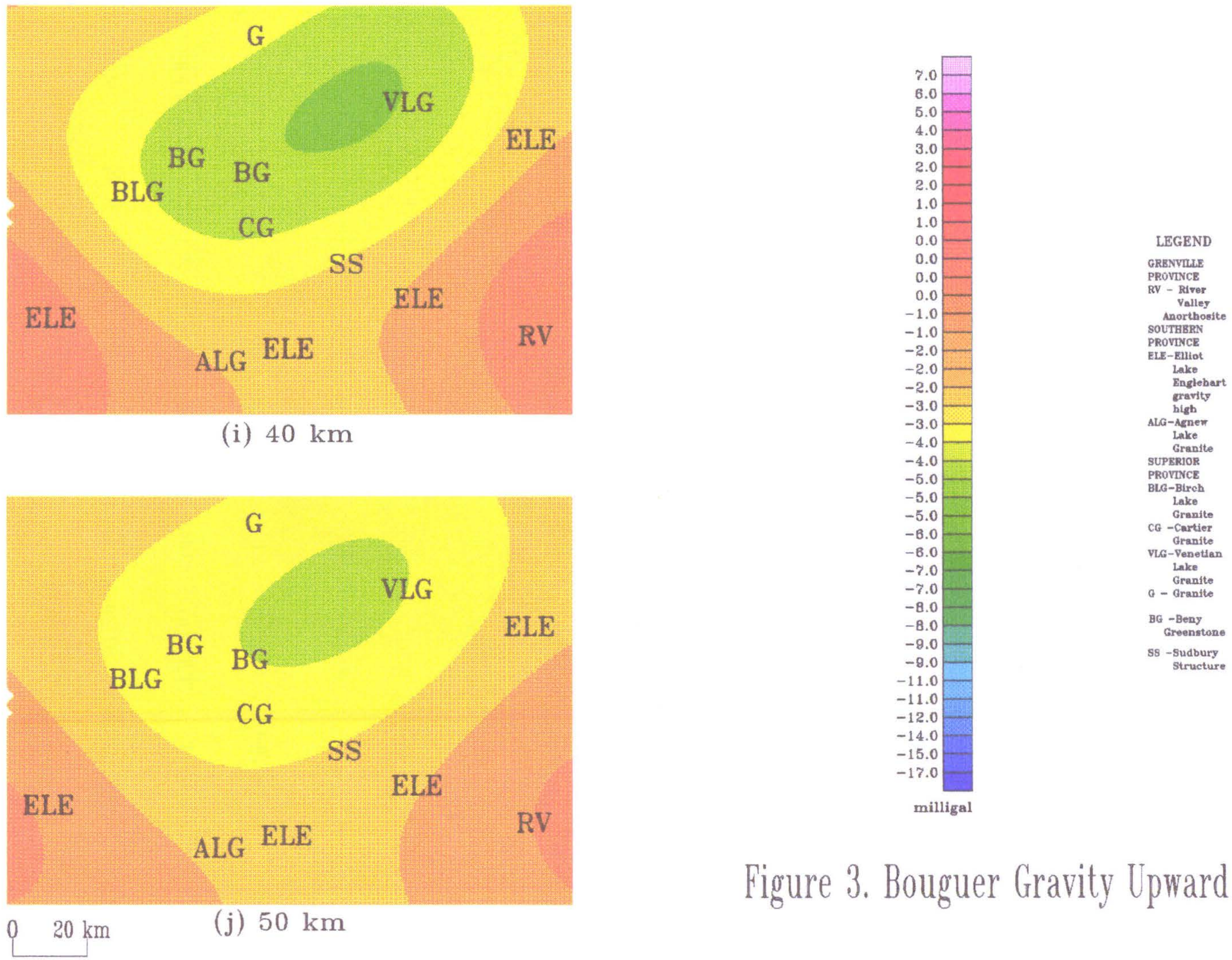


Figure 3. Bouguer Gravity Upward Continuation

A major limitation of wavelength filtering is that gravity anomaly spectrum due to a specific causative body is composed of a broad band of wavelengths and not restricted to a finite range of wavelengths. The implication is that different causative bodies at varying depths will have overlapping spectra and therefore can not be entirely deconvolved into separate features by filtering.

