TECHNICAL REPORT

U.S. GEOLOGICAL SURVEY STATEMAP Award #**G16AC00192**

Geologic Mapping in Minnesota, 2016

Submitted by

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Minnesota Geological Survey
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INTRODUCTION

The Minnesota Geological Survey received $105,073 to support bedrock geologic mapping in what we refer to as the Southern Arrowhead Area of northeastern Minnesota at scale 1:100,000. The map covers an area bounded by latitude 47°30´30" on the north, and 7.5-minute quadrangle boundaries that extend just beyond the borders of St. Louis and Lake counties on the east, west, and south (Fig. 1). It includes parts of Superior National Forest and several State forests, and all or parts of the cities of Duluth, Two Harbors, Silver Bay, Keewatin, Hibbing, Eveleth, and Virginia. The map is the second in a series of 3 that collectively will provide data and interpretations for county geologic atlases of 2 of the largest counties in Minnesota, St. Louis and Lake. The first map of the series covered the Central Arrowhead area, which was funded in part by USGS Award #G15AC00239 and published in 2016. On July 1, 2017, we begin work on the third and final bedrock map in the Arrowhead series, supported in part by USGS Award #G17AS00006. County geologic atlases consist of a suite of comprehensive map products that provide information essential to sustainable management of ground water resources, and provide an array of information about geology, mineral resources, and natural history. Funding from this USGS award was augmented with support from individual counties and the Minnesota State Legislature via the Environment and Natural Resources Trust Fund, as recommended by the Legislative-Citizen Commission on Minnesota Resources. The State funding source also supported parallel studies of unconsolidated surficial deposits, bedrock topography, and depth to bedrock that will become part of the County atlases, but are not discussed further in this report.

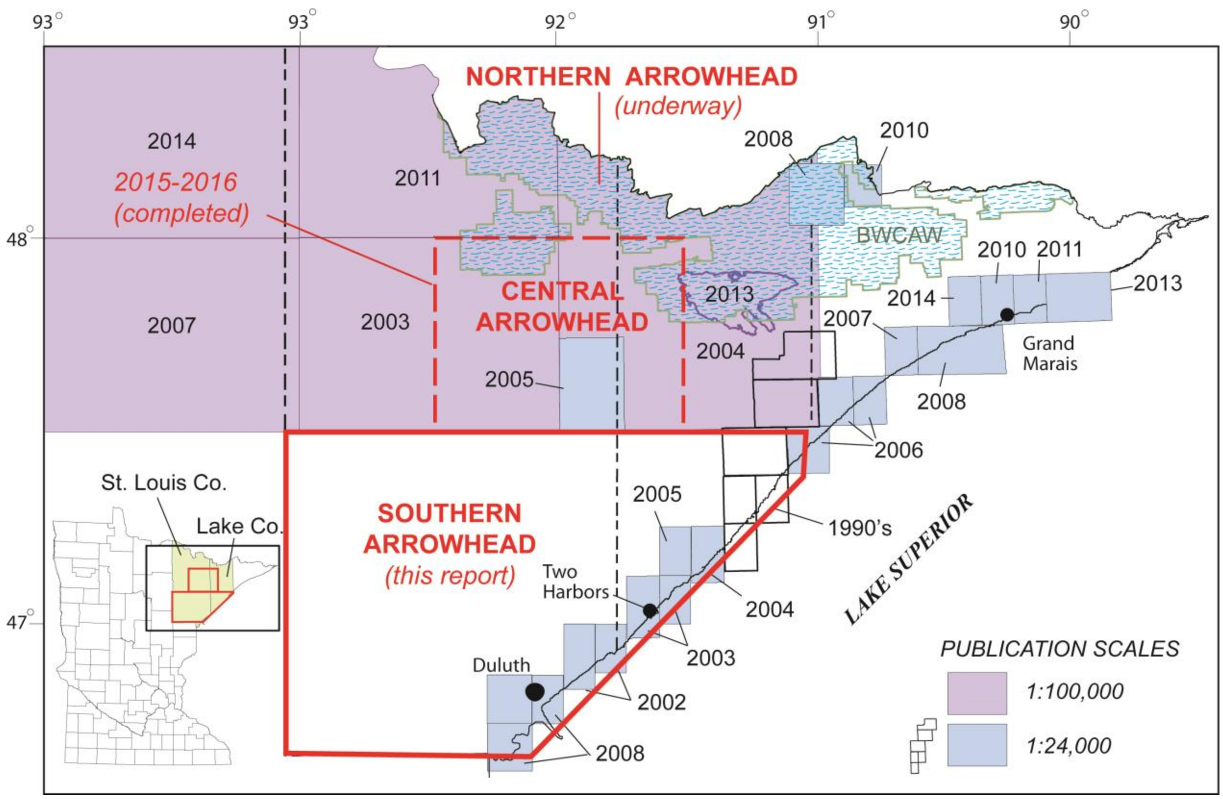


Figure 1. Map of northeastern Minnesota showing the location of the Southern Arrowhead area in the context of published geologic maps funded in large part by the USGS STATEMAP (colored) and COGEOMAP (open outlines) programs. Publication years are shown. Boundary Waters Canoe Area Wilderness (BWCAW) is shown by green outline and blue dashed fill. Inset map of the state shows counties (pale green).

GEOLOGIC SETTING

The Southern Arrowhead map portrays Archean and Proterozoic bedrock, including portions of the Wawa subprovince of the Archean Superior Province, Paleoproterozoic iron-formation and associated rocks of the Mesabi Iron Range, and portions of the Mesoproterozoic Duluth Complex (Fig. 2). The Mesabi range and Duluth Complex are hosts to iron and polymetallic mineral deposits (copper, nickel, platinum, palladium, gold, cobalt) under consideration for new mining. The map area encompasses mineral deposits that are currently in various stages of exploration, permitting, mine development, extraction, and closure.

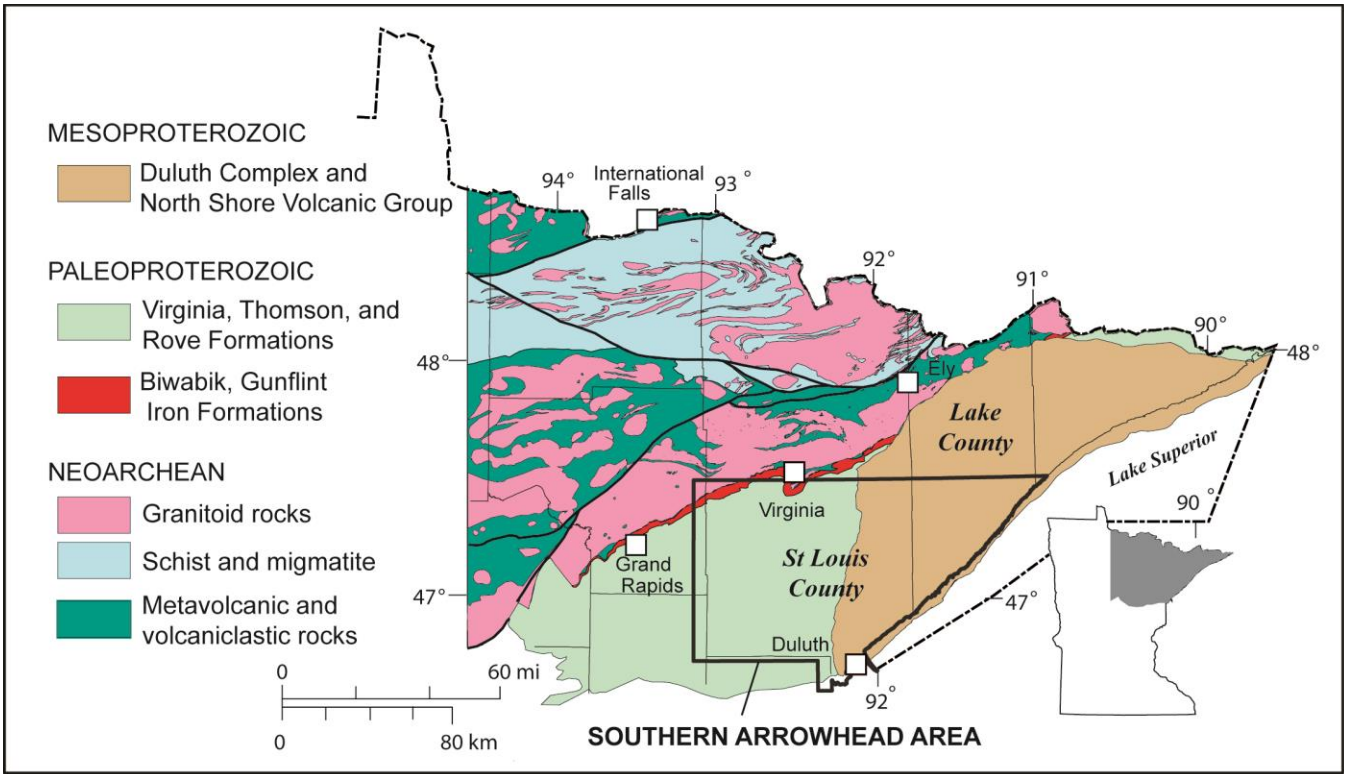


Figure 2. Generalized bedrock geologic map of northeastern Minnesota showing the location of the Southern Arrowhead map area.

