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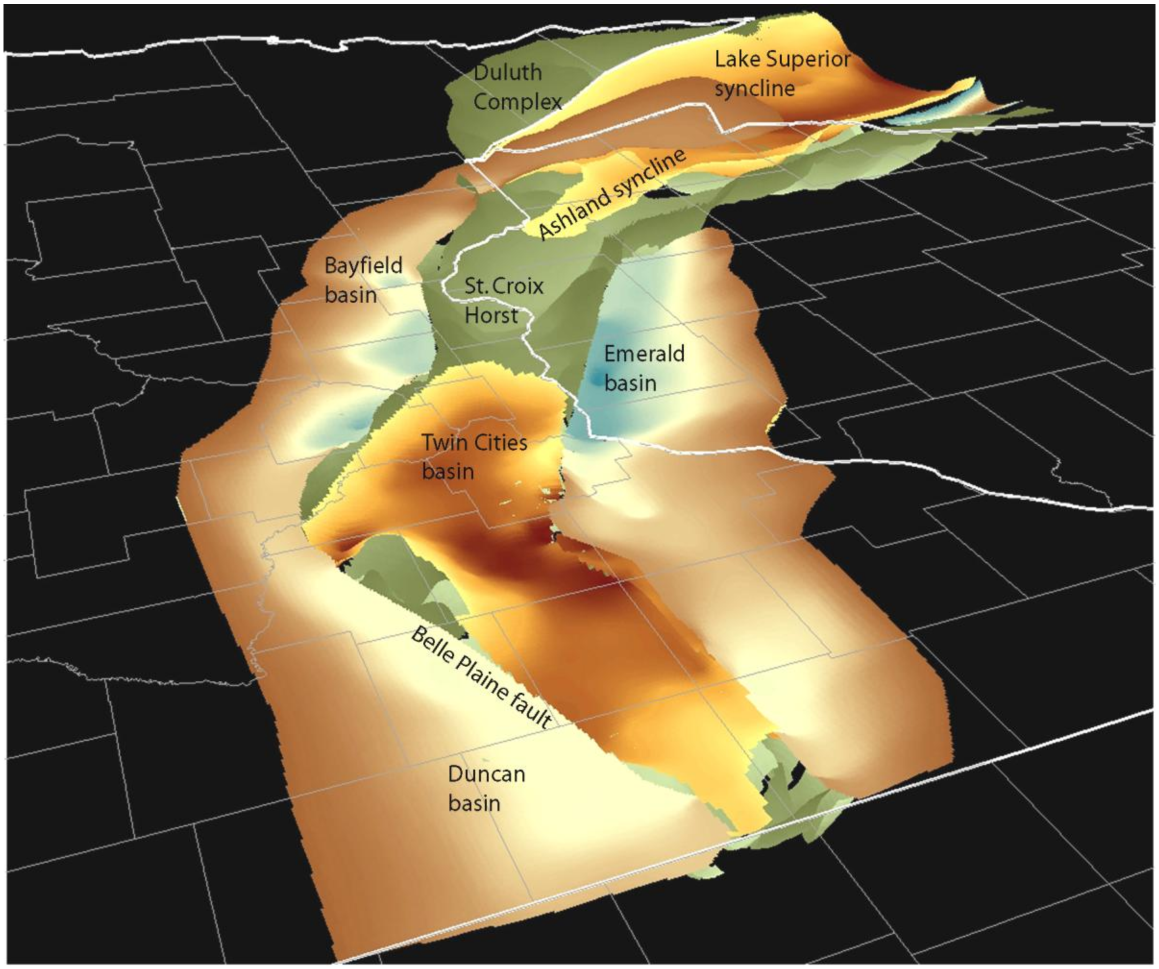

COMPILATION OF MINNESOTA AND WESTERN WISCONSIN GEOSCIENCE FOR THE USGS NATIONAL GEOLOGIC CARBON DIOXIDE SEQUESTRATION ASSESSMENT: ENHANCED GEOPHYSICAL MODEL FOR EXTENT AND THICKNESS OF DEEP SEDIMENTARY ROCKS

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COMPILATION OF MINNESOTA AND WESTERN WISCONSIN GEOSCIENCE FOR THE USGS NATIONAL GEOLOGIC CARBON DIOXIDE SEQUESTRATION ASSESSMENT: ENHANCED GEOPHYSICAL MODEL FOR EXTENT AND THICKNESS OF DEEP SEDIMENTARY ROCKS: EXECUTIVE SUMMARY

In 2010, Minnesota Geological Survey (MGS) was commissioned by the U.S. Geological Survey (USGS) to clarify available knowledge on the rocks that are most prospective for subsurface carbon dioxide sequestration in Minnesota and western Wisconsin. Although the prospective rocks, late Precambrian sedimentary basins of the Midcontinent Rift system (MRS), are at depths greater than the 1 km depth required for efficient carbon dioxide storage, and there is some potential for adequate porosity, permeability, and seals, the overall prospects for reservoir suitability are not promising from several perspectives. Nevertheless, the current USGS National Geologic Carbon Dioxide Sequestration Assessment project is presently seeking to clarify potential sequestration sites across the US. In response to a request from the USGS under this program, therefore, a summary of knowledge was assembled and enhanced, to provide the best readily available information on inferred geological tops, cross-sections, maps, geological history, and likely composition of the potential reservoirs and seals.

Knowledge of these rocks was originally developed on the basis of exposures near Lake Superior, and was substantially developed in the middle of the past century as geophysical surveys became available. By the 1980s, a broad outline of the extent, thickness, and characteristics of the rocks had been developed (Chandler et al., 1989), although to date, there has been very little drilling. Available information was summarized, however, in a standardized manner by a USGS National Oil and Gas Assessment report on the Superior Province (Palacas, 1995), which outlined the reservoir potential of the Midcontinent Rift sedimentary basins. The USGS report indicated that volcanic horsts in the rift axis are bounded by high-angle faults and flanked by asymmetric sedimentary basins up to 30,000' thick, with basins up to 6500' thick atop the horsts. With respect to reservoirs, structural traps were inferred to have formed during extensional and compressional tectonism, while sandstone stratigraphic traps and fractured shales also were recognized to be present. Varying styles of structures were inferred, including large anticlinal features and drag folds against reverse faulting, with stratigraphic traps considered likely. Likely seals were seen as shales, tight horizons, and fault gouge. The basins were regarded by USGS as a high risk hydrocarbon play.

Previous work on the potential for carbon dioxide sequestration in Minnesota has been carried out as a result of support from the Minnesota Legislature. In 2007, Minnesota Geological Survey was commissioned to prepare a report on the topic (MGS Open File 08-01; Thorleifson, 2008) that concluded that currently available data indicate that there is a very low probability of success in confirming suitable geologic conditions for deep geologic sequestration of CO_2 in Minnesota. At the same time, it was acknowledged that the data are inadequate to rule out the most prospective rocks. Sedimentary rocks were reported to be of adequate thickness in two north-south belts on either side of the Twin Cities, but limited data were cited as indicating that their properties are not favorable for CO_2 storage. It was finally concluded that interested parties may eventually require knowledge at a higher level of certainty than presently possible to indicate whether geologic carbon sequestration is a potential option for implementation within the State. For this, it was indicated that more geophysical surveys, drilling, and numerical modeling of CO_2 storage would be required, at a cost of tens of millions of dollars, to permit a reasonably informed judgment on the next phases of assessment.

In addition, the Minnesota Legislature has also funded an assessment of the potential for implementation of mineral carbonation as another geologic carbon sequestration method in Minnesota. An analysis presently underway therefore is examining the potential for olivine and serpentine-bearing mining wastes to be used to react with carbon dioxide, resulting in benign solid products.

With respect to the deep injection option, however, a modest step toward the agenda outlined in the 2008 Minnesota Geological Survey report is reported here. As the Minnesota contribution to the USGS National Geologic Carbon Dioxide Sequestration Assessment project, it was agreed that the work would assemble and enhance readily available information on saline formations that have potential for carbon dioxide sequestration in Minnesota and western Wisconsin.

Plans called for the investigation to consist of three-dimensional modeling of rift structure in Minnesota and adjacent parts of Wisconsin, primarily involving gravity and magnetic data. During the previous work summarized in MGS Open File 08-01 (Chandler, 2008), a three-dimensional gravity model by Allen (1994) was translated into current three-dimensional modeling software, and improvements were begun. However, the model needed to be extended to the north and south to complete coverage in Minnesota and Wisconsin, and constraints from independent data such as drill holes and seismic data needed to be worked into the model. In addition, three-dimensional magnetic modeling also was needed. The work was planned to provide an improved perspective on the geometry of the sedimentary basins and on structures that may be pertinent to sequestration.

In addition, at the outset of the work reported here, it was recognized that it would be desirable, in the medium term, to compile all pertinent information on sedimentary rock thickness, from sources such as drill holes, available seismic surveys, and Euler analysis, into a 3D model. The 3D gravity model by Allen (1994) was to form the starting point, although coverage would be extended from the Minnesota-Iowa border to western Lake Superior. Prior to modeling, all of these data would need to be placed into a 3D visualization scheme. A 3D gravity and magnetic model would then be created and at least a general fit to observed gravity and magnetic data would be completed. It was concluded, at the outset of the current investigation, however, that completion of this model would be beyond the scope of the current project.

Plans therefore were made to make progress that would immediately be useful to all persons contemplating deep geologic CO2 sequestration in Minnesota and western Wisconsin. The project was to consist of compilation and 3D visualization only, and the area would be restricted to that of David Allen's original model. Added to his interpretation was to be information on sedimentary rocks from drill-hole data and previous geophysical interpretations. It was agreed that, although this model could be used later to construct a 3D gravity and magnetic model, no such activity would be planned for the current proposed project. Nevertheless, during the progress of the current project, additional support was found, so that the work reported here goes beyond that agreed to between USGS and MGS, in that the compilation extends beyond the Allen model, to Lake Superior.

Having clarified what could be accomplished, available data and achievable interpretations regarding the thickness and extent of the Midcontinent Rift sedimentary basins, from western Lake Superior to Minnesota and western Wisconsin, were assembled in appropriate software. Three-dimensional gravity modeling by Allen (1994) formed the core of the reconstruction. Combined with seismic soundings and results from new Euler, 2-D gravity, and magnetic modeling, the complete visualization can now form a foundation for future 3-D gravity and magnetic modeling, which would further improve our understanding of the regional geometry and history of the sedimentary basins associated with the rift. Although the results presented here do not dramatically change our views on the thickness, extent, and character of the rocks, the enhanced visualization is a much improved depiction of sedimentary basin thickness and extent, and thus a tool for better assessing these large and little-explored sedimentary basins.

INTRODUCTION

Increasing concern about climate change has necessitated the assessment of ways to reduce greenhouse gas emissions, while concurrently increasing our preparedness for climate change and variability. In 2007, the Minnesota Legislature set goals to reduce our emissions 15% by 2015, 30% by 2025, and 80% by 2050. These reductions can be achieved by reducing combustion of fossil fuels, and by reducing other activity that generates greenhouse gases. In addition, changes in land use can induce increased storage of carbon in soil and vegetation, thus facilitating terrestrial sequestration of emissions. Furthermore, in the case of stationary sources of carbon dioxide (CO2) emissions, the technology to capture CO_2 is available, contingent upon acceptability of costs. The likely fate of CO_2 captured from stationary sources would be storage by geologic sequestration, by deep injection into underground saline geologic formations, or by mineral carbonation, in which CO_2 is reacted with material from mining, producing mineral products for disposal or use in construction.

With respect to the deep injection method, a conceivable option for Minnesota is export of CO_2 by pipeline to one or more potentially willing jurisdictions, where apparently suitable geologic repositories have been confirmed. It is possible, however, that saline formations in Minnesota could be confirmed as geologic CO_2 repositories, possibly enabling carbon storage without the requirement for negotiations with neighboring jurisdictions and export by pipeline. The only rocks in Minnesota that potentially have the required reservoir properties below about a kilometer depth, the depth required for efficient CO_2 storage, are sequences of sedimentary rocks associated with the Midcontinent Rift System (MRS), a southwestward extension of the Lake Superior basin that extends to Kansas that in this region includes the upper, more mature Bayfield Group, and the lower, less mature Oronto Group (Chandler et al., 1989; Palacas, 1995). Concurrently, it is noted that Minnesota has favorable geology for the mineral carbonation option, and this geologic carbon sequestration technique could enhance the economic viability of potential mining proposals near Duluth, although the method is not fully developed and the costs remain high.

To ensure availability of adequate knowledge on options, a spring 2007 bill passed by the Minnesota Legislature provided for carbon sequestration studies, including funding to the MGS for the purpose of geologic carbon sequestration assessment. As a result, a report was prepared by staff of MGS and University of Minnesota Department of Geology and Geophysics, summarizing current knowledge and knowledge gaps regarding the potential capacity for geologic carbon sequestration in the Midcontinent Rift System (MRS) in Minnesota, while also briefly discussing the mineral carbonation option.

The report, MGS Open File 08-01 (Thorleifson, 2008), reviewed published, unpublished, and new data pertinent to the potential long-term storage of carbon in Minnesota geologic formations, and identified the most promising areas in Minnesota for potential carbon sequestration. In addition, computer modeling methods were discussed and applied to the Minnesota context to the extent that could readily be achieved.

The rocks most prospective for potential deep injection identified by the report, known with respect to their depth and thickness on the basis of geophysical surveys, consist of sandstones occurring as two north-south belts on either side of the Twin Cities, and extending into Wisconsin. Available geophysical information, based on seismic data and gravity and magnetic surveys, indicated that there is sufficient sedimentary rock depth and thickness in the Midcontinent Rift System sedimentary basins for further consideration of sequestration capacity to be warranted.

The MGS report further noted, however, that rock sampling data that were available at the time, a situation that remains unchanged, provide negative indications of the potential for deep sequestration. The known and inferred properties of the rocks in Minnesota and neighboring areas indicate that there is only a very small probability for geologic attributes necessary to serve as a site for deep geologic sequestration of CO_2. Geophysical logs of deep exploratory boreholes in Iowa and Wisconsin, petrographic analyses of sandstone in those states as well as

Michigan and Minnesota, and tests on samples from Minnesota and Iowa cores indicate that sandstone at the depth required for sequestration is relatively low in porosity and permeability. Permeability has been measured to be orders of magnitude too low for sequestration to be viable everywhere it has been tested in the MRS. In addition, although factors other than porosity can affect seismic velocity, the available velocity data from seismic refraction surveys do not look promising, as most values exceed 12,000 ft/sec, which are values higher than those typical of highly porous rock. Furthermore, the MRS is associated with a more complex tectonic history compared to other sites being investigated, and therefore features such as faults and fractures may play a larger role in site evaluation. For example, low permeability beds in the MRS that are necessary to serve as seals on top of potential CO2 reservoirs are known to contain fractures with evidence of fluid flow. Fractures associated with faults are believed to serve as conduits for deep MRS groundwater to travel upward across such seals to overlying freshwater aquifers today.

