A GEOPHYSICAL INVESTIGATION OF THE ELY GREENSTONE BELT IN THE SOUDAN AREA, NORTHEASTERN MINNESOPTA:
A PRELIMINARY INVESTIGATION FOR THE PROPOSED DEEP UNDERGROUND SCIENCE AND ENGINEERING LABORATORY (DUSEL), THE UNIVERSITY OF MINNESOTA

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ABSTRACT

Gravity and magnetic data were used investigate the subsurface structure of the Ely Greenstone belt in the vicinity of the DUSEL site in Northeastern Minnesota. The main part of the work consisted of regional-scale gravity and magnetic model studies along 5 profiles, which were constrained by rock property determinations of density, magnetic susceptibility, and natural remanent magnetization (NRM). The results indicate that the steep northward dips that are observed at the surface persist at depth, and the greenstone belt extends down to roughly 5 kilometers depth, or possibly more. It is reasonable to assume that the major geologic units of the greenstone belt extend down to similar depths. The results of the model studies imply that major changes in greenstone belt stratigraphy or structure should not be expected at the 2.5 km depth that is currently proposed for the DUSEL site.

Model studies to the west of the Tower-Soudan anticline, a major fold in the Ely Greenstone sequence, imply that rocks of the Ely Greenstone sequence do not extend to the west, beneath relatively younger Lake Vermilion Formation. Anomaly sources in this region most likely reflect minor stringers of iron formation within the Lake Vermilion Formation or intrusive rocks below the Lake Vermilion Formation.

A detailed gravity profile was conducted to investigate the continuity at depth of the Sugar Mountain diorite, a sill-like unit that has been proposed as a principal host for underground galleries. Unfortunately the diorite itself does not appear to have a distinctive gravity signature, and consequently nothing can be discerned regarding thickness variations of this unit with depth. The apparent lack of a gravity signature is supported by rock property data, which shows that dioritic rocks in the area has nearly the same average density (2830 SI) as the massive pillowed flows of the Central Basalt sequence to the north (2840 SI). Minor variations observed along the profile most likely reflect variations in thickness of the glacial deposits and the road fill, and not deep structure. However, detailed profiling might still provide us with some information on the subsurface geometry of the contact of the diorite with the Five Mile volcanic sequence to the south, which according to the rock property data has a lower average density (2760 SI). Gravity profiling in the DUSEL area may also tell us something about the thickness of glacial deposits in areas lacking outcrop, which may be pertinent to evaluating potential drill-hole sites.

INTRODUCTION

This report summarizes geophysical work that was conducted as part of a preliminary evaluation of a proposed site for a Deep Underground Science and Engineering Laboratory (DUSEL, Figure 1), located adjacent to the Soudan Underground Laboratory in northeastern Minnesota. The purpose of this study is to use geophysical methods to investigate the geologic structure at depth in the region surrounding the DUSEL site, and to see if geologic units and structures recognized at the bedrock surface can be reliably extrapolated to the 1.5 to 2.5 km depths being proposed for the

DUSEL facility. Gravity and magnetic methods were selected for this investigation for two reasons: (1) The geologic bodies in the area are commonly associated near-vertical contacts and strong contrasts in density and magnetization, resulting in strong and interpretable gravity and magnetic anomaly signatures, and (2) state-wide gravity and magnetic databases already exist at MGS, which can be used for the DUSEL investigation with minimal acquisition of new data.

In their selection of the proposed DUSEL site (Figure 1) Peterson and Patelke (2003) recognized rock units that are potentially favorable hosts for the underground tunnels and galleries, but little is actually known about the extension of these and adjacent units to the 1.5 to 2.5 km. depths that are being considered for the DUSEL facility. Direct observation of underground geology is available nearby at the Soudan Mine and the adjoining Soudan Underground Laboratory, but these facilities only afford a view to depths of about 710 meters. In this study we will investigate the basic structure of the greenstone belt to several kilometers depth using model studies of gravity and magnetic anomalies. Such an approach is subject to considerable ambiguity, in that a variety of sources with varying properties and shapes can be advanced to fit a given anomaly, but ambiguity can be reduced significantly through use of rock property data and geologic control at the bedrock surface.

This investigation is on a fairly broad scale, with modeling along 5 selected profiles (Figure 1), and it depends primarily on pre-existing gravity and magnetic data. Detailed gravity profiling was originally planned at the DUSEL site, in order to investigate the subsurface structure of the Sugar Mountain diorite. However, legal access to the property was not granted by the land-owner in time for this project, and an alternative profile was acquired to the east of the DUSEL site (Figure 1), across an eastern extension of the diorite. This profile is described in greater detail below.

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GENERALIZED GEOLOGY

The area selected for this study lies within the greenstone-granite terrane of the neo-Archean (ca. 2700 my) Wawa Subprovince of the Canadian Shield and is roughly centered over the DUSEL site (Figures 1 and 2). Detailed geologic mapping by Peterson and Patelke, 2003) at the DUSEL site, as well as regional-scale mapping by previous workers (Southwick, 1993; Sims and Southwick, 1980; Sims and Southwick, 1985; Peterson and Jirsa; 1999; Jirsa and Boerboom, 2003; Jirsa and Miller, 2004) in the surrounding region, reveal that a large part of the area is underlain by rocks associated with the Ely Greenstone (Figure 2), a belt consisting chiefly of metamorphosed volcanic rocks which have been deformed so that original bedding stands nearly vertical. In the Soudan area the Ely Greenstone has been tightly folded and slightly overturned southwards into what is known as the Tower-Soudan Anticline (Figure 2), and bedding along both limbs of this anticline are inclined 70-80 degrees to the north (Peterson and Patelke, 2003; Sims and Southwick, 1980). The volcanic rocks of the Ely Greenstone are divided into a lower and upper sequence, with the lower sequence consisting chiefly of pillowed and and massive basalt and andesite flows, and the upper sequence consisting chiefly of pillowed to massive basalt flows with minor iron-formation (Peterson and Patelke, 2003; Sims and Southwick, 1985). The upper and lower volcanic sequences of the Ely Greenstone are separated by the Soudan Iron Formation (Figure 2), a 50 to 3000-meter unit that is transitional with the lower volcanic sequence, which consists chiefly of banded iron-formation, epiclastic rocks and tuff.

In the area that was to be selected as the DUSEL site, Peterson and Patelke (2003) recognized two sub-units of the lower Ely Greenstone volcanic sequence, the Central Basalt sequence, and the Fivemile Lake sequence (Figure 2). The Central Basalt sequence consists chiefly of pillowed and massive basalt flows, with lesser amounts of foliated basalt, tuff and iron-formation, whereas the Fivemile Lake sequence consists of a more heterogeneous mixture of basaltic to rhyolitic flows and breccias. The two volcanic sub-units are locally separated by the Sugar Mountain diorite (not shown in Figure 2), a sill-like mass of medium grained and well-indurated diorite. The selection of this area as the DUSEL site was based on the geology observed here; the massive Central Basalt Sequence appeared to be a suitable host for access tunnels, whereas the tough Sugar Mountain diorite appeared to be a suitable host for underground galleries.

A variety of neo-Archean rocks flank the Ely Greenstone in the study area (Figure 2). To the immediate south and west lie stratigraphically younger rocks of the Lake Vermillion Formation, which consist chiefly of metamorphosed sedimentary rocks of volcanic provenance. To the north, across the Mud Lake shear zone, lie mafic to ultramafic metavolcanic rocks and metasedimentary rocks of the Newton belt (Bass Lake sequence and Newton Lake Formation). Further north, across the Vermilion Fault, lie migmatized granites and schists of the Vermilion granitic complex (Figure 2). Southeast of the Soudan area, rocks of the Ely Greenstone and Lake Vermilion Formation are cut by granitic rocks of the Giants Range batholith (Figure 2). Model studies elsewhere in the Wawa Subprovince indicate that contacts associated with the Giants Range Granite appear to stand nearly vertical (Chandler, 1993 and Chandler and others, 2003). The southeastern corner of the current study area is underlain by a variety of Proterozoic rocks, including the low-dipping sedimentary rocks of the Paleoproterozoic Virginia Formation and Biwabik Iron Formation, as well as mafic intrusive rocks of the Mesoproterozoic Duluth Complex (Figure 2).

DENSITY, MAGNETIC SUSCEPTIBILITY, AND NATURAL REMANENT MAGNETIZATION (NRM) DATA

Geologic interpretation of gravity and magnetic anomaly data in a given area is greatly enhanced by density and magnetization data for representative rock-types. Rock property data help in relating anomaly signatures to probable rock units, and thereby provide essential constraints for using anomaly data to model geology at depth. Unfortunately, the existing rock property database at the MGS (Chandler and Lively, 2003) is fairly sparse in the DUSEL area (Figure 1), including only 120 determinations of density, 156 determinations of magnetic susceptibility, and 15 measurements of natural remanent magnetization. Consequently, considerable effort was made on expanding the rock property database for the DUSEL area.

Some data for this study were derived from unpublished records of rock property measurements, and some data were based on new measurements of previously collected rock samples. Unpublished data include a series of magnetic susceptibility and natural remanent magnetization (NRM) determinations that were taken in the 1950’s and 1960’s by G. D. Bath and C. E. Jahren of the U. S. Geological Survey, and a suite of density determinations that were taken in the 1960’s by R. J. Ikola of the Minnesota Geological Survey. New rock-property measurements were conducted on rock samples that are on-file at the MGS, including density measurements on samples from the Bath-Jahren study mentioned above, as well a density and magnetic susceptibility measurements on samples that were collected for earlier mapping projects in the Soudan area (Southwick, 1993; Sims and Southwick, 1985). Measurements at MGS were made using a Jolly balance for density and an EDA instruments model K-2 meter for magnetic susceptibility. The sample sites for all the new data were geographically recovered from field notes and maps, and were combined with the existing rock property data (Chandler and Lively, 2003) to form a new, GIS-compatible database (Appendix A, Figure1). The rock properties of the major geologic units from this database are summarized in Table 1.

A second rock property database focuses on the detailed geology around the DUSEL site. Measurements for this database were conducted at NRRI, and were based on samples that were collected as part of the geologic mapping project by Peterson and Patelke (2003). Density determinations were conducted on selected hand samples using mass and water- displacement measurements, and magnetic susceptibility determinations were conducted on virtually all hand samples using a model KT-9 Kappameter magnetic susceptibility meter. The resulting database (Appendix B, Figure 1), includes 171 determinations of density and 552 determinations of magnetic susceptibility, and the properties of the major geologic units at the DUSEL site is summarized in Table

A cursory examination of NRM data (Appendix A) revealed commonly weak magnetizations and widely scattered directions for the Archean rocks in the study area. Unstable NRM of this sort is typical for similar-aged rocks over the Lake Superior region (Chandler, 1993), and it is probably safe to ignore its net contribution to producing the observed anomalies. Thus, magnetic susceptibility will be the key property in the magnetic anomaly interpretations to follow.

DESCRIPTION OF THE GRAVITY AND MAGNETIC DATA

Gravity Data

The pre-existing gravity data used in this study are part of a statewide database that was compiled from various sources by Chandler and Schaap (1991). Gravity stations typically are located at spot elevations on 7.5-minute topographic sheets and are spaced from 0.5 to 1.0 mile apart along all drivable public roads and trails. These roads are spaced approximately from 1 to 2 miles apart in developed areas, and from 3 to 6 miles apart in remote areas. An additional 41 gravity stations were added to the database by the author during May, 2005, 22 of which were to help fill a few large gaps in areal coverage, and 19 of which to conduct a detailed profile (Figures 1 and 3) across the Sugar Mountain diorite, as described above. The new stations were acquired, using LaCoste Romberg gravity meter number 320, with horizontal location provided by a Brunton model MNS Global Positioning System (GPS) unit, which includes an altimeter. Elevations were determined by cross-checking altimeter elevations with those determined from topographic map contours at GPS-located points. Because no previously established gravity base stations were available in the Soudan area, a new field base was established using two complete loop ties to a previously established gravity base at Ely, Minnesota. Pertinent base station information is presented in Appendix C.

All gravity data have been reduced using standard procedures. Drift corrections on both the new and old data were conducted by assuming linear segments between base checks, which were generally taken every 2 to 4 hours. The gravity data were converted to milligals using instrument-specific coefficients, and were subsequently reduced according to the 1967 Geodetic Reference System (International Association of Geodesy, 1971), assuming a sea level datum, a Bouguer reduction density of 2.67 g/cm3, and correction for earth curvature. The principal fact gravity data are presented in Appendix D.