PROJECT SUMMARY

The Southern Arrowhead bedrock map incorporates all or parts of 15 detailed (1:24,000 scale) maps (USGS-funded maps shown on Fig. 1), and several regional-scale (1:100,000 and 1:200,000) published bedrock maps. It reflects compilation of those earlier publications where their authors had adequate ground control, and new interpretation based on subsequent outcrop mapping, drill core logging, LiDAR imagery, and geophysical data where they did not. Although the earlier maps were adequate for the time, proposed new mining—and the potential environmental issues related to it—required more comprehensive regional maps and associated databases. Those maps identified several areas needing significant amounts of additional field and geophysical work, which guided effort during the current mapping. In addition, new data were acquired from some of the companies and agencies involved in the process of mine development, environmental review, and permitting. The earlier maps were created prior to the availability of LiDAR topographic imagery, which allowed more accurate portrayal of observations, and highlighted areas requiring additional field work. The new map provides geologic framework for national and state forests, counties, and municipalities at a scale and level of detail suitable for use by government and industry personnel. It provides a bedrock geologic backdrop for ongoing local and regional studies of bedrock, Quaternary sediments, and waters. The resulting map and related products will be available via the MGS website (http://www.mngs.umn.edu) in coming weeks—the citation is:

Boerboom, T.J., Radakovich, A.L., Jirsa, M.A., and Chandler, V.W., 2017, Bedrock geologic map of the Southern Arrowhead area, St. Louis and Lake Counties, Minnesota, , scale 1:100,000: *in* Preliminary geologic maps of Lake and St. Louis Counties, Minnesota, Minnesota Geological Survey Open-File Report 2016-04.

Note: Because the map at scale 1:100,000 is very large (~75"X60"), it is best viewed on-screen. If prints are required, a 50% reduction of the PDF retains most features.

Project Statistics

- >40,000 outcrops were compiled from published and unpublished mapping;
- >1500 outcrops were mapped and described by 3 of the authors during 8 weeks of field work;
- The positions and geometries of thousands of outcrops were delineated and modified by LiDAR topographic imagery, and attributed;
- The records of ~800 bedrock drill holes with associated drill core or drill cuttings sets were considered;
- 30 of those cores were described by 2 of the authors;
- The records of ~10,000 water wells and test borings were considered;
- 7 new geophysical models improved the position and characteristics of bounding structures;
- Geophysical map imagery employed several new (to us) derivative techniques (see discussion below).

Significant Project Results

Map detail

This is one of the largest detailed maps in MGS publishing history, consisting of 168 map units covering an area of ~4,000 mi^2. Although the geologic depiction is broadly similar to previous maps of the region, considerable detail has been added. Map unit contacts were refined, and several new units were created by subdivision of previously mapped composite units. This results from targeted mapping by the authors; reprocessed derivative geophysical maps and models created for this project; and incorporation of work by geologists from academic, industry, and government entities. The use of 1-meter LiDAR imagery placed geologic contacts and faults more accurately, and allowed depiction of what are inferred to be fractures and foliation in areas where the land surface appears to be controlled largely by bedrock and little field work has occurred. Some of these structures may have hydrogeologic significance; however, none were investigated to assess hydrologic characteristics.

Integrated and fully attributed data sets

One important objective of this endeavor was to consolidate disparate data sets and populate associated attribute tables. Attributing the outcrop data base was remarkably time-consuming, and is an extremely valuable contribution.

Utility of geophysical imagery

Several derivative maps of aeromagnetic and gravity data were created to help refine geologic contacts in areas having scant outcrop and drill hole control. Most useful for interpreting the complex Mesoproterozoic rocks (eastern half of the map) is imagery of tilt-filtered, micro-leveled aeromagnetic data (Fig. 3). Tilt-filtering is calculated by dividing the vertical derivative by the total horizontal derivative. The technique removes the effect of anomaly amplitude, and instead emphasizes anomaly texture. This enhances continuity of signatures and definition of potential unit boundaries. The tilt imagery is particularly useful in tandem with more traditional derivatives.

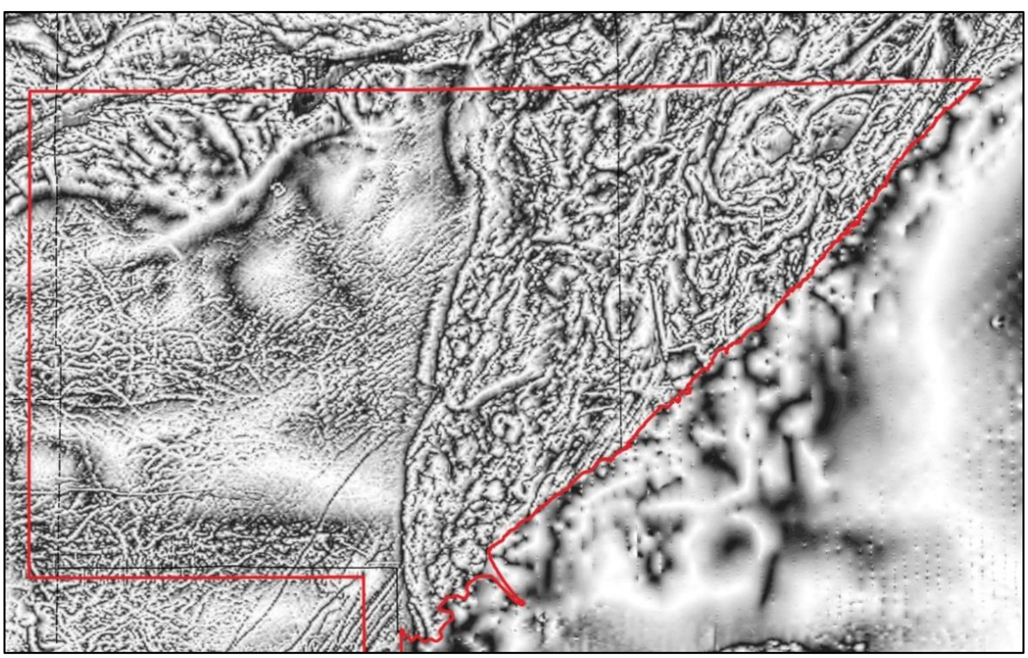


Figure 3. Southern Arrowhead map area (red) superimposed on imagery of tilt-filtered, micro-leveled aeromagnetic data. Dendritic pattern in southwestern part of the map may represent relict stream channels on the buried surface of magnetically subdued bedrock. Narrow linear features in the south-central part of the map are diabasic dikes.

GEOPHYSICAL MODELS AND MAP IMAGES
of the Southern Arrowhead map area

Val W. Chandler and Mark A. Jirsa

INTRODUCTION

Seven geophysical models were created for this project, with two being reprocessed and revised from previously published versions. A graphic summary of the models and a select set of geophysical map images are presented here. The model sections are shown with no vertical exaggeration. Contact the authors if more information is required.

IMAGERY

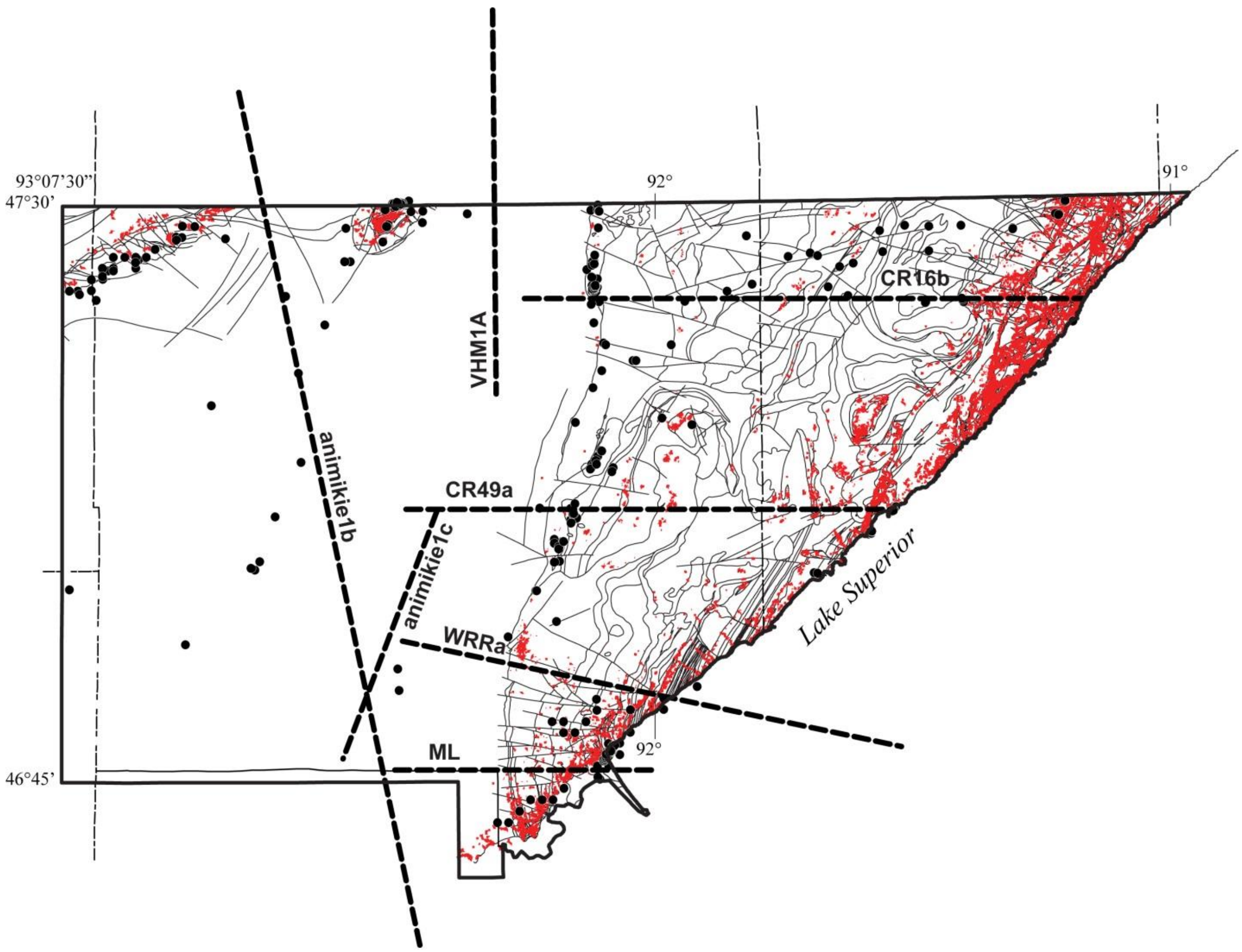


Figure 1. Map of geophysical model profiles (bold dashed), bedrock unit contacts and faults (thin solid lines), outcrop (red), and locations of holes for which drill core exists (black circles).