The 2008 MGS report suggested, however, that our understanding of the three-dimensional geometry of the rift basins and of bounding structures remains incomplete, and that rock property data is limited, and therefore additional data and analyses could clarify potential for deep sequestration. It was anticipated that interested parties may at some point require a higher level of certainty than presently is possible to indicate whether geologic carbon sequestration is a potential option for implementation within the State. In relation to current efforts by USGS to assemble information needed for a national geologic carbon dioxide sequestration assessment, therefore, it was agreed that MGS would provide a report that would extend, improve, and update the regional geoscience information previously released as MGS Open File 08-01.

REGIONAL GEOLOGY INDICATED BY HYDROCARBON ASSESSMENT

The 1995 USGS National Oil and Gas Assessment (Palacas, 1995) indicated that the hypothetical Precambrian Midcontinent Rift System (MRS; Chandler et al., 1989) play consists of possible oil and gas accumulations in structural and stratigraphic traps within the 800 mile long Midcontinent Rift System. Gravity and magnetic surveys were seen as indicating that this middle Proterozoic, 1.1 billion year-old rift extends from Kansas to Michigan. Broad, transverse-faulted medial volcanic horsts were reported to be bounded by high-angle faults and flanked by asymmetric sedimentary basins up to 30,000’ thick, with basins up to 6500’ thick atop the horsts.

Structural and stratigraphic traps were thought to possibly have formed by crustal extension and sedimentary facies distribution, with tectonic inversion late in rift development likely producing compressional and wrench structures. Primary targets were thoughts to be fluvial, deltaic, and shoreline sandstones of the Nonesuch Formation and the underlying upper Copper Harbor Conglomerate, both with porosities reported by Palacas (1995) to be up to 13%. Fractured shales were reported to occur in the Nonesuch Formation, with sandstones with porosities up to 18% occurring in the overlying Freda Sandstone.

Nonesuch Formation shales up to 700’ thick were reported to contain up to 3% total organic carbon (TOC) by weight, and live oil seeps in the White Pine Copper Mine in Michigan were thought to confirm that liquid hydrocarbons have been generated. Kerogens are type II and type I, and moderately mature Tmax values of 435-440°C have been determined, according to Palacas (1995). Although the organic matter was thought to be oil prone, gas was considered the more likely target due to the typical degree of thermal maturity.

It was thought that, during extensional tectonism, the Nonesuch Formation and equivalents may have generated oil and gas, especially in the deeper portions of the basins, prior to compressional tectonism. In the shallower portions of flanking basins, a second phase of oil and gas generation was considered probably to have occurred following deposition of Paleozoic sediments. In addition, hydrocarbons that might have accumulated during initial rifting may have re-migrated into structures formed during compression.

Dual stages of tectonism would have produced a broad range of trapping conditions, with varying styles of fault-related structures. Tectonic inversion may also have created structural features of varying scale that could contain giant accumulations of hydrocarbons. In Minnesota, seismic reflection has documented large anticlinal features, while drag folds against reverse faulting offer multiple reservoir possibilities. Stratigraphic traps also likely occur, according to Palacas (1995).

Probable seals were thought to include shales of the Nonesuch Formation, as well as tight horizons in the overlying Freda Sandstone and Bayfield Group. Fault gouge may also account for some seals.

Palacas (1995) described how only five wells have penetrated the lower Keweenawan Supergroup rocks that have the highest potential for hydrocarbon reserves. No commercial oil or gas accumulations have been confirmed. Drilling in the 1980s at sites from Kansas to Michigan was stimulated by increasing awareness of source rock potential and oil seeps, as well as improved knowledge of large reserves in other rift basins such as the North Sea, Gulf of Suez, and Pripyat Basin, as well other Precambrian terranes such as the Lena-Tunguska Petroleum Province of Eastern Siberia, the Sichuan Basin of southern China, and the Upper Proterozoic Huqf Group of Oman.

The rift thus was regarded as a high risk play by USGS, as few wells have been drilled, potential source rocks are known to be or may be overmature, while reservoir porosities in some regions may be unfavorable. However, it seems reasonable to speculate that source rocks may have more favorable levels of thermal maturity if present at shallower depths of burial along the basin flanks. Drilling depths would vary from 3,000' to as much as 25,000'.

BACKGROUND TO THE GEOPHYSICAL COMPILATION

The Midcontinent Rift is a major tectonic feature that extends across much of the central United States (Figure 1). Much of the Midcontinent Rift is concealed beneath a cover of Pleistocene glacial materials and Phanerozoic rocks, and there has been little drilling, so geologic studies of rift features rely on geophysical data. In addition to mapping rift features at or near the surface, geophysical data provide the only tools to investigate rift structure at depth. Gravity, magnetic and seismic data have been of particular importance to geologic studies of the rift (Figures 2 and 3). With emphasis on the suitability of rift-related sedimentary rocks for CO_2 sequestration, Chandler (2008) described the geophysical characteristics of the Midcontinent Rift in Minnesota and Wisconsin, and summarized the geologic interpretations that have been derived from gravity, magnetic and seismic studies. Among the products from this work was a three-dimensional (3-D) visualization of a 3-D gravity model by Allen (1994), which portrayed rift structure in Minnesota and Wisconsin. Allen also produced a 3-D gravity model of the rift beneath western Lake Superior, but this was not included in the 2008 visualization. In both models, Allen carefully constrained his 3-D gravity interpretation with known geology and all of the seismic reflection sections that were available (Figures 2 and 3). 3-D models were also cross-checked with 2-D gravity and magnetic modeling along 10 profiles (Figures 2, 3, and 14). As a consequence, Allen's 3-D gravity models are the most comprehensive portrayals of rift structure between western Lake Superior and Iowa. A recently-completed 3-D reconstruction that incorporates both of Allen's Minnesota-Wisconsin and the western Lake Superior models is shown in Figure 4.

In spite of the authoritative appearance of this model, 3-D modeling of the Midcontinent Rift along and southwest of Lake Superior can be significantly improved in several areas. This is particularly true for the sedimentary basins associated with the rift. Areas with seismic reflection coverage (Figures 2 and 3) represent the best-constrained parts of Allen's 3-D modeling and are not likely to be significantly revised for the foreseeable future. However, many other areas lack seismic reflection coverage, and interpretations there are likely to change as the results of new geophysical studies become available. Some recent studies by the Minnesota Geological Survey (MGS) have provided new perspectives on rift structure, including a new application of the Euler method - a magnetic inversion scheme that estimates depth to sources, and 2-D gravity and magnetic model studies that were conducted as part of this and other MGS investigations. The primary objective of this project is to incorporate recent work into a new 3-D visualization that includes Allen's 3-D modeling of the rift in western lake Superior, Minnesota, and Wisconsin (Figure 4), along with the earlier work by Allen (1994) of 2-D gravity and magnetic modeling and seismic interpretations. The results and visualizations will provide a means to display, compare and evaluate the various interpretations along this part of the rift and provide an effective starting point for future 3-D gravity and magnetic model studies.

Originally, this project was planned to only allow for the inclusion of Allen's Minnesota-Wisconsin 3-D gravity model, and not his western Lake Superior interpretation. However, when additional funds became available through the University of Minnesota's Initiative for Renewable Energy and the Environment (IREE), Allen's western Lake Superior model was geo-referenced and merged with the visualization of his Minnesota-Wisconsin model (Figure 4). That process, as well as summary of a 2-D gravity and magnetic model that was conducted to assist in the merging, will be reported on separately (Val Chandler, MGS report in preparation).

DESCRIPTION OF THE GRAVITY AND MAGNETIC DATA

Gravity and magnetic data have been the primary tools for investigating the Midcontinent Rift System (Chandler, 2008), and they are particularly pertinent to this project. With the advent of high-quality gravity and magnetic data, geologic mapping of portions of the Midcontinent Rift System and adjacent Precambrian terranes (Jirsa et al., 2011) was able to rely heavily on the geophysical interpretations. Recent compilations of the gravity and aeromagnetic data for the rift in Minnesota and Wisconsin are shown in Figures 2 and 3, respectively. The gravity data in Minnesota and Wisconsin are based on ground stations that are typically spaced 1 to 5 km apart (Chandler and Schaap, 1991; Daniels and Snyder, 2002), whereas the aeromagnetic data were acquired along flight lines that were spaced 400 to 1000 meters apart (Chandler, 1991). Aeromagnetic and gravity coverage over western Lake Superior is much more widely spaced (Chandler and Schaap, 1991; Chandler et al., 2007).

In Minnesota and Wisconsin, the rift is characterized by a prominent, northeast-striking belt of intense magnetic and gravity highs (Figures 2 and 3). These highs delineate blocks of predominantly mafic volcanic rocks and associated intrusions that, following their deposition in grabens or half-grabens, were uplifted along bounding faults to form the St. Croix horst (Allen et al., 1997; Chandler et al., 1989). The volcanic rocks are structurally flanked and locally overlain by the slightly younger sedimentary rocks of the Oronto and Bayfield groups. These sedimentary rocks have relatively low densities and are essentially non-magnetic. They are characterized by strongly negative gravity anomalies and subdued magnetic signatures that flank the strongly positive signatures of the axial horst (Figures 2 and 3, respectively). In southeastern Minnesota, the axial block of volcanic rocks narrows and is deflected abruptly to the south-southeast along the Belle Plaine Fault zone (Allen et al., 1997).

EULER ANALYSIS OF THE MIDCONTINENT RIFT

Much of the interpreted structure of the Midcontinent Rift was based on 2-D and 3-D gravity and magnetic modeling data (Chandler et al., 1989, Allen, 1994; and Allen et al., 1997). These studies used forward modeling, where a model was altered by the user until the calculated anomaly suitably fit the observed anomaly. In contrast, the Euler method, sometimes referred to as Euler deconvolution, is an inverse approach where solutions are mathematically inverted directly from the anomaly data. Most commonly, the Euler method is applied to gridded magnetic data, and the resulting solutions estimate the positions of the anomaly sources in three dimensions. The Euler method is particularly useful in estimating the thickness of non-magnetic sedimentary rocks that overlie a magnetic basement, which is precisely the situation of the sedimentary basins along the Midcontinent Rift. The Euler method can thereby provide a cross-check to some of the forward magnetic modeling along the rift.

The Euler method is based on Euler's homogeneity equation, which is a differential equation that relates the gradient components of gravity or magnetic anomalies to the location of the source (Reid et al., 1990). The Euler method requires no *a priori* information regarding source magnetization. Unlike some inversion schemes, no specific type of geologic source is assumed for Euler applications (vertical sheet, vertical prism, etc.). Instead, a structural index (SI) value is selected, which expresses the power of the rate of field change related to a given source-type. For example, SI=1 is consistent with a thin vertical dike or the edge of a horizontal sill (anomalies falls off as 1/r, where r is the distance to the source), whereas SI=2 is consistent with a thin vertical pipe or a horizontal cylinder (anomalies fall of as 1/r^2). A contact (infinitely deep) would have a structural index of 0, but because this value can lead to mathematical instabilities, a structural index of 0.5 is often used to approximate contact solutions (Geosoft Inc., 2008).

A preliminary application of the Euler method on magnetic data from the Midcontinent Rift produced encouraging results (Chandler, 2008). No rigorous evaluation was conducted, but the results using a structural index of 0.5 yielded thickness estimates of the sedimentary rocks that appeared to be generally consistent with those from seismic data and three-dimensional gravity modeling by Allen (1994). Chandler (2009) applied a more robust form of the Euler method, known as located Euler analysis (see Geosoft, 2008 or Chandler, 2009 for an explanation), and applied a somewhat more rigorous evaluation using the seismic refraction interpretations by Mooney et al. (1970) as control. The magnetic data were continued upward to a level of 1000 meters to attenuate near-surface interference followed by located Euler analysis using structural indices of 1.0 and 0.5. Comparison of the Euler results with the seismic refraction interpretations showed considerable scatter, but results using a structural index of 0.5 provided generally better agreement than those using in index of 1.0. Consequently, a structural index of 0.5 is preferred for the sedimentary basins along the rift.

The current study investigated Euler analysis derived from two levels of continuation for the aeromagnetic data grid as follows: (1) a relatively low level of 300 meters above surface, to accentuate the contribution of near-surface and shallow anomaly sources in the bedrock, and (2) a higher level of 1000 meters above surface, to accentuate deeper anomaly sources in the bedrock. As mentioned above, upward continuation is performed to smooth out the noise related to data errors as well as cultural and natural sources at the surface. The 300 meter-level data were produced by upward continuing the aeromagnetic grid from its compilation level of 150 meters (Chandler, 2007) to a level of 300 meters, and by decimating the grid interval from 100 meters to 200 meters. The 1000 meter-level data was produced by upward continuing the aeromagnetic grid from its compilation level of 150 meters to a level of 1000 meters, and by decimating the grid interval from 100 meters to 500 meters. Located Euler analysis was then applied to the two grids. The Located Euler method uses maxima in the analytical signal grid (Blakely, 1996), to locate maximum anomaly gradient areas where Euler solutions are most likely to be significant, thereby eliminating many of the spurious solutions that tend to confound standard Euler applications (Chandler, 2008). Besides focusing the Euler analysis to these optimal areas, the located approach also automatically selects the window sizes for Euler analysis. Detailed grids summarize the 300-level and 1000-level located Euler solutions in Figures 5 and 6, respectively.

The results from the 300 meter-level data, yield many solutions along the rims and shallower parts of the rift basins (Figure 5). The results also appear to be tracking some deeper parts of the sedimentary basins along the rift, although significant interference from shallower sources are evident in several places, such as the northern Twin Cities basin and adjacent parts of the Emerald and Bayfield basins (Figure 4). The 1000 meter-level results (Figure 6) appear to be tracking the deeper parts of the basin more reliably, although the shallow structures near the edges of the basins do not appear to be delineated quite as sharply as with the 300 meter-level data.

The 300 meter-level and 1000 meter-level solutions were windowed and combined in such a way to emphasize the strengths of each dataset, the former for detail near basin edges and the latter for the deeper parts of the basins. A polygon was created that approximated the thickness contour at 1500 meters. This was used to window the results such that the shallow (300 meter-level) solutions were outside of the polygon and the deep (1000 meter-level) solutions were inside the polygon. Both the combined and windowed data sets were edited to eliminate some persistent near-surface effects in the Twin Cities basin, suspected to be cultural, and east of the Bayfield Peninsula, suspected to be glacial. The detailed grid of the combined datasets is shown in Figure 7, along with the polygons that were used for the window and edits. A smoothed grid from the combined datasets showing general trends and patterns is provided in Figure 8, while Figure 9 shows a 3-D visualization of the combined 300 and 1000 meter-level solutions.