Errors vary somewhat between the new and old gravity data. In the new data errors associated with unaccounted drift and reading error were assessed by repeat readings at 5 stations, which indicated a maximum error of +/- 0.03 miligals. Locational (latitude) errors are probably on the order of +/- 10 meters for the new data and +/-200m for the pre-existing data, which would equate to errors of +/- 0.008 and 0.16 milligals, respectively. The elevations of pre-existing stations, which were base on spot elevations on topographic maps are accurate to about 0.3 meter, equating to an error of 0.06 milligals. Most new stations, which depended on topographic contours and altimeter data, probably have a maximum elevation error on the order of 1.0 meters, equating to a Bouguer anomaly error of 0.20 milligals. Because of the low relief in most of the area, terrain corrections were assumed to be negligible. All things considered, the maximum error in the Bouguer anomaly is probably around +/-0.25 milligal for the new data and around +/- 0.30 milligals for the old data. The combined, principal-fact gravity data are presented in Appendix D.

The combined principal fact Bouguer gravity anomaly data were transformed to a 800 meter, UTM grid using a minimum curvature program MINC (Phillips and others, 1997), and for display purposes this was subsequently regridded to a 100-meter grid using the bicubic spline program REGRID (Phillips and others, 1997; Figure 3). The 100-meter grid has a southwest origin with UTM easting of 534,985 meters N. and UTM northing of 5,274,209 meters E. (NAD 83, 500,000 meters false easting), and has 440 rows and 600 columns. The gridded gravity data were enhanced by calculating the second vertical derivative of the anomaly data. Such a procedure sharply attenuates the regional-scale contributions arising from deep-seated sources, and strongly amplifies the short-wavelength features reflecting near-surface geology. Prior to derivation, the Bouguer anomaly gravity grid was slightly smoothed for minor errors and irregularities by upward continuation to 2 kilometers above surface. The second vertical derivative gravity data for our study area are shown in Figure 4. Continued and derivative data grids were generated using the Fast Fourier Transform Filtering (FFTFIL) program, included in the U.S. Geological Survey's potential field software package (Phillips, 1997). The Bouguer gravity and second vertical derivative grids are available in Appendix E.

Magnetic data

The magnetic data used in this study were derived from the high-resolution aeromagnetic survey of the state of Minnesota (Chandler, 1991). All data used in this study were acquired at either a 50 or 75-meter interval along north–south lines that were flown 400 meters apart and 150 meters above the ground surface. East–west tie lines were spaced 4 kilometers apart. Regional geomagnetic field removal was based on the International Geomagnetic Reference Field (IGRF). All data were composited into a statewide, 426.72-meter-spaced Lambert Conformal grid, which has a central meridian at 93° W., a base latitude of 33° N., and parallels of 33° N. and 45° N. Additional details on survey and compilation specifications are given by Chandler (1991). The grids for this study were converted to a 100-meter-spaced UTM (NAD83) grid (Figure 5) that registers with the gravity grid, as described above, using programs G2XYZ, GENPROJ, and MINC (Phillips, 1997). The gridded magnetic data were enhanced by reducing it to vertical polarization, and subsequently calculating the first vertical derivative of the anomaly data. The first procedure helps place anomalies more directly above their sources, whereas the second procedure sharply enhances the short-wavelength contribution of near-surface geology at the expense of long-wavelength anomalies arising from deep sources. The first vertical derivative magnetic data for our study area are shown in Figure 6. Reduced-to-pole and derivative data grids were generated using the Fast Fourier Transform Filtering (FFTFIL) program, included in the U.S. Geological Survey's potential field software package (Phillips, 1997). The magnetic and first vertical derivative magnetic grids are available in Appendix E.

INTERPRETATION OF GRAVITY AND MAGNETIC GRIDS

Bouguer Gravity Data

The Bouguer gravity anomaly expression in the Soudan area (Figure 3) is dominated by the strongly positive signature that is associated with the Ely Greenstone. This gravity high stands 25-30 milligals above the adjacent gravity lows and doubtlessly reflects the generally high densities of the associated volcanic rocks and the Soudan Iron Formation (Tables 1 and 2). Correspondingly the flanking gravity lows reflect the low to moderate densities of metasedimentary rocks of the Vermilion Lake Formation and the granitic rocks associated with the Giant's Range batholith (Table 1). The locally steep gradients between the positive and negative gravity signatures are consistent with steeply-inclined contacts. .

The second-derivative-enhanced gravity anomaly data (Figure 4) sharpen the signature of the Ely Greenstone belt as well as that of several adjacent features. The zero level closely follows many geologic contacts (Figures 2 and 4), which is consistent with a near-vertical geometry for the contacts. The north and south limbs of the Tower-Soudan anticline are characterized by strongly positive signatures, with that of the south limb being the strongest (Figure 4). A relative low in the second derivative gravity data is evident between the two limbs of the Tower-Soudan anticline just southeast of the detailed gravity profile (Figures 1 and 4); according to the detailed mapping by Peterson and Patelke (2003), this low corresponds to an area underlain by the Fivemile volcanic sequence (lower Ely Greenstone), schistose rocks associated with the Murray and Mine Trend shear zones, and felsic members of the Soudan iron formation. According to the rock-property data in Table 2, the former two groups of rocks indeed have low average densities, relative to rocks of the Central Basalt sequence (Table 2) and the volcanic rocks of the Upper Ely Greesntone (Table 1). The gravity high associated with the north limb of the Tower-Soudan anticline continues to the northeast to the Ely area, which reflects the high densities of the upper Ely Greenstone volcanic rocks (Table 1), which are dominant here (Figure 2). To the north of the Ely Greenstone belt, a second belt-like high parallels the Ely Greenstone belt (Figure 4), and reflects mafic to ultramafic rocks that are associated with the Newton belt (Figure 2). The rock property data for Newton belt rocks in Table 1 (Bass Lake sequence and the Newton Lake Formation) include some high-density values. Southwards of the Ely greenstone belt, minor highs and lows in the second derivative of gravity signature reflect minor lithologic variations within the Lake Vermilion Formation and the Giants Range batholith (Figures 1 and 4). A rise in anomaly values in the southeast corner of the study area reflects the high-density rocks that are associated with the Mesoproterozoic Duluth Complex (Table 1).

Magnetic Data

The magnetic signature of the area is dominated by the extremely strong, positive signatures that are associated with the strongly magnetic Soudan Iron Formation (Figures 2 and 5). Some of the strongest signatures occur near the nose of the Tower –Soudan Anticline, where amplitudes commonly exceed 10,000 nT. Linear highs with amplitudes of 2,000 nT or less lie to the north of the Ely Greenstone, and correspond to ultramafic sills within the Newton belt (Figures 2 and 5). Considerably weaker anomalies (generally a few 100's nT) characterize the grantic rocks, including those of the Vermilion Granitic Complex in the northern part of the study area and the Giant's Range batholith in the southern and southeastern part of the study area. The subdued magnetic signature to the immediate south and west of the Tower-Soudan anticline reflects the weakly magnetic rocks of the Lake Vermilion Formation (Table 1). The smooth magnetic high west of the Tower-Soudan Anticline reflects an unknown source buried beneath weakly magnetic rocks of the Vermilion Lake formation. The strong, irregular magnetic high in the southeastern corner of the area represents the Paleoproterozoic Biwabik Iron Formation, which has been contact-metamorphosed by emplacement of the Mesoproterozoic Duluth Complex to the southeast (Figure 2 and 5).

Although not a major focus of this study, first vertical derivative- enhanced magnetic data have been a useful supplement for much of the geologic mapping in the region, and a brief description of these data is included here. The first vertical derivative-enhanced magnetic data (Figure 6) better delineate layers and lenses of the Soudan Iron Formation, as well as the ultramafic sills within the Newton belt (Figures 2 and 6). The weak, stringy magnetic highs to the southwest of the Tower-Soudan anticline most likely reflect minor belts of intrusive and metavolcanic rocks within the Lake Vermilion Formation. Sharply bounded bands of highs to the southeast of the Tower-Soudan anticline reflect magnetic phases of the Giants Range Batholith, which are interpreted to locally be fault bounded (Jirsa and Miller, 2004; Figure 2). The derivative-enhanced magnetic data also clarifies the signature of the Biwabik Iron formation and the contact of the Duluth Complex in the southeastern corner of the study area (Figures 2 and 6).

GRAVITY AND MAGNETIC MODEL STUDY

Preparation of the Model Data

Gravity and magnetic model studies were used to investigate geologic structure beneath the study area. Modeling was conducted along five profiles that were positioned to lie roughly at right angles to the bedrock structural grain of the area (Figures 1, 2 3 and 5), and was based on programs from the U. S. Geological Survey software package for potential fields (Phillips, 1997). Anomaly profiles were interpolated at a 400-meter interval from the Bouguer gravity (Figure 3) and total field magnetic (Figure 5) data grids using programs SF2PROF. The observed data for the five profiles are presented in the upper parts of Figures 7 through 11. Modeling was conducted for each profile by using program SAKI, which is a two-dimensional program that assumes strike-infinite sources, although an end correction for finite strike-length is applied where needed. Magnetic modeling was conducted assuming induced magnetization along an earth's field that had an intensity of 59943 nT, a declination of 2.8^{o}E, and an inclination of 75.5^{o}, as derived for the study area using Program

GEOMAG (National Oceanic and Atmospheric Administration, 1995). Demagnetization, which can be pronounced in iron-formations (Bath, 1962), is assumed here to be insignificant; earth's inducing field in the study area is nearly parallel with the steeply-inclined beds of the iron-formation, and the effects of demagnetization should therefore be minimal.

General Constraints on Modeling

Gravity and magnetic model studies are inherently ambiguous, and a variety of models can be made to fit the same set of observed data. This ambiguity can be significantly reduced, however, by incorporating all available geologic control. The bedrock surface has been mapped at a level of detail that is somewhat unusual for Minnesota, and the positions and dips of major faults and contacts can be used to constrain the upper parts of the model. The model studies are further constrained by rock property data, which provide estimates of density and magnetization for most of the major rock units in the area (Tables 1 and 2).

Constraints Based on Magnetic Anomaly Signature

Magnetic modeling can be very effective in determining the upper geometry and the depth to the top of an anomaly source, but it seldom is useful in investigating the deeper parts of a source, in particular its depth-extent. This is largely because the magnetic signatures arising from the deeper parts of the source are most evident on the low flanks and adjoining side-lobes of an anomaly, which are areas that are commonly overwhelmed by the signature of adjacent sources. In the case of the Soudan Iron Formation, however, magnetic signatures are extremely strong, and the flanking rocks, such as the upper and lower volcanic sequences and the Lake Vermillion Formation, are essentially non-magnetic (Tables 1 and 2). Consequently, the low flanks and side-lobes of the iron-formation-related anomalies are clearly discernable, and can be used to help estimate the depth extent of the iron formation, and presumably the entire greenstone belt.

To investigate the effect of depth-extent, a series of synthetic anomalies was created for a thin sheet source that approximated a layer of Soudan Iron Formation. The model sheet, was assigned an east-west strike and a magnetic susceptibility of 0.2512 SI, and was assumed to be polarized along an earth's field with an inclination of 75.5^o, a declination2.8o, and an intensity of 59,943 nT. In order to investigate the effect of dip, two model cases were investigated, one for a vertical sheet and one for a sheet inclined 75^o to the north, with the latter case being in closer agreement with dips observed from geologic mapping. For each case a series of anomaly curves were generated for depth extents ranging 0.01 km to 10 km, and results are presented in Figure 12. The most obvious effect on depth extent in the models is amplitude of the positive anomaly (Figure 12), but in practice, separating the effect of depth extent from the effects of magnetic susceptibility vs. thickness would negate the effectiveness of using amplitude by itself in determining depth extent.

A more reliable indicator of depth extent from the models in Figure 12 appears to be the configuration of the negative side-lobe on the north side of the sheet. On the curves derived for the vertical sheet, a tight negative cloture in anomaly values persists at the north toe of the calculated anomalies (Figure 12 a), which is not observed at the northern side-lobes of the observed magnetic data (Locations A on Figure 7, B on Figure 8, and C and D on Figure 9). On the curves derived for the 75^o North-inclined sheet, this tight negative cloture exists at shallower depth extents, but begins to disappear at a depth extent of about 5 km (Figure 12 b). At greater depth extents the negative side-lobe becomes a broad, flat-bottomed feature that gently rises to the north (Figure 12 b), which more closely resembles the northern side lobes from the observed anomalies (Locations A on Figure 7, B on Figure 8, and C and D on Figure 9). This implies that the steep, northward dips observed at the surface persist at depth, and that the iron formation, and presumably the enclosing greenstone belt, extends downwards on the order of 5 km or more. Consequently, in the model studies to follow a 5 km depth extent is assumed, and most anomaly sources were initially assigned a dip of 75^o north. Source dips, densities, and magnetic susceptibilities were then allowed to vary until suitable fits were attained.