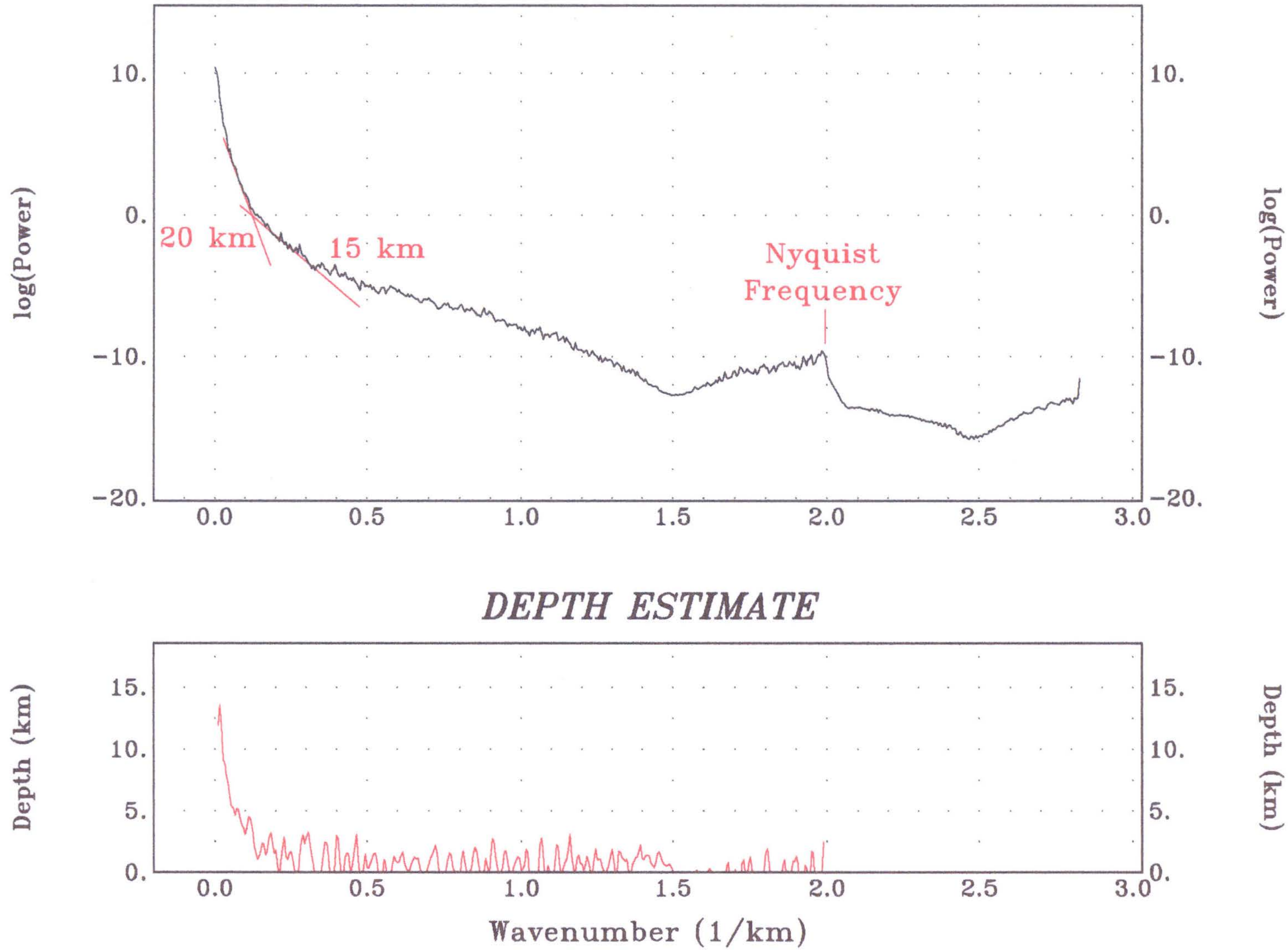
Examination of the radially averaged power spectrum of the Bouguer anomaly reveals a distribution of wavelengths influenced by the gravity observation station spacing and to a lesser extent the grid cell sample size (Figure 4). Prominent features of the semi logarithmic distribution are:

1. The grid cell size is reflected in the spectrum by the sharp gradient at a wavenumber of 2.0. This correlates to a value of 2 times the grid cell sample size (500 m) and is the Nyquist Frequency.

2. Signal aliasing, probably resulting from gridding is reflected in the significant energy (increasing in amplitude) for wavenumbers greater than 2.5 (wavelength of 400 m). This is probably a third order harmonic distortion product of the energy drop out visible at wavenumber 1.5 (wavelength of 666 m).

Figure 4.

RADIALLY AVERAGED POWER SPECTRUM



3. The energy drop out at wavenumber 1.5 and accompanying increase in energy as the Nyquist Frequency is approached is probably indicative of the original sampling interval of the observed gravity field. Gravity observation station density is throughout most of the Sudbury Structure averaging between 100 m and 500m. Outside of the Sudbury Structure, particularly in the Cartier Granite Complex to the north and west of the Sudbury Structure the gravity station density ranges between a separation of 750 m to 15 km.

4. The spectrum can be divided into 4 main linear sections: (i) from wavenumber 0 to 0.05 (wavelengths of infinity to 20 km); (ii) from wavenumber 0.05 to 0.12 (wavelengths of 20 km to 8.3 km); (iii) from 0.012 to 0.325 (wavelengths of 8.3 km to 3.125 km); and (iv) wavenumber 0.325 to 1.3 (wavelengths 3.125 km to 750 m).

5. From examination of the spectrum, the regional field is probably defined by wavenumbers between 0.05 and 0.1 (wavelengths 20 km to 10 km).

From examination of the regional maps derived from wavelength filtering (Figure 5), the Sudbury Structure does not completely disappear. The South Range is merged into the large arcuate east-west structure. The Vermilion Lake Fault gravity structure is no longer visible as a separate anomaly on the 17.5 km regional map (Figure 5(d)). The Benny Greenstone Belt and Wanapitei Lake anomaly become unfocussed on the regional maps of wavelength 15 km and longer. The Cartier Granite Complex and River Valley Anorthosite are dominate features on all the regional maps.

Trend Surface Analysis

Trend surface analysis as applied in this instance, involves the calculation of a 2-D polynomial surface of the third order to the Bouguer anomaly gravity field (Figure 6) utilising the gridded data. As in the wavelength filtering, the residual Bouguer anomaly gravity is calculated by removing the third order regional surface from the Bouguer anomaly gravity (Figure 1). A limitation of using a low order regional surface for obtaining a residual is that the residual surface may contain appreciable regional information.

The third order surface removed is remarkable for the simplicity of it's form. There is a large regional high corresponding to the River Valley Anorthosite and a pronounced low correlating with the Cartier Granite Complex. The effect of the Sudbury Structure is entirely removed from the surface. The residual, by default contains a great deal of regional information. The South Range of the Sudbury Structure is amalgamated with the arcuate east-west gravity anomaly. The character of the Wanapitei Structure differs from the enclosed circular low of the other methods used in that the Structure is now open to the south.