The thickness estimates of the Precambrian sedimentary rocks from the Euler analysis are in general agreement with those derived by Allen's (1994) 3-D gravity models, although a few noticeable departures are evident. In western Lake Superior both approaches indicate up to 6-8 km of Oronto Group rocks, with maxima northeast of the Bayfield Peninsula and in central Lake Superior. Allen's models and the Euler analysis also indicated thicknesses of 1-2 km for Oronto Group rocks in the Ashland Syncline. Along the Emerald basin in Wisconsin, Euler estimates of 4-5 km correspond well with Allen's estimates of 4- 5 km of Bayfield Group rocks (no Oronto Group rocks). To the southwest into Minnesota, Euler estimates in the Emerald basin of 5-6 km compare favorably with Allen's estimate of about 6 km for the combined Oronto-Bayfield Group sequence. In the Twin Cities basin, Euler solutions indicate a 3-5 km thickness of Oronto Group rocks whereas Allen estimated 3-4 km. In contrast, 2-D gravity and magnetic modeling across the Twin Cities basin by Allen (Profile E-E') indicated only about 2 km of Oronto group rocks. The biggest departure between the Euler solutions and Allen's 3-D modeling occurs along the central part of the Belle Plaine fault where Euler solutions imply thicknesses of 6-8 km of non-magnetic rocks, and Allen's models estimate only about 4 km of combined Bayfield-Oronto rocks. Part of the thick, non-magnetic sequence that is implied by the Euler solutions may reflect felsic volcanic rocks. Allen (1994) reported felsic lava in a drill hole in the vicinity, and on the basis of modeling along his profiles B-B', C-C' and D-D', he implied a zone of felsic volcanic rocks along the Belle Plaine fault (Figures 2 and 3). These parts of the rift as well as the Twin Cities basin to the north therefore were further investigated using 2-D modeling.

NEW MODEL STUDIES OF THE RIFT

All new modeling was conducted along selected profiles (Figures 2 and 3) using the GM-SYS module of the OAISIS-MONTAJ software system by Geosoft, Inc. This approach is based on two-dimensional (strike-infinite) sources, although end corrections are allowed for sources with limited strike-lengths. This software was also used to extract profiles for the models from gridded data, including observed gravity and magnetic data, surface topography and bedrock topography. Except for igneous rocks that are presumed to be related to the rift, induced magnetization is assumed, with geomagnetic parameters determined from the IGRF (International Geomagnetic Reference Field; http://www.ngdc.noaa.gov/geomag/). Rift-related igneous rocks are commonly associated with strong NRM (natural remanent magnetization) typically directed either westwards at moderately downward inclinations (normal) or eastwards at steeply upward inclinations (reversed). In the discussions to follow, the following terms are used to describe magnetic properties: moderate magnetic susceptibility = greater than 0.00314 SI (0.00025 cgs), moderate NRM = greater than 0.25 SI (0.00025 cgs); high magnetic susceptibility = greater than 0.01257 SI (0.001 cgs); strong NRM = greater than 1.0 SI (0.001 cgs)

Profiles SE1-SE1' and SE3-SE3' were developed to investigate a segment along the Belle Plaine fault where Euler solutions indicated non-magnetic rocks that were as thick as 8 km. No seismic data are available in the vicinity, nor have any gravity and magnetic model studies been conducted directly over this area. The non-magnetic sequence could plausibly represent basins of rift-related sedimentary rocks, for basins with similar thickness have been delineated in western Lake Superior (Allen, 1994). Alternatively the non-magnetic sequence could in part reflect felsic volcanic rocks, as proposed along the Belle Plaine fault by Allen (1994) on the basis of a single drill hole and gravity and magnetic modeling along profiles B-B', C-C', and D-D' (Figures 2 and 3). Assuming that the non magnetic sequence is roughly divided evenly between Bayfield and Oronto equivalent rocks, plausible fits were achieved along both profiles with maximum sedimentary thicknesses of 8 km (Figures 10 and 11). Non-magnetic rhyolite could feasibly replace the Oronto Group rocks in the interpretations, but sedimentary rocks are here tentatively favored. Most of the bodies that were interpreted on Allen's models to contain felsic volcanic rocks were associated with moderate to high magnetic susceptibilities and NRM values. Beneath the inferred sedimentary rocks, a steep-sided, 10 km-thick block of mafic igneous rocks is interpreted, indicated in green, which has a high magnetic susceptibility and a strong NRM that is directed westwards at moderate to steep angles - consistent with normally polarized Precambrian Keweenawan rocks (Allen, 1994). A moderately dense (2.75 gm/cc) mass with high magnetic susceptibility values is inferred beneath the western parts of the models, coded red on Figures 10 and 11. Similar bodies reported by Allen (1994) on his profiles A-A' and B-B' were attributed to pre-rift intrusions.

Modeling along Profile TCB-TCB', which is nearly coincident with Allen's profile E-E' (Figures 2 and 3), was conducted to see if 5 km of Oronto Group equivalent strata could be placed in the Twin Cities basin and still yield a plausible fit to the observed gravity and magnetic data. Euler solutions in the vicinity indicate a thickness of about 5 km, whereas Allen's model along E-E' indicated only about 2 km thickness. A plausible fit was readily achieved, but the base of the volcanic rocks beneath the basin had to be increased from Allen's depth of about 10 km to a depth of about 17 km (Figure 12), demonstrating the ambiguity of gravity modeling. Due to the somewhat independent support from the Euler analysis, this deeper model is favored. The volcanic rocks that underlie the Twin Cities basin are interpreted to include an upper sequence with normally directed NRM and a lower sequence with reversely directed NRM (Figure 12). Although the relative proportions are different, Allen's model E-E' also included a substantial lower sequence of magnetically reversed lavas. Both the normal and the reversed lava sequences are interpreted to be associated with high magnetic susceptibility values and strong NRM values.

Line SC-SC' (Figure 13) was modeled as part of a separate study, but several features are worth pointing out here. The profile crosses a part of the rift that has very limited seismic coverage, and the area was not investigated by Allen's (1994) 2-D modeling. Euler analysis in this area implies that the sedimentary rocks in the Bayfield basin, the western flanking basin of the rift, are only 1-2 km thick, and those in the Emerald basin nearly pinch out (Figures 5-8). Euler results also imply that the Oronto Group rocks in the Ashland Syncline are only about 1 km thick. The model in Figure 13 supports these interpretations. The model also implies that about 10 km of normally polarized volcanic rocks underlie the St. Croix Horst, and that this sequence is truncated rather abruptly along the southeastern margin of the horst.

ASSEMBLY OF THE ENHANCED DEPICTION

Three-dimensional modeling of gravity and magnetic data can be facilitated if the results of 2-D model studies are geo-referenced and incorporated into a common 3-D visualization scheme. Generally, 2-D models are much easier to create, and they can serve as a skeletal framework for building a more complicated 3-D model. A straightforward way to incorporate 2-D models would be to use geo-referenced images of the models, and insert them as vertical sections into a 3-D visualization scheme. Unfortunately, readily available 3-D visualization software as yet do not support that option. Instead, we inferred vertical geologic sections as virtual drill holes, at key points along the model section, and placed them into the 3-D visualization. The resulting line of virtual drill holes, color-coded to show geology, is an effective way of portraying a section in 3-D space and does not have the drawbacks of viewing an opaque image section.

The GM-SYS 2-D modeling software and the Oasis-Montaj grid and map imaging system provide a means of readily creating a geo-referenced, vertical section from 2-D models. The two systems are linked, so that when a cursor is placed on a geo-referenced model section, a corresponding cursor appears at its correct location on the Oasis-Montaj map display. Staying in the same horizontal position, the cursor on the model section can be moved vertically to determine the depths to the layers of the model, thereby providing a vertical section view.

The horizontal position and corresponding depths of each vertical section are recorded in a data table that can be imported into 3-D visualization software.

In spite of their vintage, 2-D gravity and magnetic models by Allen (1994) present an effective perspective on rift structure in Western Lake Superior, Minnesota, and Wisconsin (Figure 14), and they still are very helpful in constructing new 3-D models. The older models need to be located, which was achieved by geo-referencing a map image that contains profile locations. The end points of the profiles were digitized and entered into the GM-SYS software which, in conjunction with gravity and magnetic grids (Figures 2 and 3) produced geo-referenced profiles of observed gravity and magnetic data, as well as an interim model. A GM-SYS option allows an image of the model section to be imported as a back-drop for the dummy model. The linked map-model cursor system described above was then used to create vertical sections, based on the backdrop image. The 3-D visualization of Allen's model sections is shown in Figure 15.

The two dimensional models presented here were incorporated into the ESRI ArcScene 3-D visualization software. These included models SE1-SE1', SE3-SE3', TCB-TCB', and SC-SC' (Figures 10-13). The models were wholly created within the GM-SYS/Oasis-Montaj system, so already contained coordinate information. The linked map-model cursor system described above was used to create vertical sections from the models.

The MGS has also recently completed a series of 2-D gravity and magnetic models as part of County Geologic Atlas (CGA) studies in south central Minnesota (Figures 2 and 3). These models, which were used to help construct geologic cross sections (Chandler, 2009; Mossler and Chandler, A and B, in preparation), are summarized in Figure 16. Five of the northernmost models cross an intriguing but relatively under-studied part of the rift, which is distinguished by a semi-circular gravity high and ring- like magnetic high that lies to the immediate west of the St. Croix Horst (Figures 1-3). After an initial model study, Brandt (1977) proposed that the semi-circular anomalies reflects a basin of rift-related volcanic rocks, with a lower sequence of magnetically reversed lavas and an upper sequence of magnetically normal lavas. The CGA model studies confirm this interpretation, and imply that reversed lavas may even comprise a substantial part of the section beneath the St. Croix Horst (Figure 16). The recent model studies also imply that up to 2 km of rift sedimentary rocks overlie the western lava basin, which agrees generally with Euler solutions in the area (Figures 5 to 8). A 3-D visualization of virtual drill holes from the CGA models and from the four models produced for this study is shown in Figure 17.

INCORPORATION OF SEISMIC DATA

In the absence of seismic reflection data, the seismic refraction interpretations of Mooney et al. (1970) provide the only independent constraints for gravity and magnetic model studies. These soundings were limited in their depth interpretations, at most only 4 to 5 kilometers, but that is adequate for the sedimentary rock sequences that are of interest for CO_2 sequestration. Consequently, all of the refraction interpretations of Mooney et al. (1970) were geo-referenced as vertical sections by Chandler (2008). These sections, which are color coded to indicate seismic (P-wave) velocity, are shown in Figure 18. Emphasis in this study was not placed on seismic reflection data. As pointed out above, the parts of Allen's models that correspond to seismic reflection coverage are already reasonably well-constrained and not likely to be revised significantly, unless new or re-processed seismic reflection data become available. Focus therefore was placed on areas where interpretations are less constrained. Furthermore, some of the seismic lines used by Allen remain either privately owned or underwritten, and are not available. Other section images are greatly reduced from much larger sections and consequently are of low quality. Finally, the ArcScene visualization used in this study does not support vertical images as cross-sections, which would be the most effective way of presenting seismic sections. As a means of visualizing the locations and information in the seismic sections, a few were geo-referenced and are shown in Figure 19 as flat lying sections, with their top edge corresponding approximately to their surface trace.

CONCLUSIONS

Available data and new interpretations regarding geometry of the Midcontinent Rift in western Lake Superior, Minnesota, and Wisconsin have been assembled as a new 3-D reconstruction. Three-dimensional gravity modeling by Allen (1994) forms the core of this visualization. Combined with seismic soundings and results from new Euler, 2-D gravity, and magnetic modeling, the complete visualization can now support updated thinking on rift sedimentary basin thickness and extent, while also offering a basis for future 3-D gravity and magnetic modeling. Improved 3-D modeling will improve our understanding of the regional geometry of the sedimentary basins associated with the rift. This in turn could lead to new ideas regarding basin development, that in turn could be useful for evaluating the basins for CO_2 sequestration. Even without additional 3-D modeling, the present visualization is a highly effective means to study multiple datasets and interpretations regarding rift structure. In addition, the visualization can be augmented and updated, thereby assuring its continued utility well into the future.

ACKNOWLEDGMENTS

The following tasks were conducted with the support of U. S. Geological Survey Project #G10AC00648 (Current Project):

- --New two-dimensional gravity and magnetic modeling of the Midcontinent Rift, including two profiles across the Belle Plaine Fault and one profile across the St. Croix Horst in the Twin Cities area
- --Detailed analysis of Located Euler solutions derived over the Midcontinent Rift in Minnesota, Wisconsin, and Western Lake Superior
- --Assembly of geophysical interpretations of the Midcontinent Rift from this and previous studies into a single three-dimensional visualization that includes Minnesota, Wisconsin, and western Lake Superior.
- --Compilation of this Report

Some products used in this project were created with support from other recent programs, and include the following:

- --A visualization that merges David Allen's (PhD. Thesis, Purdue University) three-dimensional gravity models of the Minnesota-Wisconsin area and the western Lake Superior area. This work included a two-dimensional gravity and magnetic model across the northern end of the St. Croix Horst. Work supported by a grant from the University of Minnesota's Institute for Renewable Energy and the Environment.
- --Preliminary analysis of located Euler solutions and creation of three two-dimensional gravity and magnetic models across the southwestern part of the St. Croix Horst supported by the Minnesota Legislature through the County Geologic Atlas Program (Carver County).
- --Creation of four two-dimensional gravity and magnetic models across the southwestern St Croix Horst and Belle Plaine Fault supported by the U. S. Geological Survey's STATEMAP Program for Nicollet and Sibley Counties (Project G09AC00187)

The support for all of these projects is deeply appreciated.

