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**PROCESSING AND INTERPRETATION OF REGIONAL GEOPHYSICAL DATA
FROM THE AMER LAKE/WAGER BAY AREA,
DISTRICT OF KEEWATIN.**

by

H. JOHN BROOME

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of Master of Science

Department of Earth Sciences
Carleton University
Ottawa, Ontario
April, 1989

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Processing and Interpretation of Regional Geophysical Data
from the Amer Lake/Wager Bay Area,
District of Keewatin

Submitted by H.J. Broome, B.Sc.,
in partial fulfilment of the requirements for
the degree of Master of Science

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ABSTRACT

Geophysical data can be used to support geological mapping in shield terranes. Since the Amer Lake/Wager Bay area of the District of Keewatin, N.W.T. has not been mapped in detail and gravity, aeromagnetic, and gamma-ray spectrometry data were available, it was chosen to test existing and new methods of processing, imaging, and interpretation of geophysical data.

Geophysical images generated for the study area were compared with existing geological maps. Colour intensity, shaded-relief, and shaded-colour images were compared in order to determine optimal display methods for different types of data. Shaded-colour images were the preferred display for aeromagnetic data. Continuation and derivative operators were used to enhance anomalies in particular wavenumber ranges.

Composite images generated from three different geophysical parameters were found useful for testing the correlations between geophysical responses and the geology. A simple image overlay method, which assigns different primary colours to each data set, was effective for poorly to moderately correlated data. Ternary radioelement images highlighted subtle variations in uranium, thorium, and potassium concentrations determined by gamma-ray spectrometry, and multi-directional shaded-relief images generated from aeromagnetic data proved useful for analysis of structural trends.

Gamma-ray spectrometry and aeromagnetic data were used to extrapolate surface mapping of plutons in a small portion of a calc-alkaline magmatic belt near Ford Lake to a larger portion of the belt. In another application, 2½ and 3-dimensional modelling were used to investigate possible causes for the large Bouguer gravity anomaly centred over Brown Lake. It was shown that, without additional constraints, the anomaly could be explained by a wide range of sources including a Moho depression and an intrusive body. A large intrusive body is the preferred interpretation, based on constraints offered by the aeromagnetic and radiometric data.

The structure and origin of the Wager Bay and Amer Lake Shear Zones were studied using potential field data. A first vertical derivative image generated from the gravity data revealed a continuous gravity feature between the two shear zones that had been masked by a superimposed regional anomaly. Continuous aeromagnetic and gravity anomalies between the two shear zones were interpreted to indicate a common origin.

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CHAPTER 1
INTRODUCTION

1.1 PURPOSE

This study involves the development and application of geophysical techniques to assist geological mapping in an 800 by 500 km area of the Precambrian Shield. Although the study area is located in the Canadian Shield, many of the techniques are applicable to other geological environments. The geophysical interpretation techniques utilized in this project can be divided into two categories: qualitative interpretation of geophysical data in image form, and quantitative interpretation by modelling.

Regional geophysical measurements are usually considered to be samples of a continuous function. A grid of discrete estimates of that function can be generated by interpolation to allow contour maps or images to be produced. Contour maps are generated by drawing lines through points of equal value, determined by a second phase of interpolation, whereas images are generated by assigning different colours to each grid element. Since the human visual system is more adept at interpreting images than line drawings, displaying geophysical

data in image form can often reveal information that is hidden in contour or profile maps (Duval, 1983; Broome, 1985; Cordell and Knepper, 1987; Sharpton et al., 1987). In the initial part of this study, standard image processing techniques and new methods developed by the author are used to enhance anomalies and generate composite images to help correlate the various geophysical responses. The effect on the imagery of fundamental differences in the wavenumber response of the geophysical parameters is considered and the utility of geophysical data for mapping geology is analyzed in more detail in three specific applications.

In the first application, images and models based on potential field data are used to assist in the structural interpretation of two shear zones. The second application involves the use of composite images to discriminate between plutons with different lithology in a calc-alkaline magmatic arc. Ground geological data, collected by GSC geologists, are integrated with the geophysical information in both areas.

Finally, computer modelling of gravity data is used to investigate the cause of a large Bouguer gravity anomaly. Both 2½ and 3-dimensional models are generated with a microcomputer workstation and software developed by the author. A 3-dimensional modelling program designed for a mainframe computer was rewritten for a microcomputer

workstation specifically for this study. Density estimates for modelling are based on a combination of field sample measurements and theoretical considerations.

1.2 STUDY AREA

The study area is located in the District of Keewatin, N.W.T. between latitudes 64°N and 68°N and longitudes 80°W and 96°W, and corresponding to International Map of the World: NQ 15/16/17 (Quoich River). This area is particularly suitable for this investigation because of the availability of regional aeromagnetic, gravity and gamma-ray spectrometry data containing interesting anomalies.

CHAPTER 2
REGIONAL GEOLOGY AND PREVIOUS WORK

2.1 REGIONAL GEOLOGY AND TECTONIC PERSPECTIVE

The study area lies in the northwestern part of the Canadian Shield (Figure 1), within the Churchill Province. Geological interpretation of the western part of the Churchill Province is currently controversial and in a state of flux. This chapter will provide a snapshot of current thinking based on the nomenclature and tectonic divisions proposed by Hoffman (1987, 1988). Other regional interpretations have been documented by Stockwell (1961) and Lewry (1985).

The nomenclature used in this study was introduced by Hoffman (1988) who divided the Churchill Province into the Rae and Hearne Provinces and the Trans-Hudson Orogen. According to Hoffman, the Archean Provinces were independent microcontinents prior to their confluence along collision zones represented by Early Proterozoic orogenic belts. These orogens are typically asymmetric, with one side characterized by a sedimentary prism overthrust towards an Archean foreland and the other side, the hinterland, characterized by major

Figure 1 :

Principal geological elements of the Rae Province, Hearne Province, and Trans-Hudson Orogen (modified from Hoffman, 1988).

calc-alkaline magmatic belts, high metamorphic grades and complex patterns of ductile deformation. Geochronological data suggest that amalgamation of the Archean provinces occurred in a relatively brief period between 2000 and 1800 Ma.

The major crustal components and areas of Archean and Early Proterozoic supracrustals are shown in Figure 1. The Rae and Hearne Provinces are geologically similar, both containing old granites ranging in age from 2950 to 3480 Ma (U-Pb) and late Archean belts of granite and metasedimentary rocks. The study area lies wholly within the Rae Province, in an area composed primarily of amphibolite to granulite facies felsic gneiss, with narrow belts of Archean supracrustal rocks and early Proterozoic sedimentary cover. The Rae Province is bounded to the northwest by the Thelon Orogen and McDonald Fault Zone. The Thelon Orogen is believed to have resulted from dextral-oblique subduction of oceanic lithosphere beneath the Rae Province between 2050 and 1850 Ma (Hoffman, 1987; 1988). The Queen Maud Uplift, located immediately west of the study area, is part of the Thelon Orogen. This Archean hinterland is composed of mainly granulite-grade gneiss that has been affected by Early Proterozoic shearing, cataclasis and retrograde metamorphism.

The Rae-Hearne boundary, or Snowbird Tectonic Zone, is interpreted to be a suture that extends 3000 km from the Rocky Mountains to Hudson Bay (Figure 1; Hoffman, 1988). It is characterized by zones of mylonite several kilometres wide and contains bodies of banded gabbro-anorthosite-pyroxenite (Taylor, 1963). Truncation of major magnetic anomalies of the Taltson Magmatic Zone, part of the Thelon Orogen, by the Snowbird Tectonic Zone is interpreted (Hoffman, 1988) as additional evidence for a suture. The age of the proposed suture is estimated to be less than 1920 Ma and older than 1850 Ma (U-Pb). The Snowbird Zone was first interpreted as a major structure by Gibb and Halliday (1974) based on paired linear gravity anomalies and later by Cavanaugh and Seyfert (1977) using paleomagnetic data. Other interpretations for the Snowbird Zone have also been proposed. Thomas and Gibb (1985) pointed out that there is little substantial geological evidence to support the suture hypothesis. They suggested that the lack of evidence for a central suture and the presence of a relatively unreactivated Archean central core may support the bilateral plate model proposed by Gibb and Halliday (1974). In this model, shallow-dipping subducted slabs are interpreted to have reached far beneath the Rae and Hearne Provinces from both sides.

Hoffman (1988) also acknowledges difficulties with the interpretation of the Snowbird Zone as a suture. The location

of a magmatic arc (usually parallel to suture zones) has not been established, although granites ranging in age from 2360 to 1870 Ma (U-Pb) are present 100 to 150 km to the northwest (Van Schmus et al., 1986). In the Rae Province, most structural trends are northeast, parallel to the Snowbird Zone, but the expected increases in metamorphic grade and deformation toward the proposed suture zone have not been observed.

Limited kinematic data are available for the proposed suture zone. The Chesterfield Fault Zone, located north of Baker Lake in the southwest corner of the study area, consists of steeply-dipping easterly to east-northeasterly striking sheared or foliated granitic rocks and local mylonites (Schau et al., 1982). Schau et al. thought little strike-slip movement occurred in the Chesterfield Fault Zone but several episodes of movement are indicated. Such movement must have occurred both before emplacement of an undeformed pluton that cuts across the fault zone, dated at 2500 to 2400 Ma (Rb-Sr), and after emplacement of 1900 Ma (U-Pb) mafic stocks which are deformed within the zone (Schau et al., 1982).

Extension of the Snowbird Suture Zone northeast of the Baker Basin is uncertain. Gibb and Halliday (1974) linked the Snowbird Suture with the Chantrey Mylonite Zone northeast of the Thelon Basin, and LeCheminant et al. (1987) documented

major northwest trending faults that may link the Chantrey and Snowbird Zones. Although the Foxe Fold Belt is directly on strike with the proposed suture (Figure 1), no obvious geological or geophysical evidence exists to link the two features. Hoffman (1988) extended the Snowbird Suture to the east parallel to steep horizontal gravity gradients (Sharpton et al., 1987), past Daly Bay into Hudson Bay. This eastward route links the mylonite-bounded, layered mafic granulite-anorthosite Daly Bay and Kramanituar Complexes with similar lithologies observed to the southwest along the path of the Snowbird Suture.

The Trans-Hudson Orogen separates the Hearne Province from the older Superior Province to the south. The Superior and Hearne Provinces are believed to have acted as foreland and hinterland respectively during a sinistral collision that occurred between 1910 and 1790 Ma (Hoffman, 1988).

2.2 GEOLOGY OF THE STUDY AREA

The principal geological map of the study area is GSC Open File 1138 (Paterson and LeCheminant, 1985). This 1:10⁶ scale map was compiled from 22 different GSC publications. Areas around Baker Lake, Ford Lake, Wager Bay and north of Lyon Inlet have been mapped in detail but much of the rest of

the map has been studied only on a regional scale. Large areas have been mapped as undifferentiated Archean/Aphebian mixed gneiss and granitic gneiss. The age relationships between most of the Archean/Aphebian intrusive and gneissic rocks are unknown, and many of the contacts indicated are known to be inaccurate (LeCheminant, personal communication, 1988). Figure 2 is a simplified geological map, derived from Open File 1138, which was used to correlate geophysical responses to the geology. Since geophysical methods can only differentiate between units with different physical parameters and it is likely that many of the mapped units are equivalent, the 43 units identified on Open File 1138 were simplified to 5 supracrustal and metamorphic units and 3 intrusive units.

2.2.1 SUPRACRUSTAL/METAMORPHIC UNITS

Approximately 60 percent of the area on Figure 2 is shown as a mixed gneissic unit. This unit includes the 11 Archean and Early Aphebian gneissic units shown on Open File 1138. There is a wide range of rocks in this unit including granite, granodiorite, quartz diorite, amphibolite gneiss, granitoid gneiss, tonalite gneiss, and amphibolite. Contacts between the original gneissic units have been retained although some may be inaccurate (LeCheminant, personal communication). Granulite-grade gneisses are mapped as a separate unit because of their association with major structural features.

Figure 2:

Simplified geology of the study area showing lithology and principal structural elements including the Wager Bay Shear Zone (WBSZ) and the Amer Lake Shear Zone (ALSZ). The location of 6 gravity profiles and a subarea selected for 3-dimensional gravity modelling are also shown.

Three supracrustal units are shown, the Penrhyn Group, Prince Albert Group, and the "uncorrelated supracrustals" which comprise all other supracrustals. The Archean Prince Albert Group contains the oldest known rocks in the study area. A 2953 Ma concordant zircon date for the acid volcanics of the Prince Albert Group has been documented by Henderson (1983). U-Pb zircon dating on Melville Peninsula indicates that felsic volcanism occurred at about 2880 Ma. This date is bracketed by older and younger plutonism ranging from 2950 to 2680 Ma (Hoffman, 1988). The unit is composed of metasedimentary and metavolcanic rocks including conglomerate, iron formation, pelitic schist, biotite schist, phyllite, amphibolite, and minor metagabbro. Extensive deformation and granitic intrusion make it difficult to determine the original stratigraphic succession or thicknesses of the rocks (Henderson, 1983).

The Penrhyn Group metasediments are Archean in age and are unconformable with surrounding Archean granitoid gneisses. An 1804 Ma Rb-Sr whole rock isochron age obtained from pelitic gneiss is considered as a minimum age for the group (Henderson, 1983). Lithologically, the group contains an interbedded succession of quartzite, pelitic and psammitic gneiss, calcium-silicate gneiss, marble and minor amphibolite. Total thickness of the group is probably less than 2000 m but several periods of metamorphism and isoclinal folding have

made stratigraphic succession and thickness determination difficult.

Other supracrustal units in the study area were combined in a unit referred to as "uncorrelated supracrustals". This unit combines the Chantrey, Woodburn, and Ketyet River Groups, the Christopher Island and South Channel Formations, and other unnamed supracrustal rocks. The combined unit is lithologically varied and includes quartzite, conglomerate, arkose, marble, schist, amphibolite, iron formation, unmetamorphosed volcanics and greenstone.