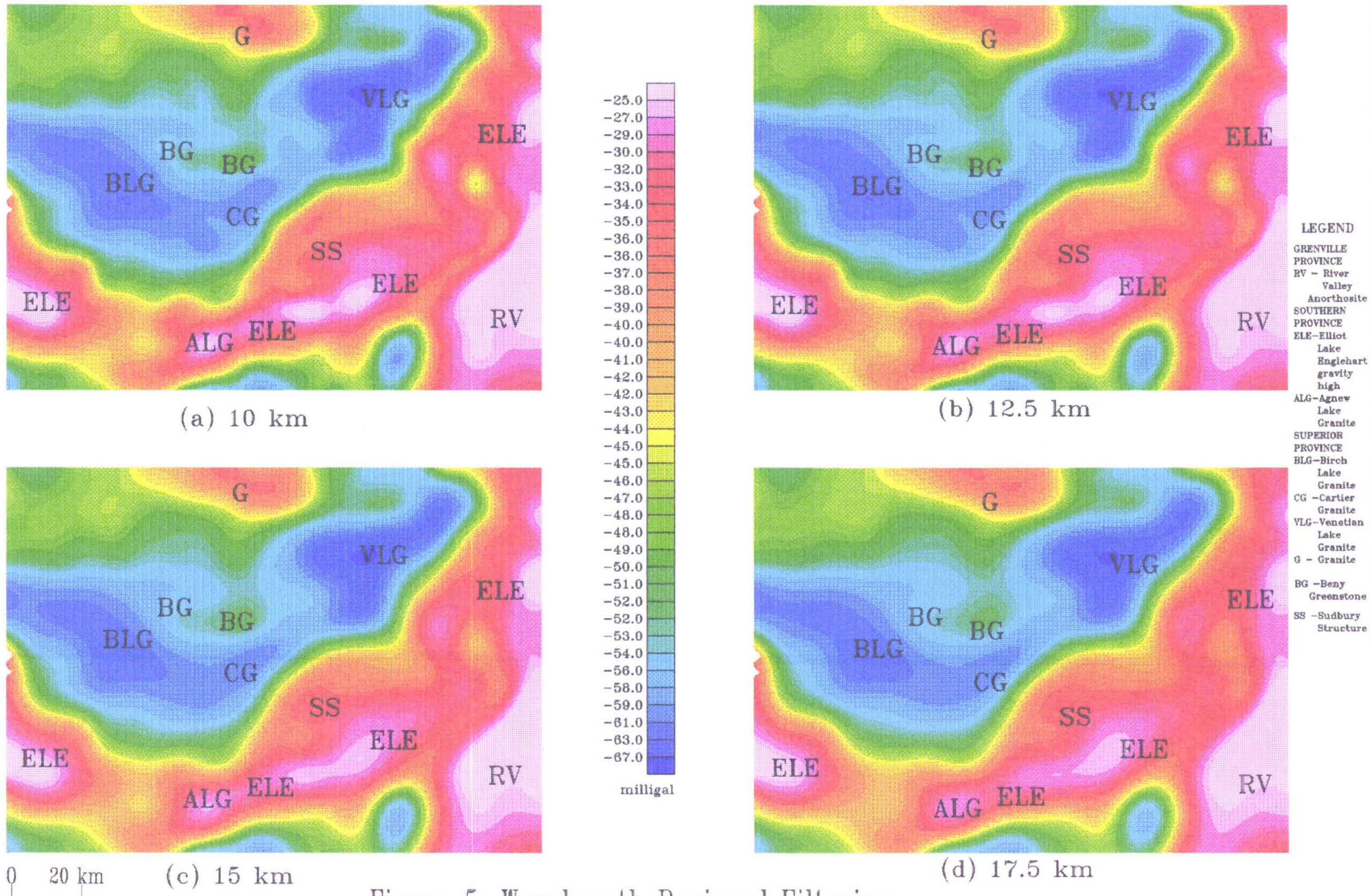


Figure 5: Wavelength Regional Filtering

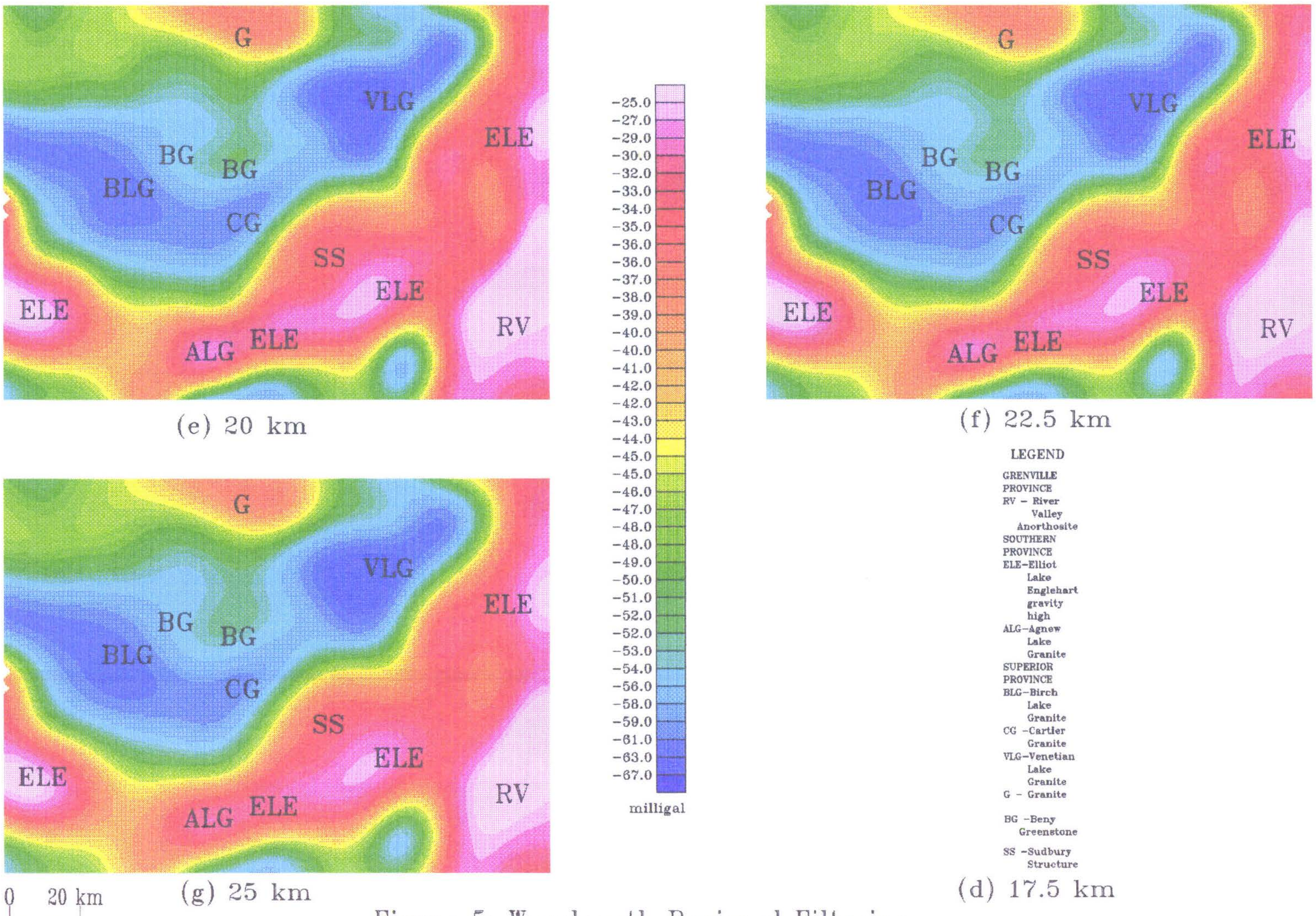


Figure 5: Wavelength Regional Filtering

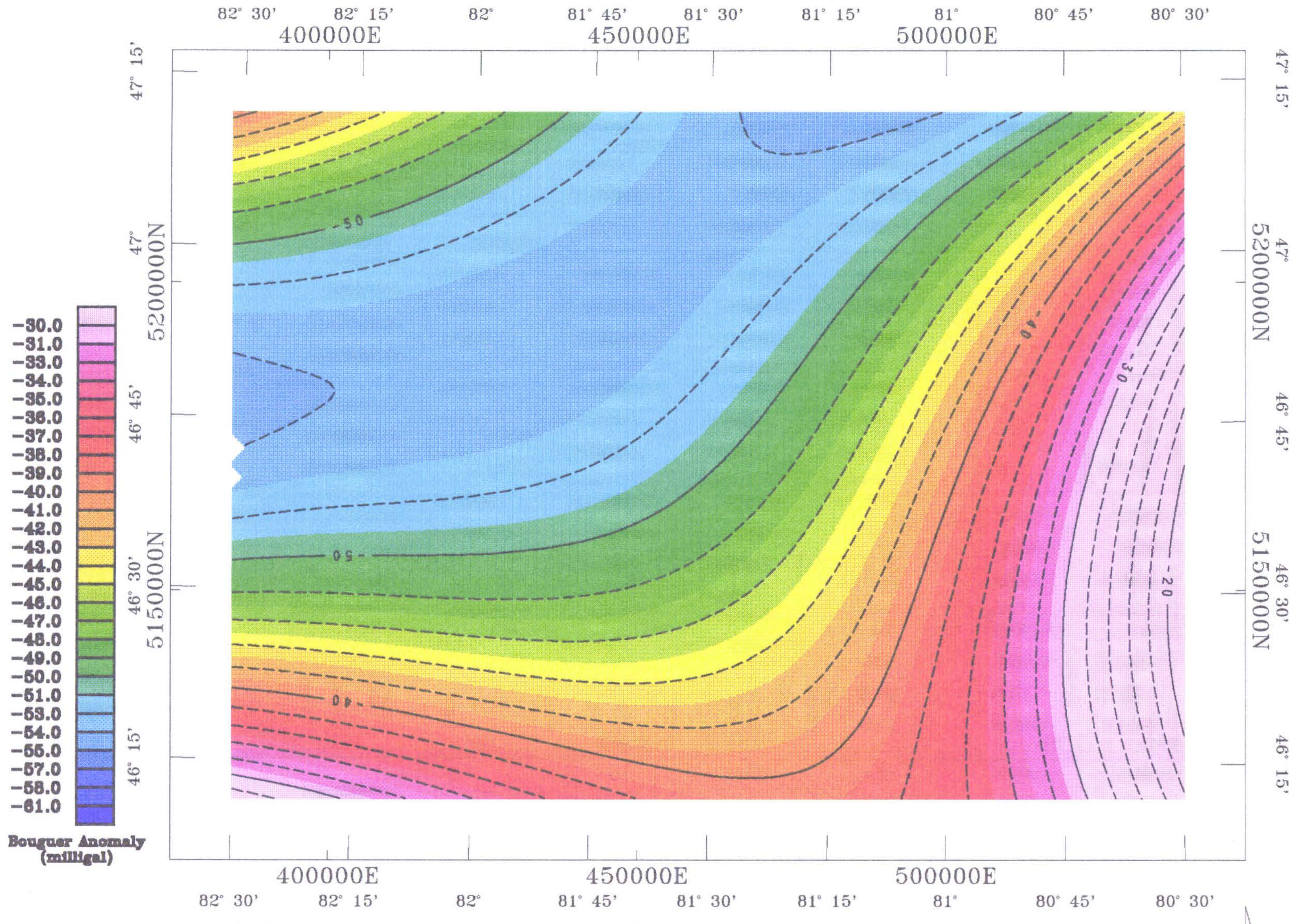


Figure 6: Third Order Trend Surface Analysis

Elliot Lake – Englehart Regional Gravity Field

10000 0 10000 20000 30000

(meters)

Discussion and Significance of Regional - Residual Extraction Methods and Results

Analysis of the principle methods of regional - residual extraction as they apply to the Sudbury Structure highlights the limitations of some of the methods and the advantages of others. The most unsatisfactory results were obtained through trend surface removal. The main problem in application to the Sudbury Structure is that a satisfactory balance between regional and residual information can not be obtained using a low order (third order, quadratic) surface. The regional obtained is best described as a supra regional containing only the longest wavelength data (deep crust, upper mantle) and the residual contains high levels of regional information from shallower than deep crust sources. Trials with higher order surfaces up (15th order maximum) did not significantly improve either the regional or the residual anomaly maps over those provided by the third order surface.

Wavelength filtering using spectrum analysis produced better results than the trend surface method, but was not immune from leakage of the regional field into the residual field and vice versa. This in part arises from the fact that a gravity anomaly is not the product of a finite range of wavelengths and hence in the case of a regional - residual separation, components of a single anomaly will continue to exist in both data sets. It is up to the interpreter of the data to determine if the amount of signal "contamination" is acceptable with respect to the information required.