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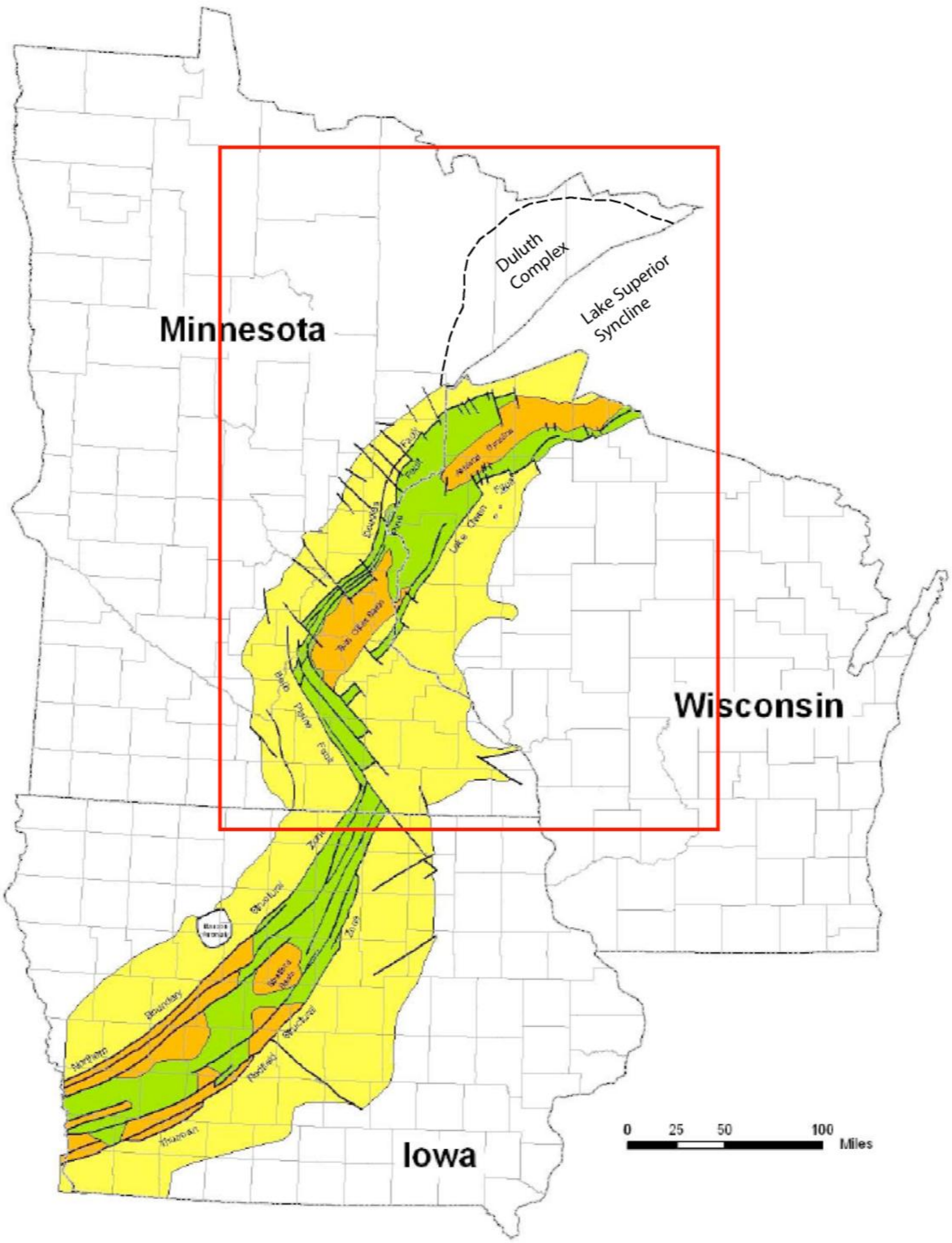

Figure 1. Generalized geologic map of the western arm of the Midcontinent Rift in Minnesota, Wisconsin, and Iowa, showing sandstone-dominated rocks of the Bayfield Group and equivalents in yellow, less mature clastic rocks of the Oronto Group and equivalents in orange, and generally mafic volcanic rocks and associated intrusions in green. Box delineates area shown in Figures 2-9. Modified after Chandler et al. (1989)

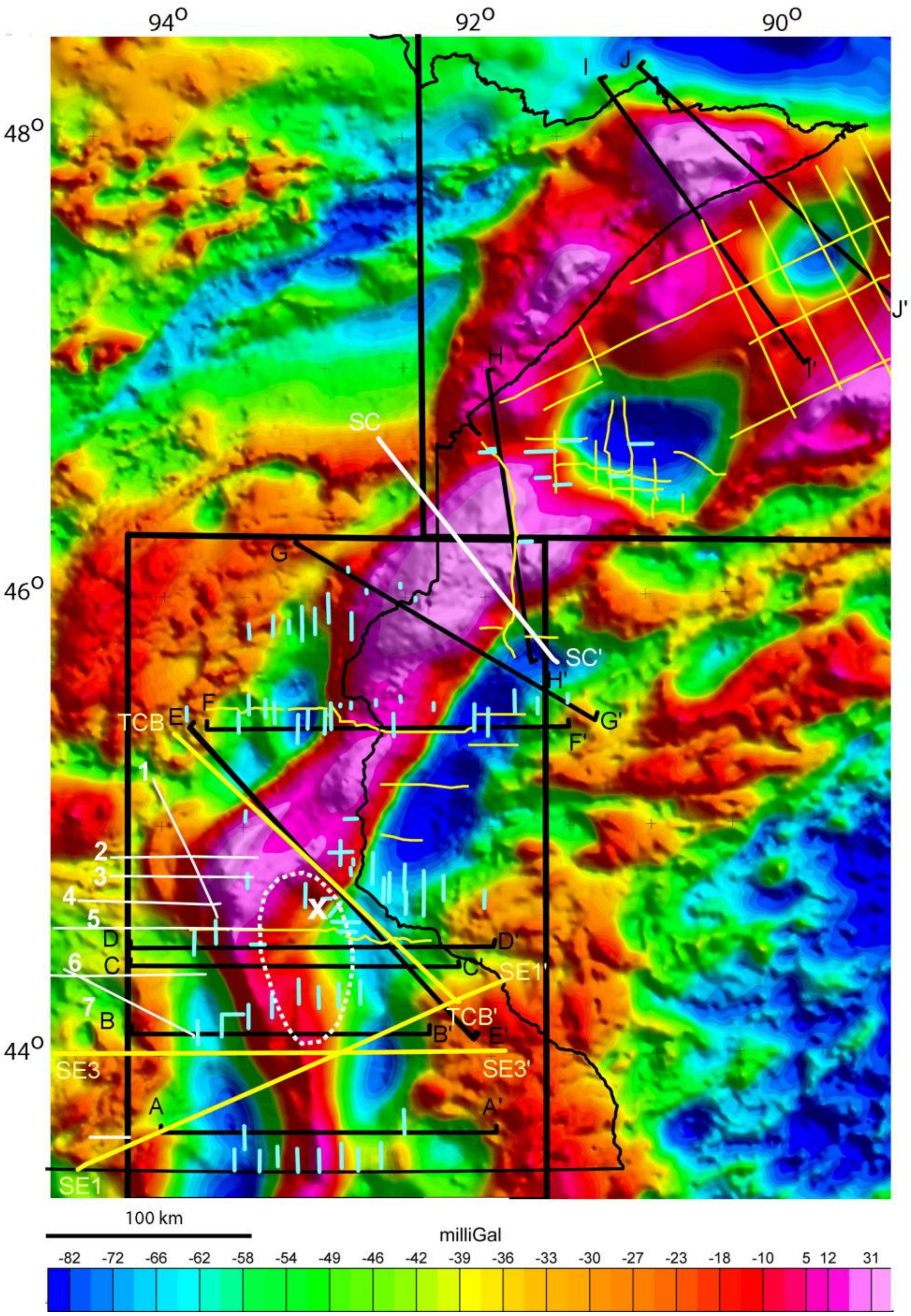

Figure 2 Bouguer gravity anomaly map of Minnesota and adjacent areas; color shaded relief presentation with false illumination from north at 45 degrees inclination. Boxes delineate Allen's (1994) 3-D gravity models for the western Lake Superior and the Minnesota-Wisconsin areas. Heavy black lines locate 2-D (profile) gravity and magnetic models by Allen (1994). Wherever possible, Allen's 2-D and 3-D models were constrained by seismic reflection profiles, which are indicated here by the thin yellow lines. Thin white lines represent 2-D gravity and magnetic models produced in support of the County Geologic Atlas Mapping program of the MGS (Chandler, 2009; Chandler and Mossler, in preparation A and B), and heavy yellow lines represent 2-D gravity and magnetic models produced by this study. Heavy white lines represent a 2-D gravity and magnetic model that was recently produced from a separate study (V. W. Chandler, open file data at MGS). Light blue segments locate seismic refraction soundings reported by Mooney et al., 1970. The white dashed line delineates a zone of felsic volcanic rocks proposed by Allen et al. (1997), and the white x is the approximate location of a drill hole that encountered felsic volcanic rocks.

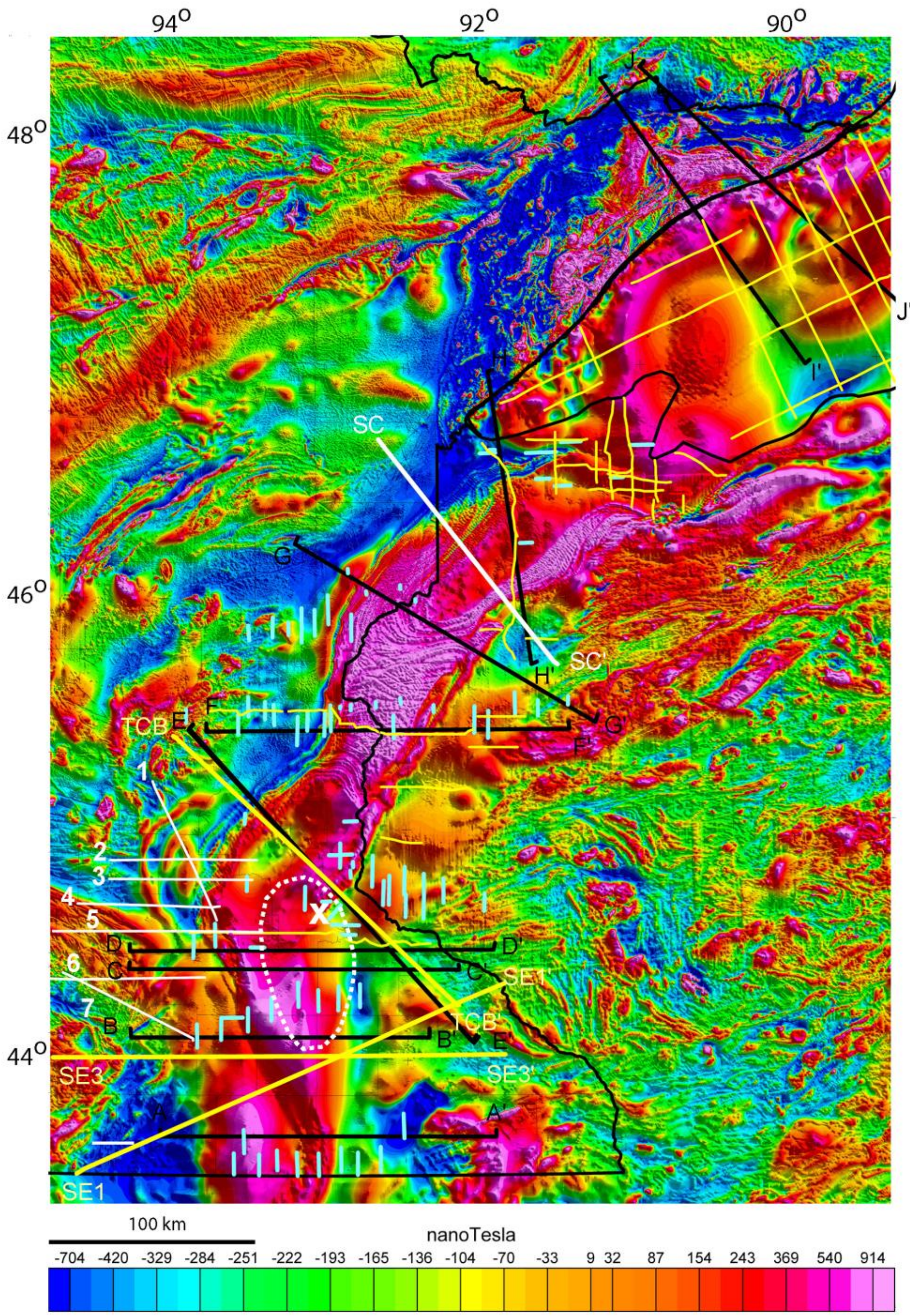

Figure 3. Aeromagnetic anomaly map of Minnesota and adjacent areas; color shaded relief presentation with false illumination from north at 45 degrees inclination. Heavy black lines locate 2-D (profile) gravity and magnetic models by Allen (1994). Wherever possible, Allen's 2-D and 3-D models were constrained by seismic reflection profiles, which are indicated here by the thin yellow lines. Thin white lines represent 2-D gravity and magnetic models produced in support of the County Geologic Atlas Mapping program of the MGS (Chandler, 2009; Chandler and Mossler, in preparation A and B), and heavy yellow lines represent 2-D gravity and magnetic models produced by this study. Heavy white lines represent a 2-D gravity and magnetic model that was recently produced from a separate study (V. W. Chandler, open file data at MGS). Light blue segments locate seismic refraction soundings reported by Mooney et al., 1970. The white dashed line delineates a zone of felsic volcanic rocks proposed by Allen et al. (1997), and the white x is the approximate location of a drill hole that encountered felsic volcanic rocks.