2.2.2 INTRUSIVE UNITS

West of Melville Peninsula, along regional strike, plutonic rocks are widespread, but the degree of associated basement reworking is poorly documented (LeCheminant et al., 1987). Intrusive rocks, including biotite granite, granodiorite, monzogranite, ferrodiorite, and syenogranite, ranging in age from Archean to Early Proterozoic, have been mapped as a single granitic unit. At least two periods of Early Proterozoic plutonism are recognized on the basis of mapping in the Ford Lake area. U-Pb dating of zircons in a biotite granite south of Ford Lake yielded preliminary ages of 2700 Ma indicating the possible presence of an Archean suite as well

(LeCheminant, personal communication, 1988). Discrimination of different plutons in the Ford Lake area will be discussed in more detail in Chapter 5. Other intrusive rocks in the study area include Archean gabbro and anorthosite (Figure 1).

2.2.3 STRUCTURE

Major structural elements of the study area include the Amer Lake Shear Zone (ALSZ) and Wager Bay Shear Zone (WBSZ), the Daly Bay Complex, the Foxe Fold Belt and the Kramanituar Complex. The structure and lithology of the ALSZ and WBSZ are discussed in more detail in Chapter 7.

The Daly Bay Complex is an allochthon composed of Archean granulite gneiss, gabbroic anorthosite, and migmatite (Gordon, 1988). A 1 to 15 km wide ductile shear zone, composed of strongly deformed equivalents of the core, surrounds the complex. A U-Pb date of 2067 Ma from pyroxene granulite and a K-Ar date of 1951 ± 26 Ma for biotite from a pegmatite are interpreted by Gordon to indicate that granulite-facies metamorphism of rocks, initially deposited in the Archean, occurred at approximately 2050 Ma. Metamorphism was followed by northward and upward movement of the allochthon that ended about 1950 Ma.

In the Foxe Fold Belt, which continues eastward from Wager Bay across Foxe Basin to Baffin Island, recumbent basement-cored nappe structures developed during the Early Proterozoic. These structures have been refolded to produce an interference geometry (Henderson, 1983). A kinematic model has been proposed by Henderson (1983) in which, due to sinistral shear, the belt was progressively squeezed between southwest-convergent bounding basement blocks. The youngest fold set is dated at 1810 Ma (U-Pb) from a syntectonic pegmatite (Henderson and Loveridge, 1981).

The Kramanituar Complex Outlier, located east of Baker Lake and directly south of the Chesterfield Fault Zone, is composed of a suite of granulites and anorthosites that may have been emplaced tectonically (Schau et al., 1982). Dating of zircons indicate a minimum age of 2573 Ma for the complex (Schau et al., 1982).

The geology of areas selected for detailed study are described in the relevant chapters. An early-Proterozoic I-type calc-alkaline plutonic suite that extends northeast from Wager Bay is discussed in some detail in Chapter 5.

CHAPTER 3
GEOPHYSICAL DATA AND IMAGERY

3.1 INTRODUCTION TO GEOPHYSICAL IMAGERY

Interpretation of geophysical data is an important component of modern resource exploration and geological mapping programs. The interpretation process is usually divided into two stages: qualitative analysis of the data in map or image form and detailed quantitative analysis of anomalies.

Qualitative analysis of aeromagnetic, gravity, and radiometric data is usually part of the early stages of the interpretation process. Since geophysical data are now commonly available in digital form, information in addition to that visible on standard contour maps can be utilized by proper application of image display and enhancement techniques. To obtain maximum benefit, display methods must be selected on the basis of the data characteristics and objectives of the study.

The portrayal of data sets as images is not new. Geologists and geophysicists have been making colour-coded intensity maps for many years by hand-colouring contour maps. Interpreters found that it was easier to correlate levels across a coloured map than across a line drawing. Computer technology now allows coloured maps, or images, to be generated quickly. Coloured images are generated from gridded data by assigning colours to each grid cell based on some data attribute, such as amplitude or reflectance. An image is then created on a monitor or hard copy device by drawing coloured squares or pixels to represent the grid cells.

The simplest type of image is a colour-coded intensity or pseudo-colour image produced by assigning different colours to grid cells based on their intensity. Factors that must be considered are choice of colours, number of colours and dynamic range assigned to each colour.

Selection of colours is a personal decision. However, it is best to use a standard palette, or set of colours, to avoid confusion when interpreting numerous images. The colour palette used in this study was created at the Geological Survey of Canada for total field magnetic maps and is shown on the legend in Figure 3. This palette was chosen because most people intuitively relate red to hot, or high values, and blue to cold, or low values. Thirty nine colours are used,

which is adequate for a palette that changes colour gradually. Increasing the number of colours improves the quality of the image, but the experience of the author indicates that a minimum number of useful colours is 16, and that most people do not perceive significant improvement when the number of colours exceeds 64.

When viewing a coloured image, a person subconsciously divides the image into zones with consistent colour. This tendency, and other characteristics of the human visual system, can cause a data set to appear to change when it is displayed using a different colour palette (Hall, 1979). Impressions of the data can; therefore, be dependent on the colour palette used.

Another major consideration when creating an image is the method used to divide the dynamic range of the data into discrete levels, a process known as quantization. A simple quantization method, called linear quantization, involves finding minimum and maximum values and linearly dividing the data between them. The problem with this method is that the population of some levels may be small, resulting in an image with limited detail.

Although linear quantization often produces a useful image, it can be shown that the most detailed image is

produced when each quantization level has an equal population (Hall, 1979). Quantization using the equal-population criterion is called histogram-equalized quantization, or simply histogram equalization. It is important to realise that the histogram equalization method optimizes the quantization for a particular data set; therefore, each data set must be quantized individually. The dynamic range of each level is likely to vary, so image interpretation requires regular reference to the legend.

In this chapter, the geophysical data, computer facilities, and software used to bring the geophysical data to a common format and generate the images are outlined. The different enhancement techniques available and the geological significance of different types of anomaly are discussed.

Although gravity, aeromagnetic and airborne gamma-ray spectrometry data were available for the study area, each data set was stored in a different format. To enable the different geophysical responses to be compared, the data were interpolated on to a standard-format grid. A common grid format is particularly important for the generation of composite images, which require exact grid cell correspondence between data sets. The grid format used in the national aeromagnetic database was selected because it is compatible with the author's software for image generation, enhancement

and display.

The standard format for regional aeromagnetic data is an orthogonal grid with a spacing of 812.8 m. Data are stored sequentially in the computer file column by column, with a preceding header. The header contains projection information, grid size, geographic limits of the area, and descriptive text. The standard Lambert Conformal Projection was used for gridding so that images would correspond to International Map of the World, NQ 15/16/17 (Quoich River).

Irregularly-spaced gravity data were interpolated from an original spacing of 6 to 12 km on to the standard grid, and the gamma-ray spectrometry data were interpolated from flight lines spaced 5 km apart. Detailed acquisition specifications for the three data sets can be found in Appendix A.

To facilitate correlation of the geology with the geophysical images, a transparent copy of Figure 2 is located in the pocket attached to the back cover of this thesis. This overlay has been scaled to match the geophysical images and can be registered with the images using the circular targets located along their southern limit.

3.2 COMPUTER FACILITIES AND SOFTWARE

Computer equipment used at the GSC for compilation of geophysical data and generation of imagery included mainframe computers, minicomputers and associated peripheral equipment operated by the Computer Science Centre, Energy Mines and Resources. A VAX 8700 minicomputer was used for image generation and Applicon colour ink-jet and Versatec electrostatic plotters were used to produce coloured hard copies. An IBM-PC/AT-based microcomputer workstation was used for generation and interactive display of imagery created from data downloaded from the VAX 8700. The workstation and related software for the interpretation of potential field data were developed by the author (Broome, 1986, 1987, 1988). All software for data compilation and image generation, on both the VAX 8700 and microcomputer workstation, were written by the author in FORTRAN 77 or converted to that language. Routines from the Uniras (VAX) and Halo (IBM-PC) graphic subroutine libraries were used to generate graphic and image output.

3.3 GRAVITY IMAGES

A 39-colour, histogram-equalized image generated from gridded Bouguer gravity data is shown in Figure 3. The high

Figure 3:

Colour image of Bouguer gravity intensity generated using the standard 39-colour palette and histogram-equalized quantization.

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wavenumber content of the Bouguer gravity image is limited by the wide gravity station spacing. The effect of station spacing on the Bouguer gravity image is discussed in more detail in Section 3.6. Specific features of the Bouguer gravity field that were interpreted in some detail are the large negative Bouguer anomaly centred at approximately 91°W longitude and 66°N latitude. This anomaly will be referred to as the Brown Lake Gravity Low. Modelling and interpretation of the Brown Lake Gravity Low are discussed in detail in Chapter 6, and changes in the gravity field associated with the WBSZ and ALSZ are discussed in Chapter 7.

The first vertical derivative of a gravitational or magnetic field is a useful tool for improving the resolution of local anomalies and for suppressing the effect of regional anomalies (Paine, 1986). A histogram-equalized colour image of the first vertical derivative of the Bouguer gravity field is shown in Figure 4. The method used to generate this image is described in Appendix B. Many of the small circular anomalies on this image are caused by single gravity measurements. The large number of these anomalies indicate that the number of gravity stations is inadequate to resolve accurately high-wavenumber variations in the field. Some point anomalies may also be due to measurement or compilation errors.

Figure 4:

Colour image of the first vertical derivative of the Bouguer gravity field. The image was generated using the standard 39-colour palette and histogram-equalized quantization.

3.4 AEROMAGNETIC IMAGES

3.4.1 REGIONAL IMAGES

The aeromagnetic data set is better suited for demonstrating different imaging techniques than the gravity data set because of the high density of field measurements. Since the original flight line spacing of 800 m is close to the grid spacing of 812.8 m., the gridded data are accurately defined by the flight line data with a minimum of interpolation.

3.4.1.1 COLOUR INTENSITY IMAGES

Canadian aeromagnetic data are published as contour maps and colour-intensity images. To ensure that adjacent maps can be joined without colour discontinuity, a fixed, non-linear set of quantization levels is used. The published map for the study area is shown in Figure 5. Figure 6 is an image generated from the same data using the standard 39-colour palette and histogram-equalized quantization. By using the histogram-equalized quantization method, an image with significantly more detail is produced.

Figure 5:

Colour image of magnetic intensity for the study area.
This image was generated using the standard non-linear
quantization levels used for published Canadian magnetic
anomaly maps and the standard 39-colour palette.

Figure 6:

Colour image of magnetic intensity generated using the standard 39-colour palette and histogram-equalized quantization.

3.4.1.2 SHADED-RELIEF IMAGES

The shaded-relief imaging method (Horn and Bachman, 1978) is useful for enhancing weak high-wavenumber anomalies. Shaded-relief images of magnetic data are generated by calculating and quantizing the reflectance or apparent brightness of an imaginary surface defined by the magnetic intensity. The reflectance is a measure of the proportion of illuminating light reflected from the surface and is dependent on the angular relationship between illumination direction and the tangent to the surface. Maximum reflectance occurs when the illumination direction and surface tangent are perpendicular. Although a number of different algorithms are available for calculating reflectance (Horn and Bachman, 1978), the cosine of the angle between the illumination direction and surface normal is an adequate approximation of reflectance for aeromagnetic data. The surface normal is defined at each grid cell as the normal to the plane defined by that cell and two of the adjacent cells. The relationships between reflectance, illumination direction, and surface slope are illustrated in Figure 7. Reflectance values are calculated for the entire grid, and then are quantized and displayed as a grey-tone image. The palette used for shaded-relief images consists of grey tones, ranging from black, for low reflectance, through to white, for high reflectance.

$$\text{REFLECTANCE} = \cos(\lambda)$$

$$\text{ILLUMINATION INCLINATION} = \phi$$

$$\text{ILLUMINATION DECLINATION} = \theta$$

Figure 7:

Geometry used to calculate reflectance values for the production of shaded-relief images. The reflectance equals the cosine of the angle between the surface normal and the illumination direction.

Small weak anomalies, with amplitudes less than the quantization intervals, are often invisible on conventional colour-intensity images. Since reflectance is determined by the local surface gradient, small high-wavenumber anomalies are enhanced relative to low-wavenumber features. Variations in the high-wavenumber content generate textural variations in the image that can often be related to regional structure and lithology. The shaded-relief method does not produce useful enhancement of data containing predominantly low-wavenumber variations since reflectance contrast between adjacent grid cells is small. For this reason, the shaded-relief method is usually not used for gravity data enhancement except at scales larger than 1:4 000 000.

Since reflectance is dependent on illumination direction, this method of data enhancement is directional in nature with features striking perpendicular to the illumination direction preferentially enhanced. The method is, therefore, similar to applying a high-pass directional filter. Directional enhancement is often useful for clarifying trends in a geologically-significant direction while simultaneously de-emphasizing anomalies in other directions. For example, the masking effect of parallel anomalies due to dike swarms can be reduced by setting the illumination direction parallel to the trend of the dikes. The first published application of the shaded-relief method to magnetic field data was Broome et

al. (1985).

Figure 8 is a shaded-relief aeromagnetic image generated for the study area using an illumination declination of 45° and inclination of 40°. The author has experimented with numerous illumination directions and found that an illumination inclination of 40° produces the most detailed images, and that illumination declinations of from 0° to 90° and 270° to 360° produce the most easily-interpreted images.

The illumination declination was set to 45° in this case to enhance northwest-southeast striking linear anomalies. Many parallel to subparallel linear magnetic anomalies, which are not apparent on the colour intensity map, can be seen throughout the study area on the shaded-relief image.

3.4.1.3 SHADED-COLOUR IMAGES

The shaded-colour image is a hybrid between shaded-relief and colour-intensity images. In a shaded colour image, most of the detail visible on shaded-relief images is combined with the regional intensity information observed on colour intensity images. Shaded-colour images are produced by quantizing the data intensity, defining the colour palette as described for colour intensity images, and then modulating the colour intensity with the reflectance.

Figure 8:

Shaded-relief image of magnetic intensity generated using a 32-level grey-tone palette and histogram-equalized quantization. Illumination declination and inclination were 45° and 40° respectively.

In the resulting image, regional intensity variations are indicated by colour hue and high-wavenumber detail is shown by colour intensity variations. For example, if the colour red is assigned to a grid cell based on its intensity, coincident high reflectance would change the colour to a lighter, brighter red and low reflectance would result in a darker, deeper red. Modulation of the colour hue with the reflectance produces an apparent relief in the colour image similar to that observed in grey-tone shaded-relief images.