Description of Model Profiles

Profile D (DUSEL MAIN)

Profile D crosses directly through the DUSEL area (Figure 1) and the fitting model (Figure 7) consists of geologically reasonable sources that extend vertically to steeply northwards. Body 1 at the south end of the profile corresponds to an area underlain by the Vermilion Lake Formation, and the moderate density of 2745 SI (kilograms/cubic meter) and zero magnetic susceptibility closely approximates the average values observed from rock property measurements (Table 1). Body 2 corresponds most closely to the upper Ely Greenstone volcanic rocks (Figure 2), and the model density of 2806 SI is somewhat low for the 2952 SI average value from the rock property data (Table 1), although it falls well within the range of observed values. Body 3 most likely represents a zone that includes both lower Ely Greenstone basalts and Soudan Iron Formation, and the very high magnetic susceptibility value (0.0980 SI) implies that the latter unit may be dominant. Bodies 4, 5, 7, 9 and 10, correspond at the surface to areas underlain chiefly by Soudan Iron Formation, and the range of moderate-to high densities (2765-2926 SI) and very strong magnetic susceptibilities (0.2765-0.4616) fall generally within the range of values observed in the rock property data (Tables 1 and 2). The somewhat low value of density for body 10 may reflect some sort of a transition to either the upper Ely Greenstone sequence or to the Lake Vermilion Formation. The steep, northward inclination of Body 10 was important in matching the observed magnetic signature, in particular over the north side of the body (location A in Figure 7). Bodies 6 and 8 correspond to the volcanic rocks of the lower Ely Greenstone Volcanic sequence and the model densities of 2842 and 2846, respectively, fall with the observed range of densities for volcanic rocks of the lower Ely Greenstone sequence (Tables 1 and 2). The model magnetic susceptibility values of 0.1722 and .2050 SI for bodies 6 and 8, respectively, are substantially higher that the values observed for the lower Ely Greenstone sequence in the rock-property data (Tables 1 and 2) and may reflect stringers of iron formation, which are know to occur in the central Basalt sequence (Peterson and Patelke, 2003; Jirsa and Boerboom, 2003).

Bodies 11, 12 and 13 are inferred to represent steeply-inclined sources along the Mud Creek shear zone and the Vermilion Fault.

Profile D-1E (DUSEL 1 EAST)

The model for profile D-1E is dominated by sources that are inclined steeply to the north (Figure 8), implying that the step northward dips observed at and near the surface persist at depth. This northward inclination was useful in matching the observed magnetic data, in particular along the north flanks of anomalies, such as at location B. Bodies 1, 2 and 3 correspond to the Lake Vermilion Formation, and their moderate densities (2741, 2738 and 2747 SI, respectively) and zero magnetic susceptibilities closely match the average density and median magnetic susceptibility values for that formation (Table 1). Body 15 represents upper Ely Greenstone volcanic rocks along the south limb of the Tower-Soudan anticline, and its high density (2926 SI) and zero magnetic susceptibility are consistent with values observed for these rocks in the rock property data (Table 1). Bodies 4, 6, 7, and 9 correspond primarily with the Soudan Iron Formation, although the range of densities (2851-2953 SI) and magnetic susceptibilities (0.2184-0.2815 SI) are somewhat low, compared to the mean and median rock property values for the iron formation in Table 1. These lower values may reflect a component of less dense and magnetic rocks in these zones, such as the hematite-rich phases of the Soudan Iron Formation, or the metavolcanic rocks of the lower Ely Greenstone (Table 2). Intervening bodies 5 and 12 most likely represent lower Ely Greenstone volcanic rocks, which may have enough stringers of iron formation to boost magnetic susceptibility values. Bodies 8 and 16 correspond with the lower Ely Greenstone sequence volcanic rocks and the moderate to high densities of 2810 and 2885 SI, respectively, compares favorably with the values derived from the rock property data (see values for the Fivemile and Central Basalt sequences in Table 2). The high magnetic susceptibilies of 0.0343 and 0.0478 SI, respectively for these two bodies may reflect scattered stringers of iron-formation. Body 10 most likely represents a mass of upper Ely Greenstone volcanic rocks, whereas bodies 13 and 14 represent Newton belt rocks along the north side of the Mud Creek shear zone (Figure 8). Body 11 represents moderate-density, weakly magnetic rocks of the Vermilion Granitic Complex (Table 1) along the north side of the Vermilion Fault.

Profile D-2E (DUSEL 2 EAST)

The model for Profile D-2E consists largely of bodies that are inclined steeply to the north (figure 9). As with previous models the northward dip of sources was important in matching the observed magnetic signature along the north flanks of anomalies (locations C and D in Figure 9). Bodies 1 and 2 correspond to non- magnetic, granitic rocks of the Giant's Range Batholith (Figure 2), although the model densities (2763 and 2780 SI) are a bit higher than the average values presented in Table 1 for these rocks. The higher densities may reflect schist inclusions and diorite enclaves, which are typical for this part of the Giant's Range Batholith (Jirsa and Boerboom, 2003). Body 3 probably represents a combination of the Lake Vermilion Formation and the upper Ely Greenstone volcanic rocks (Figure 1). Bodies 4, 5 and 8 represent the zones that consist chiefly of the Soudan Iron Formation; the range of density (2784 - 2955 SI) and magnetic susceptibility (0.1899-0.2319 SI) for these bodies are considerably lower than the rock-property values given for the Soudan Iron Formation in Table 1, and may reflect the presence of less dense and magnetic rocks, such as the lower Ely Greenstone volcanic rocks (Table 2). Body 6, with a density of 2728 SI and zero magnetic susceptibility represents the encroachment of Archean granitic rocks along the axis of the Tower-Soudan anticline (Figure 1). Body 7, with a density of 2914 and zero magnetic susceptibility, represents volcanic rocks of the lower Ely Greenstone volcanic sequence. Bodies 9 and 10, respectively with model densities of 2975 and 3003 SI and magnetic susceptibilies of 0.1095 and 0.1298 SI, most likely represent upper Ely Greenstone sequence volcanic rocks that include layers of iron-formation (Jirsa and Boerboom, 2003; Table 1). Body 11 most likely represents both upper Ely and Newton belt rocks extending along the Mud Creek Shear zone, whereas Body 12 represents rocks of the Vermilion Granitic Complex north of the Vermilion Fault (Figure 10).

Profile D-1W (DUSEL 1 WEST)

Modeling was conducted along Profile D-1W to investigate subsurface geologic structure to the west of the Tower-Soudan anticline (Figures 2 and 11). The author initially speculated that the broad magnetic highs to the west of the Tower-Soudan anticline (Figure 5) might represent Ely Greenstone sequence rocks that are buried by the non-magnetic Lake Vermilion Formation. Body 13 (Figure 11) along the south end of the profile represents Lake Vermilion Formation, and the model density of 2750 SI and zero magnetic susceptibility agree closely with average values observed for this formation in the rock property data (Table 1). Body 1 has similar properties to Body 13 and most likely also reflects Lake Vermilion Formation. Bodies 2, 12 and 3 represent unknown sources that lie beneath roughly 1 km of Lake Vermilion Formation; the moderate densities and moderate to high magnetic susceptibilities of these bodies, combined with their broad character, are suggestive of intermediate composition intrusive rocks. Bodies 4 and 5 might represent a slightly buried (about 200 meters) extension of Soudan Iron Formation, but their densities (2772 and 2790 SI, respectively,) and magnetic susceptibilities (0.0656 and 0.0951 SI, respectively) are considerably lower that the average and median values observed for the unit in Table 1. It is feasible that bodies 4 and 5 might represent Soudan Iron Formation that is hematite-enriched, such as presented in Table 2, but their densities are still somewhat low for this unit. Perhaps more likely, bodies 4 and 5 represent a member of the Vermilion Formation that includes stringers of iron formation; such rocks have been mapped just to the east of this profile (Jirsa and Boerboom, 2003). Body 6 might represent a buried member of the Vermilion Lake Formation, or it might represent an intrusion similar to one mapped along the Mud Creek Shear Zone near the east shore of Lake Vermilion (Jirsa and Boerboom, 2003). Bodies 7and 8, which has moderate densities (2873 and 2834 SI, respectively and moderate magnetic susceptibilities (0.0464 and 0.0333 SI, respectively), represent metavolcanic rocks of the Newton Belt along the north side of the Mud Creek Shear Zone (Figures 1 and 11). Bodies 9.10 and 11, which have densities of 2774 to 2771 SI and magnetic susceptibilities of 0.0301 to 0.0333 SI represent rocks of the Vermilion Granitic Complex along the Vermilion Fault (Figure 2).

Profile D-2W (DUSEL 2 WEST)

Profile D-2 W was selected primarily to investigate a strong positive magnetic anomaly, whose smooth character implies a buried source (Figure 5). Sims (1972) proposed that the magnetic high reflected intrusive rocks, but, owing to proximity, it could also feasibly reflect a buried sliver of Soudan Iron Formation along the projected axis of the Tower-Soudan anticline. Body 11 at the south end of the profile (Figure 12) represents Lake Vermilion Formation. The large magnetic anomaly is modeled primarily by bodies 2, 3, and 4 whose tops lie beneath 0.5 to 2.0 km of Lake Vermilion Formation. The densities (2732-2807 SI) and magnetic susceptibilities (0.0374-0.0986 SI) for bodies 2, 3 and 4 are a bit low for typical Soudan Iron Formation (Tables 1 and 2), and they may more likely represent intermediate -composition intrusive rocks, as was proposed initially by Sims (1972). Moderately dense and magnetic bodies north of the Mud Creek Shear Zone (Bodies 6-8) most likely represent metavolcanic rocks associated with the Newton Belt. Body 9 most likely represents rocks of the Vermilion Granitic Complex.

RESULTS OF DETAILED GRAVITY PROFILING EAST OF THE DUSEL SITE

The Bouguer gravity anomaly data in Figure 13 were acquired to investigate the subsurface structure of the Sugar Mountain diorite, which was one of the proposed host-rocks for the DUSEL facility. The diorite's massive and tough character made it an ideal candidate hosting underground galleries (Peterson and Patelke, 2003), but it has a thin sill-like character and could feasibly pinch out at depth. Previously-existing rock property data for Wawa Subprovince rocks (Chandler, 1993 and Chandler and others, 2003) indicated that dioritic rocks are generally less dense than the mafic metavolcanic rocks that typify greenstone belts, and the Sugar Mountain diorite could feasibly produce a negative gravity anomaly. This anomaly in turn could be used to investigate the subsurface structure of the diorite through model studies. Access problems precluded acquiring the gravity data across the diorite at the DUSEL site, and the author defaulted to a location about 1 mile to the east (Figures 1 and 3), where an abandoned right-of-way of U.S. Hwy. 169 crossed the eastern extension of the Sugar Mountain diorite (Peterson and Patelke, 2003).

Contrary to initial hopes, the detailed gravity profile indicate that the Sugar Mountain diorite itself does not have a distinctive signature, and the minor variations observed along the detailed profile more likely reflect variations in thickness of the glacial cover and road fill (Figure 13). The lack of a signature for the diorite is consistent with the newly-derived density data (Table 2) that shows that the diorite has essentially the same density as the massive pillowed flows of the Central Basalt sequence to the north. The gravity values along the detailed profile show a progressive rise to the north (Figure 13), reflecting the contact between the relatively lower density FiveMile volcanic sequence to the south and the relatively denser diorite and Central Basalt sequence volcanic rocks to the north (Table 2). A local minimum of about 0.3 milligals occurs at the the southern contact of the diorite, but this is likely an effect of low-density fill over a depression in the bedrock surface, as evidenced by an elongate topographic depression of about 30 feet depth that was observed to the immediate north of the road. This fill may include some glacial deposits, but is more likely to consist chiefly of materials that were used to create the road grade. The depression in the bedrock surface may have been caused a zone of weakness that is associated with the contact of the Sugar Mountain diorite with the Five Mile volcanic sequence. In any case, the results indicate that detailed profiling as initially proposed over the DUSEL site will tell us little about variations in thickness of the Sugar mountain diorite at depth. Such profiling, however, might still be useful in clarifying the subsurface geometry of the contact between the Sugar Mountain diorite and the Five Mile volcanic sequence to the south. The results of the detailed gravity profile also indicate a good sensitivity of to variations in fill thickness on the bedrock surface, and detailed gravity profiling may therefore be a useful tool in determining the thickness of glacial fill in areas where bedrock outcrops are lacking.