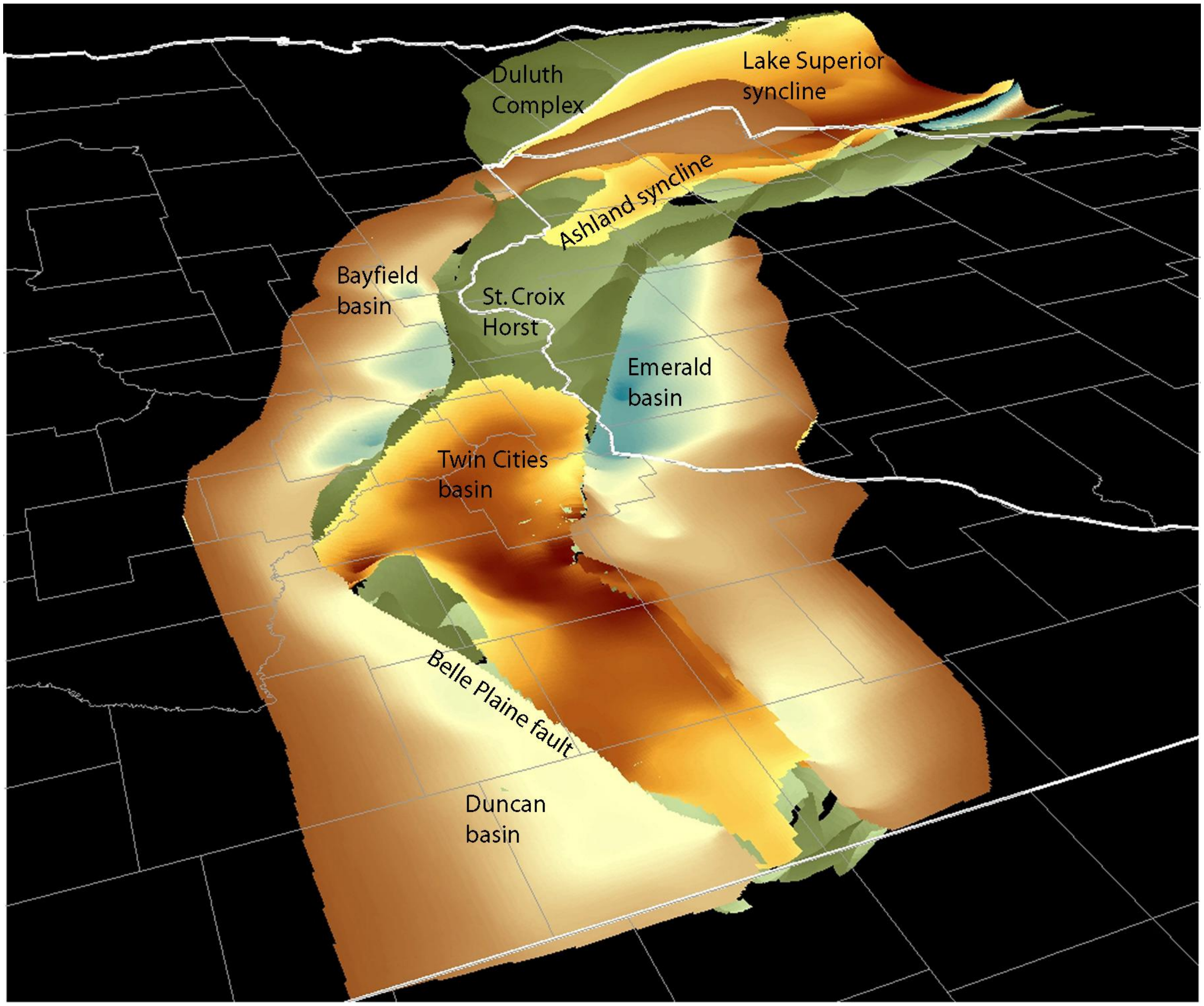

Figure 4. Merged, three-dimensional (3-D) visualization of the 3-D gravity models derived by Allen (1994). View is towards the northeast from above. Individual units are transparent, but the colors representing elevation are rendered onto the base of each respective unit. The elevations (relative to mean sea level) of the main stratigraphic units of the rift sequence are individually color-coded as follows: Bayfield Group (eastern and western basins) -- brown (near-surface) to blue green (below -5 km), the Oronto Group -- yellow (near-surface) to dark brown (below -4 km), and the volcanic sequence -- dark green (near-surface) to light green (-15 km or below). Vertical exaggeration is 2X. The visualization is derived from the merging of two of Allen's 3-D models--for western Lake Superior and Minnesota-Wisconsin (see Figure1 for geographic reference). Merging of the two 3-D models was accomplished by inferring model elevation or depth contours across joins and gaps and by a 2-D gravity and magnetic model study along the join (Figure 2). This merging and related modeling was conducted as part of a separate project sponsored by the University of Minnesota (V. W. Chandler, on-file, MGS)

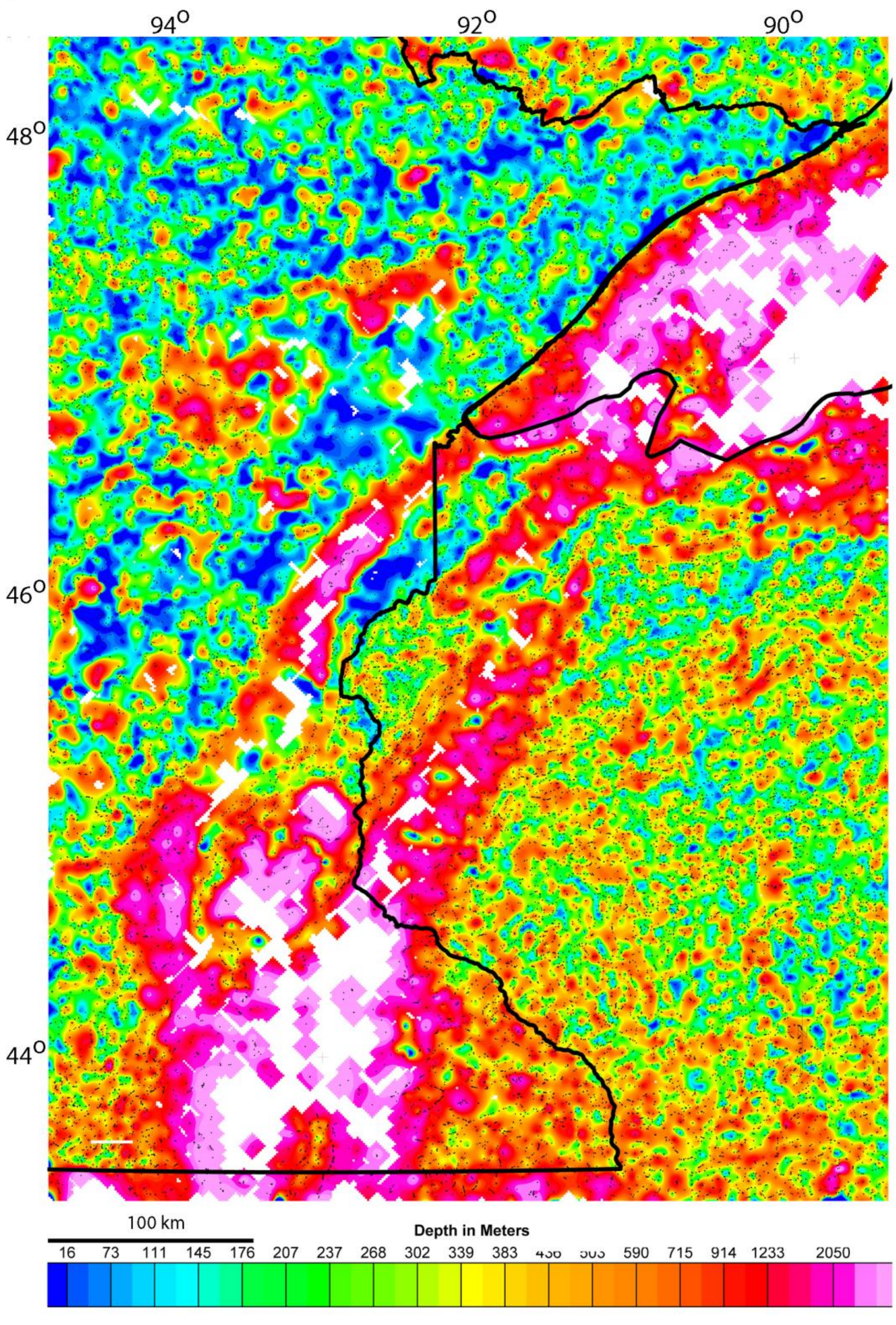

Figure 5. Located Euler depth analysis of the Midcontinent Rift area, Wisconsin, and western Lake Superior; color format. Small dots = individual Euler solutions, which are based on a structural index of 0.5 (contact-like solutions). Solutions are derived from an analysis of a near-surface (300 meter elevation) magnetic grid. The 300 meter-level magnetic grid was produced by upward continuing the aeromagnetic grid from its original compilation level of 150 meters to 300 meters above surface (Chandler, 2007) and decimating grid from 100 meter to 200 meter spacing.

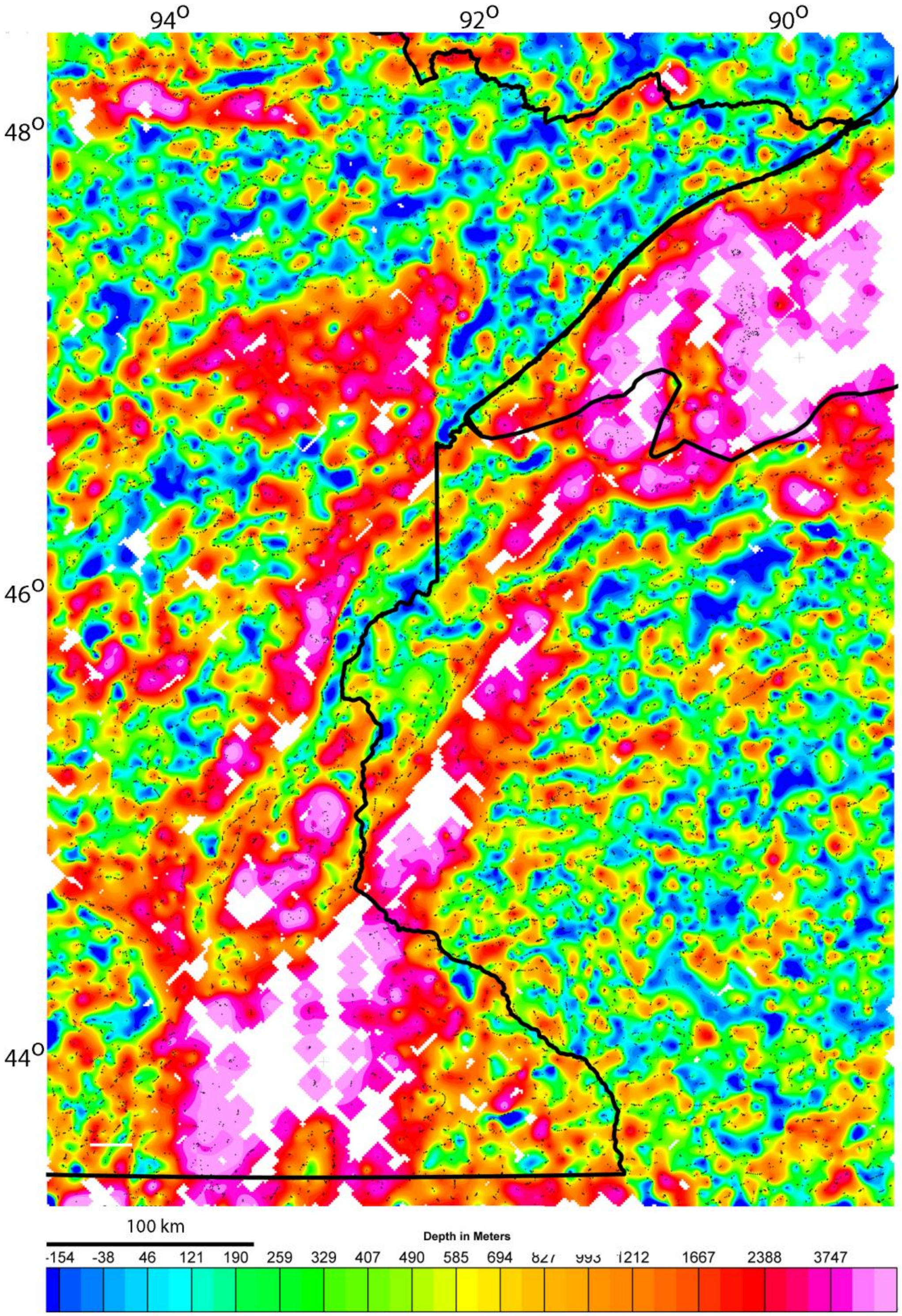

Figure 6. Located Euler depth analysis of the Midcontinent Rift area, Wisconsin, and western Lake Superior; color format. Small dots = individual Euler solutions, which are based on a structural index of 0.5 (contact-like solutions). Solutions are derived from an analysis of a high-level (1000 meter elevation) magnetic grid. The 1000 meter-level magnetic grid was produced by upward continuing the aeromagnetic grid from its original compilation level of 150 meters to 1000 meters above surface (Chandler, 2007) and decimating grid from 100 meter to 500 meter spacing

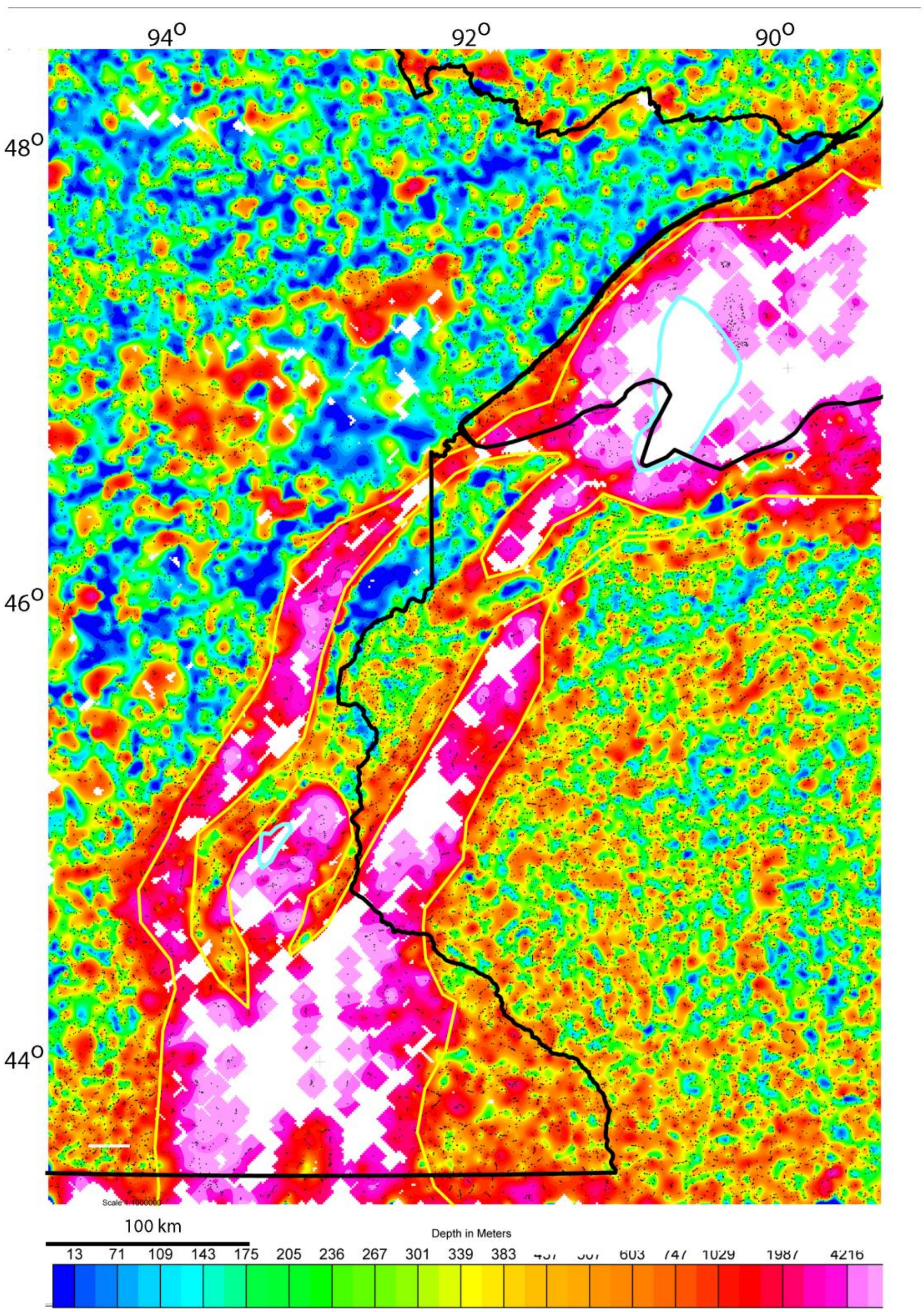

Figure 7. Located Euler depth analysis of the Midcontinent Rift area, Wisconsin, and western Lake Superior; color format. Small dots = individual Euler solutions, which are based on a structural index of 0.5 (contact-like solutions). Most solutions are derived from an analysis of a near-surface (300 meter elevation) magnetic grid, but deeper solutions along the rift basins (within yellow polygons) are based on an upward-continued magnetic grid (1000 meter elevation). Yellow polygons approximate a 1500 meter thickness contour from a previous Euler investigation (Chandler, 2009). Light blue polygons delineate areas where deep solutions have been rejected due to interference from near-surface magnetic sources.