A shaded-colour aeromagnetic image for the area is shown in Figure 9. Many features can be seen more easily on the shaded-colour image than on either the grey-tone shaded-relief (Figure 8) or colour intensity images (Figures 5 and 6). Both the regional magnetic high and the strong linear anomalies south of the WBSZ and ALSZ are enhanced on the shaded-colour image. The magnetic trend that represents the eastern extension of the ALSZ curves to the north near the Paliak Islands, but anomalies associated with the WBSZ maintain an east-west trend south of the islands. Small arcuate linear anomalies can be seen within magnetic highs over the calc-alkaline magmatic belt north and east of Ford Lake. Other obvious features on this image include linear anomalies (positive values in a regionally low field) associated with the Prince Albert Group iron formations, which strike northeast from the eastern end of the ALSZ to Committee Bay.

Figure 9:

Shaded-colour image of the magnetic intensity. Colour hue is defined using the standard 39-colour palette and histogram-equalized quantization. Shading corresponds to an illumination declination and inclination of 45° and 40° respectively.

An 50 km long east-west truncation of a magnetic high located at 91° 30' W longitude and 66° 40' N latitude on Figure 9 is similar to the magnetic expression of the Amer Lake and Wager Bay shear zones and may represent a shear zone.

A number of other images have been generated from the aeromagnetic data, but due to colour reproduction costs, only one of these images is reproduced here, a colour-intensity image of the data upward-continued by 5 km (Figure 10). Upward continuation is a technique for calculating the potential field that would be observed on a plane above the plane of observation (Henderson, 1960). The method used to upward continue the magnetic data is described in more detail in Appendix B. The image shown in Figure 10 was produced using histogram-equalized quantization and the standard 39-colour palette.

Since upward continuation is a low-pass operator, the contribution to the magnetic field due to small near-surface sources is reduced. The upward-continued magnetic field is more representative of larger, sometimes deeper, source bodies. Comparison of the magnetic field continued by 5 km with the data at the 305 m level (Figure 6) reveals that, as expected, the upward-continued field is much smoother. Small high-wavenumber anomalies due to the northwest-striking Mackenzie Dikes are not observed on the upward continued

Figure 10:

Image of the magnetic intensity after upward continuation by 5 km. The standard 39-colour palette and histogram-equalized quantization were used.

MAGNETIC DATA
UPWARD CONTINUED 5 KM

image, whereas larger and deeper-penetrating regional features, such as the WBSZ and ALSZ are clearly visible.

3.4.2 REGRIDDED MAGNETIC IMAGES

The aeromagnetic data set has the highest sampling density of the three data sets used in this study. During interpolation of the flight-line data on to the 812.8 m grid, some information was lost. To recover this information, data along the flight lines were resampled at a 200 m interval over the area covering the ALSZ and WBSZ. By regridding, additional detail can be generated along the flight lines, where a typical sampling interval is 50 m, but no additional information can be generated between the flight lines. When interpreting images produced from gridded data in which the original sampling density varies with direction, care must be taken to recognize interpolation artifacts caused by spatial aliasing.

To assist structural interpretations, first-vertical-derivative images were generated from the regridded magnetic data. Magnetic offsets and lineations can be traced more easily on vertical-derivative images than on magnetic-intensity images because they are high-wavenumber features. Figures 11 and 12 are first-vertical-derivative images

Figure 11:

Colour image of the first vertical derivative of the magnetic field for the Amer Lake Shear Zone (ALSZ) area. The data were gridded at a 200 m interval to improve image detail. The image was generated using the standard 39-colour palette and histogram-equalized quantization.

Figure 12:

Colour image of the first vertical derivative of the magnetic field for the Wager Bay Shear Zone (WBSZ) area. The data were gridded at a 200 m interval to improve image detail. The image was generated using the standard 39-colour palette and histogram-equalized quantization.

1ST VERTICAL DERIVATIVE OF MAGNETIC DATA
WAGER BAY SHEAR ZONE
(200 M GRID)

calculated from the 200 m gridded data for the ALSZ and WBSZ. These images were generated using the method described in Appendix B. Structures visible on these images will be discussed in Chapter 7.

3.5 GRAVITY AND MAGNETIC IMAGE COMPARISON

To interpret gravity and magnetic imagery over the same area, it is important to understand the relationship between them. This is particularly important for interpretation of the composite images discussed in Chapter 4.

Although gravity and magnetic fields are both potential fields, the gravity field (Figure 3) is generally much smoother than the magnetic field (Figure 6). There are a number of reasons for the lack of high-wavenumber detail in the gravity field including the larger sampling interval, and the limited range of rock densities compared to the orders of magnitude range of magnetic susceptibility. In Precambrian terrains, rock density typically varies from 2600 to 3300 kg m⁻³, whereas magnetic susceptibility varies from 10⁻⁶ to 10⁻³. Another reason for the lower high-wavenumber content in the Bouguer gravity field can be illustrated using Poisson's Theorem (Nettleton, 1976). Poisson showed that the magnetic potential (W) and the gravitational potential (U) are related

as follows :

$$W = - \frac{I}{G\sigma} \frac{dU}{dx} \quad \text{where}$$

σ - rock density
 I - intensity of magnetization
 x - direction of magnetization
 G - universal gravitational constant

From potential theory, the magnetic force in any direction is the negative of the derivative of the magnetic potential in that direction. Thus for the special case where polarization is vertical, the vertical component (V) of the magnetic field is given by:

$$V = - \frac{dW}{dz} = \frac{I}{G\sigma} \frac{d^2 U}{dz^2}$$

The magnetic field is clearly one derivative with respect to distance higher than the gravity field. Since the Earth's magnetic field is nearly vertical in northern latitudes, this relationship is a good approximation in the study area for the Earth's gravity and magnetic fields. The application of this relation to interpretation is limited to sources above the Curie point isotherm since bodies below that depth generate no measurable magnetic fields (840°K for magnetite). The present day temperature at the Moho in Precambrian shields may be as low as 600°K (Ranalli, 1987) but since ferrimagnetic minerals are inferred to be restricted mainly to the crust,

the Moho is likely the limiting depth for magnetic sources.

Poisson's Theorem implies that the first vertical derivative of the gravity field will have a wavenumber distribution similar to that of the magnetic field.

3.6 GAMMA-RAY SPECTROMETRY IMAGES

Gamma-ray spectrometry provides a method for estimating uranium, thorium and potassium concentrations in material near the surface of the earth. Different rock types have different characteristic concentrations of radioelements, thus concentrations calculated from gamma-ray spectrometry data can be used to help identify zones of consistent lithology and contacts between contrasting lithologies. Gamma radiation in the energy range of interest, 1.46-2.62 MeV, is strongly attenuated by most materials including water, overburden and rock. For example, in rock of density 2700 kg m^{-3} , approximately 90% of the measured gamma radiation originates in the top 15 to 23 cm, and in 1500 kg m^{-3} overburden 90%, originates in the upper 30 to 45 cm (Darnley et al., 1971; Duval et al., 1971). Any body of water, or layer of water-saturated overburden, can severely attenuate gamma radiation. The attenuation properties limit the utility of gamma-ray spectrometry data as a tool for geological mapping since

radiation may be due to surface material unrelated to the bedrock, and radiation due to bedrock may be attenuated by unrelated overburden. Nevertheless, in areas where overburden is thicker than the depth of penetration, good correlation is common between mapped lithology and calculated radioelement concentrations. When this relationship is observed, it suggests that glacial transport is minimal and that much of the overburden originates from nearby bedrock (Broome et al., 1987).

Figures 13 to 16 are histogram-equalized colour images of equivalent uranium, equivalent thorium, percent potassium and total gamma-ray count respectively. Uranium and thorium concentrations are determined by measurement of gamma radiation from daughter elements in their respective decay series. For accurate estimates of the concentrations, uranium and thorium isotopes must be in equilibrium with their decay products. To indicate that uranium and thorium concentrations are based on the equilibrium assumption, the calculated concentrations are called equivalent uranium and equivalent thorium.

North-south linear anomalies are seen on all radioelement images. These 5-km-wide anomalies follow flight lines and are likely due to spectrometer drift during data collection, or errors in background removal and flight path recovery.

Figure 13:

Image showing equivalent uranium concentration determined by gamma-ray spectrometry. The standard 39-colour palette and histogram-equalized quantization were used.

Figure 14:

Image showing equivalent thorium concentration determined by gamma-ray spectrometry. The standard 39-colour palette and histogram-equalized quantization were used.

Figure 15:

Image showing potassium concentration determined by gamma-ray spectrometry. The standard 39-colour palette and histogram-equalized quantization were used.

POTASSIUM CONCENTRATION

XXXXXXXXXXXX

XXXXXXXXXXXX

XXXXXX

Figure 16:

Image showing total radioactivity as indicated by total gamma-ray count. The standard 39-colour palette and histogram-equalized quantization were used.

[illegible]

TOTAL RADIOACTIVITY

Wider north-south zones of regionally anomalous concentrations are probably due to instrument calibration errors. Clearly, interpretation of these images is complicated by the relatively wide flight-line spacing. At 135 m flight elevation, 70 percent of the measured gamma radiation originates from a strip beneath the aircraft less than 200 m wide (Grasty, 1979). Although this width was calculated assuming mono-energetic unscattered gamma radiation, it indicates that the airborne data represent elemental concentrations in a narrow band beneath the aircraft. The highly-variable nature of elemental concentrations combined with the limited field of view result in spatial aliasing of the interpolated data perpendicular to the flight lines. A more accurate representation of the data could be produced by generating an image consisting of coloured bands located directly over the flight lines which are equal in width to the field of view. At the scale of this study, gamma-ray spectrometry data collected at a 1 km flight line spacing would produce much more useful images (Broome et al., 1987).

In spite of these limitations, the concentration images do provide useful regional information. All images show strong regional elemental variations that can be related to lithology. High radiation levels are generally found over areas mapped as Aphebian and Archean granites, granodiorites and granitic gneisses. A discontinuous band of increased

radioactivity, related to the presence of these rocks, crosses the study area from southwest to northeast (Figures 13 to 16). The high radioactivity that coincides with the Brown Lake Gravity Low is one of the major radiometric anomalies over the Canadian Shield (Geological Survey of Canada, 1986).

Some regional variations seemingly unrelated to mapped lithologies can also be seen on the four images. For example, a broad radioactivity low extends south of the strong anomaly just described, and narrows farther north along the western limit of the study area. The significance of this feature is unknown.

Heat generation in the Earth's crust is an important factor in heat flow, geothermal potential and ore genesis studies. Since the principal source of heat in the crust is the decay of radioelement isotopes, radiogenic heat generation can be calculated from radioelement concentrations. Richardson and Killeen (1980) have shown that radioelement concentrations determined by gamma-ray spectrometry can be used to calculate approximate heat generation values for the upper crust.

Radioelement concentrations calculated by gamma-ray spectrometry are due to near-surface material. Because near-surface materials include vegetation, water, and overburden in addition to bedrock, computed radioelement concentrations

are usually lower than actual bedrock concentrations. Charbonneau et al. (1976) studied the relationship between radioelement concentrations, calculated by airborne gamma-ray spectrometry, and measured overburden and bedrock concentrations. They measured elemental concentrations at over 1000 locations in the Mount Laurier and Elliot Lake areas and plotted these estimates against concentrations calculated from airborne data. Airborne concentrations were found to be closer to measured overburden concentrations and averaged 50% of bedrock concentrations. Heat generation values, calculated using conversion factors from Roy et al. (1968) and doubled to account for Charbonneau et al.'s observation are shown in Figure 17. Heat generation, A , in μWm^{-3} ($1 \mu\text{Wm}^{-3} = 2.39 \text{ cal cm}^{-3} \text{ sec}^{-1}$) is

$$A = 0.192(K \%) + 0.518(eU \text{ ppm}) + 0.142(eTh \text{ ppm})$$

assuming a rock density of 2670 kg m^{-3} .

Since heat-generation is computed from the three major radioelements, it is similar in some respects to the response in the total-count radioactivity window. When potassium, uranium and thorium occur in their normal crustal abundances (12000 ppm, 1 ppm, 3.7 ppm), their relative contributions to heat generation are 18%, 41%, and 41%, whereas their relative contributions to total count are 56%, 15.5% and 28.5%

Figure 17:

Image of upper-crustal heat generation derived from gamma-ray spectrometry data. The standard 39-colour palette and histogram-equalized quantization were used.

(Richardson and Killeen, 1980). Heat generation is, therefore, more sensitive to uranium concentrations and total count is more sensitive to potassium concentrations. The major radioactivity high associated with the Brown Lake Gravity Low appears on the image as an area of anomalously high heat generation.

CHAPTER 4

COMPOSITE IMAGES

4.1 INTRODUCTION

Composite images are created by combining information from two or more data sets in a single display. Such images facilitate the spatial correlation of features in the various input data sets. Line drawings of multiple data sets are often compared by laying them one over the other on a light table. This method is not satisfactory for comparing multi-colour images, because the image resulting from the superposition of these images is difficult to interpret.

4.2 COMPOSITE IMAGE GENERATION

Composite images are generated by quantizing data intensity (or any other attribute) and assigning a different primary colour to each data set, and then superimposing the results. Using primary colours, the number of attributes that can be combined is limited to three. In this study, the number of quantization levels is limited to 17 or 32 by the colour intensity range of the Applicon or Versatec plotters

respectively. More sophisticated methods of combining the various data sets, such as the ternary imaging technique used for gamma-ray spectrometry data by Broome et al. (1987), are possible, but the results were found to be difficult to interpret unless the data are strongly correlated.

4.3 COMPOSITE IMAGE INTERPRETATION

A basic understanding of colour theory is required to interpret composite images. Colours can be defined in a number of ways. They can be defined by primary colour component concentrations, or in terms of hue, lightness and saturation. An intuitive understanding of the relationship between these two definitions is important, because colours found in composite images are generated using the primary colour definition, and interpreted and described in terms of the hue-lightness-saturation definition. A comprehensive discussion of colour theory is beyond the scope of this study but can be found in Gonzalez and Wintz (1977) and Hall (1979).

The characteristics and interpretation of each data set must also be appreciated. Gravity, magnetic and gamma-ray spectrometry data each provide information about the physical properties at different crustal levels. Based on information

in Chapter 3 a simplified guide to the relationship between the measured physical properties and the scale and depth of penetration is given in Table 1.

Table 1 : Relative size and depth of sources producing anomalies on different types of images.

gravity intensity	- large scale, shallow to deep
1st Vertical derivative of gravity	- variable scale, shallow to intermediate depths
total magnetic field intensity	- variable scale, shallow to intermediate depths
shaded-relief magnetic	- small scale, shallow depths
gamma-ray spectrometry	- variable scale, very shallow depths

The vast amount of information contained in the composite images, combined with the size and geological complexity of the study-area, make it difficult to interpret all features. In this chapter, interpretation is limited to a description of a few major features to demonstrate how composite images may be used.