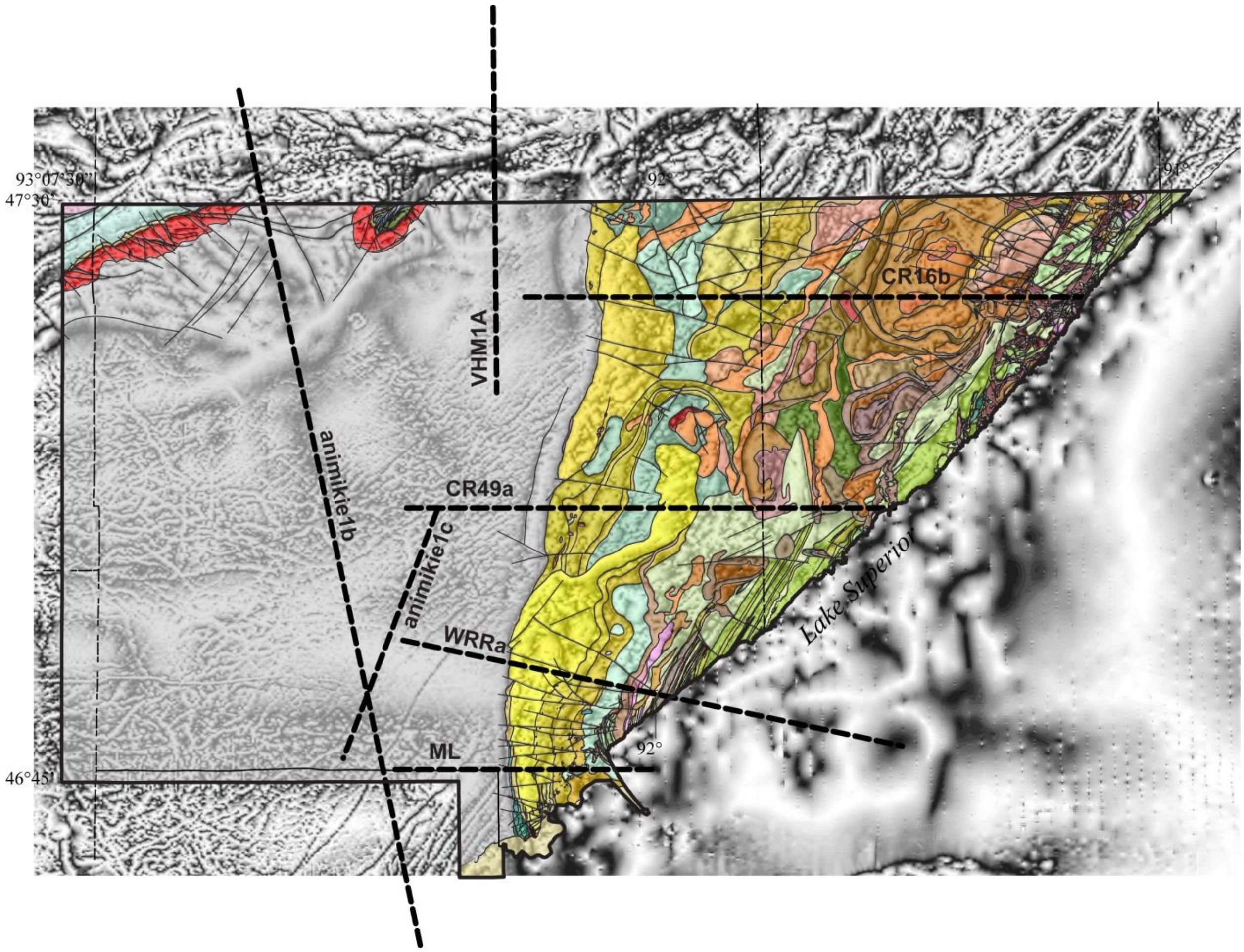


Figure 2. Model profiles and geologic units (colored) superimposed on imagery of tilt-filtered, micro-leveled aeromagnetic data. This technique removes the effect of anomaly amplitude and enhances anomaly texture.