CONCLUSIONS

The main part of the work consisted of regional-scale gravity and magnetic model studies of the Ely Greenstone belt in the DUSEL area. Modeling was conducted along 5 profiles, and was constrained by several-hundred rock property determinations that were made at MGS and NRRI. The results indicate that the steep northward dips that are observed at the surface persist at depth, and the greenstone belt extends down to depths of 5 kilometers, or possibly more. It is reasonable to assume that the major geologic units comprising the greenstone belt at the surface extend down to similar depths. Therefore, no major changes in greenstone belt structure are anticipated at the 2.5 km depth that is currently being proposed for the DUSEL facility.

A second part of the project was to conduct detailed gravity profiling over the Sugar Mountain diorite to see if it persists in thickness at depth. A gravity signature was initially expected for the diorite, because diorites generally have a lower density than basaltic greenstones. Due to access problems at the DUSEL site, we could not conduct this profiling, and we defaulted to a test profile along the abandoned stretch of Highway 169 about 1 mile to the west, which also crosses the diorite. The diorite did not appear to have a distinctive signature, which is now supported by rock property data, which surprisingly shows that the diorite has nearly the same density as the massive pillowed flows to the north (about 2.84 gm/cc as I recall). Minor variations observed along our profile most likely reflect variations in thickness of the glacial deposits and the road fill. It therefore appears that detailed profiling at the Dusel site will not tell us much about the thickness of the Sugar Mountain diorite at depth. However, it might still provide us with some information on the contact of the diorite with the Five Mile sequence to the south, which according to the rock property data is lower in density. Gravity profiling in the DUSEL area might also provide information about the thickness of glacial deposits in areas lacking outcrop.

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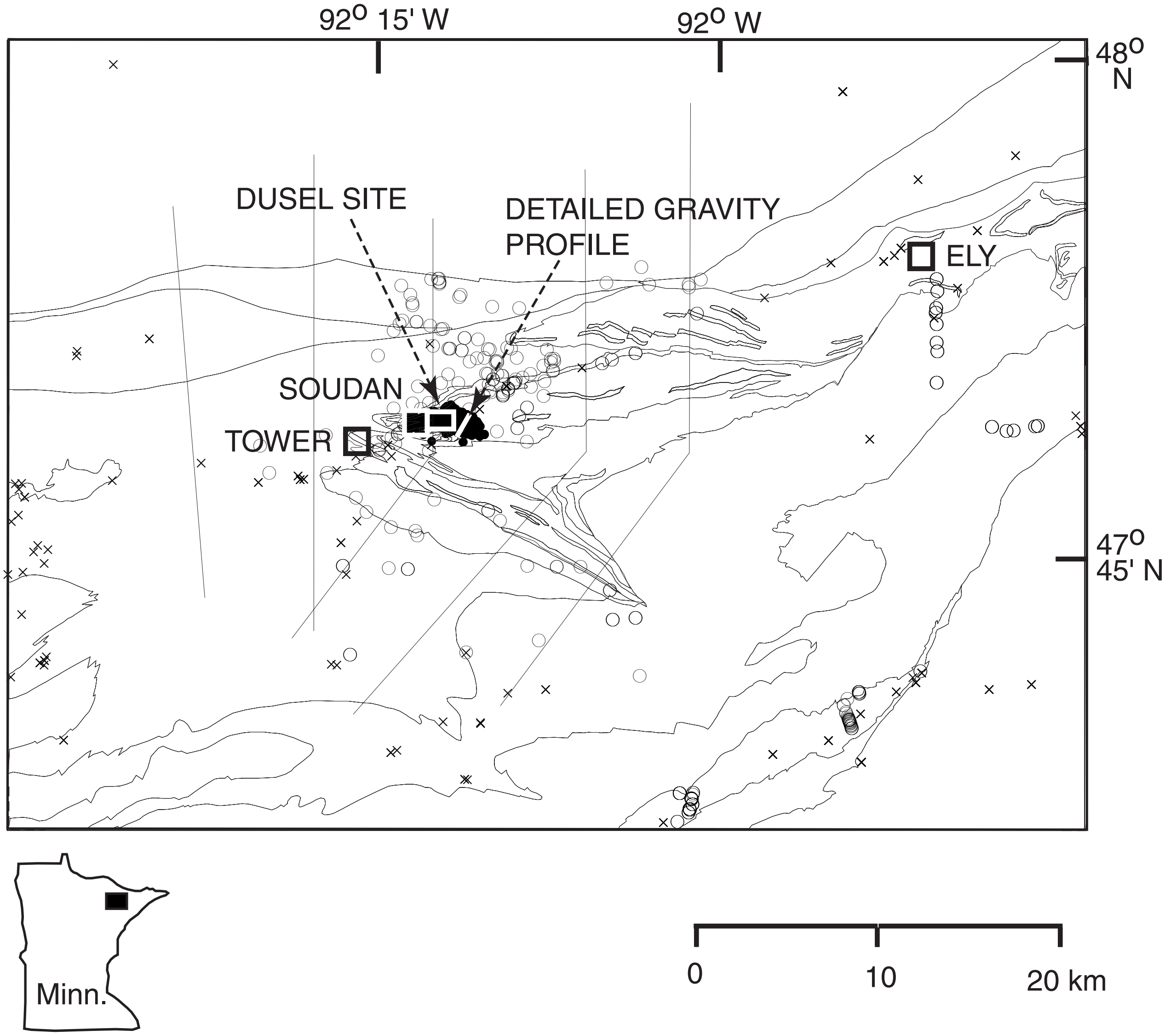


Figure 1. Index map of study area. Irregular light lines designate geologic contacts, as described in more detail on Figure 2. Straight light lines delineate profiles for gravity and model studies (See Figures 3 and 5). Rock property sites used in this study are shown as follows: crosses designate previously existing rock property sites (Chandler and Lively, 2003), open symbols represent new rock property sites that were added by the Minnesota Geological Survey, closed symbols (tightly clustered near the DUSEL site) represent rock property sites where data was added by the Natural Resources Research Institute.

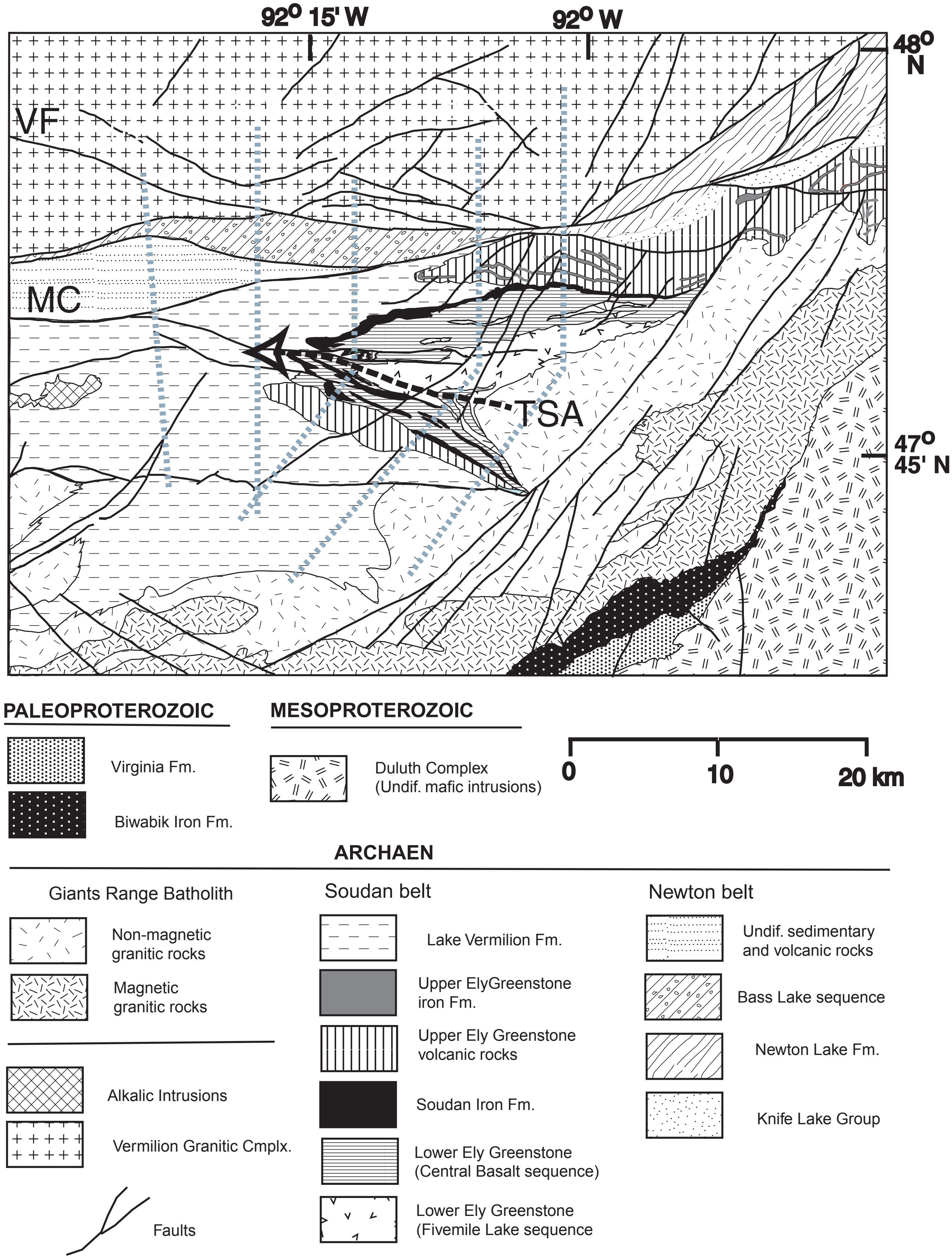


Figure 2. Generalized geologic map of Precambrian rocks in the study area. TSA designates the axis of the Tower-Soudan anticline. MC designates the Mud Creek shear zone and VF designates the Vermilion Fault. Gray dashed lines delineate profiles for gravity and model studies (See Figures 3 and 5). Modified from Jirsa and Boerboom (2003) and Jirsa and Miller (2005).

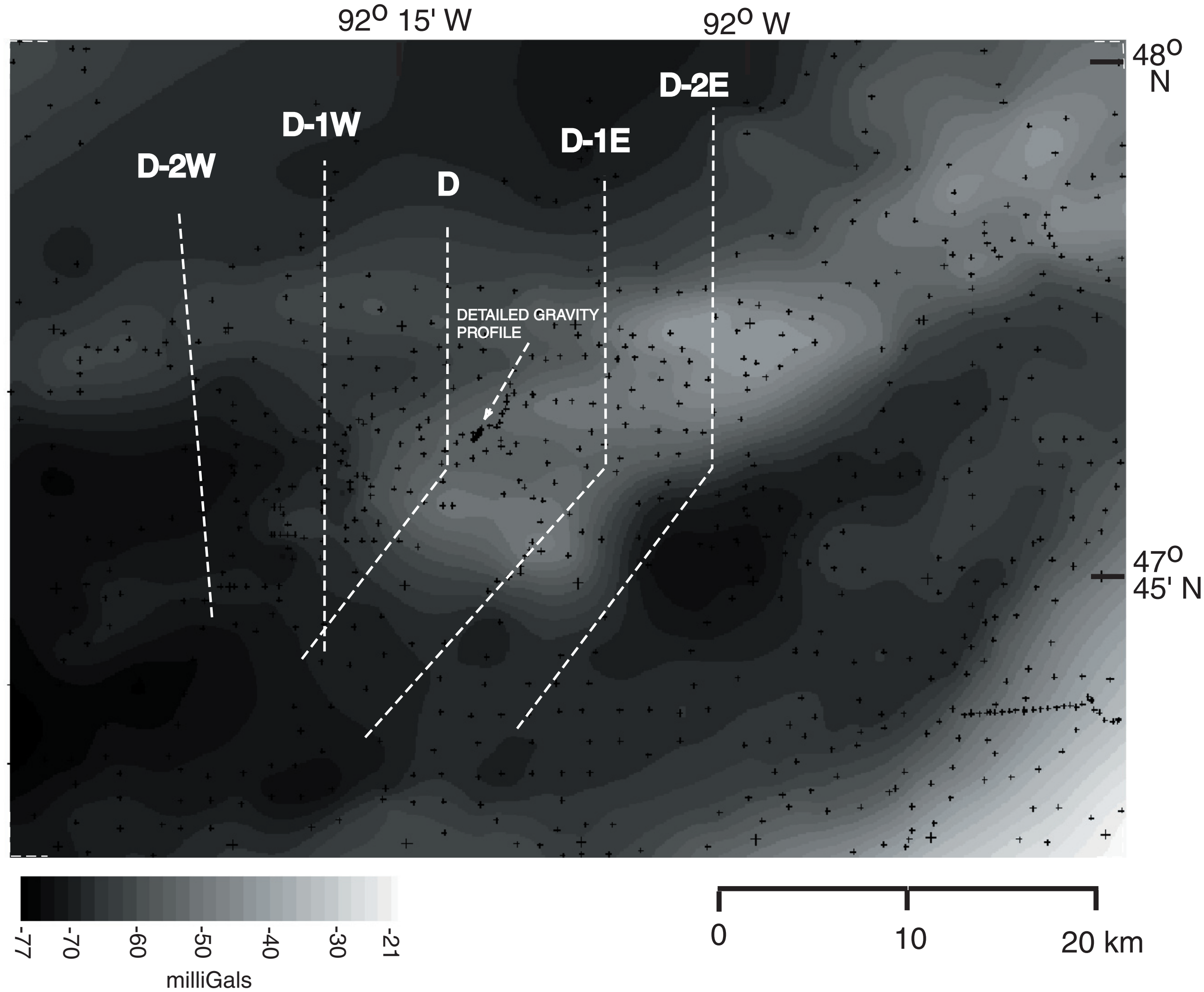


Figure 3. Bouguer gravity anomaly map of study area. Small crosses designate individual gravity stations. Lines D-2W, D-1W, D, D-1E and D-2E delineate profiles for model studies (Figures 7-11).