4.4 COMPOSITE POTENTIAL FIELD IMAGE

Figure 18 was created by combining Bouguer gravity

intensity (cyan), magnetic reflectance (a shaded-relief image; magenta), and magnetic intensity (yellow). This composite potential-field image helps the user correlate features in the magnetic and gravity fields, some of which originate from sources at different levels in the crust. Areas with low Bouguer-gravity intensity have little cyan component, but they may have a yellow magnetic-intensity component and a magenta reflectance component. This results in colour hues ranging from yellow through orange to red, depending on the relative magnetic intensity and reflectance of the area.

Coincident positive gravity and magnetic anomalies (green) are observed south of the WBSZ and ALSZ. The ALSZ sharply defines the northern limit of the gravity/magnetic high that extends approximately 35 km to the south and is characterized by superimposed, linear, east-west trending anomalies. Other areas have magnetic anomalies comparable in amplitude to those over the shear zones, but few have a coincident gravity anomaly. Outside the shear zones, the orientation of magnetic lineations is variable but has a dominant southwest-northeast trend. The significance of the coincident gravity and magnetic anomalies over the two shear zones is discussed in more detail in Chapter 7.

Figure 18:

Composite potential field image generated from Bouguer gravity intensity (cyan), magnetic data reflectance (magenta), and magnetic intensity (yellow). Each data set was quantized into 16 levels of colour intensity using histogram equalization. High data values correspond to high colour intensity.

COMPOSITE IMAGE

■ CYAN: BOUSSIER GRAVITY INTENSITY
■ CYAN: BOUSSIER GRAVITY DATA REFLECTANCE
■ MAGENTA: MAGNETIC DATA REFLECTANCE
■ MAGENTA: MAGNETIC INTENSITY
■ YELLOW: MAGNETIC INTENSITY

4.5 COMPOSITE POTENTIAL FIELD/TOTAL RADIOACTIVITY IMAGE

Figure 19 results from combining gamma-ray spectrometry data with potential field data. It was generated by superimposing images generated from magnetic intensity (magenta), the first vertical derivative of the Bouguer gravity (cyan), and total-count radiometric data (yellow). Unfortunately there is no gamma-ray spectrometry coverage south of Wager Bay. This image has higher colour variability than the composite potential field image (Figure 18) due to generally weaker correlation between the data sets and their increased high-wavenumber content. Radioactivity is highest over Archean and Aphebian granites and granodiorites. These bodies produce magnetic anomalies of variable amplitude, with the granodiorites generating the stronger anomalies. The region south of the ALSZ is purple because of its high gravity gradient and magnetic field values and low radioactivity, whereas the granites and granodiorites to the east are yellow to orange as a result of their high radioactivity, variable magnetic anomalies and weak gravity anomalies. By using the first vertical derivative of gravity in this image, rather than total Bouguer gravity, high-wavenumber variations in the gravity field due to near-surface sources are enhanced. This causes the positive linear gravity anomalies associated with the ALSZ and WBSZ to be highlighted and the long wavelength Brown Lake Gravity Low to be suppressed.

Figure 19:

Composite image generated from the first vertical derivative of the Bouguer gravity intensity (cyan), magnetic data reflectance (magenta), and total radioactivity (yellow) as indicated by the total count from gamma-ray spectrometry. Each data set was quantized into 16 levels of colour intensity using histogram equalization. High data values correspond to high colour intensity.

4.6 MULTI-DIRECTIONAL SHADED-RELIEF IMAGE

Due to their directional nature, more than one shaded-relief image is required to display all trends in a particular data set. To avoid making two or three separate images, a method was invented by the author where a single colour composite image can be created by combining shaded-relief images generated using different illumination directions and coloured illumination. On the resulting multi-directional shaded-relief image, features striking in different directions are coloured according to their orientation and amplitude. Experimentation has shown that the most useful composite shaded-relief images are produced by using orthogonal illumination directions with an inclination of 40° for the cyan and magenta images, and illumination at low inclination, with the cyan declination, for the yellow image. Using this illumination configuration, high-relief areas are displayed in magenta or cyan, depending on the azimuth of the anomaly trends, and other areas are grey. Figure 20 shows a multi-directional, shaded-relief image generated from the aeromagnetic data. Parallel northeast-southwest trending linear anomalies are predominantly magenta on this image, and northwest-southeast trending anomalies are cyan. Many linear anomalies, invisible on the published aeromagnetic map (Figure 5), are apparent on this image.

Figure 20:

Multi-directional shaded-relief image generated from the magnetic field intensity. The illumination inclinations and declinations used were $(40^\circ, 45^\circ)$ for magenta, $(40^\circ, 135^\circ)$ for cyan; and $(10^\circ, 45^\circ)$ for yellow.

MULTI-DIRECTIONAL SHADED-RELIEF IMAGE

4.7 TERNARY RADIOELEMENT IMAGE

The concentrations of the three common radioelements, uranium, thorium, and potassium, vary in different lithologies. To use gamma-ray spectrometry for regional mapping, subtle variations in the elemental ratios must be made visible. Variations in elemental ratios are difficult to determine from the individual concentration images because they are often masked by overall changes in the radioactivity level and because the concentrations are strongly correlated. Previously, simple composite radioelement images were produced with the overlay method (Duval, 1983); however, these images do not display subtle variations in the radioelement ratios. An improved ternary radioelement mapping technique was developed by Broome et al. (1987) that eliminates many of the shortcomings of previously developed methods.

The ternary radioelement image (Figure 21) displays elemental ratio variations by changes in hue and uses the total radioactivity to control the colour saturation allowing both ratio and intensity information to be displayed in a single image. The triangular legend allows colour hues to be related directly to radioelement ratios. Cyan indicates relative uranium enrichment, magenta indicates relative potassium enrichment and yellow indicates relative thorium enrichment. Zones of combined thorium and potassium

2 of/de 2

MicroD

Figure 21:

Ternary radioelement image generated from gamma-ray spectrometry data. The colour shown at each corner of the triangular legend indicates a 100% concentration of the indicated element. Colours at points inside the triangle represent different ratios of the three elements. Colour intensity is modulated by total count to emphasize high radioactivity areas.

enrichment are coloured orange. Areas with low count-rates have unstable ratios which produce high colour variability on the image. By varying colour saturation with overall radioactivity, responses in low-count areas are suppressed and those in highly radioactive areas are highlighted. Since colours on the legend are 100% saturated, they indicate only the hues assigned to elemental ratios.

Radioelement ratio variations can be more easily seen on the ternary image (Figure 21) than on individual radioelement images (Figures 13 to 15) within the southwest-northeast trending belt of high radioactivity. Small zones with distinctly different colours are interpreted as plutons of different composition or as compositional variations within individual plutons. One such zone, purple in colour and approximately 20 km across, is recorded south of Ford Lake. The colour over this pluton indicates that it is relatively rich in uranium and potassium. Discrimination of plutons using radiometric data will be discussed in more detail in Chapter 5.

The large radioactivity low, discussed with reference to the individual radioelement images, is uniformly red-orange on the ternary image, indicating relative uranium depletion. Two zones of relative uranium depletion can also be seen on Melville Peninsula. These zones converge to the southwest

and appear to have symmetry about the axis of the Foxe Fold Belt. The problem of vertical-derivative anomalies based on single gravity measurements was discussed in Section 3.6. Although some of these anomalies may be due to measurement and compilation errors, others that coincide with magnetic or radiation anomalies are also observed. For example, on the vertical gravity gradient image (Figure 4) a circular gravity anomaly, approximately 25 km south of Ford Lake, is based on a single gravity measurement. On the composite potential field/radioactivity image (Figure 19), the gravity high is coloured black, indicating coincident radioactivity and magnetic anomalies. The black circular anomaly is surrounded by a red-to-orange, approximately 10 km-wide, magnetic/radioactivity halo. Since the concentric anomaly represents more than one data set, the individual data sets were analyzed in more detail. The shaded magnetic-intensity image (Figure 10) shows distinct concentric features centred around the single point gravity-anomaly. On the ternary radiometric image, the generally green/blue colour of the surrounding area is disrupted directly over the gravity anomaly, indicating a local variation in the radioelement concentrations. From the combined geophysical response, it is concluded that the feature may be due a more-mafic, denser pluton, possibly granodiorite, within surrounding granitic rock. This example illustrates how composite images can draw attention to a feature and assist in its interpretation.

CHAPTER 5
DISCRIMINATION OF PLUTONS USING
GEOPHYSICAL IMAGERY

5.1 INTRODUCTION

Geophysical data in image form can be useful for distinguishing between zones of contrasting lithology. In this chapter, gamma-ray spectrometry and aeromagnetic data are used to map plutons or various phases of a composite pluton within an intrusive belt. The characteristic geophysical signatures of the different lithologies are determined in a 25 by 25 km part of the belt, which has been geologically mapped in some detail, and used to interpret a 150 by 150 km area of the belt.

5.2 DETAILED GEOLOGY

Ford Lake Intrusive Belt is a major suite of Early Proterozoic granitic and granodioritic rocks extending more than 300 km from west of Wager Bay to Committee Bay (Heywood, 1967; LeCheminant, 1987). Only the Ford Lake Batholith, immediately north of Ford Lake has been mapped in detail (LeCheminant, 1987).

Figure 22:

Geology of the Ford Lake Batholith as derived from surface mapping. (LeCheminant et al., 1987)

LEGEND FOR FIGURES 22 AND 25

Early Proterozoic

Ford Lake Batholith

- — magnetite-sphene-biotite monzogranite
- — quartz monzodiorite
- — fluorite-biotite syenogranite, hornblende-biotite monzogranite; megacrystic
- — sphene-hornblende-biotite granodiorite; medium grained
- — biotite granite; fine to medium grained
- — ferrodiorite
- — psammitic gneiss (Penrhyn Group ?)
- — potassium-rich granite

Archean/Early Proterozoic

- — migmatitic, granitic, and granodioritic gneiss with biotite-hornblende granite
- — banded biotite and biotite-hornblende granodiorite and quartz-diorite gneiss
- contacts from detailed mapping
- - - - - contacts from helicopter reconnaissance mapping
- - contacts from petrographic and geophysical data
- zero gradient contours from aeromagnetic data (grey)

The Early Proterozoic suite comprises more than a dozen large, composite intrusions of granite, granodiorite, monzonite, ferrodiorite and gabbro. This suite of rocks is truncated to the south by the Wager Bay Shear Zone. Henderson (1986) suggested that the megacrystic Ford Lake Batholith is similar to plutons commonly associated with destructive plate margin igneous activity. It intrudes Archean banded granitoid gneisses and granites as well as metasediments that are lithologically, structurally and stratigraphically similar to the Early Proterozoic Penrhyn Group exposed to the northeast on the Melville Peninsula (Henderson, 1983). An outcrop of Archean biotite granite north of Ford Lake has yielded a U-Pb date of approximately 2700 Ma (LeCheminant, personal communication 1988).

The Penrhyn Group metasediments are inferred to have been deposited in a shallow marine environment on continental basement. The plutonic and host rock character suggest that a continental magmatic arc is a likely tectonic setting for this Early Proterozoic belt (LeCheminant, 1987).

Although the relative ages of intrusion are not known, precise crystallization ages for two plutons in the Ford Lake Batholith have been determined by U-Pb geochronology (LeCheminant, 1987). A date of $1826 \pm 4/-3$ Ma was obtained for a syenogranite and 1823 ± 3 Ma for a monzogranite. The ages

Figure 23:

Ternary radioelement image for the Ford Lake area generated from gamma-ray spectrometry data. The colour shown at each corner of the triangular legend indicates a 100% concentration of the indicated element. Colours at points inside the triangle represent different ratios of the three elements. Colour intensity is modulated by total count to emphasize high radioactivity areas. The geological contacts overlaid on the image were derived from detailed surface mapping of the Ford Lake plutons (solid lines), reconnaissance mapping (dashed lines), and analysis of the geophysical data (dash-dot lines).

TERNARY RADIOELEMENT IMAGE
FORD LAKE AREA

Figure 24:

Shaded-colour image of magnetic data for the Ford Lake area. The data were gridded at a 200 m interval to improve detail. The geological contacts overlaid on the image were derived from detailed surface mapping of the Ford Lake plutons (solid lines), reconnaissance mapping (dashed lines), and analysis of the geophysical data (dash-dot lines).

variability of the magnetic susceptibility throughout the pluton. Radioelement signatures were determined using the ternary radioelement image. The wide flight line spacing (5 km) used for the gamma-ray spectrometry survey made determination of radioelement signatures difficult for large plutons and impossible for the smaller plutons. Characteristic geophysical responses for mapped plutons are presented in Table 2.

To evaluate the correspondence between the magnetic anomaly data and the mapped geology, the geological interpretation was superimposed on a map of contacts derived by computer from the magnetic data. The contacts were extracted from calculated vertical magnetic gradient data on the assumption that the zero vertical gradient contours coincide with vertical contacts between bodies of contrasting magnetic susceptibility (Hood, 1965). Although the boundaries of plutons are not necessarily vertical, the locations of the magnetically-derived contacts are often close to contacts observed on the ground. A calculated vertical magnetic gradient image for the area of granitic rocks is shown in Figure 12. A reinterpretation of the outlines of the southernmost plutons in the belt, partly based on the characteristics given in Table 2 and the contacts derived from the vertical magnetic gradient image is shown in Figure 25. Solid contacts are based on detailed geological mapping,

dashed contacts are based on 1960 and 1964 helicopter reconnaissance geological mapping, and dash-dot contacts are interpreted from the geophysical data.

TABLE 2 : Characteristic geophysical responses of intrusive units in the Ford Lake Area

Unit Number (see Figure 25)	geophysical parameters				
	magnetic		relative conc.		
	ampl.	texture	Th	K	U
1 - biotite granite	L	L	M	H	H
2 - Ford L. B., monzogranite	M	H	H	M	M
3 - Ford L. B. syenogranite	L	L	H	M	M
4 - Ford L. B. quartz monzodiorite	M	-	-	-	-
5 - Ferrodiorite	H	-	-	-	-
6 - porphyritic granodiorite	M/H	M	M	H	M
7 - potassium granite	M	M	L	H	M
L = low M = moderate H = high

Figure 25:

Geological map of the Ford Lake intrusive suite (refer to Figure 22 for the legend). The geological contacts were derived from detailed surface mapping of the Ford lake plutons (solid lines), reconnaissance mapping (dashed lines), and analysis of the geophysical data (dash-dot lines).