Spectral analysis of the Bouguer gravity grid is an effective and important step in the analysis of a data set. It will expose problems with the data set which can have a significant impact on the methodologies being employed that may otherwise go unnoticed. Problems which can be highlighted are those common to signal processing, namely signal aliasing, sample size problems, and sample distribution problems. As applied in this study, wavelength filtering was effective in helping to isolate where significant contributions to the regional gravity field were originating. A drawback to wavelength filtering, relating back to the broadband nature of anomalies in general, is that in spite of using a broad range of wavelengths for the regional - residual separation, all the maps exhibit a "family" appearance, with only subtle differences in the regional field. This can be interpreted as indicating that the Sudbury Structure and environs is underlain by significant deep crustle structure.

Analysis of the upward and downward continuation products has provided the most insight into the regional setting of the Sudbury Structure. Downward continuation of the Bouguer anomaly has proven to be of particular importance. The results from this process imply that the primary sources of the gravity response observed in the Sudbury Structure originate within 5 km of the surface. However, there is also the implication that the these shallow sources may be spatially controlled in part by a preexisting set of deep crust fault structures.

Upward continuation of the Bouguer anomaly field also provides supporting evidence for the shallow origin of the main sources of the Sudbury Structure. The effect of the Sudbury Structure is not evident after upward continuation of 2.5 km. The continuous deep nature of both the Elliot Lake - Englehart arcuate gravity high and the Cartier Granite Complex is effectively illustrated by this procedure.

Common to all of the methods applied are a series of regional faults which appear to extend deep into the crust and possibly into the upper mantle. These faults can be divided into two families, a northwest striking family, and a east northeast striking family. A member of the northwest striking family of faults offsets the Elliot Lake - Englehart Structure to the west of the Agnew Lake pluton while another member appears to control the eastward extent of the Agnew Lake pluton and the westward extent of the Benny Greenstone Belt. A major fault of this family which is spatially coincident with the East Range of the Sudbury Structure also appears to control the eastward extent of the Sudbury Basin. Northward continuation of this same deep fault also separates the Cartier Granite from the Venetian Lake Granite. Further evidence from additional geophysical data sets for the location and importance of these faults has been discussed in Chapter 4.

The east - northeast family of faults is no less significant. The presence of these faults at depth may explain the presence of the arcuate structures observed in the Cartier Granite (Chapter 4). This family of faults is subparallel to the orientation of the North Range of the Sudbury Structure and the northern boundary of both the Cartier Granite and the Venetian Lake Granite. A member of this fault family controls the southern extent of the Elliot Lake - Englehart gravity anomaly and possibly the northern margin of the Grenville Province to the east of Sudbury.

Conclusions

A significant factor in the selection of a regional - residual separation technique is the bias of the interpreter and the ultimate goal of performing the separation. In the case of this study the goal was to use quantitative methods to extract a regional gravity field, or suite of fields, to isolate a residual gravity field for the Sudbury Structure. This permits a valuation of the regional fields used in the modelling of the Sudbury Structure by past researchers. Our related goal was to examine the regional gravity for deep seated structures that might have influence on the Sudbury Structure. Several methods of analysing the regional gravity setting of the Sudbury Structure have been applied and evaluated with the goal of obtaining a quantitative calculation of the regional gravity field. Of the methods used, the upward and downward continuation operators provided the most insight into the deep structural controls of the Sudbury Basin and environs. The methods of wavelength filtering and trend analysis have proven useful, but have not provided the same quality of information. Wavelength filtering suffered from the broadband nature of anomalies in general; not being able to completely eliminate or significantly reduce the contribution of high frequency (residual) information leaking into the regional product. Trend analysis has suffered the opposite problem, removing too much information from the regional so that a product, aptly described as a supra regional, is produced.

With respect to previous regional - residual separations used in modelling the Sudbury Structure, the method and regional of Gupta and Grant (1984) is the most problematical. The regional field derived by Gupta et al. (1984) can not be duplicated using standard quantitative methods. The 20 km wavelength filter contains no direct evidence of the Sudbury Structure, but does define a broad continuous regional feature, the Elliot Lake - Englehart Structure. The upward and downward continued gravity fields both indicate that the Sudbury Structure can be adequately explained by gravity sources placed within 5 km of surface. After continuation above 5 km there is no trace of any anomaly that can be associated with the Sudbury Structure; the gravity field is dominated by the larger, deeper Elliot Lake - Englehart Structure. In the immediate area of the Sudbury Structure, the Elliot Lake - Englehart Structure is defined by a long wavelength surface. The most closely approximates the planar regional previously adopted by McGrath and Broome (1994). The anomalous (residual) gravity field derived by Gupta and Grant (1984) probably contains a large regional component, and to explain this feature necessitated the emplacement of dense deep (5 to 10 km deep) bodies beneath the Sudbury Structure.

The lateral continuity and homogeneity of the Elliot Lake - Englehart Structure suggests the whole of the Sudbury Structure is underlain by a dense deep seated source body. The northern and southern extremities of this feature are sharply defined. To the north the boundary closely coincides to the contact between the Levack Gneiss and the Cartier Granite. The Levack Gneiss represents a dense phase adjacent to the less dense granite. At least some of this boundary is defined by steeply inclined east - northeast trending fault - the Pumphouse Creek Fault of Card (1994). The southern boundary coincides to the location (and locus) of the long fault, one of the many east - northeast trending faults that transect and controlled sedimentation in the Huronian. Together this suggests the Sudbury Structure is underlain by a continuous uplifted block of

Levack Gneiss. The tectonic geometry, lithology and geophysical signature of this feature has many similarities to the Kapuskasing Structural Zone.

Chapter 6: Conclusions

If the Sudbury Structure is examined from the perspective of the regional setting, we find that the probable source depth for the gravitational effect of the Sudbury Structure is shallow (< 5 km below surface). The regional setting is however influenced by major structures occurring within the deep crust and upper mantle. This has been effectively illustrated in chapter 5. The implication of this is that at the time of the joining of the Superior and Southern Provinces of the Canadian Shield, the major control structures that would later influence the development of the Sudbury Structure were in place. These major structures are the Elliot Lake - Englehart gravity high which straddles the contact zone between the Superior and Southern Provinces; the major granitic intrusives comprising the Birch Lake Granite, the Cartier Granite, and the Venetian Lake Granite; and the two families of faults, one north-northwest trending, the other east-northeast trending. It is significant to note that the east-northeast family of faults limits the northern extent of the Granite intrusions and in the near surface is spatially consistent with arcuate geophysical features (Chapter 4.) which appear to mimic the North Range of the Sudbury Structure and the Grenville Front. The north-northwest family of faults is not as obvious in the near surface, partially obscured by the Matachewan and Sudbury dike swarms, however, this family of faults appears to limit in east-west extent the Granite intrusions and the Sudbury Structure.