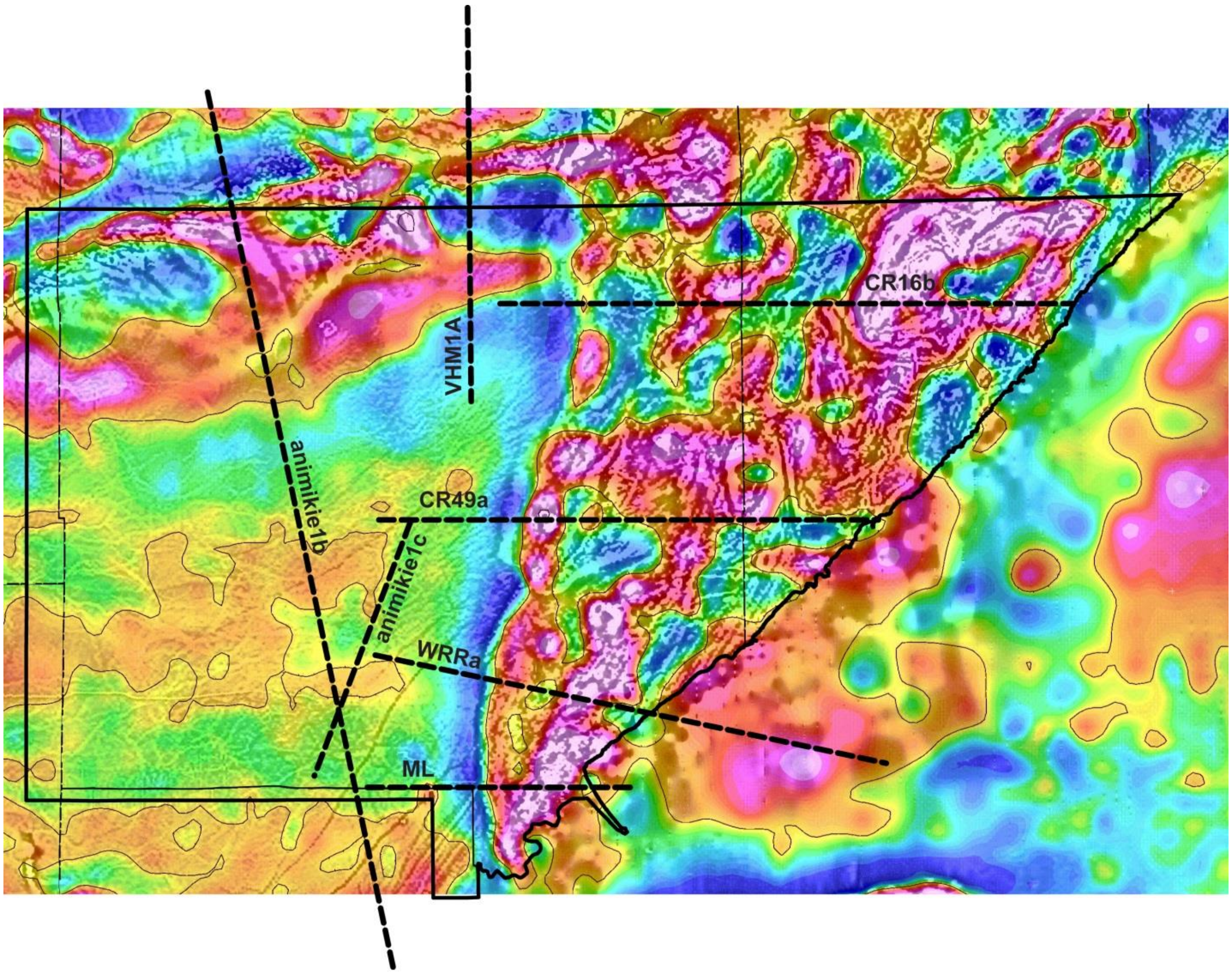
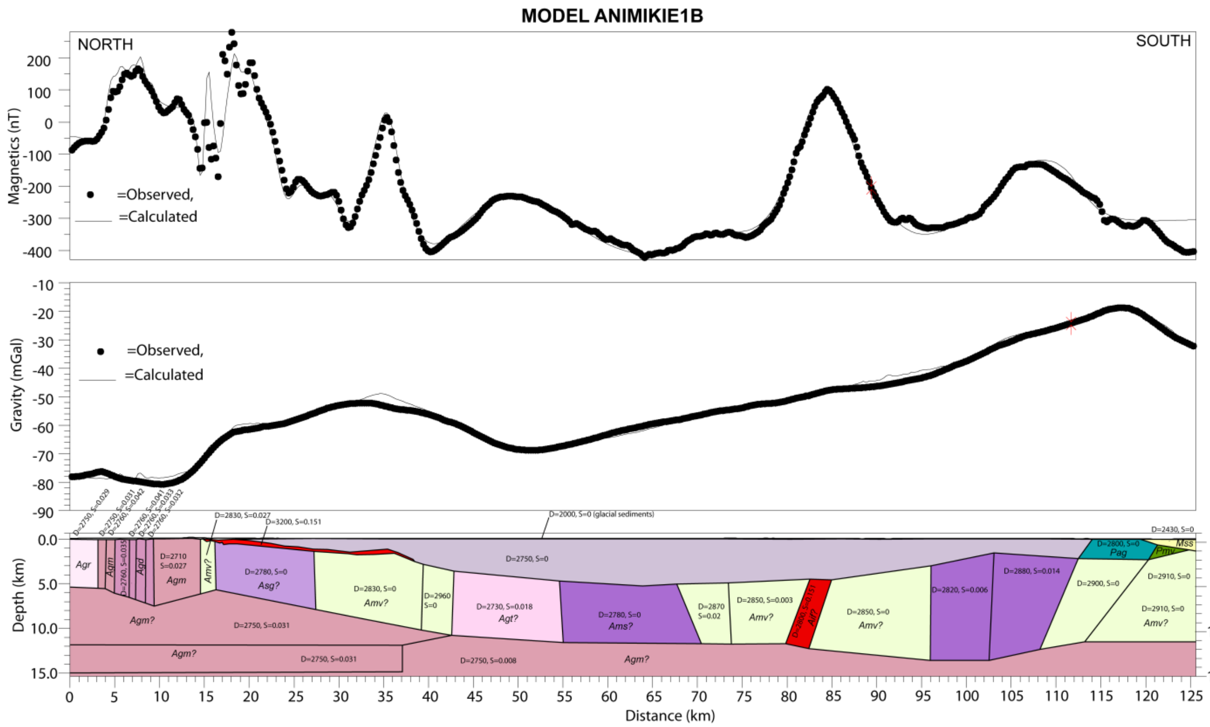
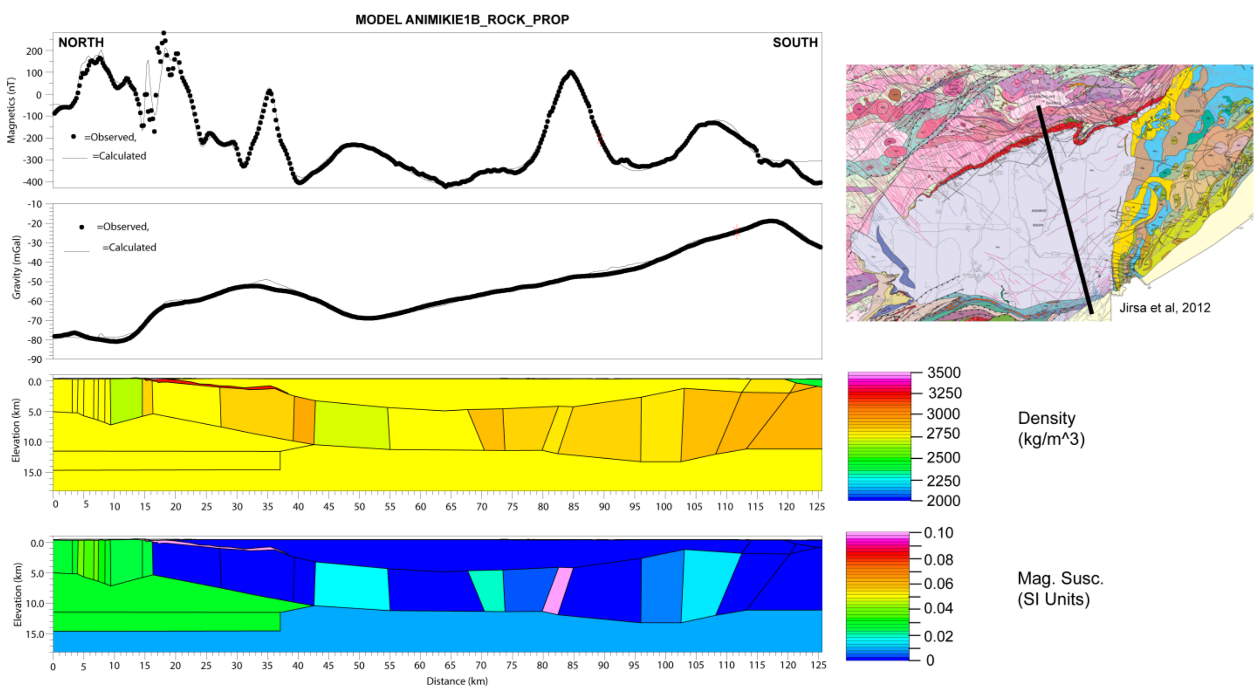


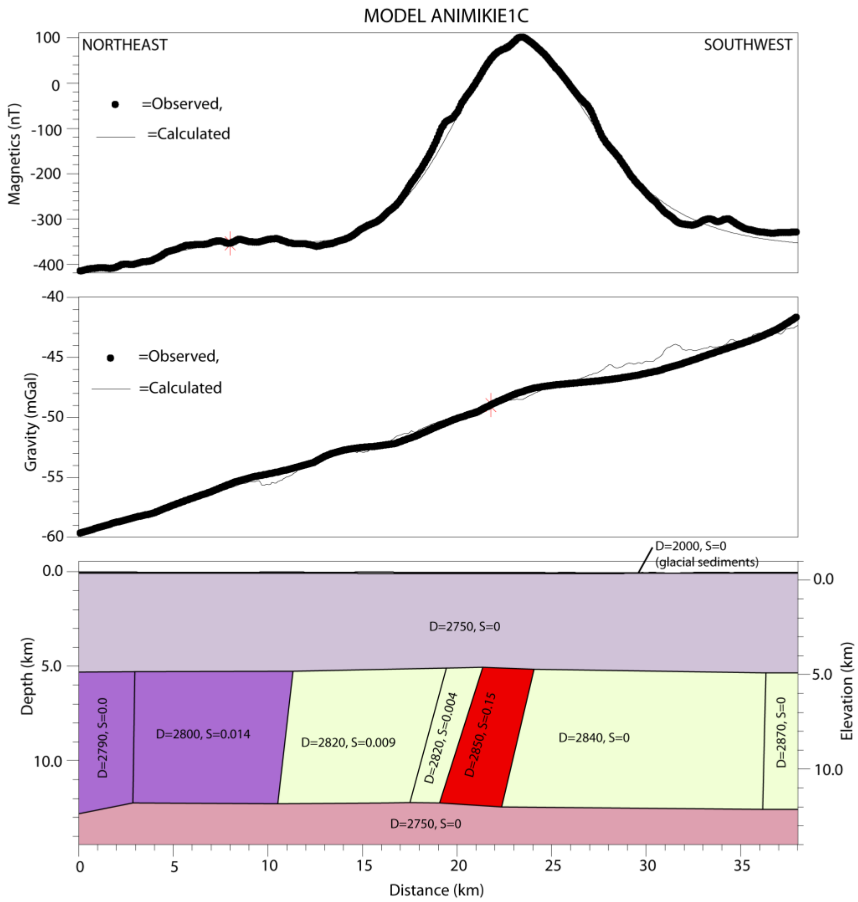
Figure 3. Geophysical profiles depicted on grid image of superimposed first vertical derivative of aeromagnetic data (gray scale) and second vertical derivative of gravity anomaly data (SMOG map).