5.4 DISCUSSION AND CONCLUSIONS

Analysis of the geophysical images allowed the results of detailed mapping in a small part of the Ford Lake Batholith to be extrapolated to other areas of the Ford Lake Intrusive Belt. For this approach to be successful, the geophysical characteristics of the different phases of intrusion must be distinctive. The individual plutons must also be large enough to allow their geophysical signature to be detected using available data. In the area studied, the radiometric data coverage was barely adequate, allowing only large plutons to be resolved. For mapping at this scale, gamma-ray spectrometry surveying at 1 km line spacing would provide more information. The higher resolution of the magnetic data was essential for determining the extent of the larger plutons and for detecting smaller plutons. The magnetic data also proved useful for indicating structure within plutons.

In this study, careful analysis of the correlations between geology and two geophysical data sets produced a preliminary geology map at minimal expense compared to ground mapping. The map may not be as accurate as one resulting from detailed ground mapping, but provides a useful guide for future geological work and it could be used to target areas where detailed ground work could produce maximum benefit.

Other geophysical parameters, such as conductivity from airborne electromagnetic surveys, or total radioactivity, could also be incorporated using this approach as long as variations in the measured parameter are caused by the bedrock characteristics.

CHAPTER 6
MODELLING OF THE BROWN LAKE GRAVITY LOW

6.1 INTRODUCTION

The large negative Bouguer gravity anomaly, which has been informally named the Brown Lake Gravity Low, is investigated in this chapter. To study the cause of this anomaly, 2½ and 3-dimensional models were created using the microcomputer workstation and software. Both modelling programs were converted by the author from existing mainframe programs for use on the microcomputer workstation. Density estimates for modelling were based on a combination of field sample measurements and theoretical considerations.

6.2 MODELLING THEORY AND METHOD

Forward modelling of gravity data is performed by defining bodies and comparing the theoretical anomalies generated by those bodies to the observed anomalies. Body geometry and density contrast are modified until the theoretical anomaly matches the observed anomaly within some predetermined limits. Due to ambiguities inherent in

potential field interpretation, an infinite number of solutions of varying complexity are possible; so, other geophysical or geological data should be used to constrain the interpretation.

Modelling can be performed using 2, 2½, or 3-dimensional algorithms. In 2-dimensional modelling, observed profile data are compared to theoretical profiles calculated from bodies with infinite strike-extent. Two-dimensional modelling with end corrections can be used to calculate anomalies for bodies with finite strike-extent and is called 2½-dimensional, or pseudo 3-dimensional modelling. Both 2 and 2½-dimensional models are symmetrical about a central cross-section. To model bodies with more complicated shapes, 3-dimensional modelling is required.

Initial models were constructed using MAGRAV2, an interactive 2½-dimensional modelling program for microcomputers (Haworth and Wells, 1980; Broome, 1986). The interactive nature of MAGRAV2 allows models to be tested more quickly and easily than using full 3-dimensional modelling programs in batch mode.

Three-dimensional models were generated using GRAVPOLY, a batch-mode modelling program written at the United States

Geological Survey (Godson, 1983), and modified by the author for a microcomputer workstation (Broome, 1987, 1988). Position, elevation and gravity measurement are entered for each gravity station to define the observed gravity field. The model is defined in plan by stacked vertical-sided polygons. Gravity values are calculated at each station using the method described by Plouff (1976). Calculated, observed and residual gravity (observed-calculated) values are gridded and plotted in grey-tone image form. Gridding of the randomly-spaced data was accomplished using a modified version of a program written at the GSC (Belanger, 1988).

6.3 DESCRIPTION OF THE BOUGUER GRAVITY FIELD

The Bouguer gravity image (Figure 3) is dominated by the Brown Lake Gravity Low, a 30 milligal anomaly approximately 200 by 300 km in size. Similar gravity lows are located southwest and northeast of this anomaly, and smaller high-wavenumber anomalies are found throughout the study area.

The simplified geology of the area is shown in Figure 2. Archean/Aphebian granites and gneisses are mapped over most of the region. The remainder of the region is composed of other Archean/Aphebian gneiss units, Aphebian Penrhyn Group sediments and gneisses, and Archean Prince Albert Group rocks.

Granulite-grade gneisses located south of the ALSZ and WBSZ correlate with local gravity highs. The area has only been mapped using reconnaissance methods, and mapping errors are suspected (LeCheminant, personal communication, 1988).

Bodies of granitic rock are typically correlated with radioactivity highs visible on the total count radioactivity image (Figure 16). Although this correlation is subject to limitations inherent in the gamma-ray spectrometry method (Section 3.7), a more extensive distribution of granites is suggested by gamma-ray spectrometry data than has been identified by regional geological mapping. Since granitic rocks have lower than average densities, the Brown Lake Gravity Low may be due to one or more large body of such rock.

6.4 DENSITY ESTIMATES

Density measurements were available for several hundred field samples from the study area; however, many samples were identified as neither granite nor gneiss. The wide range of rock types collected contrasts with the dominance of gneiss and granite indicated on the geological map. This discrepancy was probably the result of the natural tendency of field geologists to collect anomalous samples rather than accumulate a large suite of similar rock types. To compensate, the

available samples were screened to remove non-granitic and non-gneissic rocks. The 53 rock density measurements were divided into three groups; mixed gneiss, granitic gneiss and granite. The location, density and description of each sample are given in Appendix C.

Comparison of the regional geophysical imagery generated in Chapter 3 with the geological map revealed little correlation between geology and geophysical responses in the area of the Brown Lake Gravity Low. The lack of geological/geophysical correlation and suspected inaccuracies in the geological mapping of the area, led to the conclusion that modelling using three density units was not warranted. Consequently, the densities of the two groups of gneisses were combined into a single unit.

The mean and standard deviation of the densities of the 22 granite samples were 2637 and 26 kg m⁻³, respectively. This density is close to the typical granite density of 2640 kg m⁻³ reported by Telford et al. (1978). The 31 combined gneiss samples had a mean density and standard deviations of 2716 kg m⁻³ and 78 kg m⁻³ respectively. The high standard deviation of the combined gneiss samples reflects their inhomogeneity. The mean gneiss density is less than the 2800 kg m⁻³ average gneiss density reported by Telford et al. (1978), but is within the reported range of 2590 to 3000 kg m⁻³.

The density distribution of the two groups was analyzed, using standard statistical methods (Appendix C), to test if the average gneiss density was significantly greater than the average granite density. Results indicate that at the 99% confidence level the gneiss samples belonged to a population with significantly higher density. The density contrast between granite and gneiss was taken to be 80 kg m^{-3} for initial 2½-dimensional modelling. During 3-dimensional modelling, minimum and maximum density contrasts corresponding to one standard deviation from the mean granite density were used to obtain a possible depth range for the low-density body. It was assumed that density contrast does not vary with depth.

6.5 2½-DIMENSIONAL GRAVITY MODELLING

The locations of six gravity profiles extracted from the gridded data are shown on Figure 2. North-south profiles 1 to 4 and east-west profile 6 cross the Brown Lake Gravity Low. Profile 5 crosses the WBSZ and will be discussed in Chapter 7. In order to model "local" anomalies, the regional field must be defined. On the basis of regional patterns, the -40 milligal contour was selected as the regional background.

This was, however, a subjective decision, and if the regional field was defined at a different level, it would change the size and amplitude of the anomaly and the model geometry.

Initial 2½-dimensional models, generated for each profile using a density contrast of -80 kg m^{-3} for the low-density rock, are shown for the five profiles in Figure 26. These models indicate that a low density body must extend laterally beyond the mapped limits of granite in order to generate the anomaly. The attitude of the contacts between the granitic and gneissic rock has not been defined geologically. Based on this approach, the mapped extent of the granites may be incorrect or the low-density body may be convex-upward and capped by blocks of outcropping denser rock.

Figure 26:

Results of 2½-dimensional gravity modelling of 5 profiles across the Brown Lake Gravity Low. Observed profiles are solid and calculated profiles are dashed.

The low-wavenumber component of the Bouguer anomaly could alternatively be modelled by crustal thickening. Assuming a average density contrast of 400 kg m^{-3} between the upper mantle and crust (Woollard, 1966) and a Moho depth of 35 km, the low-wavenumber component of profile 6 can be produced by a Moho depression of approximately 3 km (Figure 27). The high-wavenumber anomalies can then be modelled by small bodies in the upper crust with positive density contrasts.

Turcotte and Schubert (1982) proposed a method for calculating the degree of isostatic compensation from the flexural rigidity of the lithosphere and the wavelength of the load. For a load with wavelength 500 km (approximately twice the average anomaly width) and a typical Precambrian Shield flexural rigidity of 10^{25} Nm (Ranalli, 1987), less than 1% compensation would be expected. Thus, little compensation would be expected for a feature of this size as most of the load would be supported by the current strength of the lithosphere. However, the strength of the lithosphere may be significantly reduced during regional metamorphism associated with orogenic events resulting in a higher degree of compensation.

Lacking other constraints, an infinite number of crustal models, intermediate between the two solutions shown, can be generated for the profiles. However, the shallow-body model

is preferred because it is supported by the presence of relatively low density rocks near the surface (Figure 2). The gamma-ray spectrometry data also indicate the widespread presence of granitic rocks in the area.

6.6 3-DIMENSIONAL GRAVITY MODELLING

A 3-dimensional model of the proposed low-density body was produced for an area bounded by latitude 64.75°N and 67.50°N and longitude 86.50°W and 95.50°W (Figure 2). Using the previously determined -80 kg m^{-3} density contrast, a body was defined by 7 stacked, 1.5 km thick, vertical-sided, polygons. The cross-sections, determined by 2½-dimensional modelling, were used to help define the initial 3-dimensional model. Figure 27 shows observed gravity field and elevation and Figure 28 shows the calculated gravity field and the residual (observed-calculated) field obtained from the final model. Smaller, high-frequency anomalies observed on the vertical gravity gradient image (Figure 4), can be seen on the residual gravity image. Positive linear gravity anomalies south of the ALSZ, WBSZ, and over the Prince Albert Group are visible on both images.

Figure 27:

Grey-tone image of observed Bouguer gravity field (a) and elevation (b) for the Brown Lake Gravity Low area.

Figure 28:

Grey-tone images of the calculated (a) and residual gravity field (b) created by the low-density body model for the Brown Lake Gravity Low.

The 7 polygons used to represent the low-density body are shown in plan in Figure 29, and in section in Figure 30. The body has an east-west extent of approximately 300 km and a north-south extent of approximately 200 km. In section, the body is funnel shaped with the greatest depth extent occurring near the centre of the body.

Minimum and maximum density contrasts, corresponding to one standard deviation from the mean granite density were used

Figure 29: Plan view of the body of granite proposed as the cause of the Brown Lake Gravity Low. Sections N-S and E-W are shown on Figure 30.

to obtain an indication of the depth range of the low-density body. The minimum density contrast of 54 kg m^{-3} resulted in a maximum depth extent of approximately 13 km and the maximum density contrast of 106 kg m^{-3} corresponded to a minimum depth extent of approximately 7 km.

Figure 30: Cross-sections of the low-density body proposed as the cause of the Brown Lake Gravity Low. Section locations are shown on Figure 29.

6.7 CONCLUSIONS

The low-density body defined by the 3-dimensional model extends from the surface to a depth of from 7 to 13 km. Seismic studies of the basal contacts of batholiths in Precambrian and Mesozoic terranes have indicated comparable depth extents of between 6 and 10 km (Lynn et al., 1981). The lateral extent of low-density rock indicated by geological mapping is much less than that indicated by gravity modelling. Furthermore, variations in the magnetic and radiometric data indicate a range of surface lithology over the low density body. Such a large body of low-density rock would have been emplaced in a number of episodes of intrusion which could explain the apparent range of lithology within the area with densities appropriate for granite.

The limited surface extent of mapped granite relative to the lateral extent of low-density material may be explained if the top surface of the intrusive body has a convex-upward shape that outcrops only near its centre. This shape change to the upper surface of the body could be made without changing the calculated anomaly, if the bottom surface of the body was simultaneously changed. Convex-upward granites are common and are often attributed to emplacement by stoping (Bott, 1958). Emplacement by stoping often results in

cupolas of country rock on the roof of the intrusive body. These cupolas could explain the range of surface lithology indicated by the magnetic and radiometric data over the gravity low. Emplacement of large bodies by forcible intrusion is problematic because of the required displacement of large volumes of denser host rock.

In spite of uncertainties in regional field determination, density determination, and mapped contact locations, evidence favours a large body of low-density granite as the cause of the large anomaly. Similar anomalies with associated outcrops of granite are found northeast and southwest of the Brown Lake Gravity Low. These anomalies may also be caused by large subsurface granite bodies. These bodies will likely be linked together below the surface to form a belt of granitic rock. Other granite bodies interpreted to have a subsurface extent greatly exceeding outcrop are described in Devon and Cornwall by Bott et al. (1958), in the Canadian Shield by Gibb and Van Boeckel (1970), and in the Nigeria by Alakaiye and Sweeney (1974).

CHAPTER 7
INTERPRETATION OF THE AMER LAKE AND WAGER BAY
SHEAR ZONES USING POTENTIAL FIELD DATA

7.1 INTRODUCTION

The Amer Lake Shear Zone (ALSZ) and Wager Bay Shear Zone (WBSZ) are major structures with distinctive gravity and magnetic signatures. In this chapter, detailed images derived from the potential field data are used to help interpret the two shear zones. Potential field modelling and surface observations in a small area south of Wager Bay are used to estimate the dip of the WBSZ and the geometry of the zone of granulite gneiss to the south. Evidence for a common origin for the WBSZ and ALSZ is also discussed.

7.2 DETAILED GEOLOGY

A variety of rocks, ranging from Archean to Early Proterozoic in age, underlie the Wager Bay area (Figure 2). The WBSZ juxtaposes hypersthene-bearing gneisses to the south against upper-amphibolite grade gneisses to the north. Based on a study of mineral assemblages, Derome (1988) estimated

that the southern domain formed at peak pressures ranging from 7.5 to 9.5 kb, corresponding to a maximum depth of 25 to 32 km. The northern domain appears to have formed at crustal levels approximately 10 km shallower. In the southern domain, retrograde metamorphism appears to increase northward from the southern limit of the granulite terrain, peaking near the WBSZ (Derome, 1988).