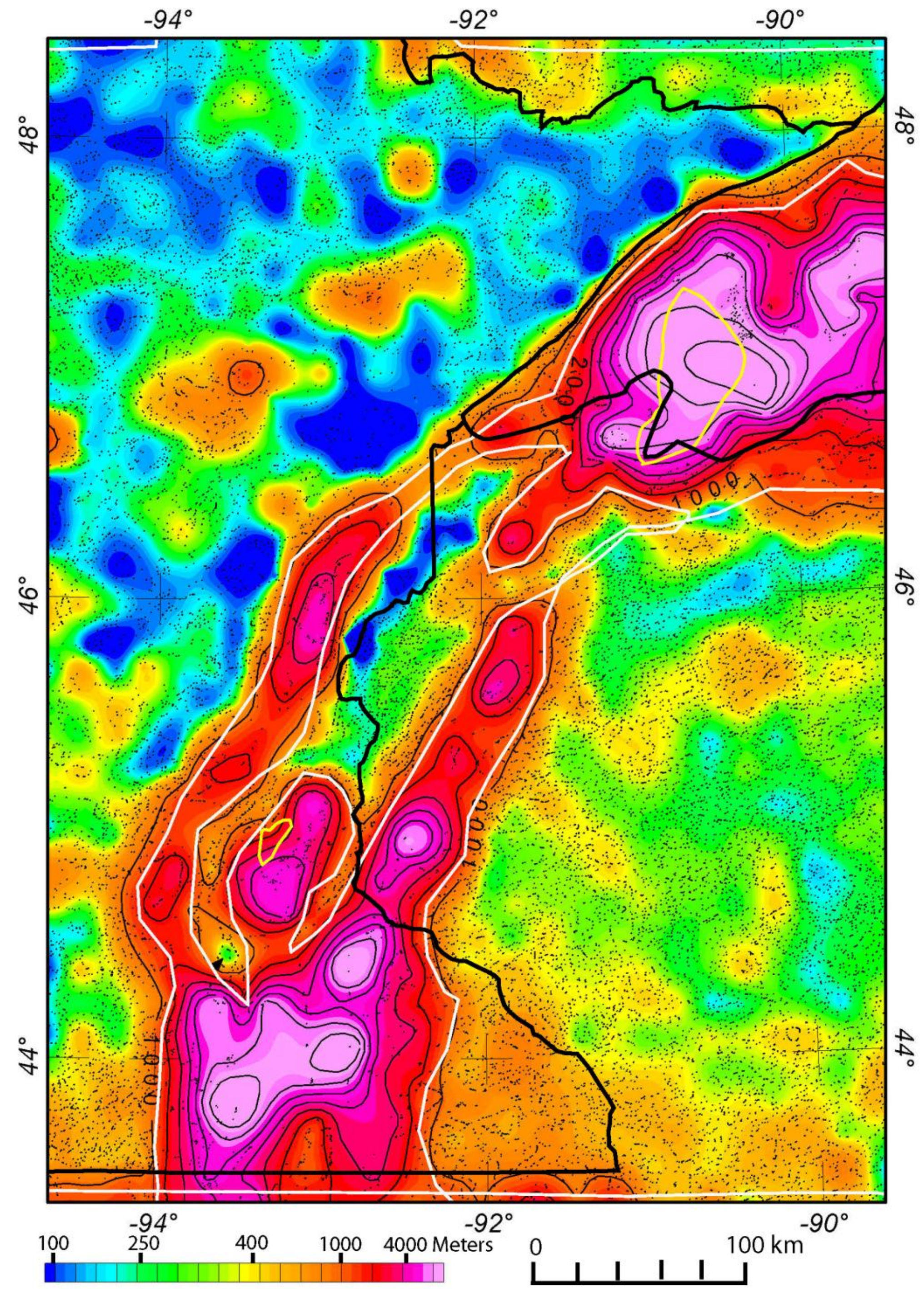

Figure 8. Located Euler depth analysis of the Midcontinent Rift area, Wisconsin, and western Lake Superior; color format. Small dots = individual Euler solutions, which are based on a structural index of 0.5 (contact-like solutions). Most solutions are derived from an analysis of a near-surface (300 meter elevation) magnetic grid, but deeper solutions along the rift basins (within yellow polygons) are based on an upward-continued magnetic grid (1000 meter elevation). Yellow polygons approximate a 1500 meter thickness contour in both the 300 meter-level and 1000 meter-level data. Light blue polygons delineate areas where deep solutions have been rejected due to interference from near-surface magnetic sources. Gridded Euler values have been smoothed by using a de-sampling factor of 16, and color portrays depth to magnetic basement from surface. Contour interval=1000 meters.

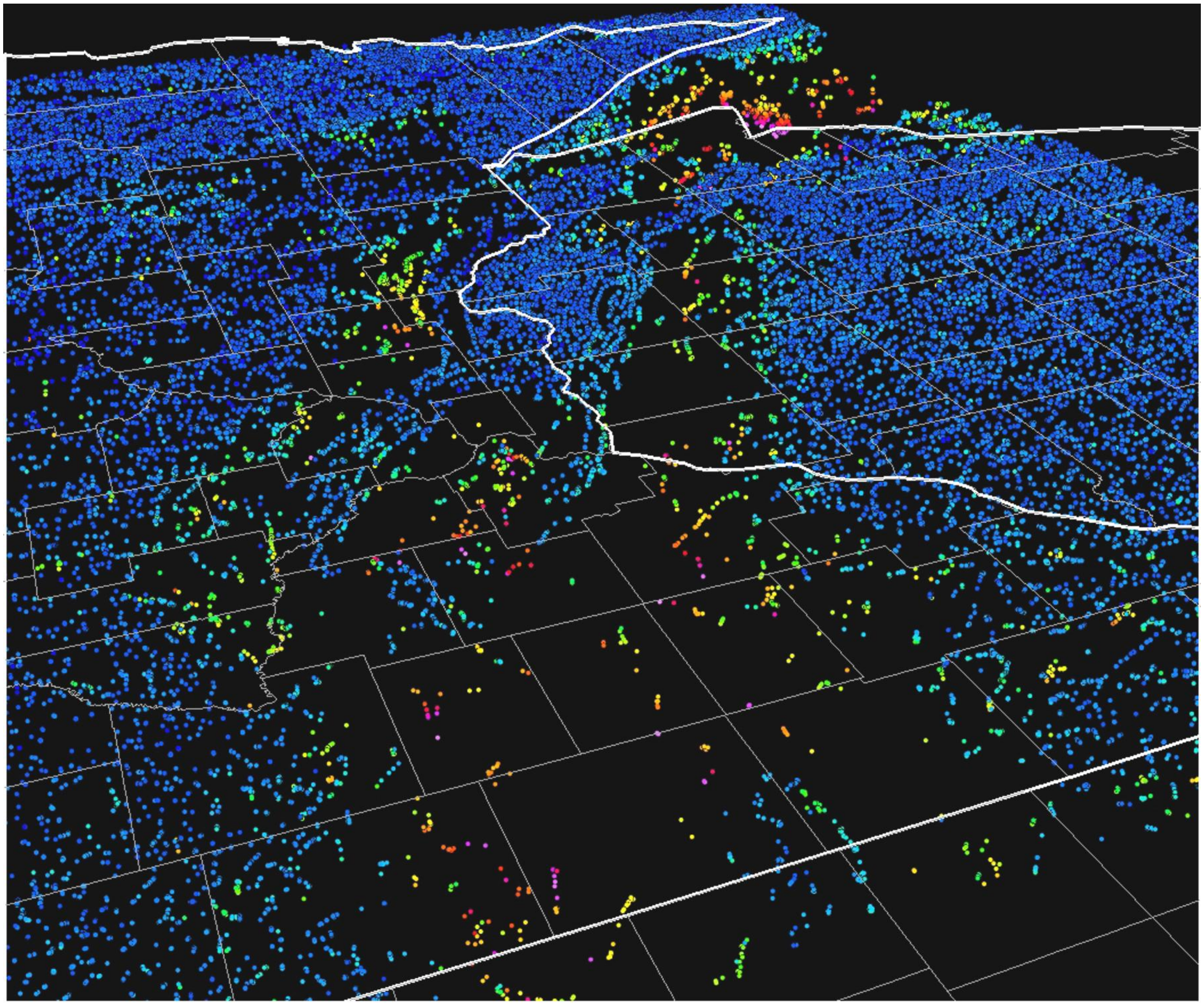

Figure 9. Three-dimensional visualization of individual Euler solutions, based on a structural index of 0.5 (contact-like structure) and on a combination of 300 meter-level and 1000 meter level data, as described in Figures 7 and 8. Perspective is the same as in Figure 2, and solutions are plotted in three-dimensional space. Solution depths are color-coded in a spectral progression with blues representing depths of 0-250 meters and reds representing depths of 5000 meters or more. Vertical exaggeration is 2X.

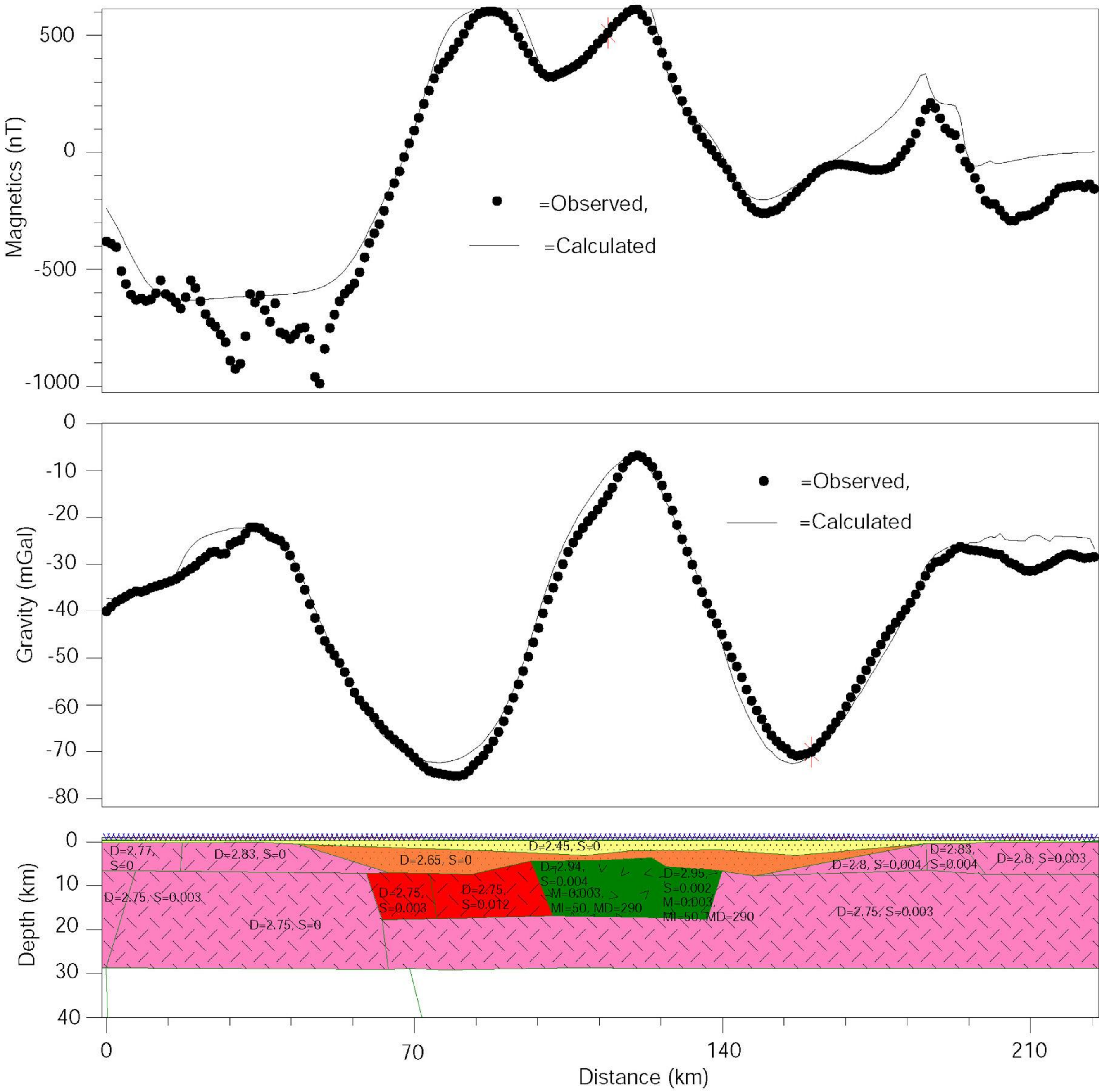

Figure 10. Gravity and magnetic model study of Profile SE1 (Figures 3 and 4). Northeast is to the right. Rift-related rocks are color coded with yellow = Bayfield Group, orange = Oronto Group, and green = volcanic rocks and associated intrusions (normal polarity). Pre-rift rocks are indicated in pink and red colors. Physical properties, in cgs units, are defined as follows: D=density, S=magnetic susceptibility, M=intensity of NRM (where present), MI=inclination of NRM in degrees (positive downwards), and MD=declination of NRM in degrees.