The mechanism of emplacement of the Sudbury Structure has not been revealed by the current study, as support for both the meteor impact origin and the intrusive origin can be extracted from the data presented. What is apparent is that the Sudbury Structure is located on the north flank of a major preexisting deep crustal structure. The North Range of the Sudbury Structure is in simple layered contact with the underlying Levack Gneiss - Cartier Granite Complex (chapters 2, 3 and 4). Major strike slip movement along a fault (No. 1 Hanging Wall Fault) within the basal Norite member of the Sudbury Structure is discernible both geologically and geophysically (chapter 3). The South Range of the Sudbury Structure is considerably more complex. There is strong evidence from the seismic, magnetics, and gravity to support the juxtaposition of rock units of the Sudbury Igneous Complex along the South Range as being produced by northward - directed thrusting (chapter 2).

Analysis of the currently available geophysical data strongly suggests that the deep seated magnetic and gravimetric bodies of Gupta et al. (1984) are not required to explain the potential fields observed coincident with the Sudbury Structure. It is, however, critical that paleomagnetic information is used in the magnetic modelling (chapter 2) and that an appropriate assessment of the gravitational field regional effect (chapter 5) be completed. The gravity model of Broome and McGrath (1994) has no deep dense bodies required, however the linear base level removed is an over simplification and obscures the complexity of the South Range and the regional gravity field (chapters 2 and 5).

References

Baranov, V., 1957, A new method for interpretation of aeromagnetic maps: psuedo-gravimetric anomalies: Geophysics, **22**, 2, 359-383.

Barnett, P.J., Henry, A.P. and Babuin, D., 1991; Quaternary geology of Ontario, east-central sheet: Ontario Geological Survey, Map 2555, scale 1:1 000 000.

Bennet, G., Dressler, B.O., and Robertson J.A., 1991, Chapter 14, The Huronian Supergroup and associated intrusive rocks: *in* Geology of Ontario, Ontario Geological Survey, Special volume 4, Part 1, 549-591.

Briggs, I.C., 1974, Machine contouring using minimum curvature: Geophysics, **39**, 39-48.

Card, K.D., 1994, Geology of the Levack gneiss complex, the northern footwall of the Sudbury structure, Ontario: **in** Current Research 1994-C; Geological Survey of Canada, 269-278.

Card, K.D., and Innes, D.G., 1981, Geology of the Benny area, District of Sudbury: Ontario Geological Survey Report 206.

Childers, R. and Durling, D., 1979, Time Series Analysis: IEEE.

Coates, C.J.A. and Snadjr, P., 1984, Chapter 14, Ore Deposits of the North Range, Onaping-Levack Area, Sudbury, *in* The Geology and Ore Deposits of the Sudbury Structure, edited by Pye, E.G., Naldrett, A.J., and Giblin, P.E., Ontario Geological Survey, Special Volume 1, 604 p. Accompanied by Map 2491, at a scale of 1:50 000, Map NL-16/17-AM Sudbury, at a scale of 1:1 000 000, and 3 charts.

Cowan, E.J. and Schwerdtner, W.M, 1994, Chapter 5, Fold Origin of the Sudbury Basin; *in* Proceedings of the Sudbury - Noril'sk Symposium, Special Volume 5, Ministry of Northern Development and Mines, 45-55.

Deutch, A., Lakomy, R. and Buhl, D., 1989, Strontium and neodymium isotopic characteristics of a heterolithic breccia in the basement of the Sudbury impact structure, Canada: Earth and Planetary Sciences Letters, **93**, 359-370.

Dobrin, M.B., 1976, Introduction To Geophysical Prospecting, Third Edition: McGraw-Hill Inc.

Dressler, B.O., 1984, Chapter 6, The effects of the Sudbury Event and the intrusion of the Sudbury Igneous Complex on the footwall rocks of the Sudbury Structure; p. 97-138, *in* The Geology and Ore Deposits of the Sudbury Structure, edited by Pye, E.G., Naldrett, A.J., and Giblin, P.E., Ontario Geological Survey, Special Volume 1, 604 p. Accompanied by Map 2491, at a scale of 1:50 000, Map NL-16/17-AM Sudbury, at a scale of 1:1 000 000, and 3 charts.

Dressler, B.O., 1984b, Sudbury geological compilation; Ontario Geological Survey Map 2491, Precambrian Geology Series, scale 1:50,000, geological compilation 1982-3.

Dressler, B.O., Gupta, V.K., and Muir, T.L., 1991, The Sudbury Structure: *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, 593-625.

Elkins, T.A., and Hammer, S., 1938, The resolution of combined effects, with applications to gravitational and magnetic data: Geophysics, **3**, 4, 315-331.

Fueten, F., Seabright, R. and Morris, W.A., 1992, A structural transect across the Levack Gneiss Cartier Batholith Complex, north-west of the Sudbury structure. LITHOPROBE Abitibi-Grenville Project, Abitibi-Grenville Report No. 33, 11-15.

Grant, F.S., 1953, A theory for the regional correction of potential field data: Geophysics, **19**, 1, 23-45.

Grant, F.S., 1957, A problem in the analysis of geophysical data: Geophysics, **22**, 2, 309-344.

Grieve, R.A.F., 1991, The Sudbury Structure: controversial or misunderstood?: Journal of Geophysical Research, Vol. 96, No. E5, 22,753-764.

Gunn, P.J., 1975, Detection of bodies with specified density-magnetization ratios by the use of multichannel Wiener filters: Geophysics, **40**, 4, 617-620.