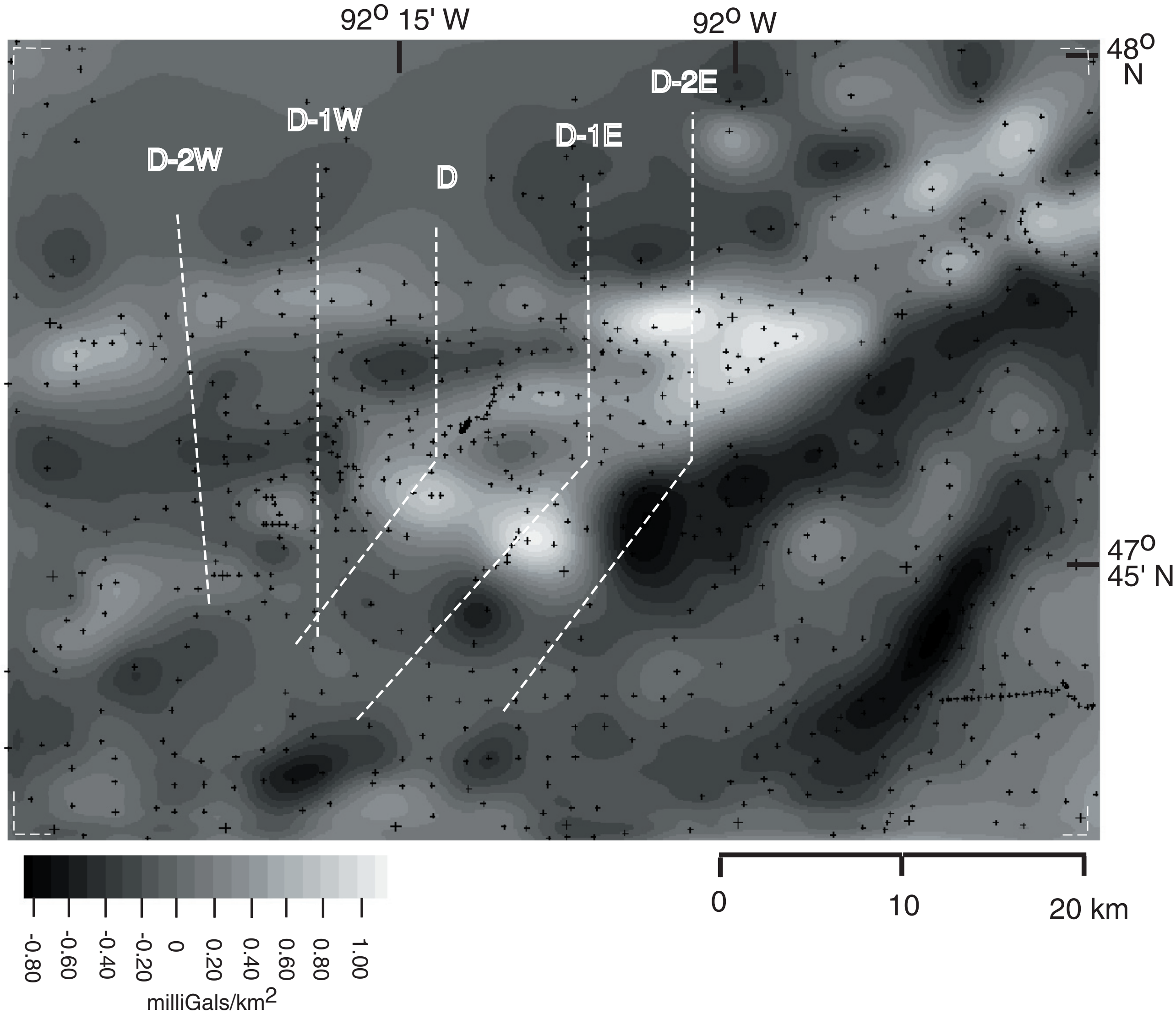


Figure 4. Second vertical derivative of the Bouguer anomaly data of study area, upward continued 2 km. Small crosses designate individual gravity stations.

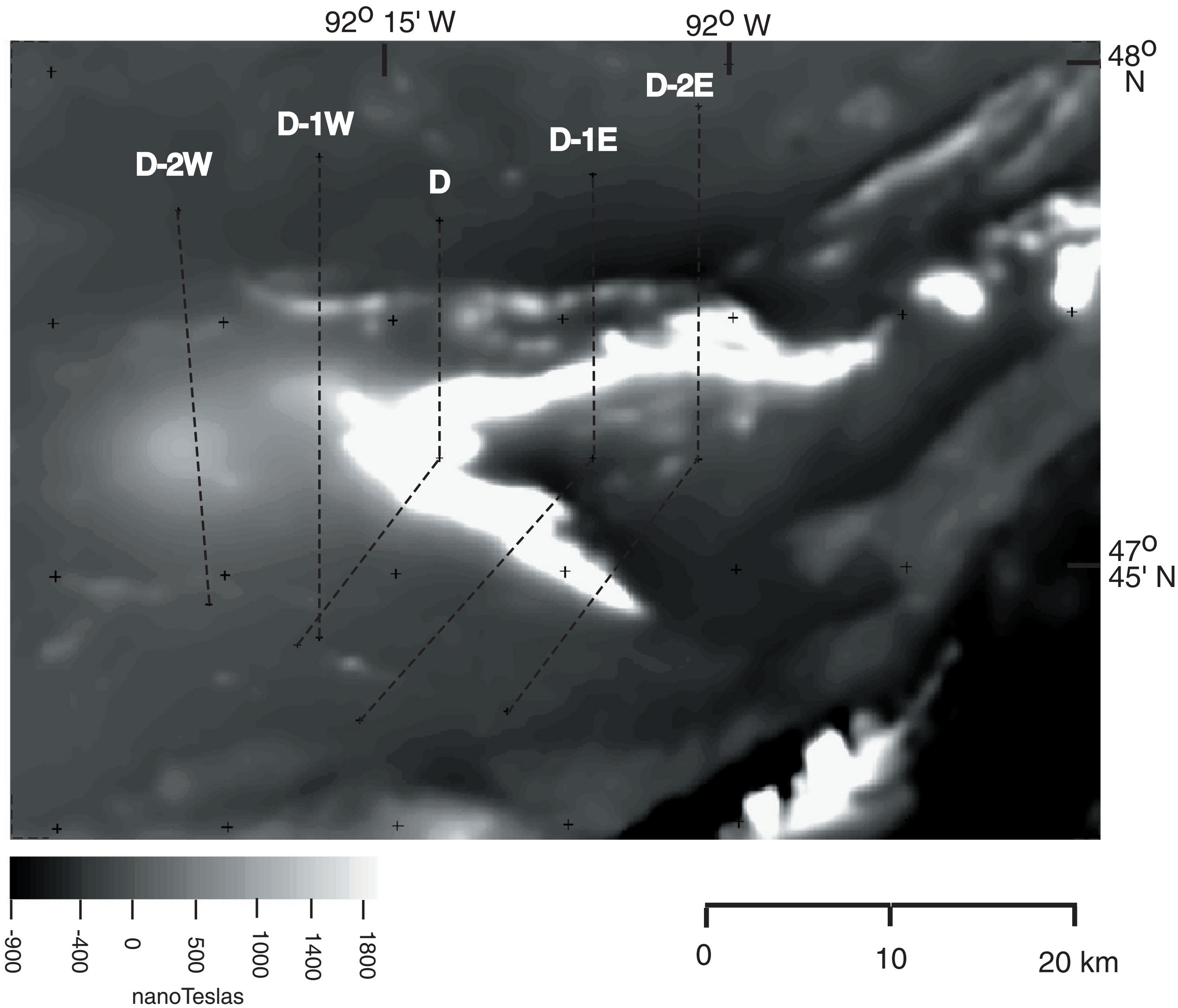


Figure 5. Total field aeromagnetic anomaly data of study area. Lines D-2W, D-1W, D, D-1E and D-2E delineate profiles for model studies (Figures 7-11).

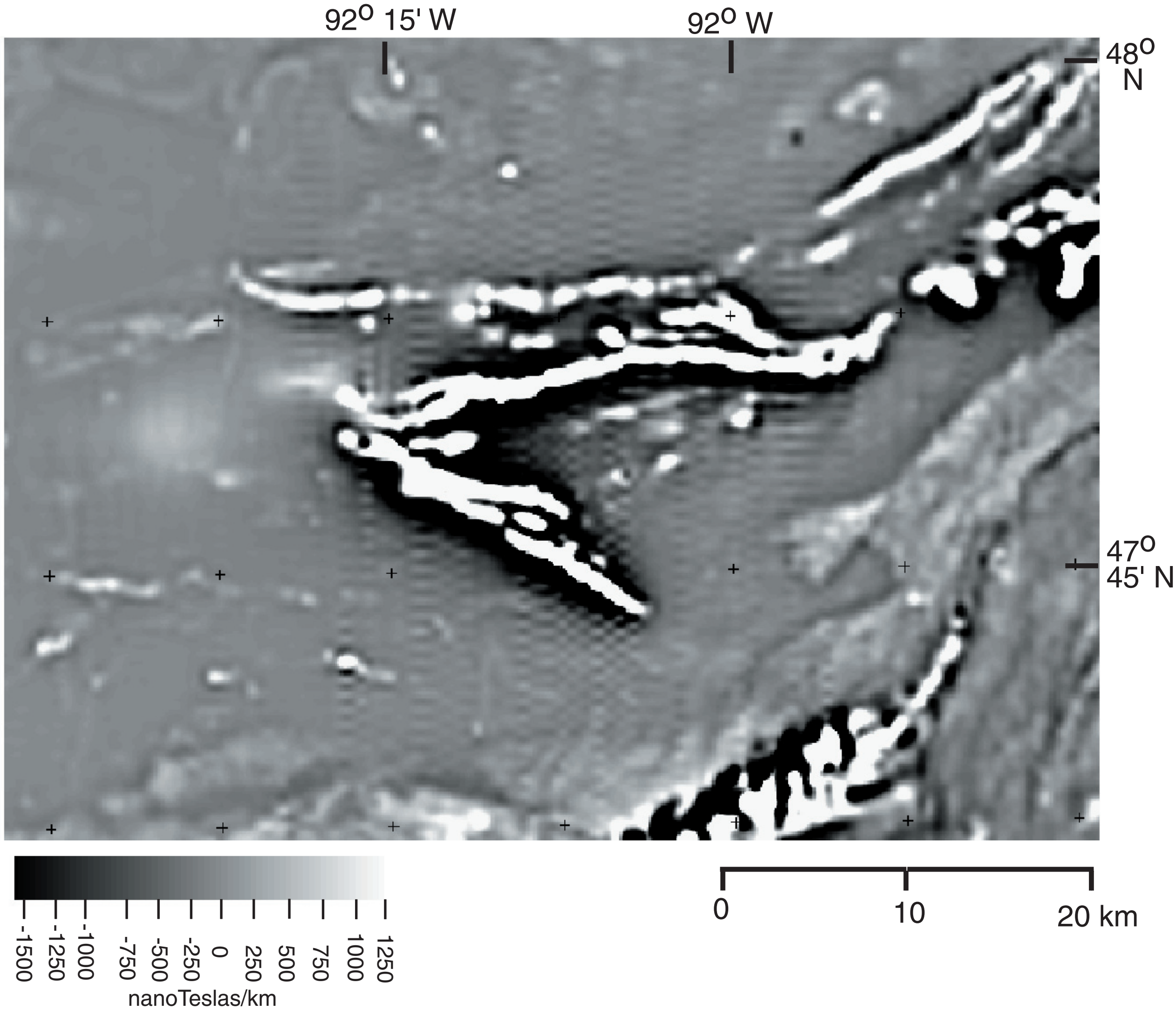


Figure 6. First vertical derivative of the total field aeromagnetic anomaly data of study area, reduced to vertical polarization.