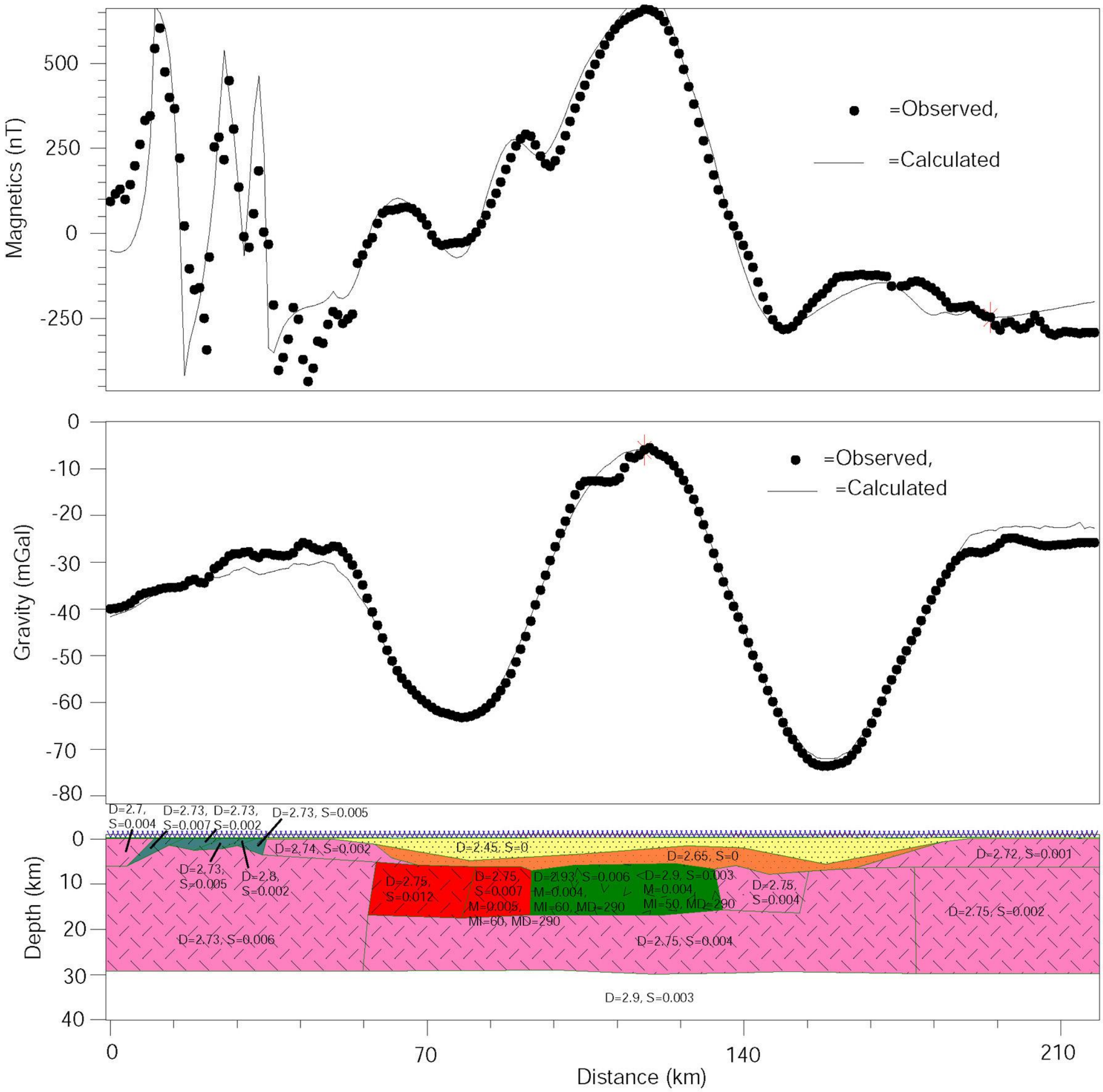

Figure 11. Gravity and magnetic model study of Profile SE3 (Figures 3 and 4). East is to the right. Rift-related rocks are color coded with yellow = Bayfield Group, orange = Oronto Group, and green = volcanic rocks and associated intrusions (normal polarity). Pre-rift rocks are indicated in pink, red and blue-green colors. Physical properties, in cgs units, are defined as follows: D=density, S=magnetic susceptibility, M=intensity of NRM (where present), MI=inclination of NRM in degrees (positive downwards), and MD=declination of NRM in degrees.

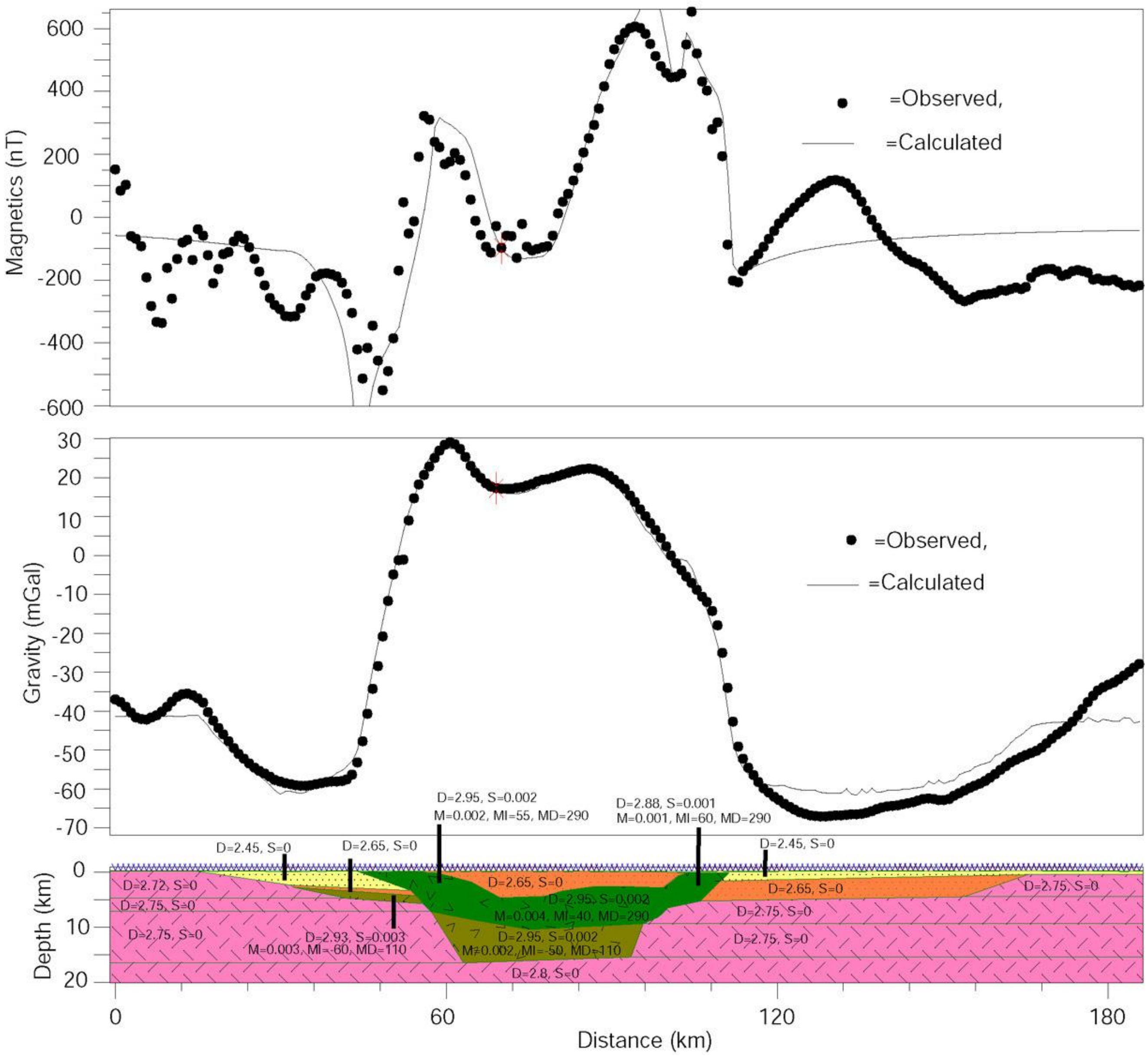

Figure 12. Gravity and magnetic model study of Profile TCB-TCB' (Figures 2 and 3). Southeast is to the right. Rift-related rocks are color coded with yellow = Bayfield Group, orange = Oronto Group, and green = volcanic rocks and associated intrusions, with drab green representing magnetically reversed rocks and brighter green representing normally polarized rocks. Pre-rift rocks are indicated in pink. Physical properties, in cgs units, are defined as follows: D=density, S=magnetic susceptibility, M=intensity of NRM (where present), MI=inclination of NRM in degrees (positive downwards), and MD=declination of NRM in degrees.

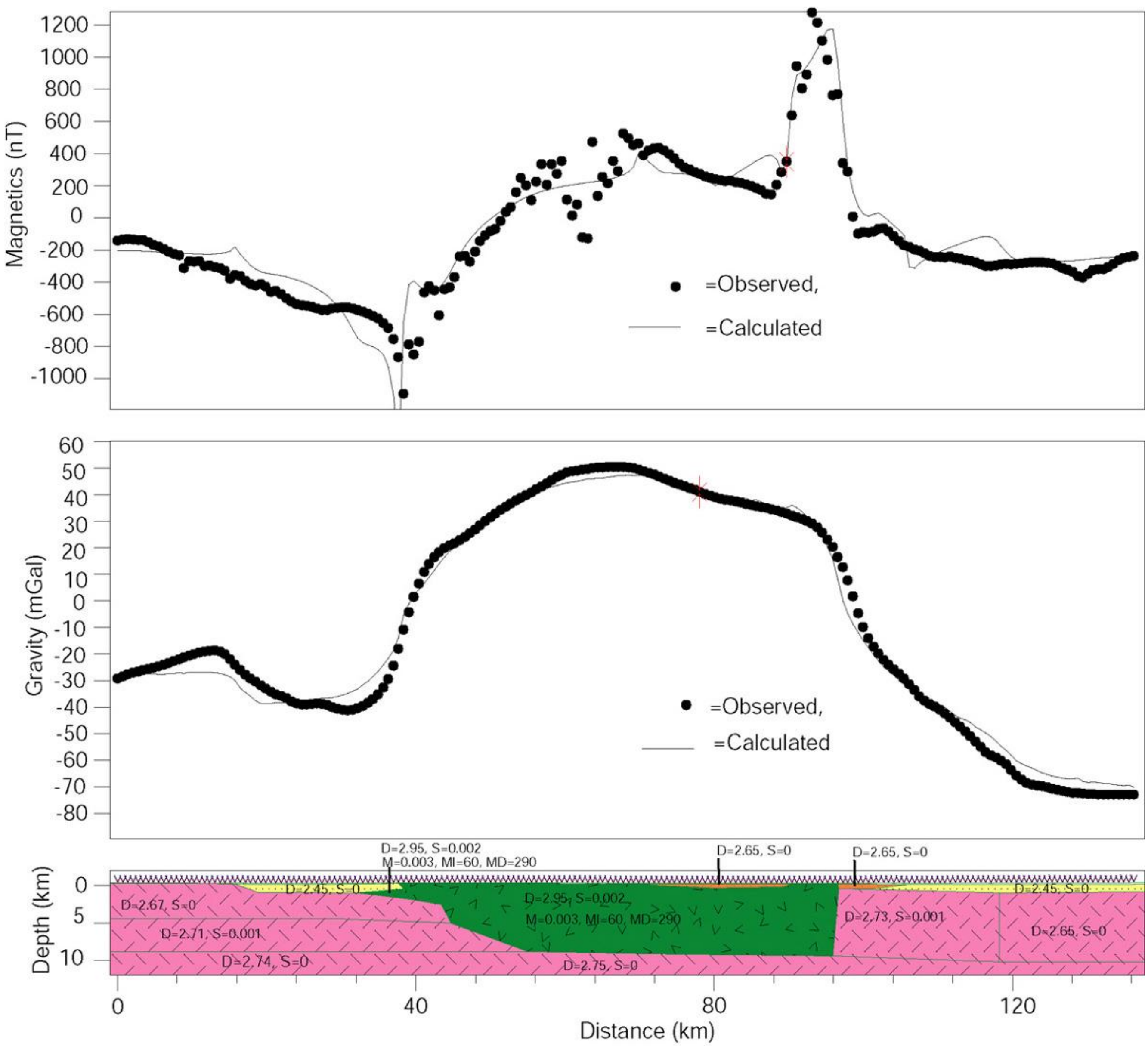

Figure 13. Gravity and magnetic model study of Profile SC-SC' (Figures 2 and 3). Southeast is to the right. Rift-related rocks are color coded with yellow = Bayfield Group, orange = Oronto Group, and green = volcanic rocks and associated intrusions (normal polarity). Pre-rift rocks are indicated in pink. Physical properties, in cgs units, are defined as follows: D=density, S=magnetic susceptibility, M=intensity of NRM (where present), MI = inclination of NRM in degrees (positive downwards), and MD=declination of NRM in degrees.