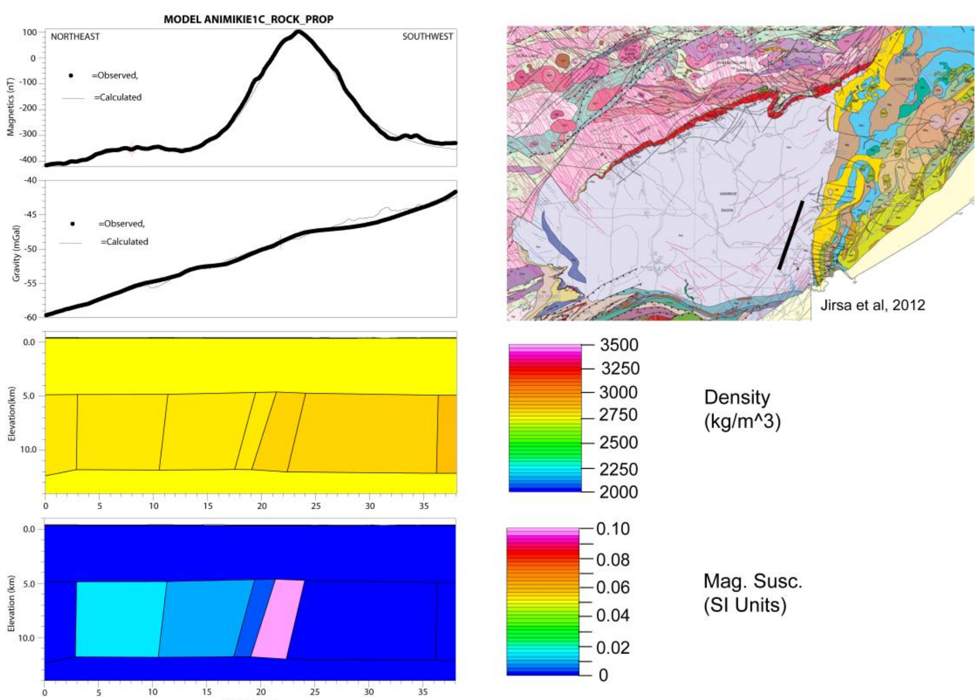
GEOPHYSICAL MODELS

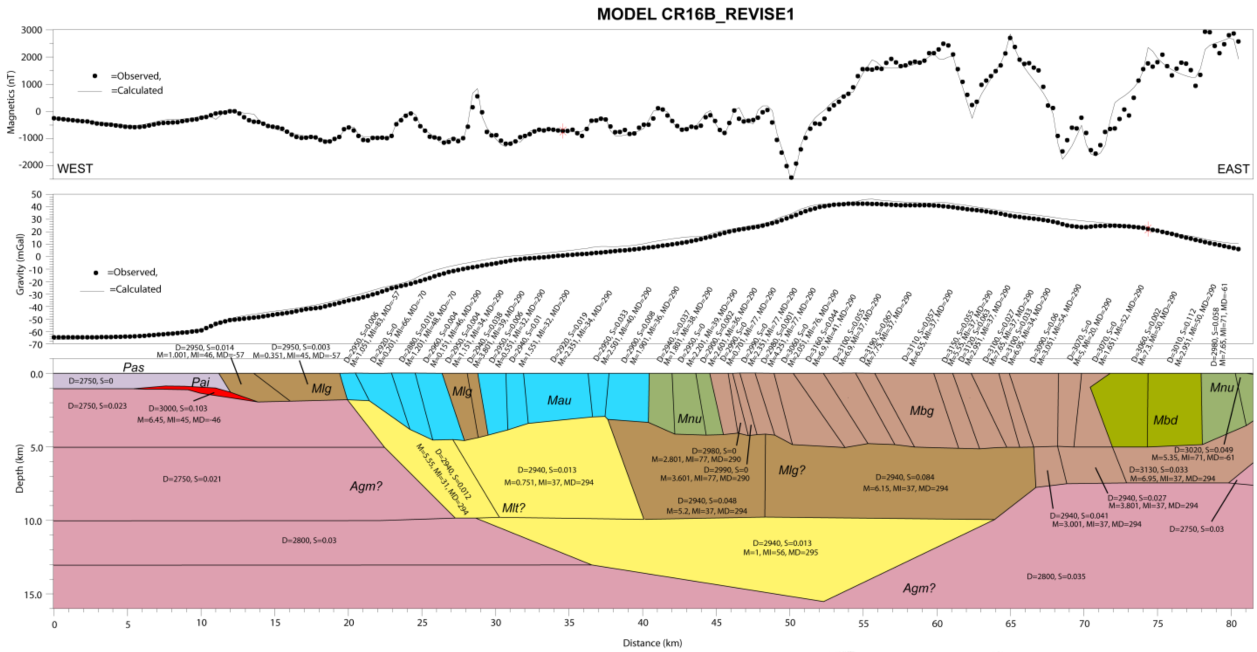
Geophysical models depicted here use various published images of bedrock geology to portray geologic units at depth. As a result, unit labels on models below may not precisely match those on the preliminary map that accompanies this report. Details are available on request.

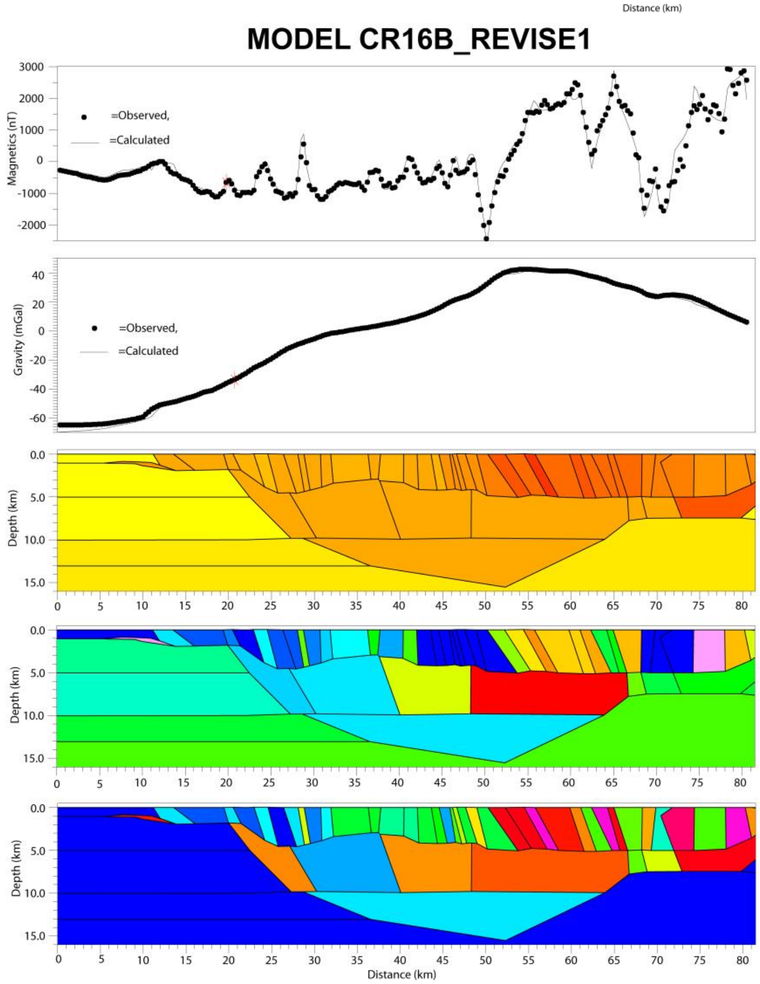


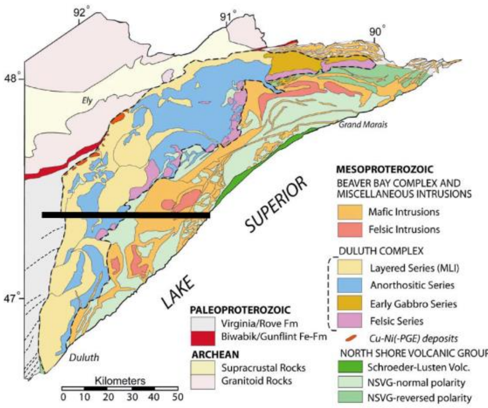


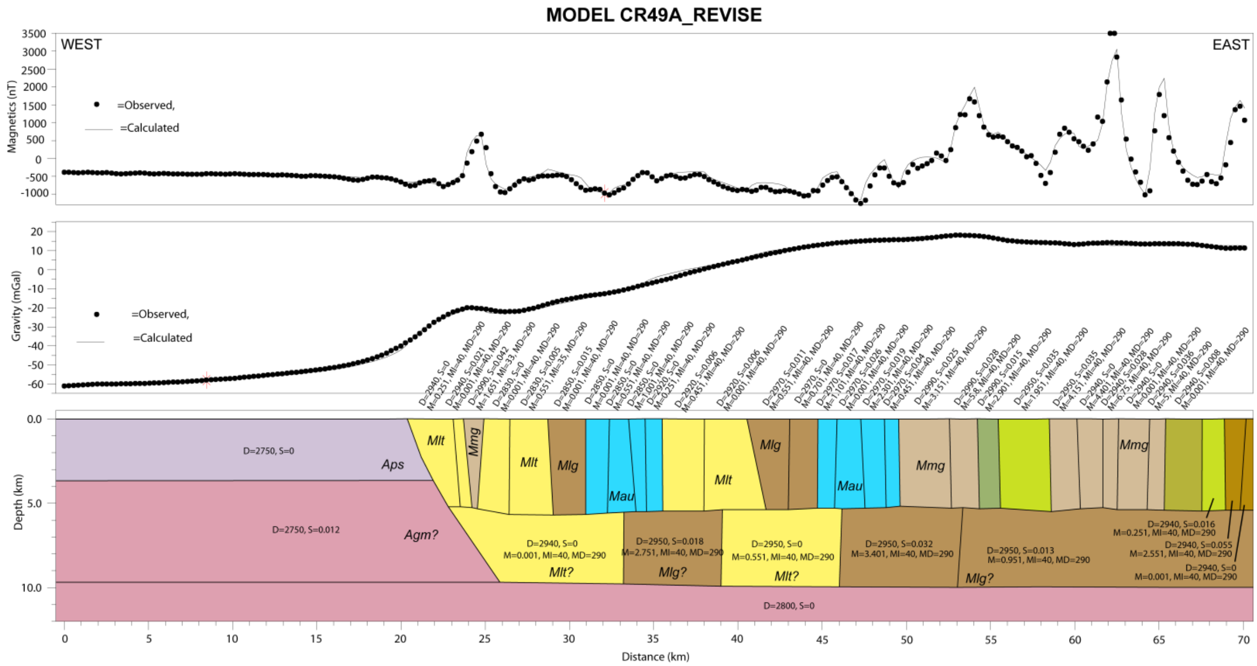

MODEL ANIMIKIE1C
NORTHEAST
SOUTHWEST
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
D=2000, S=0
(glacial sediments)
D=2750, S=0
D=2790, S=0.0
D=2800, S=0.014
D=2820, S=0.009
D=2820, S=0.004
D=2850, S=0.15
D=2840, S=0
D=2870, S=0
D=2750, S=0
Depth (km)
Elevation (km)
Distance (km)