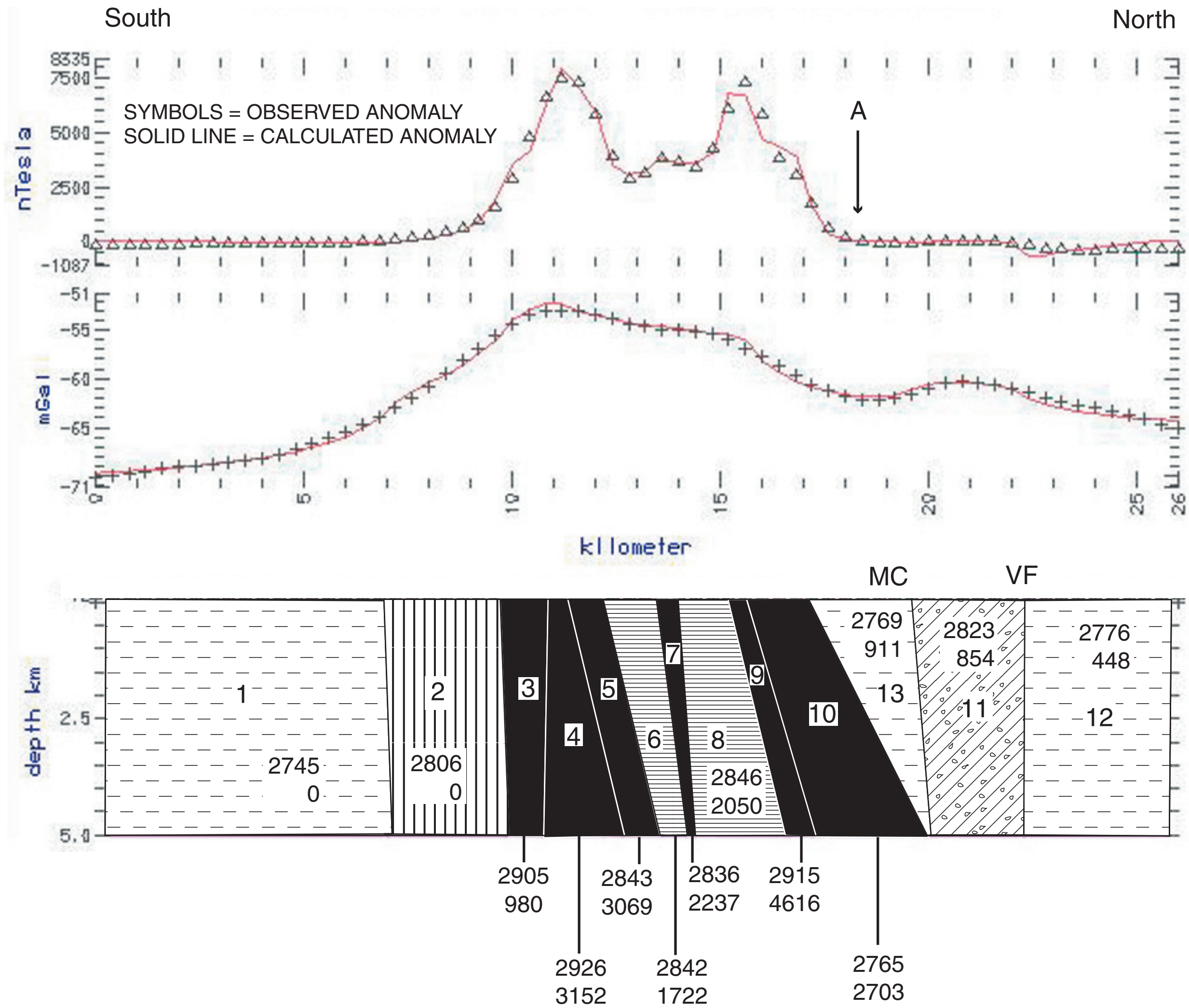


Figure 7. Gravity and magnetic models for profile D (DUSEL). Numbers near the center of individual bodies are body numbers referenced in text. Paired numbers give properties of each body, with density on top (kilograms/ cubic meter) and magnetic susceptibility on bottom (SI units x 104). "MC" indicates position of the Mud Creek shear zone, and VF indicates position of Vermilion Fault. Arrow marked "A" refers to negative side lobe of anomaly discussed in text. Patterns represent the geologic interpretation of individual bodies, as coded on Figure 2. Modeling at this scale tends to generalize geology, and contacts between differing rock properties may not necessarily match the contacts that would be mapped by geologists. Thus, the contacts in this figure may not exactly match the contacts shown on the geologic map in Figure 2.

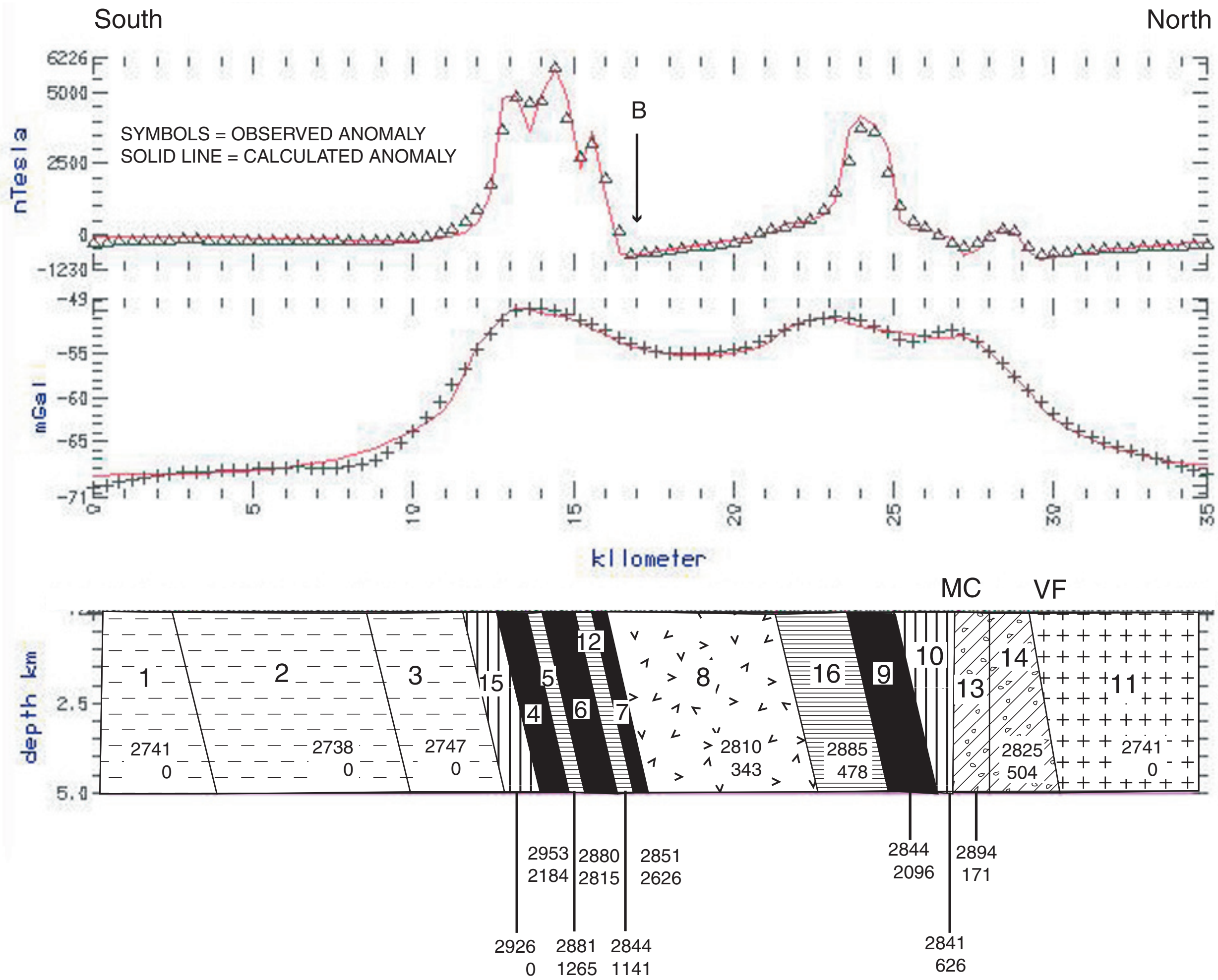


Figure 8. Gravity and magnetic models for profile D-1E (DUSEL 1 EAST). Numbers near the center of individual bodies are body numbers referenced in text. Paired numbers give properties of each body, with density on top (kilograms/ cubic meter) and magnetic susceptibility on bottom (SI units x 104). "MC" indicates position of the Mud Creek shear zone, and VF indicates position of Vermilion Fault. Arrow marked "B" refers to negative side lobe of anomaly discussed in text. Modeling at this scale tends to generalize geology, and contacts between differing rock properties may not necessarily match the contacts that would be mapped by geologists. Thus, the contacts in this figure may not exactly match the contacts shown on the geologic map in Figure 2.

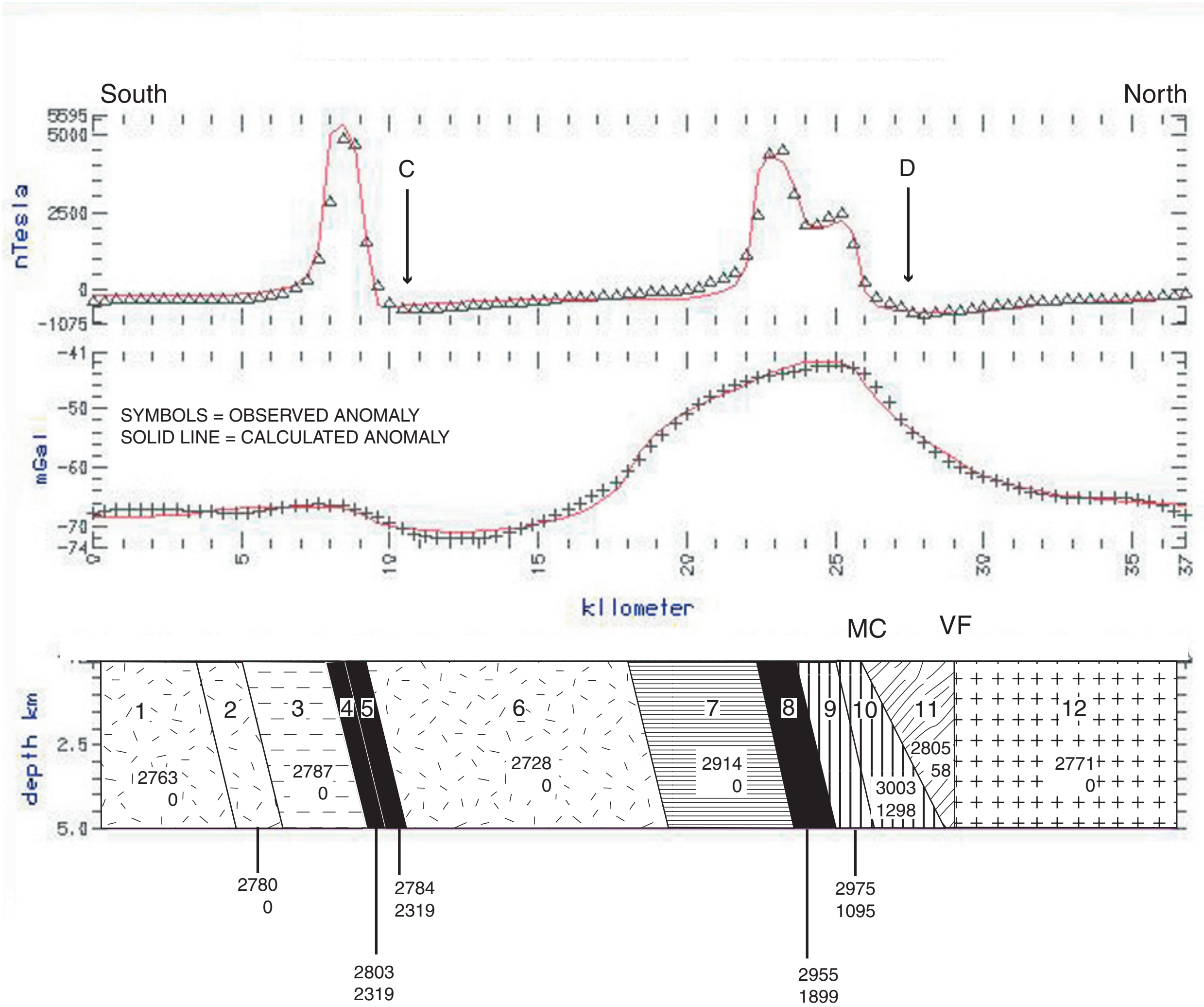


Figure 9. Gravity and magnetic models for profile D-2E (DUSEL 2 EAST). Numbers near the center of individual bodies are body numbers referenced in text. Paired numbers give properties of each body, with density on top (kilograms/ cubic meter) and magnetic susceptibility on bottom (SI units x 104). "MC" indicates position of the Mud Creek shear zone, and VF indicates position of Vermilion Fault. Arrows marked "C" and "D" refers to negative side lobes of anomaly discussed in text. . Modeling at this scale tends to generalize geology, and contacts between differing rock properties may not necessarily match the contacts that would be mapped by geologists. Thus, the contacts in this figure may not exactly match the contacts shown on the geologic map in Figure 2.