The WBSZ is a major ductile strike-slip shear zone that trends east-west along the south coast of Wager Bay (Henderson, 1986). The presence of synkinematically-recrystallized sillimanite, biotite, feldspar and hornblende, and the absence of synkinematic muscovite indicate that this 2.5 km-wide zone of mylonites formed at upper amphibolite-grade metamorphic conditions. The sense of shear is dextral and shear strain diminishes southward from the main shear zone until mylonitic fabrics are no longer found approximately 30 km south of Wager Bay. The dextral sense of movement in the WBSZ is clearly indicated by abundant kinematic indicators including rotated feldspar porphyroclasts, pull aparts, shear bands and drag folds (Derome, 1988). Total strain along the main shear zone is estimated to be between 32 and 120 km based on the simple assumption that the product of the total shear zone width and local strain equals the total strain. In a zone extending 8 to 10 km south of the principal mylonite zone, there is a concentration of smaller en-echelon shear

zones. These 10 to 20 km long shear zones are 1 to 2 km wide and like the main coastal mylonite belt contain hypersthene-bearing mylonites (Henderson, 1986).

A small pluton of biotite granite, probably belonging to the Early Proterozoic plutonic suite described in Chapter 5, is truncated by the WBSZ. The $1811 \pm 17/-6$ Ma U-Pb date determined for this granite establishes a maximum age of late movement along the Shear Zone (Henderson, personal communication, 1988). A minimum age of 1300 Ma is estimated from undeformed 1-5 m wide basaltic dikes which cut the WBSZ, and probably belonging to the Mackenzie Dike Swarm. Eastward continuation of aeromagnetic anomalies and dextral shear fabrics mapped in northwestern Southampton Island suggest the WBSZ extends at least 170 km to the east of Wager Bay. Magnetic anomaly patterns have been interpreted to indicate that the WBSZ also extends westward to connect with the ALSZ (Henderson, 1986). The ALSZ is a broad zone of brittle to plastic deformation (Tella and Heywood, 1978) which is part of the huge McDonald-Amer-Meadowbank Fault System (Heywood and Schau, 1978). Stratigraphic studies of rocks along the McDonald Shear Zone to the southwest (Hoffman et al., 1977; Heywood and Schau, 1978) suggest dextral slip of about 75 km along the fault system. In another study, offset aeromagnetic anomalies were used to estimate dextral displacements of 125 and 70 km (dependent on correlations across the fault) along

the McDonald Fault (Thomas et al., 1976). In a study of the Amer Lake mylonite zone just west of the study area, Tella and Heywood (1978) found microfaults with consistent dextral offsets, but no marker horizons were identified to allow measurement of displacement along the fault.

7.3 METHOD

Analysis of detailed gravity and aeromagnetic images are combined in this section with structural and kinematic data collected during the summers of 1985 and 1986 (Henderson, 1986). Shaded-colour images produced from 200 m gridded aeromagnetic data (Figure 13) are used to study weak high-wavenumber anomalies that appear to correlate with shear zones. Density relations are studied qualitatively using the first-vertical-derivative image (Figure 4) generated from the gridded Bouguer gravity data (Figure 3). The dip and depth extent of the WBSZ are studied using 2½-dimensional modelling of magnetic and gravity profiles.

To generate a gravity model, density contrast estimates are required for the different units present in the area. Dr. Jack Henderson of the GSC provided 3 groups of rock samples from the WBSZ area which he specifically selected to be representative of units north of the shear zone, within

the shear zone and south of the shear zone. The density of each sample is shown in Table 5, and the mean and standard deviation of the densities for each group of samples is given in Table 6 (Appendix D).

The 7 rocks collected north of the shear zone have a mean density of 2660 kg m^{-3} , which is comparable to the average density of 2667 kg m^{-3} calculated for granitic gneisses in Appendix C. The mean density and standard deviation of the mylonite samples collected within the shear zone are 2757 and 165 kg m^{-3} respectively and the values for rocks collected south of the shear zone are 2748 and 148 kg m^{-3} . The relatively high standard deviation of these two groups is likely due to the heterogeneous nature of the rocks and their variable metamorphic grade. Increases in metamorphic grade generally produce increases in density; however, this relationship is highly dependent on the lithology and metamorphic history of the rock (Telford et al., 1976). Because of the high standard deviation and the lack of detailed information about the distribution of the different rock types, the calculated mean density may not be an accurate estimate for the area.

Since the average density of rock within the shear zone is similar to that of the granulite terrane to the south, a single body was used to model both the shear zone and the

granulite terrane. Assuming a host rock density equal to the mean density of samples from north of the WBSZ, the density contrast for the body was taken to be 87 kg m^{-3} .

The gravity profiles and models are shown in Figure 31a. The observed gravity profile contains 57 points, 2 km apart, interpolated from the gridded Bouguer gravity data (Figure 3). In the profile area, gravity stations are separated by 8 to 10 km. This wide station spacing greatly limits the accuracy of the gravity profile and resulting model.

Initially the northern limit of the body was fixed at the northern edge of the WBSZ, and the southern limit was located at the southern edge of the magnetic anomaly associated with the granulite-grade terrane (Figure 9). However, the north-south extent of this body was found to be inadequate to explain the observed anomaly. To satisfactorily fit the observed anomaly for a second body with an arbitrarily chosen density contrast of 38 kg m^{-3} was used. The second body extended 65 km south of the shear zone and 15 km north of the shear zone (Figure 31). Extension of the second body north of the shear zone results in a conflict between the average measured surface density and the model density. This conflict could be explained if the rock samples collected north of the shear zone are not representative of the area. Alternately the conflict could be eliminated by changing the model so the

body does not outcrop north of the shear zone. The model yields a poorly constrained dip estimate of 60°S for the near surface part of the WBSZ and a depth extent of approximately 3 km for the granulite terrane south of the shear zone.

If error bounds are set equal to plus or minus one standard deviation of the rock density south of the shear zone, the limits for density contrast are -60 and +236 kg m⁻³. It is impossible to model a positive anomaly using a body with a negative density contrast, but clearly as the density contrast becomes very small, the body depth increases greatly. Using the upper density contrast limit, the maximum depth extent of the body is reduced to less than 1 km.

Gravity modelling is inconclusive due to both the uncertainty of the density contrast estimate and the wide spacing of the gravity field measurements.

Figure 31:

Gravity (a) and magnetic (b) models for profile 5 across the Wager Bay Shear Zone. The profile location can be seen on Figure 2. Observed profiles are drawn with solid lines and calculated profiles with dashed lines.

Magnetic modelling was used in an attempt to constrain the geometry of the body. The magnetic profile is more accurately defined than the gravity profile due to the original sampling interval of 40 to 100 m along the flight lines. The magnetic profile was extracted from gridded magnetic data upward continued 2500 m to reduce the effect of small near-surface variations in magnetic susceptibility. Since magnetic susceptibility data were unavailable for the profile area, magnetization was allowed to vary freely while modelling. Although the magnetization was unconstrained, the improved resolution of the magnetic field compared to the gravity field resulted in superior constraints on the geometry of the body.

The prominent magnetic anomaly associated with the granulite gneiss was modelled by a body with magnetization of 500×10^{-6} ampere m^{-1} (Figure 31b). The northern edge of the body corresponds to the location of the WBSZ and has a southerly dip of approximately 85° . Although the depth extent of the body is greatest near the shear zone, lack of magnetization constraints make absolute depth determinations impossible. The magnetic field, south of the modelled anomaly is approximately 70 nanoteslas higher than the field north of the WBSZ. Since this level shift was small compared to the main anomaly, no attempt was made to model it.

7.4 DISCUSSION AND CONCLUSIONS

A positive magnetic high extends approximately 30 km south of the 2.5 km wide zone of WBSZ mylonites (Figure 9). This high, which has a maximum amplitude of approximately 800 nanoteslas, is paralleled to the north by a weaker, but still prominent, negative feature. In high northern latitudes, a normally magnetized body will produce a weak low north of the high due to the dipolar nature of the magnetic field.

On the mainland, south of the Paliak Islands, there is a small "L"-shaped magnetic high located over a truncated Early Proterozoic granite (Figure 9). The smaller anomaly is separated from the main positive anomaly, south of Wager Bay, by an east-west striking, magnetic low directly over the high strain section of the WBSZ. This magnetic low is not readily apparent farther east because it is masked by the magnetic high to the south. The shear zone low also becomes less distinct to the west where it is no longer framed by adjacent magnetic highs. Subtle magnetic lineations in the shear zone low can, however, be traced 80 km west of the coast of Wager Bay before they disappear (Figure 9). Aerial photographs show a strong lineation, caused by a topographic low, following the southern edge of the mylonite zone. This lineation disappears into Wager Bay approximately 20 km east of the Paliak Is.

Kinematic indicators observed on the ground indicate dextral movement in the shear zone. The aeromagnetic imagery also show patterns indicative of dextral movement (Figures 5, 6, 8, and 9). Adjacent to the westward extension of the mylonite zone, magnetic lineaments are curve right into the shear zone. No rotation of lineaments north of the shear zone is observed east of the Paliak Islands. The lack of evidence for rotation adjacent to the WBSZ east of the Paliak Islands may indicate that strain becomes more concentrated within the shear zone in this area.

The principal magnetic mineral associated with the magnetic anomaly south of the WBSZ is magnetite (Henderson, 1986; Derome, 1988). Magnetite is often formed in prograde metamorphic reactions under granulite pressure temperature conditions (Grant, 1985a). Although magnetite formed at granulite-grade pressure/temperature conditions may contain a significant component of remanent magnetization, the induced component is usually dominant. Unfortunately, no oriented granulite-grade rock samples were available for measurement of remanent component magnetization.

Derome (1988) described two types of magnetite crystals observed in the southern domain. The most abundant type

occurred as large "blobs" which she interpreted as primary magnetite. The less abundant type, observed in some late veins, were small and crystalline. On the basis of mineralogical relationships observed in thin section, these magnetite crystals were attributed to retrograde metamorphism. Retrogression of high-grade anhydrous minerals to hydrous minerals (eg. pyroxene to amphibole) requires access to water (Beach, 1980). Since the diffusion of fluids in shear zones is controlled by the degree of shearing, the amount of retrogression should be related to strain. From the corresponding increases in magnetic anomaly amplitude and shear strain from south to north, Derome (1988) concluded that magnetite formation was contemporaneous with fluid activity and retrogression, and therefore post-dated the shearing event.

This conclusion appears inconsistent with the observation that the small well-crystallized grains of magnetite are less abundant than the "blob" form, which was interpreted to be primary. In addition, the magnetic anomaly extends 15 km to the south of the en echelon shear zone. If the magnetite formation is directly related to shear strain, the main ductile shear zone should be associated with a strong anomaly, which it is not. It seems more likely that the magnetic anomaly is due primarily to magnetite formed by prograde granulite-grade metamorphism with superimposed local

variations in concentration due to magnetite formed by secondary retrograde metamorphism.

Derome (1988) estimated that the rocks north of the WBSZ were formed at a crustal level approximately 10 km higher than those to the south. This could be explained by vertical strain along the WBSZ, or by juxtaposition of crustal blocks formed at different levels in the crust by strike slip displacements along the WBSZ. Geologists who have studied the area have not noted any indications of vertical strain (Henderson, 1986; Derome, 1988). However, evidence of vertical movement within the mylonite zone may have been overprinted by later strike slip movement.

West of the Paliak Islands, a magnetic high with strong internal east-west lineations extends northwest of the mylonite zone to approximately 93° W where it merges with the major magnetic high associated with the granulite facies rocks south of the ALSZ (Figure 9). Lineations within the magnetic anomaly northwest of the WBSZ may be caused by small right-stepping en-echelon shear zones. If this interpretation is correct, the strain may be transferred between the small shear zones by extensional strike-slip duplexes (Woodcock et al., 1986).

On the total field Bouguer gravity image (Figure 3), a positive feature can be seen south of the ALSZ and a weak positive feature is evident south of the WBSZ. The two zones do not appear to be continuous because of the masking effect of the Brown Lake Gravity Low. The gravity derivative image (Figure 4) enhances high-wavenumber variations, revealing a feature joining structures south of the WBSZ and ALSZ. The feature is continuous except for west of Wager Bay, where the anomaly narrows to less than 20 km and is defined by single gravity station measurements. There may be a dextral offset of the feature approximately 25 km west of the Paliak Islands, but the limited resolution of the data makes a confident interpretation difficult.

The gravity highs are generally coincident with a string of magnetic highs that include the magnetic anomalies related to the granulite-grade rocks south of the WBSZ and ALSZ. The positive gravity anomalies south of the shear zones may be due to an increase in density associated with increased metamorphic grade. Granulite-grade rock is not mapped between the two shear zones. However, the continuous linear feature between the two mapped granulite-grade zones suggests that high-grade rock may be continuous at shallow depths, and that the cause of the magnetic and gravity anomalies south of the ALSZ and WBSZ may be the same. Although gravity and magnetic modelling did not produce well-constrained depth estimates for

the WBSZ and the granulite-grade rocks to the south, a depth extent of more than 1 km is fairly certain and 3 km is more likely. Both models support a steep southerly dip for the shear zone.

The magnetic anomaly south of the ALSZ is variable in amplitude and shows many internal lineations which form a complex braided pattern (Figures 9 and 11). The braided pattern may be evidence of an imbricate array of shear zones, similar to those observed south of the WBSZ, linked with one or more extensional strike-slip duplexes (Woodcock and Fischer, 1986). The geometry of strike-slip duplexes is similar to that of dip-slip duplexes found in thrust and extensional systems, but there are major differences in their generation. Strike-slip faults are usually at a high angle to bedding (bedding often provides weak horizons in thrust systems), resulting in a braided, disorganized geometry in mature strike-slip zones. Strike-slip duplexes cannot accommodate thickening or thinning as easily as dip-slip duplexes, since both surfaces are constrained, usually resulting in some subsidence.