MODEL ANIMIKIE1C_ROCK_PROP
NORTHEAST
SOUTHWEST
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
Elevation (km)
Distance (km)
Jirsa et al, 2012
Density
(kg/m^3)
Mag. Susc.
(SI Units)


MODEL CR16B_REVISE1
Magnetics (nT)
=Observed,
=Calculated
WEST
EAST
Gravity (mGal)
=Observed,
=Calculated
Depth (km)
Pas
Pai
Mlg
Mau
Mnu
Mbg
Mbd
Mlg?
Mlt?
Agm?
D=2750, S=0
D=2750, S=0.023
D=3000, S=0.103
M=6.45, MI=45, MD=-46
D=2750, S=0.021
D=2800, S=0.03
D=2940, S=0.013
M=0.751, MI=37, MD=294
D=2940, S=0.013
M=1, MI=56, MD=295
D=2800, S=0.035
D=2750, S=0.03
Distance (km)


MODEL CR16B_REVISE1
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
Depth (km)
Density
(kg/m^3)
Mag. Susc.
(SI Units)
NRM
(SI Units)
NRM Dec. = 290 - 314
NRM Inc. = 20 - 83
Distance (km)


92°
91°
90°
48°
47°
Ely
Grand Marais
Duluth
SUPERIOR
LAKE
MESOPROTEROZOIC
BEAVER BAY COMPLEX AND MISCELLANEOUS INTRUSIONS
Mafic Intrusions
Felsic Intrusions
DULUTH COMPLEX
Layered Series (MLI)
Anorthositic Series
Early Gabbro Series
Felsic Series
Cu-Ni(-PGE) deposits
NORTH SHORE VOLCANIC GROUP
Schroeder-Lusten Volc.
NSVG-normal polarity
NSVG-reversed polarity
PALEOPROTEROZOIC
Virginia/Rove Fm
Biwabik/Gunflint Fe-Fm
ARCHEAN
Supracrustal Rocks
Granitoid Rocks
Kilometers
0 10 20 30 40 50


MODEL CR49A_REVISE
WEST
EAST
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
Depth (km)
D=2750, S=0
Aps
D=2750, S=0.012
Agm?
Mlt
Mmg
Mlg
Mau
D=2940, S=0
M=0.001, MI=40, MD=290
Mlt?
D=2950, S=0.018
M=2.751, MI=40, MD=290
Mlg?
D=2950, S=0
M=0.551, MI=40, MD=290
D=2950, S=0.032
M=3.401, MI=40, MD=290
D=2950, S=0.013
M=0.951, MI=40, MD=290
D=2940, S=0.016
M=0.251, MI=40, MD=290
D=2940, S=0.055
M=2.551, MI=40, MD=290
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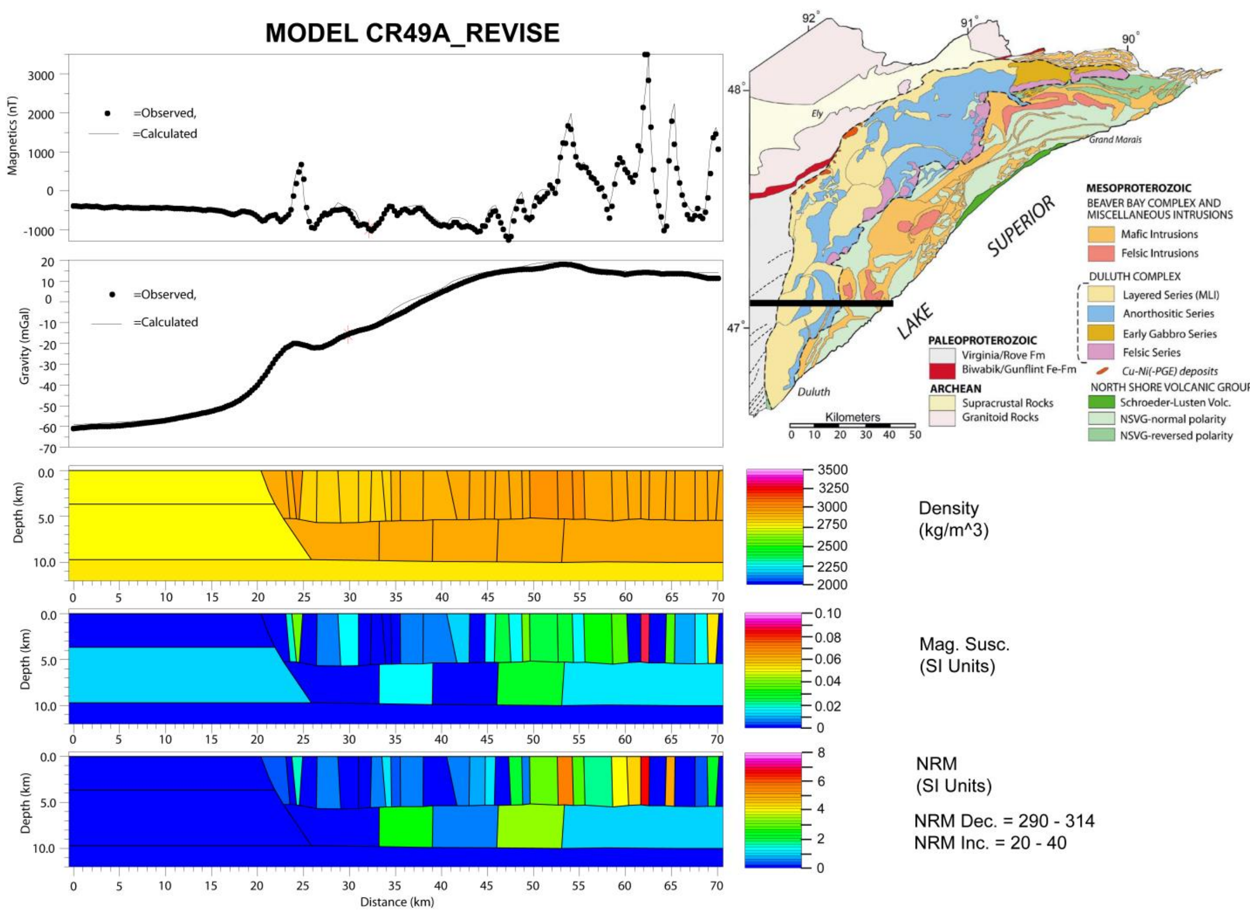
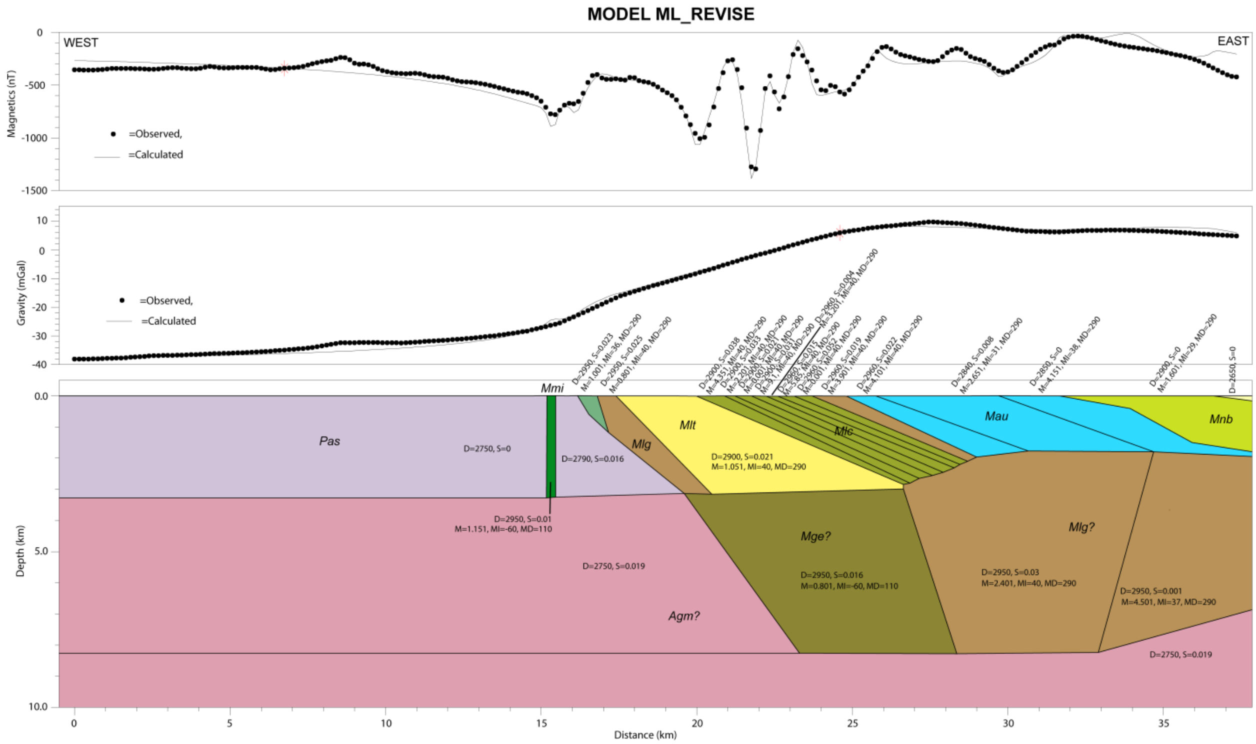
M=0.001, MI=40, MD=290
D=2800, S=0
Distance (km)