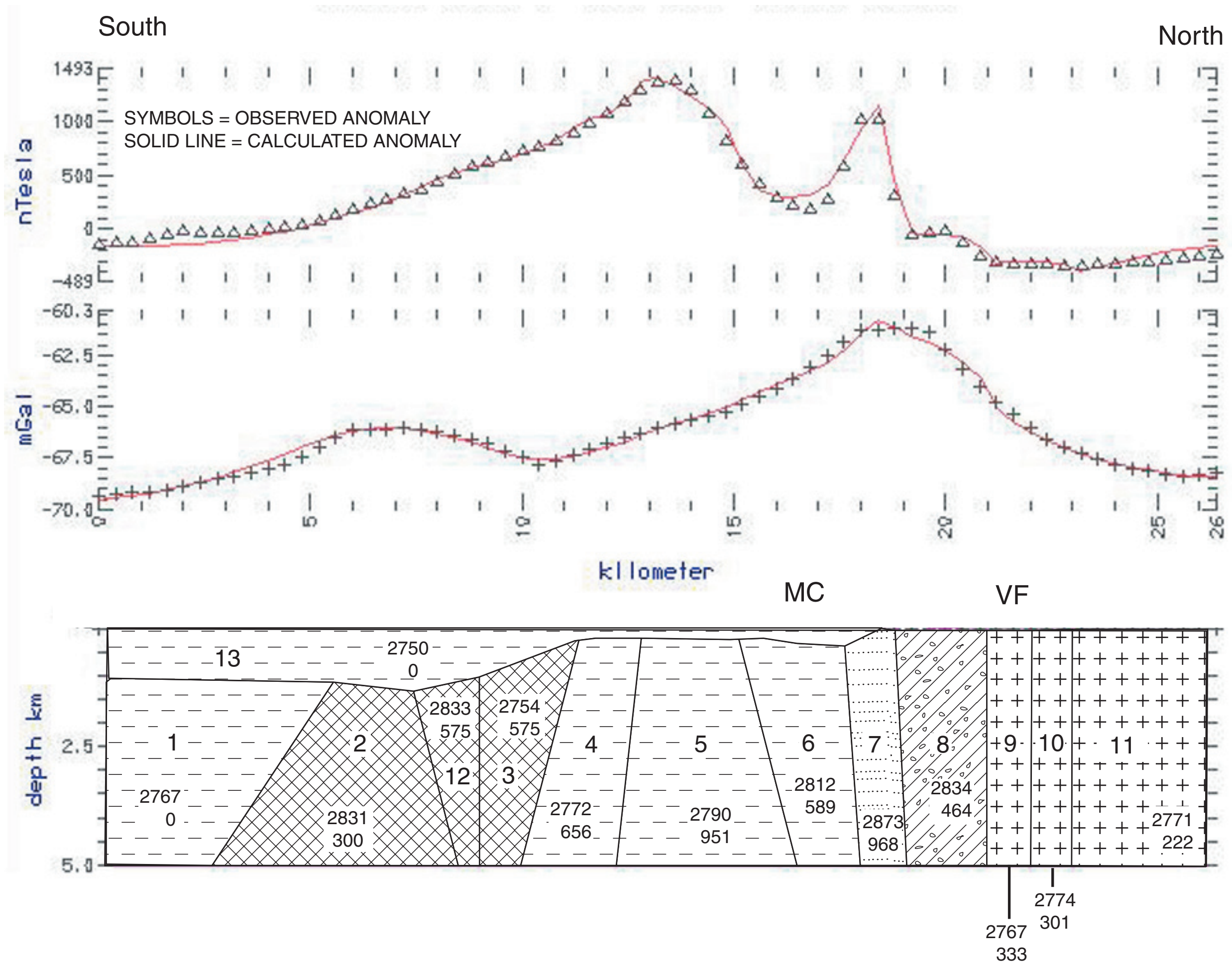


Figure 10. Gravity and magnetic models for profile D-1W (DUSEL 1 WEST) . Numbers near the center of individual bodies are body numbers referenced in text. Paired numbers give properties of each body, with density on top (kilograms/ cubic meter) and magnetic susceptibility on bottom (SI units x 104). "MC" indicates position of the Mud Creek shear zone, and VF indicates position of Vermilion Fault. . Modeling at this scale tends to generalize geology, and contacts between differing rock properties may not necessarily match the contacts that would be mapped by geologists. Thus, the contacts in this figure may not exactly match the contacts shown on the geologic map in Figure 2.

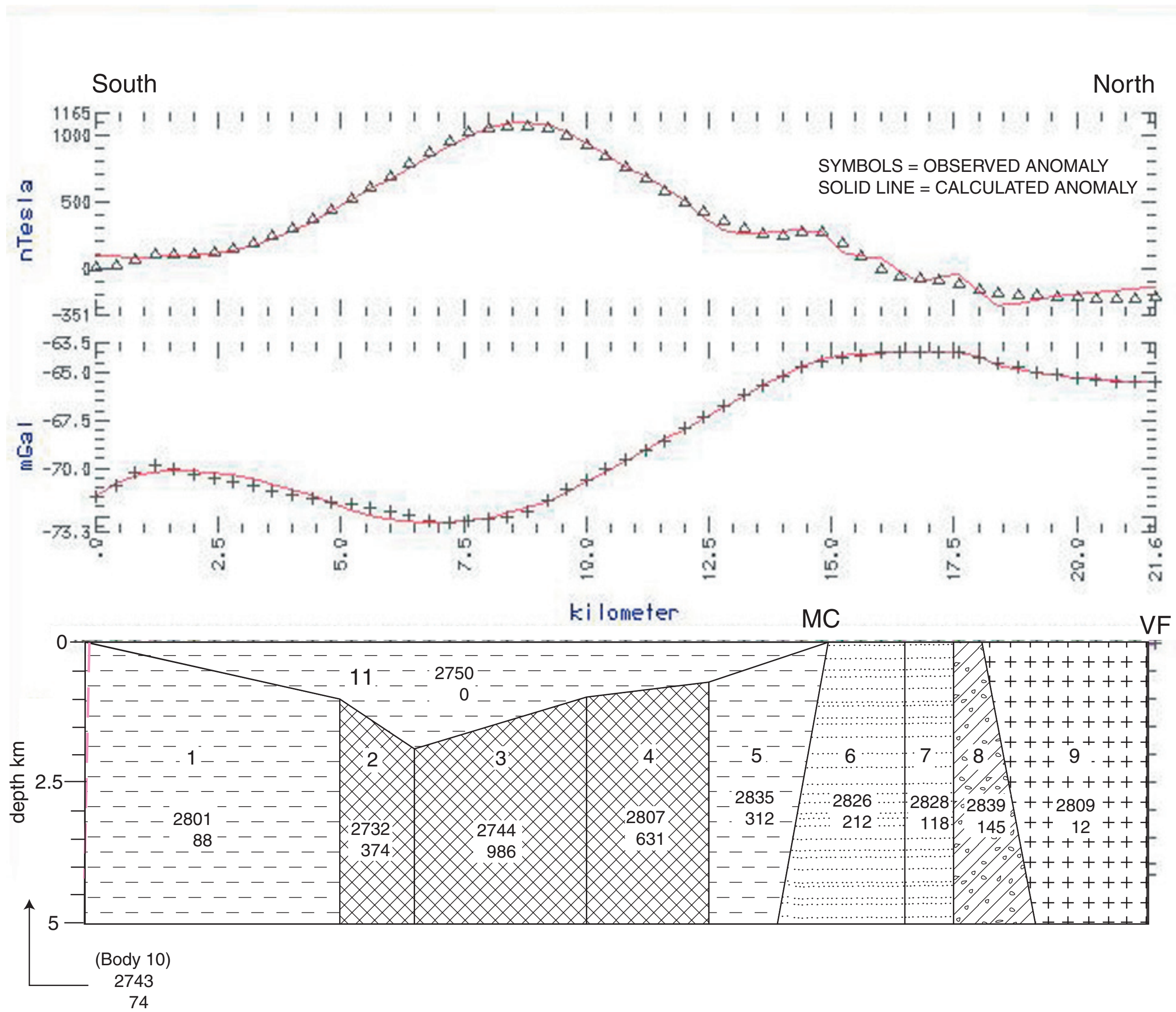
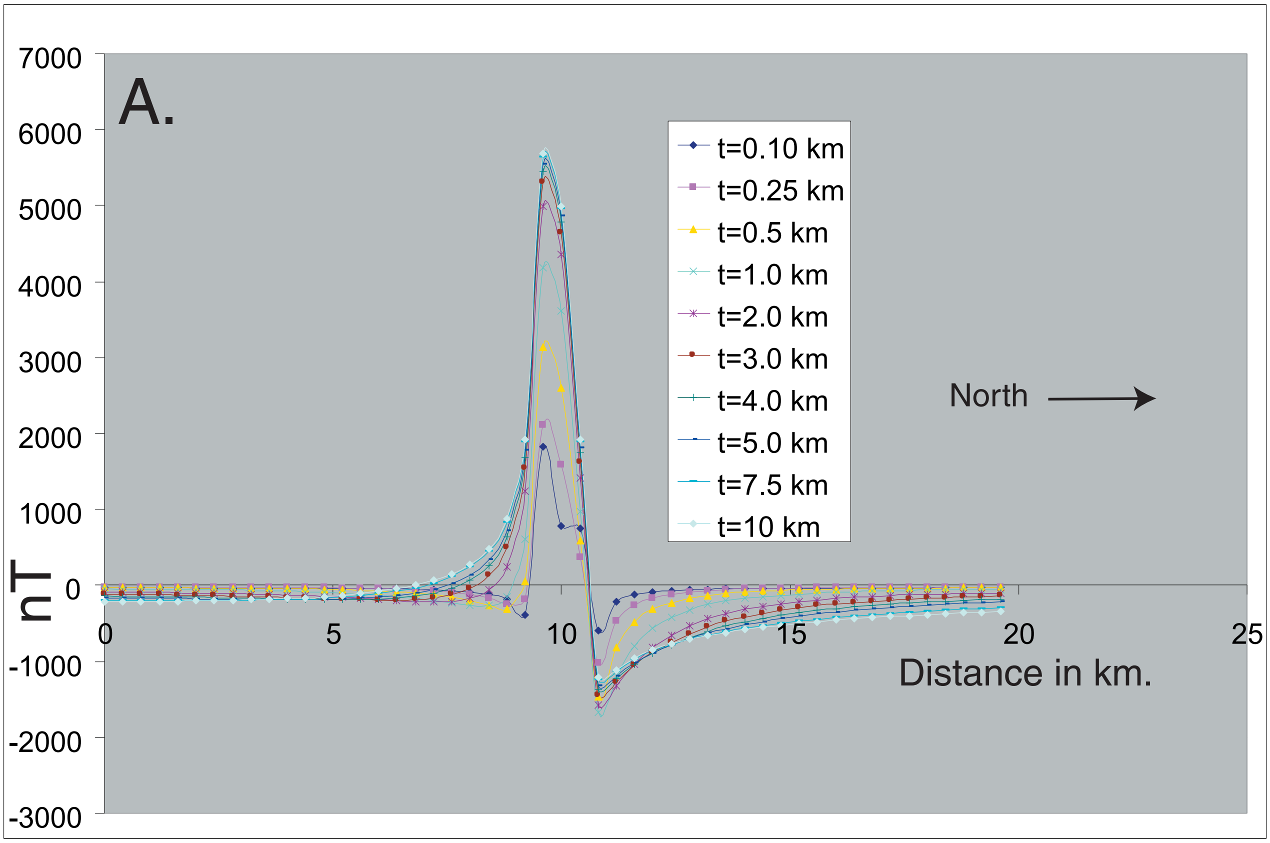


Figure 11. Gravity and magnetic models for profile D-2W (DUSEL 2 WEST). Numbers near the center of individual bodies are body numbers referenced in text. Paired numbers give properties of each body, with density on top (kilograms/ cubic meter) and magnetic susceptibility on bottom (SI units x 104). "MC" indicates position of the Mud Creek shear zone, and VF indicates position of Vermilion Fault. . Modeling at this scale tends to generalize geology, and contacts between differing rock properties may not necessarily match the contacts that would be mapped by geologists. Thus, the contacts in this figure may not exactly match the contacts shown on the geologic map in Figure 2.