Woodcock and Fischer (1986) described several examples of strike-slip duplexes. One example is a sinistral extensional strike-slip duplex within the active Dasht-e-Bayaz Fault Zone in Iran (Figure 32a). A mirror image of the

Iranian duplex shows a pattern similar to that of magnetic lineations over the ALSZ (Figure 32b). Note the difference in scale between Figures 32a and 32b. The Iranian example contains two or more internal horses of lower fracture density. If the concentration of secondary magnetite is controlled by the degree of shearing and fracturing, local variations in magnetic response may indicate variations in strain. Thus, the 20 by 40 km zone of reduced magnetic intensity south of the ALSZ (Figure 6 and 9) may represent an undeformed horse with a lower magnetite content.

Extensional strike-slip duplexes must be bounded on both sides by continuous shear zones. This requirement is met on the north (ALSZ), but a major fault has not been directly mapped along the southern edge of the proposed strike-slip duplex. Heywood and Schau (1978) speculated on the existence of a fault extending from Wager Bay west to the ALSZ, which they called the Meadowbank Fault. In addition, curvature of magnetic lineations along the western extension of the WBSZ, which were discussed previously, indicates dextral strain in this area. It is suggested that the southern bounding shear zone for the proposed extensional duplex is the western extension of the WBSZ.

Figure 32:

- a) Fault and shear zone patterns from the Dasht-e-Bayez fault zone in Iran.
- b) Magnetic lineations over the Amer Lake Shear Zone and the granulite-grade terrain to the south.

CHAPTER 8

SUMMARY AND CONCLUSIONS

In this study the design and application of geophysical methods for resolving regional mapping problems has been demonstrated. Although the project concerned a shield area, many of the methods are applicable in other geological environments. In particular, the study has shown how an integrated interpretation of gravity, magnetic, and radiometric data can improve and extend knowledge of the geology. Where possible, both qualitative and quantitative methods were used to strengthen the interpretation.

Geophysical Imagery

Colour images have been shown to be clearly superior to line contour and profile maps traditionally used to display geophysical data. Subtle trends and regional variations in the data are enhanced on colour images. Selection of the appropriate type of image and the choice of quantization method for each data set has been demonstrated to be important. Data sets with high-sampling densities, such as aeromagnetic data, are best displayed as shaded-images which

enhance low-amplitude, high-wavenumber anomalies associated with sources close to the surface. The shaded-colour imaging technique (Figure 9), combines the advantages of histogram-equalized colour images with those of shaded-relief images. Gravity and radiometric data have limited high-wavenumber content and benefit little from shading techniques.

Correct interpretation of geophysical images requires an understanding of the relative depth and size of the sources producing the anomalies. The relationships between the geometry/depth of the causative bodies and the expression of their anomalies on the various types of geophysical image have been reviewed and are summarized in Table 1.

Composite Images

To correlate the different geophysical responses, composite images were created. A simple overlay method, developed for this study, and a more complex ternary ratio method (Broome et al., 1987) were used for different combinations of data. Figures 18 and 19 were generated using the image overlay method. The composite potential field image (Figure 18) proved useful for correlating gravity and magnetic responses originating at different levels in the crust, and the multi-directional shaded-relief image (Figure 20), introduced in this study, was shown to be an excellent tool

for analyzing magnetic anomaly trends.

The second composite image (Figure 19) combined radiometric total count, first vertical derivative of Bouguer gravity, and magnetic field intensity. The resulting composite image was found to be complex and somewhat difficult to interpret but useful for displaying correlations between the different geophysical responses. The ternary radioelement imaging method was designed to (Figure 21; Broome et al., 1987) displays effectively variations in radioelement ratios not detected on the individual radioelement images because of their strong correlation. It was concluded that composite images are useful for determining the relationships between geophysical responses and geology.

Applications to Geological Problems

Three specific geological problems were addressed by appropriate geophysical interpretation methods. Regional images were used to investigate the relationships between structure, lithology, and geophysical data in the study area. The improved understanding of these relationships assisted in the selection of appropriate interpretation techniques for more detailed analyses.

The use of gamma-ray spectrometry and magnetic data to

map a composite intrusive belt was outlined in Chapter 5. Results of detailed ground work in a small part of the Ford Lake Batholith (LeCheminant et al., 1987) were used to determine the relationships between lithologies and geophysical responses. The geophysical signatures identified in this 25 by 25 km area were then used to map a larger 150 by 150 km portion of the belt (Figure 25). Gravity data were not incorporated in this component of the study because the small density contrast expected between plutons would not have been detected with the low resolution data available.

In the Ford Lake Intrusive Belt, some areas proved to have sufficient lithological variation to allow identification of several suites of plutons based on their geophysical responses. The 5 km spacing of flight lines used to collect the gamma-ray spectrometry data proved to be adequate for distinguishing only the larger bodies (Figure 23). A line spacing of 1 km would have resulted in more accurate definition of the large plutons and detection of smaller bodies. The higher resolution of the aeromagnetic data (Figures 12 and 24) permitted smaller plutons to be recognized and the contacts of the larger plutons to be accurately defined. Individually, the gamma-ray spectrometry, or aeromagnetic data would not have been adequate to distinguish many of the plutons.

The success of this approach for reconnaissance geological mapping depends on three factors: (i) the presence of measurable contrasts in the physical parameters of the different plutons, (ii) sampling intervals adequate for resolving zones of consistent lithology, and (iii) ground observations to help identify different rock units and, ideally, to measure their geophysical signature and physical properties such as density and susceptibility.

In Chapter 6, both 2½ and 3-dimensional modelling were used to investigate possible causes of the Brown Lake Gravity Low. The 3-dimensional modelling program, originally written for a mainframe computer, was modified significantly to run on a microcomputer workstation for this study. The 2½-dimensional modelling program was the result of a previous project (Broome, 1986). Statistical analysis of a limited number of sample densities demonstrated that intrusive rocks mapped within the anomaly were, on average, 80 kg m^{-3} less dense than the surrounding gneisses (Appendix C). Modelling of profiles across the Brown Lake Gravity Low revealed that it consisted of a strong low-wavenumber anomaly and weaker superimposed high-wavenumber anomalies (Figure 26). The low-wavenumber contribution could be caused by, at one limit, an approximately 9 km-thick body of exposed low-density rock, such as granite, or at the other limit, by a Moho depression of approximately 3 km. The high-wavenumber component of the

anomaly appears to be due to density variations in the upper 5 km of the crust. A 3-dimensional model was generated using the results of the profile modelling to determine initial model parameters.

On the basis of gravity modelling alone, the source of the low-wavenumber component of the anomaly is ambiguous. The radioactivity high corresponding to the gravity low (Figures 13 to 16) and the mapped lithology of the area (Figure 2) support the low-density, intrusive-body hypothesis, whereas the shape of the anomaly and the continuity of the gravity derivative feature linking the Amer Lake and Wager Bay shear zones (Figure 4) support a deeper origin for the mass deficiency causing the anomaly.

Mapping and geophysical responses in the vicinity of the gravity low indicate that surface lithology is quite varied. If the anomaly is caused by a low-density intrusive body, the surface lithology variation may be explained by emplacement in multiple phases, by a stoping process, resulting in a convex-upward intrusive body capped by roof pendants of host rock. The lateral extent of the low-density body required to fit the anomaly decreases with increasing depth, resulting in a body with a funnel-shape (Figures 29 and 30). The depth extent of the low-density body was found to be sensitive to its density contrast with the surrounding rock. Error bounds

of one standard deviation from the mean density of granite resulted in minimum and maximum depth extents of 7 km and 13 km. A density contrast based on mean values results in a depth extent of 9 km.

It was not possible to provide further information on the source of this anomaly without some additional knowledge of the subsurface density distribution. Seismic profiles across the Brown Lake Gravity Low could provide clues on velocity/density changes with depth.

Aeromagnetic and gravity data were used to interpret the structure of the Wager Bay and Amer Lake Shear Zones in Chapter 7. Regional geophysical images revealed that characteristic magnetic and gravity anomalies were associated with the two shear zones. First-vertical-derivative images, generated from the magnetic data gridded at a 200 m interval (Figures 11 and 12), proved particularly useful for enhancing low-amplitude high-wavenumber anomalies related to the shear zones. It was concluded that the regional magnetic and gravity anomalies south of the WBSZ and ALSZ are related to the high grade rocks found there. Linear magnetic anomalies following the shear zones were attributed to magnetite that recrystallized during retrograde metamorphism.

An attempt was made to model the gravity anomaly south

of the Wager Bay Shear Zone using a body with density contrast estimated from a small number of density measurements. The observed anomaly was found to have a larger north-south extent than could be generated by a body with positive density contrast representing the granulite gneiss, and an additional body of intermediate density between the host rock and granulite gneiss was required to fit the observed anomaly. Since the density of the granulite gneiss was poorly constrained and the profile was interpolated from widely-spaced gravity stations, neither the depth extent nor the dip of the shear zone could be accurately modelled using the gravity data. Mean values for density indicated a depth extent of approximately 3 km and a steep southerly dip (Figure 31a). Modelling of the magnetic data allowed the geometry of the granulite-gneiss and shear zone to be determined more accurately. Modelling of the magnetic data indicated the Wager Bay Shear Zone dips 85° to the south (Figure 31b). Although the lack of rock properties measurements precluded an accurate depth estimate for the body, the maximum depth of the body was inferred to be immediately south of the shear zone.

The magnetic anomaly south of the Wager Bay Shear Zone appears to be on strike with a similar anomaly south of the Amer Lake Shear Zone, but on the regional Bouguer gravity intensity image (Figure 3) anomalies south of both shear zones

do not appear to be connected. However, on the image generated from the first vertical derivative of Bouguer gravity (Figure 4), the masking effect of the Brown Lake Gravity Low was removed, revealing a continuous zone of positive gravity gradient connecting the two shear zones. The continuity of the gravity and magnetic anomalies connecting the shear zones was interpreted as evidence that the two shear zones may be connected. Subsequent deformation may have obscured evidence of the initial strain.

The depth and lateral extent of the body generating the potential field anomalies south of the shear zones indicate that the Amer Lake and Wager Bay Shear Zones are major structural features resulting from an important deformational event. More detailed mapping of the area surrounding the Amer Lake Shear Zone is required to test the hypothesis presented here and to provide improved constraints on the interpretation. Higher resolution gravity and magnetic profiles across both shear zones would allow more accurate modelling of the potential fields. The effect of elevation variations in the vicinity of the Wager Bay Shear Zone should also be considered in future potential field modelling.

This study has shown how computers can significantly facilitate both qualitative and quantitative interpretation of geophysical data. It has also demonstrated that the result

of an integrated interpretation is greater than the sum of the parts. Geophysical observations can be used to extrapolate geological information obtained from a small area. Computer-generated imagery is very useful for this purpose but the interpreter must understand each geophysical method before an reasonably constrained interpretation can be made.

Finally, the importance of ground geological mapping is apparent. Rock identification, rock property measurements, and surface mapping are important for a well-constrained interpretation of the geophysical data. The geological results of this study have been limited by a lack of geological data in key regions.

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APPENDIX A

DATA SOURCES AND COMPILATION METHODS

Standard Grid

The gravity, aeromagnetic, and gamma-ray spectrometry data were interpolated on to a standard grid to facilitate comparison of the different data sets and allow the generation of composite images. The Lambert Conformal projection was used with the central meridian at 88°N longitude and southern and northern parallels at 64.667°W and 67.333°W respectively. In order to cover the entire study area with a rectangular grid, the boundaries were extended beyond the geographic limits of the study area to allow for projection curvature. The corner coordinates of the grid were in latitude-longitude pairs : 63.777°N, 95.944°W; 67.930°N, 97.351°W; 67.930°N, 78.678°W; 63.778°N, 80.072°W. The grid dimensions are 952 columns by 576 rows.

Gravity Data

Gravity station spacing in the survey area is on average 8 to 12 km. Measurements for all of Canada are stored in a

database on a Cyber 730 mainframe computer and maintained by staff of the Geophysical Data Centre, Geophysics Division, GSC. A formatted listing of the original gravity station data, which were used for 3-dimensional gravity modelling, and a 812.8 m grid of Bouguer-corrected data were obtained from the Geophysical Data Centre for the study area. The Bouguer correction was made by assuming a crustal density of 2670 kg m^{-3} .

Interpolation of irregularly-spaced gravity measurements to a regular grid was achieved using the GINTPF procedure from the Uniras Geoint Package (Ver. 5). The GINTPF procedure uses a combination of double-linear interpolation, slope calculations, quadratic interpolation and smoothing, to define a smooth surface that fits the data. The gravity grid was generated using the VAX 11-780 minicomputer, which was also used for subsequent processing, so conversion to the standard format only involved reordering of the grid values from row order to column order and the addition of a standard header.

Magnetic Data

Total field aeromagnetic data for most of the Canadian Shield have been collected along regularly-spaced lines at a

sampling interval of 40 to 100 m. In areas of moderate relief, such as the study area, data were collected at constant terrain clearance. Standard specifications for regional data collection call for 800 m line spacing and 305 m mean terrain clearance (Hood and Ready, 1976). The raw survey data were then corrected and interpolated on to a regular grid. Corrections to the data included removal of levelling errors caused by diurnal variations, aircraft elevation variations and magnetometer drift, and adjustments for flight-path-recovery errors.

In the national aeromagnetic database information is stored both in flight-line form and as 812.8 m grids based on standard Lambert Conformal projections. All data are continued to a mean terrain clearance of 305 m and have the 1985 International Geomagnetic Reference Field (IGRF) removed (Cain et al., 1967). The IGRF is a 10th order spherical harmonic function designed to approximate the core-generated magnetic field of the Earth. The procedures used to create the database and the resulting series of 1:1 000 000 scale magnetic anomaly maps are described in detail by Dods et al. (1985).

Since the study area corresponds to GSC magnetic anomaly map NQ 15-16-17-M, the aeromagnetic data were readily available from the Geophysical Data Centre, GSC.

Gamma-ray Spectrometry Data

Airborne gamma-ray spectrometry surveys are conducted in a similar manner to aeromagnetic surveys. In gamma-ray spectrometry, gamma radiation from material near the Earth's surface generates light pulses in sodium iodide crystals. The light pulses are converted to electrical impulses by photomultiplier-detectors. The electrical impulses are then sorted by energy level and counted. The three principal naturally-occurring radioactive elements, uranium, thorium, and potassium, have decay products or isotopes which produce gamma radiation in particular energy ranges, indicative of the concentration of each element near Earth's surface. Determination of ground concentrations is complicated by some overlap in the responses of the different isotopes, attenuation of gamma radiation by the air, gamma radiation originating from radon in the atmosphere, and other factors. The methods used for the collection and compilation of gamma-ray spectrometry data at the GSC are described in more detail by Grasty (1972, 1979).