MODEL CR49A_REVISE
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
Depth (km)
Density
(kg/m^3)
Mag. Susc.
(SI Units)
NRM
(SI Units)
NRM Dec. = 290 - 314
NRM Inc. = 20 - 40
Distance (km)
92°
91°
90°
48°
47°
Ely
Grand Marais
Duluth
SUPERIOR
LAKE
MESOPROTEROZOIC
BEAVER BAY COMPLEX AND MISCELLANEOUS INTRUSIONS
Mafic Intrusions
Felsic Intrusions
DULUTH COMPLEX
Layered Series (MLI)
Anorthositic Series
Early Gabbro Series
Felsic Series
Cu-Ni(-PGE) deposits
NORTH SHORE VOLCANIC GROUP
Schroeder-Lusten Volc.
NSVG-normal polarity
NSVG-reversed polarity
PALEOPROTEROZOIC
Virginia/Rove Fm
Biwabik/Gunflint Fe-Fm
ARCHEAN
Supracrustal Rocks
Granitoid Rocks
Kilometers
0 10 20 30 40 50



MODEL ML_REVISE
WEST
EAST
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
Depth (km)
Distance (km)
Mmi
Pas
Mlg
Mlt
Mlc
Mau
Mnb
Mge?
Mlg?
Agm?
D=2750, S=0
D=2790, S=0.016
D=2900, S=0.021
M=1.051, MI=40, MD=290
D=2950, S=0.01
M=1.151, MI=-60, MD=110
D=2750, S=0.019
D=2950, S=0.016
M=0.801, MI=-60, MD=110
D=2950, S=0.03
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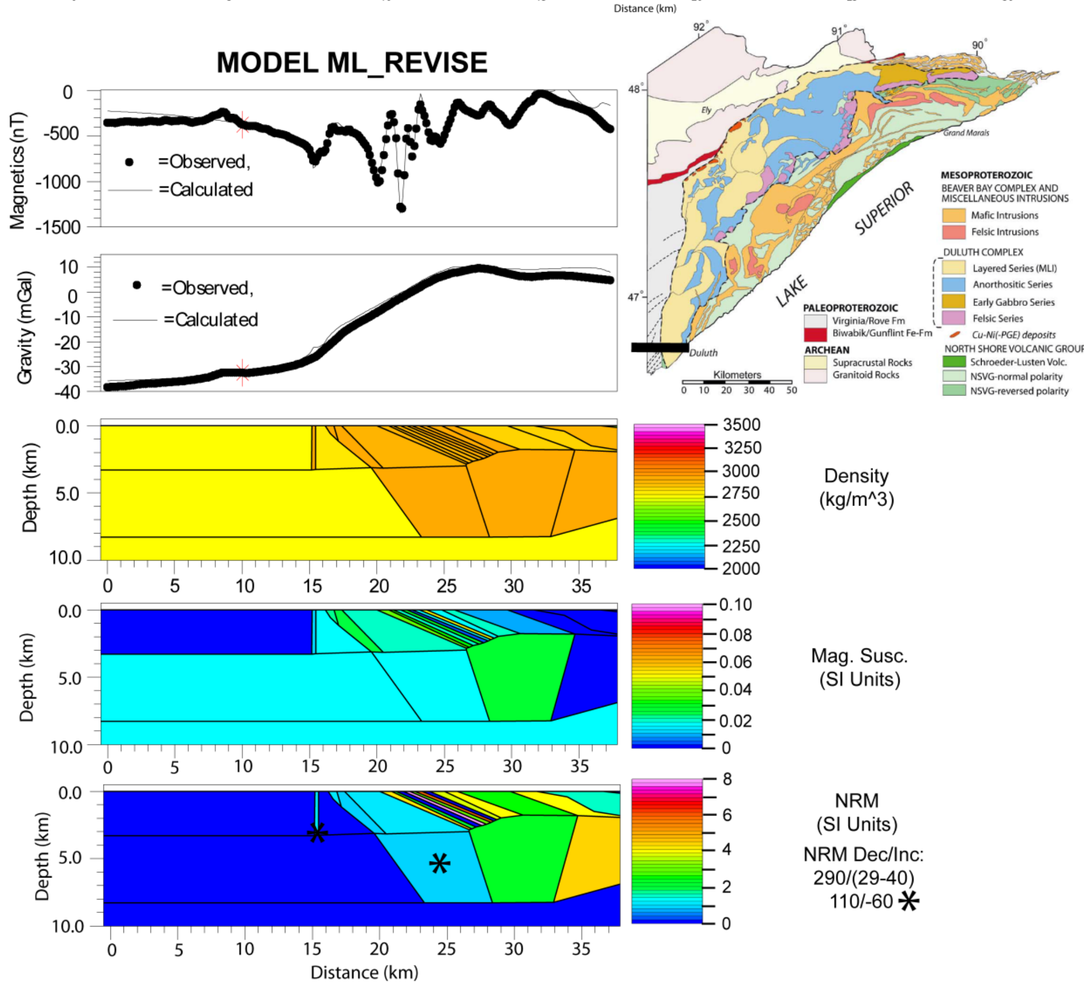
D=2750, S=0.019