Gupta, V.K., 1981a, Bouguer gravity and generalised geological map of the Gogama-Gowganda Area, Districts of Sudbury and Timiskaming; Ontario Geological Survey, Preliminary Map P. 2481, Geophysical Series, scale 1:100000.

Gupta, V.K., 1981b, Bouguer gravity and generalised geological map of the Sudbury-Onaping Lake Area, Districts of Sudbury and Algoma; Ontario Geological Survey, Preliminary Map P. 2482, Geophysical Series, scale 1:100000.

Gupta, V.K., Grant, F.S., and Card, K.D., 1984, Chapter 18, Gravity and Magnetic Characteristics of the Sudbury Structure, *in* The Geology and Ore Deposits of the Sudbury Structure, edited by Pye, E.G., Naldrett, A.J., and Giblin, P.E., Ontario Geological Survey, Special Volume 1, 604 p. Accompanied by Map 2491, at a scale of 1:50 000, Map NL-16/17-AM Sudbury, at a scale of 1:1 000 000, and 3 charts.

Gupta, V.K., Paterson, N., Reford, S., Kwan, K., Hatch, D. and MacLeod, I., 1989, Project Unit 88-25, Single master aeromagnetic grid and magnetic colour maps for the Province of Ontario, *in* Summary of Field Work and Other Activities, 1988, Ontario Geological Survey, 244-250.

Gupta, V.K. and Hearst, R.B., 1991, Project Unit 88-24. Single master Bouguer gravity grid and gravity colour maps for the Province of Ontario: *in* Summary of Field Work and Other Activities 1991, Ontario Geological Survey, Miscellaneous Paper 157, 161-164.

Hammer, S., 1981, Short Note: Magnitude of anomalies in the vertical gradient of gravity: Geophysics, **46**, 11, 1609-1610.

Hearst, R.B., McGrath, P.H., Morris, W.A., Thomas, M.D., Broome, H.J., Tanczyk, E.I., Keating, P., and Halliday, D.W., 1992, Gravity and magnetic interpretation along the LITHOPROBE Transect of the Sudbury structure: LITHOPROBE Abitibi-Grenville Transect Report No.25, 69-71.

Hearst, R.B., Morris, W.A., and Thomas, M.D., 1994a, Magnetic interpretation along the Sudbury Structure Lithoprobe Transect; *in* Proceedings of the Sudbury - Noril'sk Symposium, Special Volume 5, Ministry of Northern Development and Mines, 33-43.

Hearst, R., Morris, W., and Thomas, M., 1994b, Magnetic interpretation along the Sudbury Structure Lithoprobe Transect: Geophysical Research Letters, **21**, 10, 951-954.

Hood, P.J., 1958, Paleomagnetic Studies of some Precambrian Rocks in Ontario: PhD. Thesis, Department of Physics, University of Toronto.

Howell, L.G., Martinez, J.D. and Statham, E.H., 1958, Some observations on rock magnetism: Geophysics, **23**, 2, 285-298.

Jackson, S.L. and Fyon, J.A., 1991, Chapter 11, The western Abitibi Subprovince in Ontario: *in* Geology of Ontario, Ontario Geological Survey, Special volume 4, Part 1, 404-482.

James, R.S, Sweeny, J.M., and Peredery, W., 1992, Thermobarmetry of the Levack Gneisses-Footwall Rocks to the Sudbury Igneous Complex (SIC): *in* Abitibi Grenville Lithoprobe Workshop 1992, 179-182.

Lavin, P.M., and Devane, J.F., 1970, Direct design of two-dimensional digital wavenumber filters: Geophysics, **35**, 6, 1073-1078.

Lowman, P.D., 1991, Original shape of the Sudbury Structure, Canada: A study with airborne imaging radar: Canadian Journal of Remote Sensing, **17**, 2, 152-161.

Lowman, P.D., 1992, The Sudbury Structure as a terrestrial mare basin: Reviews of Geophysics, **30**, 3, 227-243.

Langford, F.F., 1960, Geology of Levack Township and the northern part of Dowling Township, District of Sudbury: Ontario Department of Mines, Preliminary Report 1960-5.

MacLeod, I.N., Vierra, S., and Chaves, A.C., 1993. Analytic signal and reduction-to-the-pole in the interpretation of total magnetic field data at low magnetic latitudes. Proceedings of the third international congress of the Brazilian Society of Geophysicists.

MacLeod, I.N., Jones, K., and Dai, T.F., 1993, 3-D analytic signal in the interpretation of total magnetic field data at low magnetic latitudes. Exploration Geophysics, **24**, 679-688.

Marson, I. and Klingele, E.E., 1993, Advantages of using the vertical gradient of gravity for 3-D interpretation. Geophysics, **58,** 11, 1588-1595.

McGrath, P.H. and Broome, H.J., 1994, A gravity model for the Sudbury Structure: in Proceedings of the Sudbury - Noril'sk Symposium, Ministry of Northern Development and Mines, Ontario Geological Survey, Special Volume 5, 21-31.

Mesko, C.A., 1966, Two-dimensional filtering and the second derivative method: Geophysics, **31**, 3, 606-617.

Milkereit, B., Green, A., and The Sudbury Working Group, 1992, Deep geometry of the Sudbury structure from seismic reflection profiling. Geology **20**, 807-811.

Milkereit, B., White,D., Adam, E., Boerner, D., and Salisbury, M., 1994, Implications of the Lithoprobe seismic reflection transect for Sudbury geology; in Proceedings of the Sudbury - Noril'sk Symposium, Ontario Geological Survey, Special Volume 5, 11-20.

Morris, W.A., 1984, Chapter 19, Paleomagnetic constraints on the magmatic, tectonic, and metamorphic history of the Sudbury Basin region; p. 411-427 in The geology and ore deposits of the Sudbury structure, Pye E.G., Naldrett, A.J., and Giblin, P.E., editors, 1984., Ontario Geological Survey Special Volume 1, 603p. Accompanied by Map 2491, at a scale of 1:50 000, Map NL-16/17-AM Sudbury, at a scale of 1:1 000 000, and 3 charts.