Gamma-ray spectrometry data were collected for most of the Canadian Shield under the Canadian Uranium Reconnaissance Program (Darnley et al., 1975). The survey specifications for the program were 5 km flight-line spacing, 135 m terrain

clearance, 200 km h⁻¹ aircraft speed, and sodium iodide crystals with a total volume of 50 l. Although the data have not been compiled into a computer database, they are archived in digital form on tapes supplied by the various survey contractors.

The staff of the Airborne Radiometrics Section, Mineral Resources Division, kindly initiated a special project to compile gamma-ray spectrometry data for this study. Within the study area all lines were flown in a north-south direction. Unfortunately, data were not available for the area south of Wager Bay and east of 90°W longitude, or for Southhampton Island. Data were retrieved from archival tapes, corrected using standard methods, and interpolated on to the standard grid. Separate grids were produced for; equivalent uranium, equivalent thorium, potassium, and gamma-ray total count. Final processing required to convert the data to standard format involved transferring the data from a Data General MV-4000 minicomputer to the VAX-8700 minicomputer and addition of a header.

APPENDIX B

FILTERING

First-vertical-derivative and continuation filters were applied to the gridded data in the wavenumber domain. In the wavenumber domain, data are described in terms of wavenumber or cycles per sampling interval.

A two-dimensional Fourier transform (Hall, 1979) is defined for discrete functions as

$$F(u,v) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) \exp [2\pi i (ux/M + vy/N)]$$

where $F(u,v)$ = complex Fourier transform of $f(x,y)$
 M,N = number of grid cells in the x and y directions
 u,v = wavenumbers in the x and y directions

In this study, gridded data were transformed into the wavenumber domain by a discrete algorithm called the 2-dimensional Fast Fourier Transform (FFT; Cooley and Tukey, 1965). From the fundamental sampling theorem (Hall, 1979), it can be shown that the highest resolvable wavenumber, or Nyquist wavenumber, is 0.5 cycles per sampling interval. Wavenumbers higher than 0.5 will be reflected, or aliased,

back into the wavenumber spectrum at a lower wavenumber. The possible range of wavenumbers is therefore from 0, for a constant component, to 0.5 cycles per sampling interval.

Degradation called Gibb's phenomenon occurs at the edges of the grid when perimeter values are unequal. To minimise this effect, the minimum grid value was subtracted from the grid, the grid dimensions were expanded and the perimeter values from the original grid were rolled off exponentially to zero within the expanded area. A grid expansion of 4% was found adequate to remove any visible evidence of Gibb's phenomenon.

Filters were applied in the wavenumber domain by multiplying the wavenumber domain representation of the data by a transfer function corresponding to the filter (Clement, 1973). First-vertical-derivative and continuation filters are radially symmetric allowing the filters to be easily defined and illustrated in radial section.

After the filter was applied, the data were returned to the space domain by application of an inverse FFT. The expanded part of the grid was removed and the average value removed from the data was added back.

Continuation Filters

The continuation operator (Henderson, 1960) is radially symmetric and defined in the wavenumber domain as

$$T_c(r) = \exp(hr)$$

where

h - continuation distance in units of grid spacing
(negative for upward continuation)
r - wavenumber (from 0 to 0.5)

Upward continuation results in an exponential decrease in the intensity of high-wavenumber components. The wavenumber response of the upward continuation operator used to produce Figures 11 and 12 is shown in Figure 33.

First Vertical Derivative

The first-vertical-derivative of potential field data (Grant and West, 1965) was calculated using a radially symmetric operator defined in the wavenumber domain as

$$T_d(r) = 2\pi r.$$

Figure 33: Response of 5 km upward continuation operator in the wavenumber domain.

A study by Paine (1986) indicated that errors of up to $\pm 13\%$ could be expected for vertical gradient values calculated by this method. Errors of this size are acceptable since the data will only be used for qualitative interpretation.

The linear relationship between the first vertical derivative transfer function and wavenumber results in the

amplification of high-wavenumber anomalies often enhancing noise in the data. For the gravity derivative data, some of the noise was generated during interpolation of irregularly-spaced gravity measurements onto a regular grid. This noise was removed by application of a low-pass filter with a cutoff wavenumber of 0.08 and a roll off of 0.05. The cutoff wavenumber corresponds to slightly less than twice the minimum gravity station spacing to ensure that there was no degradation of significant anomalies. The combined filter transfer function for the vertical-derivative operator and

Figure 34: Response of combined 1st vertical derivative and lowpass filter in the wavenumber domain.

low-pass filter used to generate the vertical gravity derivative image is shown in Figure 34.

APPENDIX C
STATISTICAL ANALYSIS OF DENSITY MEASUREMENTS
IN THE BROWN LAKE AREA

The selected rock samples were grouped to match the three mapped geological units: mixed gneiss, granitic gneiss and granite. The location, density, and field description of each sample is listed in Table 3. Mean and standard deviation values calculated for the 3 groups are shown in Table 4. The two groups of gneiss densities were combined to represent a single gneiss unit. The mean and standard deviation of the combined gneiss densities are also shown in Table 4.

The significance of the difference between the mean densities of the granites and gneisses was tested using standard methods. The critical ratio (CR) for difference between means is

$$CR = \frac{X_a - X_b}{\sigma} \quad \text{where}$$

$$\sigma = [(\sigma_a^2/N_a) + (\sigma_b^2/N_b)]^{\frac{1}{2}}$$

and

X_a	=	mean of distribution A
X_b	=	mean of distribution B
N_a	=	number of samples in group A
N_b	=	number of samples in group B

σ = standard error of the difference between
 means of distributions A and B.
 σ_a = standard deviation of group A
 σ_b = standard deviation of group B

Substituting values from Table 2 gives;

$$\sigma = [((78.3)^2/31) + ((26.8)^2/22)]^{1/2}$$

$$= 15.2$$

$$CR = \frac{(2716 - 2637)}{15.2} = 5.21$$

To determine if the average gneiss density is significantly greater than the average granite density the calculated critical ratio was compared to right-tail areas tabulated for the student t-distribution. The t-distribution was used because the number of samples was small. The t-distribution table indicates that for 99.5 % confidence and 22 degrees of freedom the critical ratio must exceed 2.819. Therefore, with greater than 99.5 % confidence the average density of the gneisses can be stated to be greater than the average density of the granites.

Table 3 : Density measurements for the Brown Lake area

GSC sample	latitude (deg.)	longitude (deg.)	density (kg m ⁻³)	description
Granites :				
JD085	66.32	88.00	2660	fg. mg. granite
JD086	66.32	88.14	2620	granite
JD087	66.34	88.58	2628	foliated granite
JD089	66.31	88.94	2605	fg. leuco. granite
JD091	66.30	89.25	2635	mg. pyr. granite
JD098	66.22	89.51	2640	cg. pyr. granite
JD099	66.24	89.36	2622	mg. msv. granite
JD100	66.20	89.25	2624	mg. cg. granite
TJ064	66.35	91.82	2610	f. g. b. granite
BL173	65.79	91.79	2664	pyr. granite
BL174	65.71	91.89	2624	pink granite
BL172	65.77	91.56	2635	pink granite
BL175	65.71	91.73	2637	mottled pink granite
BL176	65.63	91.55	2626	red granite
BL163	65.67	90.82	2686	cg. pyr. granite
BL167	65.67	90.66	2617	leucocratic granite
BL166	65.67	90.43	2723	bi. hb. granite
DF047	66.07	88.77	2641	foliated granite
DF054	66.14	89.80	2623	granite
DF049	66.06	89.22	2642	foliated granite
DF055	66.14	89.63	2627	granite
DF056	66.14	89.58	2634	pyr. granite
Granitic gneiss :				
DF045	66.06	88.29	2665	granitic gneiss
DF052	66.02	89.93	2628	granitic gneiss
JD105	66.20	88.45	2653	grnt. augen gneiss
JD106	66.23	88.25	2670	granitic gneiss
JD107	68.18	88.05	2636	granitic gneiss
JD108/2	66.28	88.05	2679	granitic gneiss
JD101	66.23	89.00	2657	granitic gneiss
BL424	65.09	89.55	2660	grnt. grdr. gneiss
JD119	65.35	89.37	2687	grnt. grdr. gneiss
JD110	65.71	89.75	2686	granitic gneiss
BL185	65.59	90.67	2715	granitic gneiss
Mixed gneiss :				
JD095	66.31	89.92	2685	granodiorite gneiss
JD088	66.29	88.12	2724	mg. bi. gndr. gneiss
JD096	66.24	89.93	2693	granodiorite gneiss
JD103	66.22	88.74	2673	granodiorite gneiss
continued ...				

JD104	66.20	88.65	2702	mg. cg. gndr.gneiss
DF046	66.06	88.53	2647	bi. gndr. gneiss
DF048	66.01	88.87	2758	bi. gndr. gneiss
DF044	66.05	88.00	2738	bi. grdr. gneiss
BL036	65.36	87.95	267	bi. gndr. gneiss
DF060	66.15	88.45	267	bi. gndr. gneiss
DF058	66.15	89.17	2696	bi. gndr. gneiss
BL179	65.63	91.90	2873	bi. hb. gneiss
BL180/2	65.54	91.78	2729	bi. gndr. gneiss
BL181/1	65.54	91.56	2834	layered b/w gneiss
DF050	66.05	89.50	2713	mafic gneiss
DF051	66.06	89.66	2995	mafic gneiss
DF053	66.13	89.93	2858	hb.-rich gneiss
BL425	65.09	89.85	2781	banded mafic gneiss
BL435	65.18	89.89	2686	banded grdr. gneiss
JD117	65.80	89.17	2746	layered mafic gneiss

Table 4 : Density statistics for the Brown Lake area

units = kg m ⁻³	number of samples	mean	standard deviation
granites	22	2637	26
granitic gneiss	11	2667	24
mixed gneiss	20	2744	98
combined gneiss	31	2716	78

APPENDIX D
STATISTICAL ANALYSIS OF DENSITY MEASUREMENTS NEAR
THE WAGER BAY SHEAR ZONE

The density of 31 samples from the Wager Bay area were measured to help constrain gravity modelling of the Wager Bay Shear Zone (WBSZ) and the granulite terrane to the south. Representative rock samples were selected by Dr. Jack Henderson of the GSC for the area to the north of the shear zone, for the shear zone itself and for the area south of the shear zone (Table 5).

Table 5: Density measurements for the Wager Bay area

GSC Sample	density (kg m ⁻³)	description
<hr/>		
Country Rocks from North of the Shear Zone		
5HS094-2	2670	pink granite
5HSS004	2620	aplite dike
5HS017	2680	gneiss
5HSS001-2	2630	granitic gneiss
5HSS003	2680	gneiss
5HSM024	2680	gneiss
5HS006	2660	radioactive pink granite
Rocks from the Wager Bay Shear Zone		
6HSA007	2690	mylonite
6HSA008	2660	mylonite
6HSA010	2680	mylonite
continued ...		

6HSA006-2	.....	2810	.....	mylonite
5HS083	...	2700	.....	mylonite
6HSA005	..	2690	.....	mylonite
6HSA012-3	.....	2820	.....	mylonite
6HSA023	.....	2730	.....	gneiss with phenocrysts
5HS043-B	.....	2630	.....	mylonite
5HS045	.....	2650	.....	mylonite
5HS049	.....	2750	.....	banded mylonite
6HSA006-1	.....	3270	.....	mylonite with garnets

Rocks from south of the shear zone

6HSA019-2	.....	2670	.....	granulite gneiss
6HSA014-1	.....	2710	.....	granulite gneiss
6HSB026	.....	2780	.....	granulite gneiss
6HSB038	.....	2700	.....	granulite gneiss
6HSB043	.....	2580	.....	granitic gneiss
6HSA016-2	.....	2660	.....	granulite gneiss
6HSA015-1	.....	2750	.....	granulite gneiss
6HSA017-2	.....	2670	.....	gneiss
6HSA046	.....	2690	.....	granulite gneiss
6HSA047	.....	3100	.....	garnet gneiss
6HSA050	.....	2650	.....	granulite gneiss
86CE22	.....	3020	.....	granulite with garnet

The number of samples, mean density and standard deviation are shown for each group in Table 6.

Table 6: Density statistics for the Wager Bay area

units = kg m ⁻³	number of samples	mean	standard deviation
north of WBSZ	7	2660	23
within WBSZ	12	2757	165
south of WBSZ	12	2748	148

The mean density of the samples collected within the WBSZ and south of the WBSZ are similar and are greater than the mean density of samples collected north of the WBSZ.

The significance of the high mean density of samples south of the WBSZ relative to samples north of the WBSZ was tested using the method described in Appendix C. The critical ratio was calculated to be approximately 2.0. The t-distribution table indicated that the critical ratio must exceed 1.90 for 95 % confidence and 7 degrees of freedom. Since the calculated critical ratio exceeds 1.90, the samples collected south of the WBSZ are denser than those collected north of the WBSZ at the 95 % confidence level.

APPENDIX E**GLOSSARY**

aliasing	An ambiguity in the frequency represented by sampled data. Where there are fewer than two samples per cycle, an input signal at one frequency yields the same sample values as another frequency and hence appears the same as the other frequency at the output of the system.
Bouguer gravity	Gravity data which has been corrected for latitude, elevation, the attraction of the rock between the datum and the plane of measurement
cyan	One of the three subtractive primary colours (corresponding to a mixture of pure green and blue)

free air gravity

Gravity data which has been corrected for latitude and elevation but not the density of the rock between the datum and the plane of measurement

horse

A displaced rock mass which has been caught inside a fault or shear zone or between two faults.

hue

The attribute of colours that allows them to be classed as red, blue, green or any intermediate of these colours.

magenta

One of the three subtractive primary colours (corresponding to a mixture of red and blue)

nanotesla

A unit of magnetic flux density. A nanotesla = 10^{-9} tesla = 1 gamma.

quantization

In image processing, to subdivide the range of the data to be imaged into a discrete number of levels.

- reflectance** The fraction of the incident light which is reflected from an object or surface back to the observer.
- saturation** A measure of how deep a colour is or, more precisely, for subtractive colours, the degree of difference from the grey having the same lightness.
- wavenumber** A measurement of spatial frequency. The number of wave cycles per unit distance. (The reciprocal of wavelength)

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