MODEL ML_REVISE
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
Depth (km)
Density
(kg/m^3)
Mag. Susc.
(SI Units)
NRM
(SI Units)
NRM Dec/Inc:
290/(29-40)
110/-60
Distance (km)
Ely
Grand Marais
Duluth
SUPERIOR
LAKE
MESOPROTEROZOIC
BEAVER BAY COMPLEX AND MISCELLANEOUS INTRUSIONS
Mafic Intrusions
Felsic Intrusions
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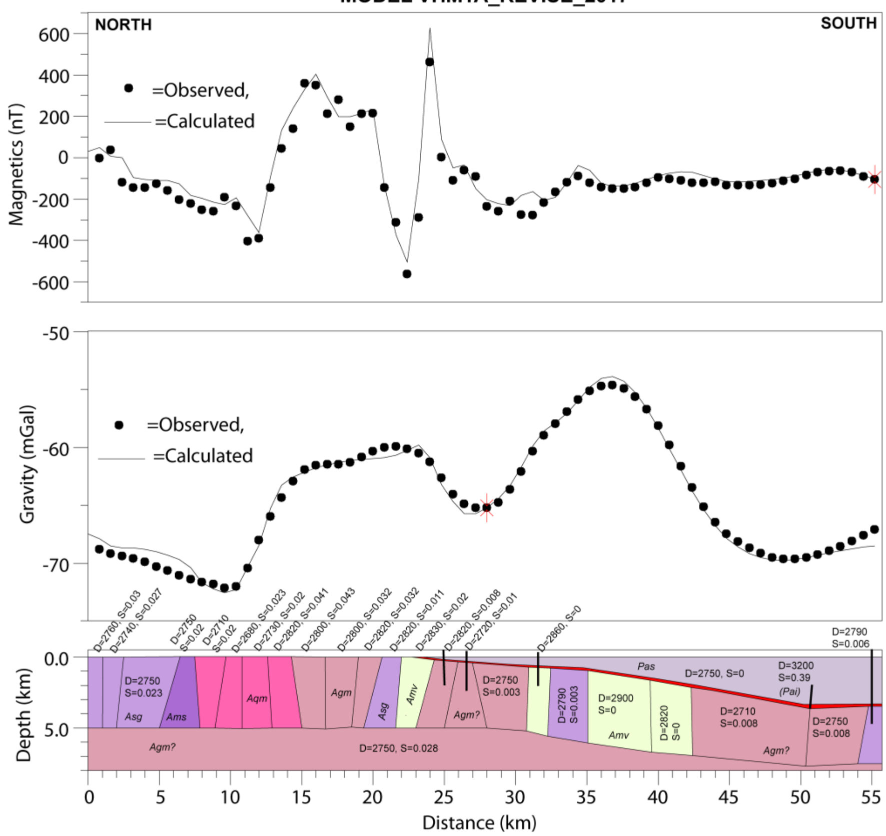
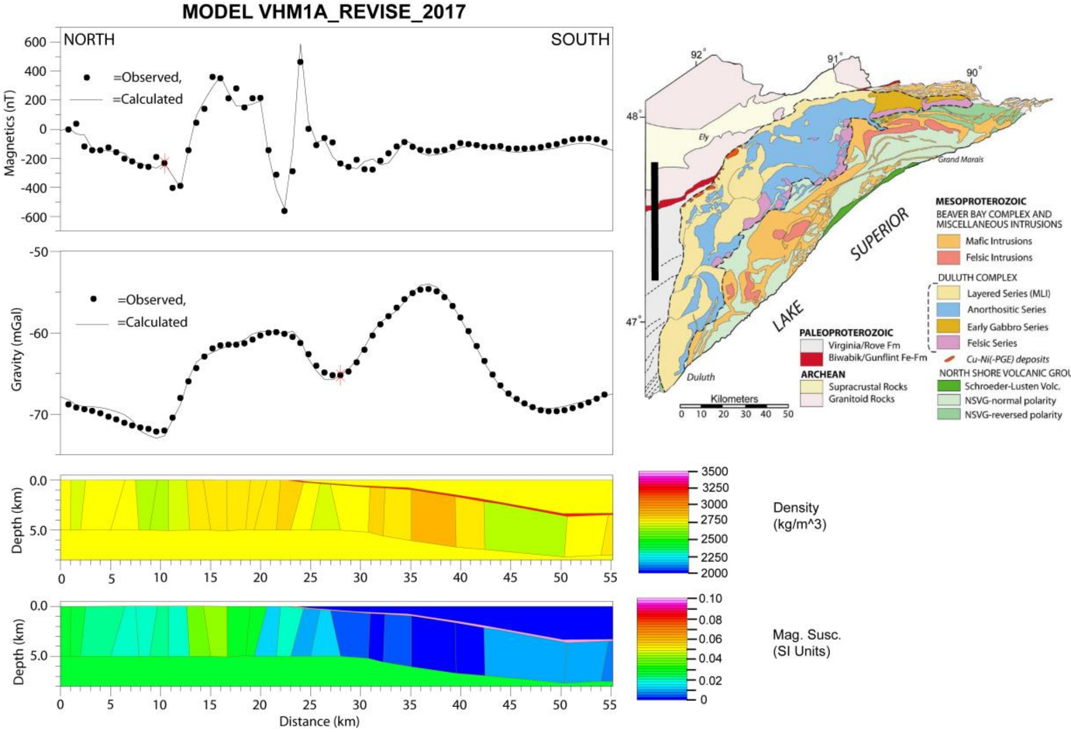
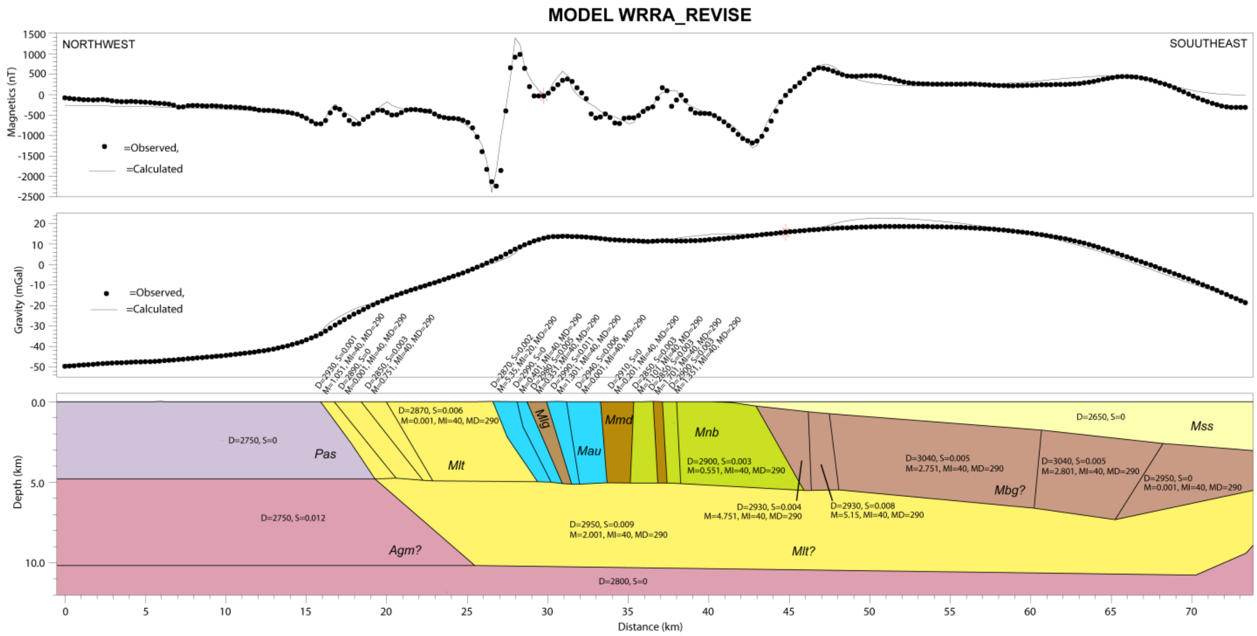
NSVG-normal polarity
NSVG-reversed polarity
PALEOPROTEROZOIC
Virginia/Rove Fm
Biwabik/Gunflint Fe-Fm
ARCHEAN
Supracrustal Rocks
Granitoid Rocks
Kilometers

MODEL VHM1A_REVISE_2017



MODEL VHM1A_REVISE_2017




MODEL WRRA_REVISE
NORTHWEST
SOUTHEAST
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
Depth (km)
D=2750, S=0
Pas
D=2870, S=0.006
M=0.001, MI=40, MD=290
Mlt
Mlg
Mau
Mmd
Mnb
D=2900, S=0.003
M=0.551, MI=40, MD=290
D=3040, S=0.005
M=2.751, MI=40, MD=290
D=3040, S=0.005
M=2.801, MI=40, MD=290
D=2950, S=0
M=0.001, MI=40, MD=290
D=2650, S=0
Mss
Mbg?
D=2930, S=0.004
M=4.751, MI=40, MD=290
D=2930, S=0.008
M=5.15, MI=40, MD=290
D=2750, S=0.012
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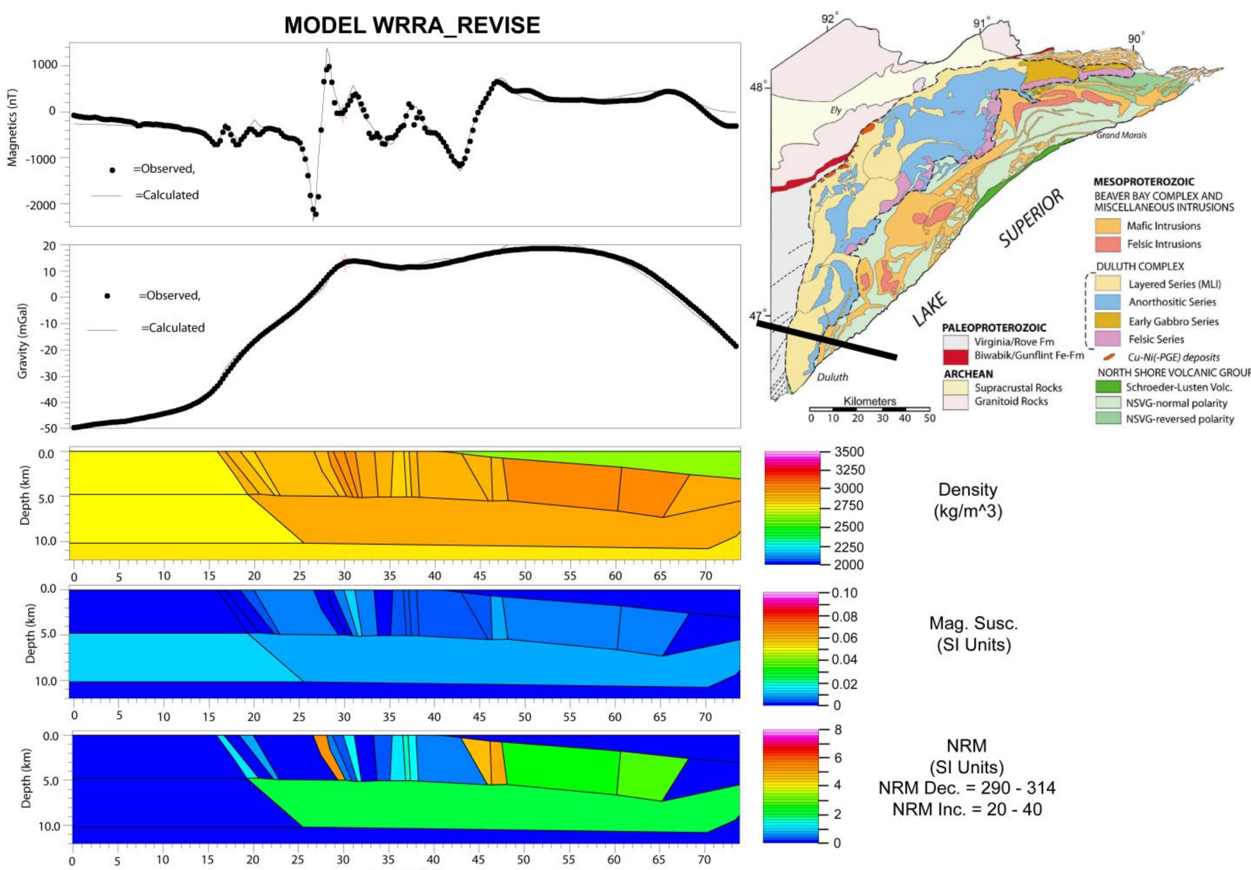
Agm?
Mlt?
D=2800, S=0
Distance (km)


MODEL WRRA_REVISE
Magnetics (nT)
=Observed,
=Calculated
Gravity (mGal)
=Observed,
=Calculated
Depth (km)
Density
(kg/m^3)
Mag. Susc.
(SI Units)
NRM
(SI Units)
NRM Dec. = 290 - 314
NRM Inc. = 20 - 40
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Schroeder-Lusten Volc.
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Virginia/Rove Fm
Biwabik/Gunflint Fe-Fm
ARCHEAN
Supracrustal Rocks
Granitoid Rocks