Morris, W.A., Hearst, R.B. and Thomas M.D., 1992, Interpretation of the deep structure of the Sudbury basin through Euler deconvolution: LITHOPROBE Abitibi-Grenville Transect Report No. 33, 121-127.

Nabighian, M.N., 1972, The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: Its properties and use for automated anomaly interpretation: Geophysics, **37**, 507-517.

Nabighian, M.N., 1974, Additional comments on the analytic signal of two-dimensional magnetic bodies with polygonal cross-section: Geophysics, **39**, 85-92.

Nabighian, M.N., 1984, Toward a three-dimensional automatic interpretation of potential field data via generalised Hilbert transforms: fundamental relations: Geophysics, **49**, 780-786.

Naldrett, A.J., Pessaran, R., Asif, M. and Li, C., Chapter 12, Compositional Variation in the Sudbury Ores and Prediction of the Proximity of Footwall Copper-PGE Orebodies: *in* Proceedings of the Sudbury - Noril'sk Symposium, Special Volume 5, Ministry of Northern Development and Mines, 1994.

Nelson, J.B., 1988, Calculation of the magnetic gradient tensor from total field gradient measurements and its application to geophysical interpretation: Geophysics, **53**, 957-966.

Nettleton, L.L., 1954, Regionals, Residuals, and Structures: Geophysics, **19**, 1, 1-22.

Nettleton, L.L. and Cannon, J.R., 1962, Investigation of upward continuation systems: Geophysics, **27**, 6, 796-806.

Oldham, C.H.G. and Sutherland, D.B., 1955, Orthogonal polynomials: Their use in estimating the regional effect: Geophysics, **20**, 2, 295-306.

Ontario Geological Survey, 1991, Bedrock geology of Ontario, east-central sheet; Ontario Geological Survey, Map 2543, scale 1:1 000 000.

Ontario Geological Survey, 1991, Bedrock geology of Ontario, explanatory notes and legend; Ontario Geological Survey, Map 2545, scale 1:1 000 000.

Osmani, I.A., 1991, Chapter 17, Proterozoic mafic dike swarms in the Superior Province of Ontario: *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, 661-681.

Paul, M.K., Datta, S., and Banerjee, B., 1966, Direct interpretation of two-dimensional structural faults from gravity data: Geophysics, **21**, 5, 940-948.

Paul, M.K., 1967, A method of computing residual anomalies from Bouguer gravity map by applying relaxation technique: Geophysics, **32**, 4, 708-719.

Peirce, J.W. and Lipkov, L., 1988, Structural Interpretation of the Rukwa Rift, Tanzania: Geophysics, **53**, 6, 824-836.

Percival, J.A. and Card, K.D., 1985, Structure and evolution of Archean crust in central Superior Province, Canada; *in* Evolution of Archean Supracrustal Sequences, Geological Association of Canada, Special Paper 28, 179-192.

Peredery, P.E. editor, 1991, Geology and ore deposits of the Sudbury structure (Field trip 7): Geological Survey of Canada Open File 2162.

Pye E.G., Naldrett, A.J., and Giblin, P.E., editors, 1984, The geology and ore deposits of the Sudbury structure, Ontario Geological Survey Special Volume 1, 603p. Accompanied by Map 2491, at a scale of 1:50 000, Map NL-16/17-AM Sudbury, at a scale of 1:1 000 000, and 3 charts.

Rao, D.A., Babu, H.V.R., and Narayan, P.V.S., 1981, Interpretation of magnetic anomalies dur to dikes: the complex gradient method: Geophysics, **46**, 1572-1578.

Rao, D.B., Prakash, M.J., Babu, N.R., 1993, Gravity interpretation using Fourier transforms and simple geometrical models with exponential density contrast: Geophysics, **58**, 1074-1083.

Reid, A.B., Allsop, J.M., Granser, H., Millett, A.J., and Somerton, I.W., 1990, Magnetic interpretation in three dimensions using Euler deconvolution: Geophysics, **55**, 80-91.

Roest, W.E., Verhoef, J., and Pilkington, M., 1992, Magnetic interpretation using 3-D analytic signal: Geophysics, **57**, 116-125.

Roest, W.E., and Pilkington, M., 1993, Identifying remanent magnetisation effects in magnetic data: Geophysics, **58**, 653-659.

Ross, H.P., and Lavin, P.M., 1966, In-situ determination of the remanent magnetic vector of two-dimensional tabular bodies: Geophysics, **31**, 5, 949-962.

Rudman, A.J., and Blakely, R.F., 1963, A geophysical study of a basement anomaly in Indiana: Geophysics, **30**, 5, 740-761.

Sabins, F.F., 1987, Remote Sensing, Principles and Interpretation, Second Edition: W.H. Freeman and Company.

Sage, R.P., 1991, Chapter 18, Alkalic rock, Carbonatite and Kimberlite complexes of Ontario, Superior Province; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, 683-709.

Shanks, W.S., and Schwerdtner, W.M., 1990, Structural analysis of the central and southwestern Sudbury Structure, Southern Province, Canadian Shield. Canadian Journal of Earth Sciences, Vol. 28, 411-430.

Singh, V., Moon, W.M., So, C.-S., and Miller, H.G., 1994, Interpretation of airborne gamma ray spectrometry data from Sudbury, Ontario: CIM Bulletin, Vol. 87, 31-35.

Skeels, D.C., 1966, Short Note: What is residual gravity?: Geophysics, **31**, 4, 872-876.

Swartz, C.A., 1953, Some geometrical properties of residual maps: Geophysics, **19**, 1, 46-70.

Telford, W. M., Geldart, L. P., Sherrif, R.E., 1990, Applied Geophysics, Second edition, Cambridge University Press.

Thompson, D.T., 1982, EULDPH-A new technique for making computer-assisted depth estimates from magnetic data: Geophysics, **47**, 31-37.

Zolnai, A.I., Price,R.A., and Helmstadt, H., 1984, Regional cross section of the Southern Province adjacent to Lake Huron, Ontario: implications for the tectonic significance of the Murray Fault Zone: Canadian Journal of Earth Sciences, 447-456.

Zurflueh, E.G., 1967, Applications of two-dimensional linear wavelength filtering: Geophysics, **32**, 6, 1015-1035.