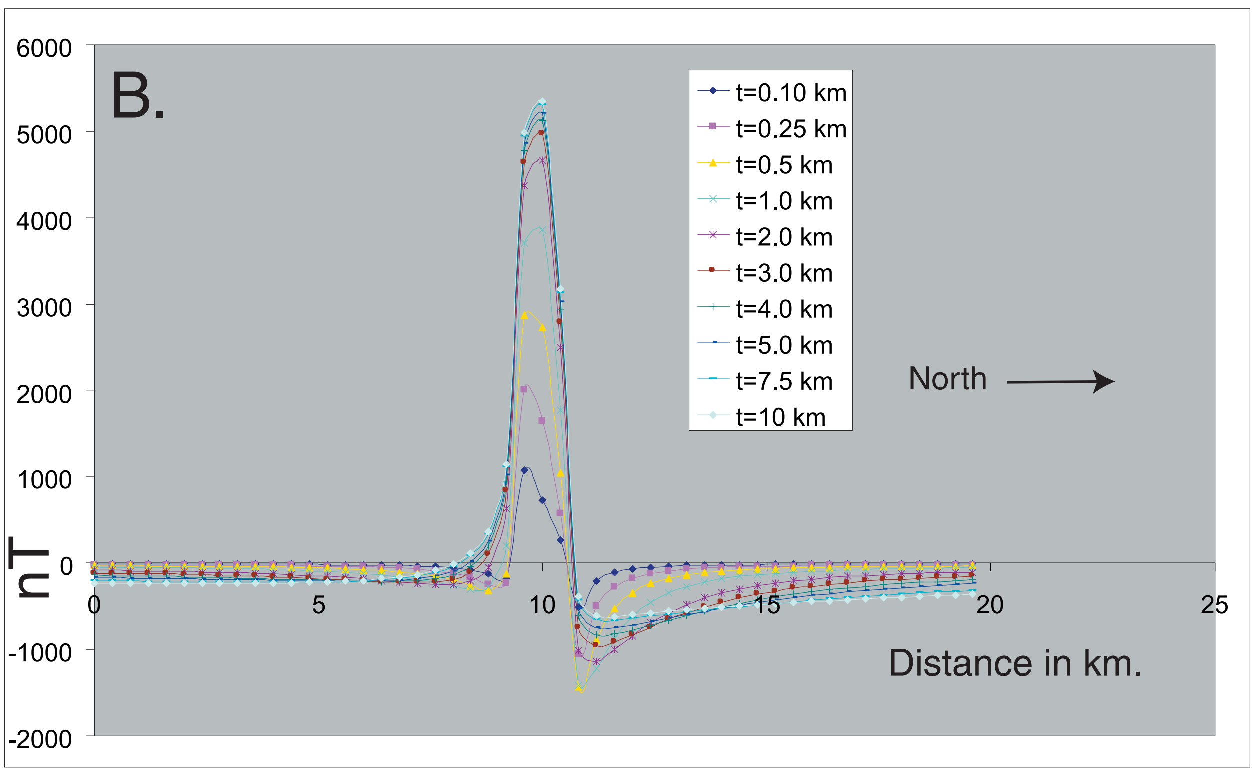


Figure 12. Depth extent tests for steeply inclined magnetic sheets. (A) Vertical magnetic sheet, anomaly curves are indexed to their depth extents given to the right. (B) Sheet inclined 75o North (right), anomaly curves are indexed to their depth extents given in the box. In all cases sheet is 100 m thick, is centered at 10 km distance, and has a top 150 meters below plane of observation.

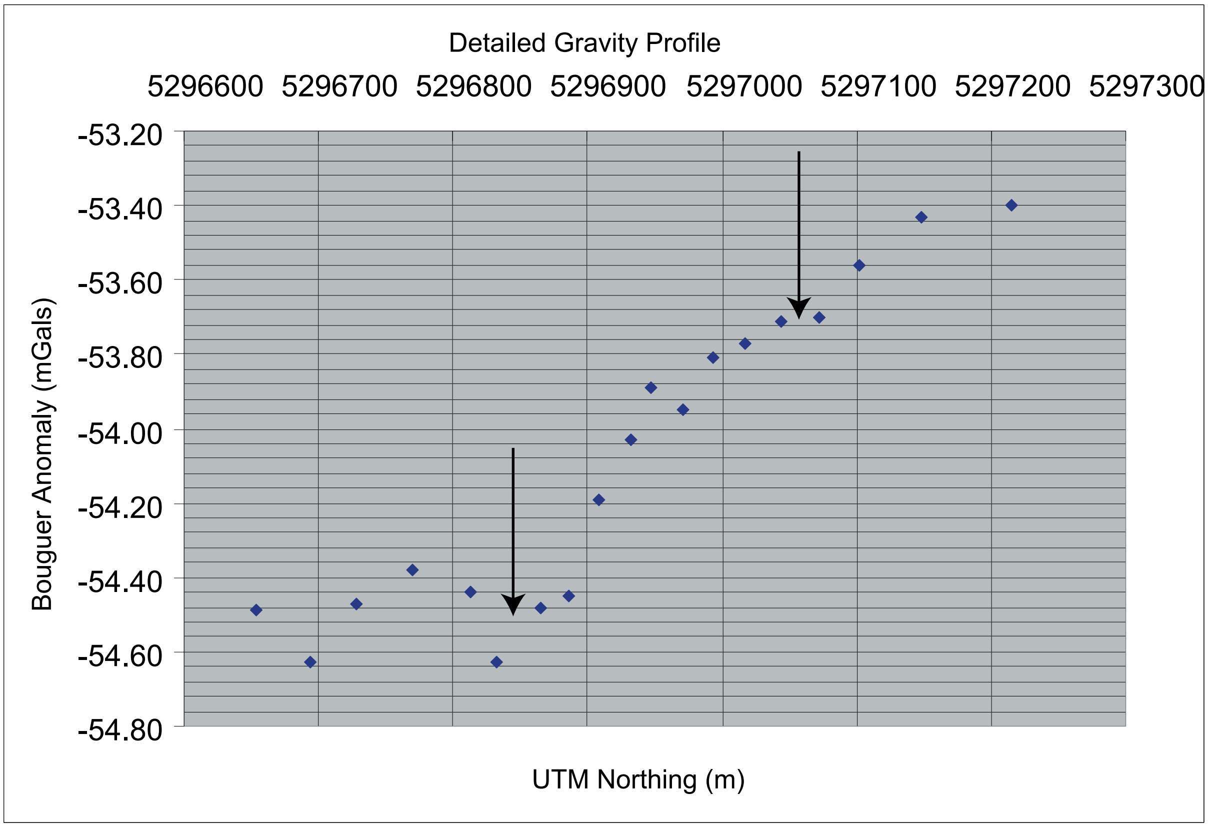


Figure 13. Detailed gravity profile along abandoned stretch of U. S. Highway 169 in Section 25, T116N-R152. Arrows show the contacts of the Sugar Mountain diorite as described by Peterson and others (2003). Profile has been projected to a north-south plane and distance is given in UTM meters N (zone 15, NAD83 datum).

	Mean Density (kgms/m3)	Min. Denstiy (kgms/m3)	Max. Density (kgms/m3)	Num. Samples	Mean k (SI)	Median k (SI)	Min. k (SI)	Max. k (SI)	Num. Samples
Mid Continent Rift System (Mesoproterozoic)									
Duluth Complex	2962	2710	3050	18	0.006	0.005	0	0.015	22
Penokean Orogen (Paleoproterozoic)									
Biwabik Iron Formation	3334	2760	4040	38	0.865	0.634	0.014	8.796	92
Wawa subprovince-Newton Belt									
Bass Lake Sequence	2831	2680	3050	27	0.000	0.000	0	0.000	8
Newton Lake Formation	2828	2630	3020	4	0.001	0.001	0.000	0.005	8
Wawa subprovince-Soudan Belt									
Giants Range Batholith, non-magnetic phases	2722	2530	3216	52	0.003	0.002	0	0.020	46
Giants Range Batholith, magnetic phases	2741	2640	2925	39	0.023	0.021	0.000	0.157	41
Vermilion Granitic Complex	2668	2630	2720	5	0.002	0.001	0	8	
Lake Vermillion Formation	2735	2410	3070	66	0.000	0	0	0.013	31
Upper Ely iron -formation	3070	2820	3270	4	0.328	0.011	0.001	1.099	6
Upper Ely Greenstone	2952	2675	3264	36	0.001	0.001	0.000	0.024	40
Soudan Iron Formation	3145	2620	4348	50	0.728	0.389	0	4.900	51
Lower Ely Greenstone	2869	2630	3150	44	0.000	0.000	0	0.011	28
			num den=	383				num k=	373

	Mean Density (kgms/ m3)	Min. Den- stiy (kgms/ m3)	Max. Density (kgms/ m3)	Num. Sam- ples	Mean k (SI)	Median k (SI)	Min. k (SI)	Max. k (SI)	Num. Sam- ples
Sheared Rocks along the Mine Trend and Murray shear zones									
Sericite schist	2771	2658	2958	9	0.001	0.000	0.000	0.031	36
Ankerite schist	2784	2631	2935	9	0.000	0.000	0.000	0.001	27
Chlorite schist	2731	2530	2929	5	0.001	0.001	0.000	0.002	29
All sheared rocks	2767	2530	2958	23	0.001	0.000	0.000	0.031	92
Central Basalt Sequence (lower Ely Greenstone)									
Massive Basalt	2818	2538	2974	16	0.000	0.000	0.000	0.002	32
Pillow Basalt	2838	2391	3069	43	0.006	0.000	0.000	0.322	63
Diorite (Sugar Mtn diorite)	2838	2567	3335	41	0.001	0.000	0	0.063	58
Fivemile-Lake Sequence (lower Ely Greenstone)									
Foliated Basalt	2757	2551	2874	5	0.001	0.000	0.000	0.006	19
Pillow Basalt	2763	2394	3078	8	0.001	0.000	0.000	0.008	28
Diorite	2800	2538	2986	14	0.001	0.001	0.000	0.002	26
Other Units									
Soudan Iron Formation	2852	2606	2987	9	0.065	0.003	0.000	0.422	20
Gabbro	2939	2638	3464	8	0.004	0.000	0.000	0.077	25
			num den=	167				num k=	363

PROFILE	Point 1		Point 2		Point 3		
NAME	UTME	UTMN	UTME	UTMN	UTME	UTMN	
D-2W	545936	5287109	544237	5308758			
Profile D-1W	551986	5285209	551988	5311707			
Profile D	550785	5284809	558586	5295109	558587		
Profile D-1E	554236	5280709	567061	5295109	567062		
Profile D-2E	562385	5281209	572886	5295009	572887		
Table III. Points defining the profiles for the gravity and magnetic model study.							
	Positions are given in UTM meters N (zone 15, NAD83 datum.						

APPENDICES (Appendicies can be obtained from MGS MapSales. (612-627-4780 x.238)

Appendix A MGS rock property data

Appendix B NRRI rock property data

Appendix C Gravity base information

Appendix D. Principal fact gravity data

Appendix E Gravity and magnetic grids

Appendix F Modeling files