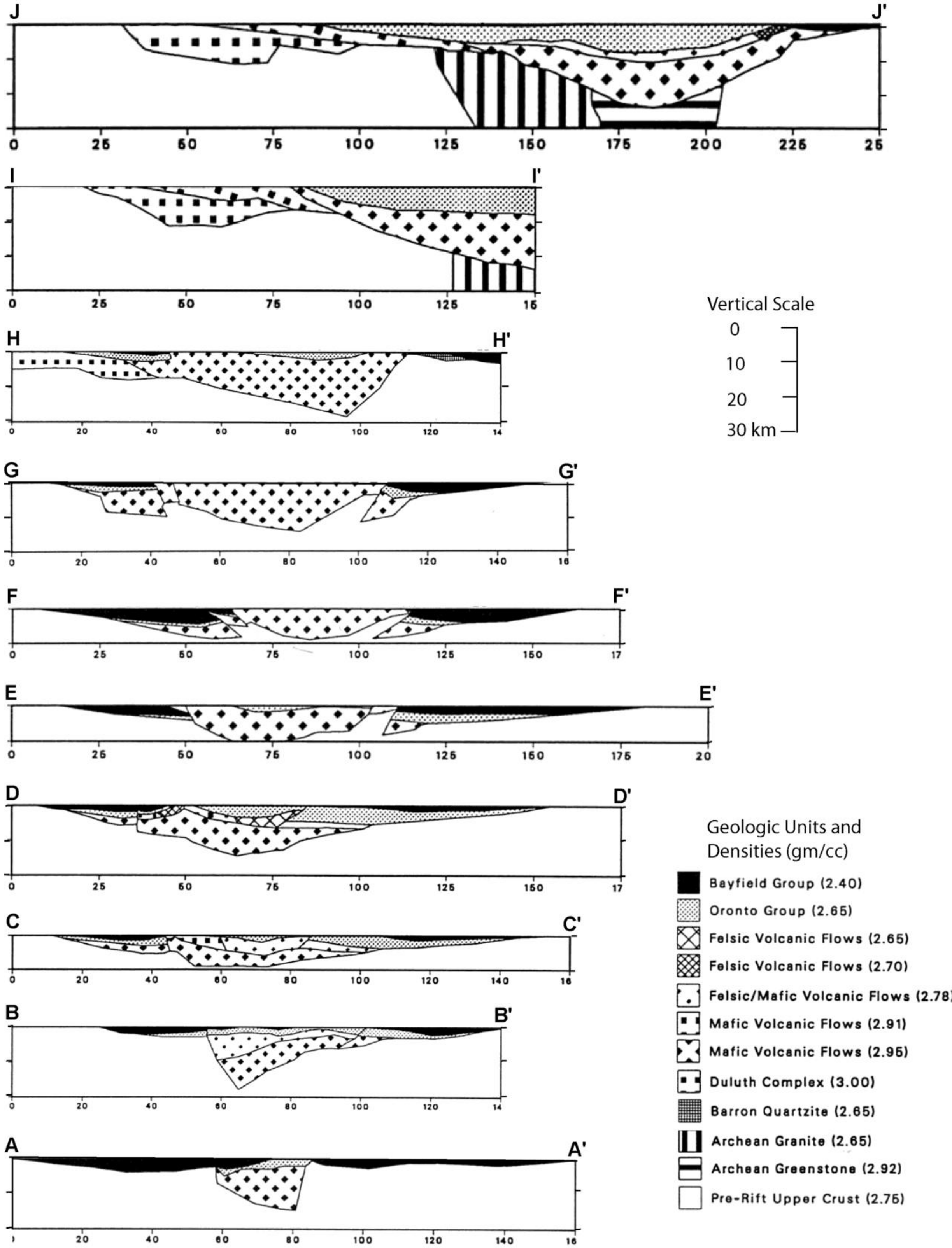

Figure 14. Summary of gravity and magnetic models by Allen (1994) along profiles A-A' through J-J' (Figures 2 and 3). East and southeast is to the right. Sections shown here are modified from Allen's gravity models, and densities are given in parentheses on the explanation for geologic units.

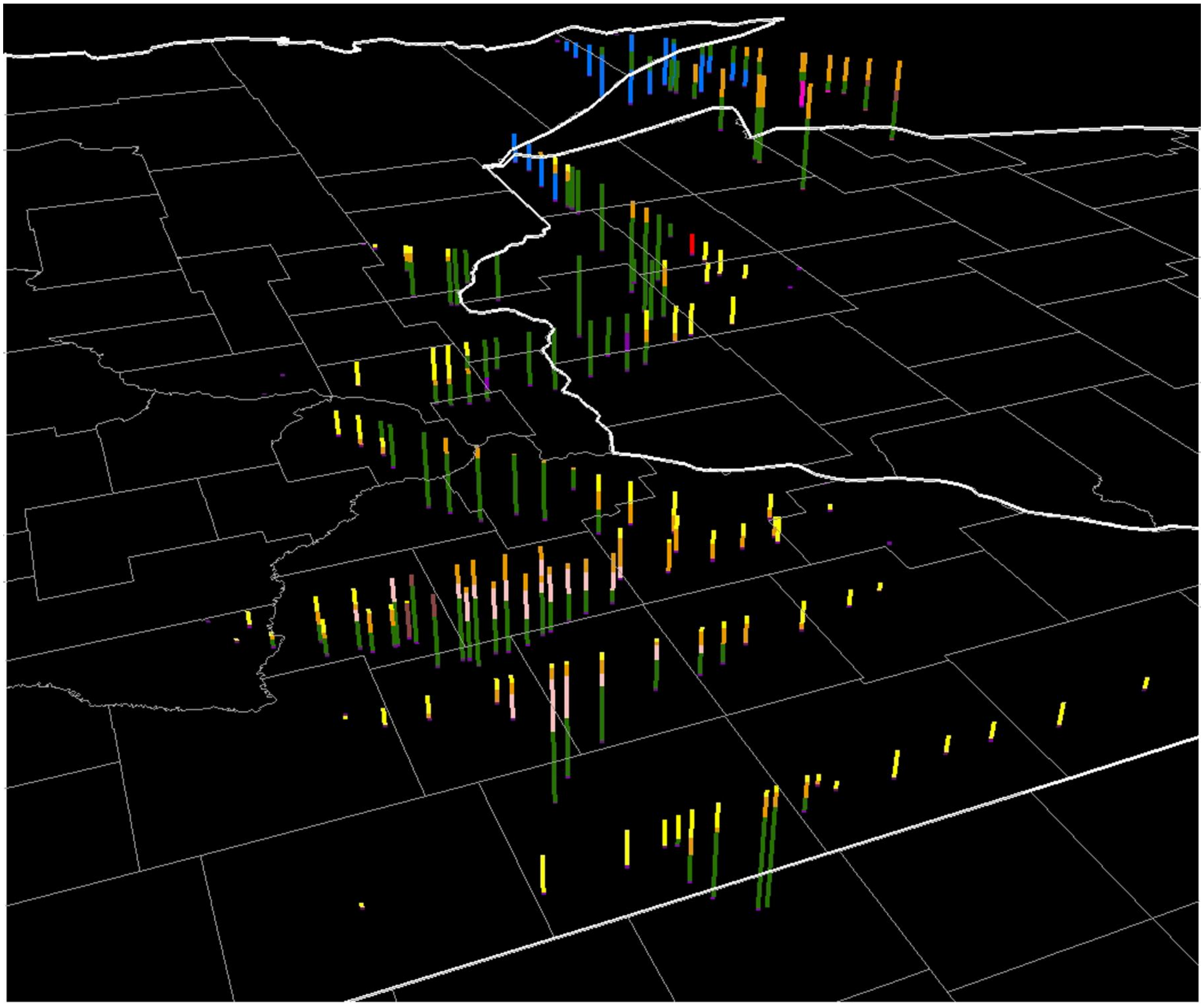

Figure 15. Three-dimensional visualization of virtual drill-holes derived from selected points along the two-dimensional gravity and magnetic models by Allen (1994; Figures 2, 3, and 14). Rift-related rocks are color coded with yellow = Bayfield Group, orange = Oronto Group, pink = felsic volcanic rocks, and dark green = mafic volcanic rocks, and blue = Duluth Complex. Pre-rift rocks are indicated in purple, red and magenta colors. Vertical exaggeration is 2X.

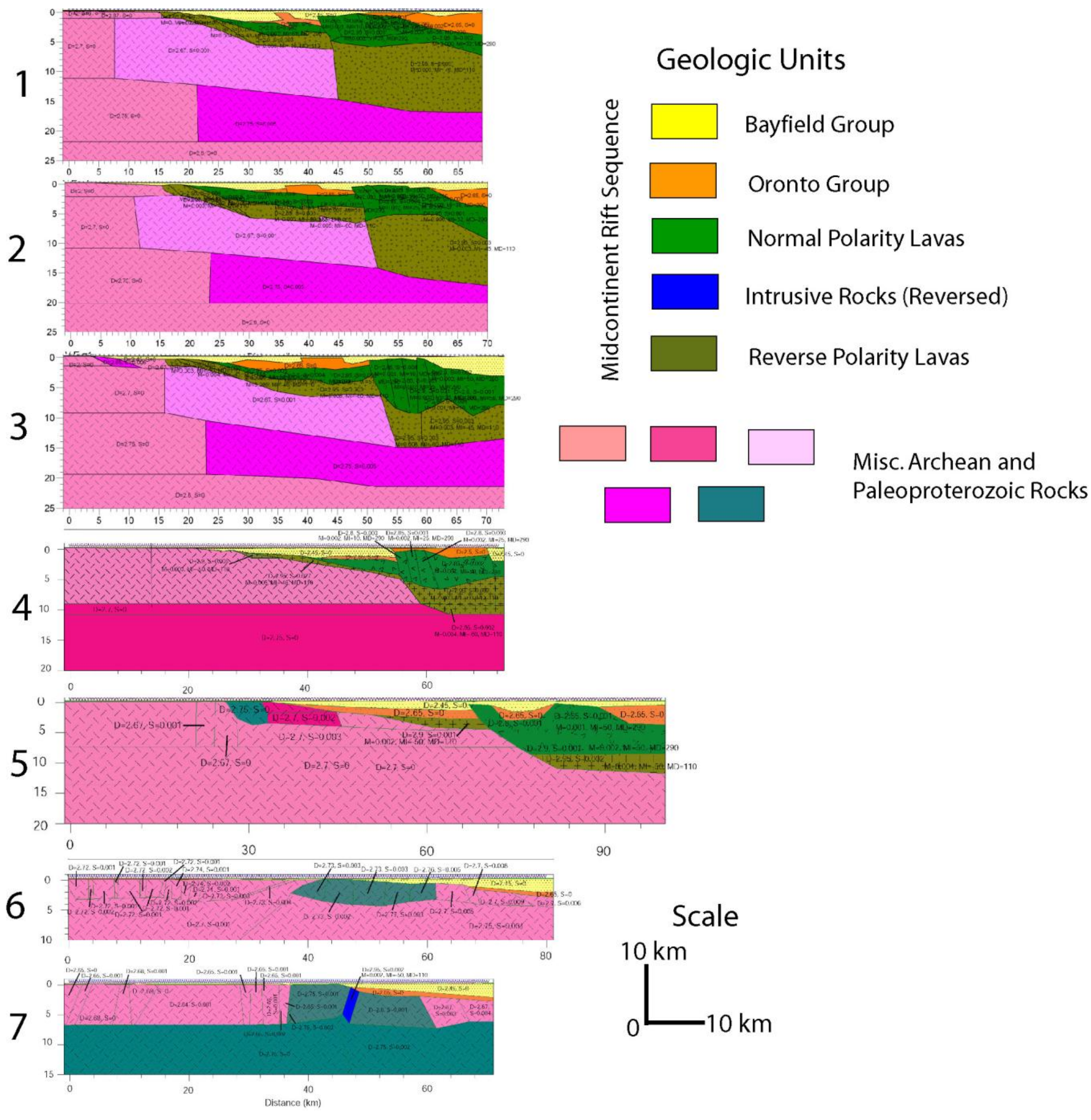

Figure 16. Summary of gravity and magnetic models for CGA studies at MGS along profiles 1 through 7 (Figures 2 and 3). East and southeast is to the right. Physical properties, in cgs units, are defined as follows: D=density, S=magnetic susceptibility, M=intensity of NRM (where present), MI=inclination of NRM in degrees (positive downwards), and MD=declination of NRM in degrees.

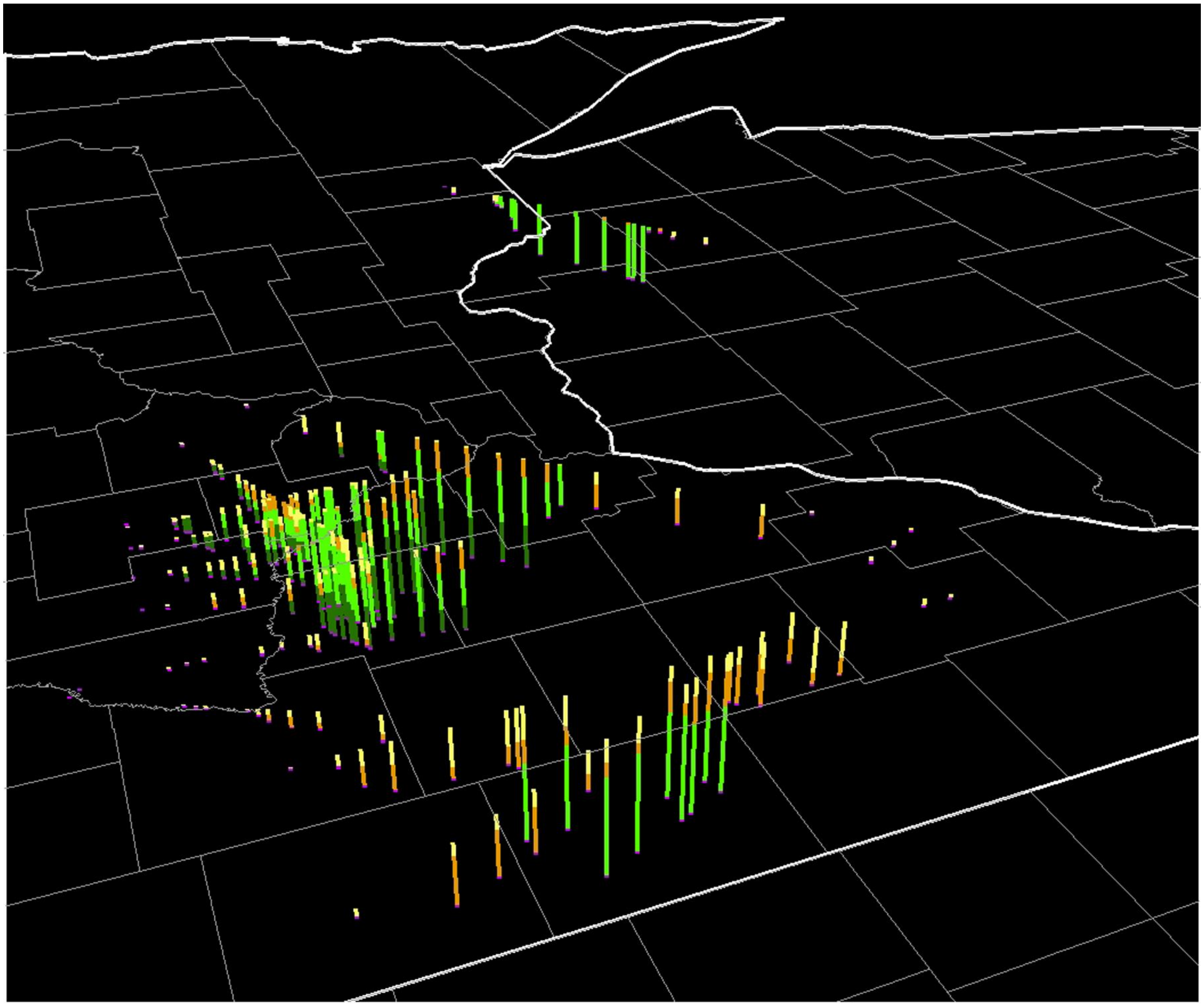

Figure 17. Three-dimensional visualization of virtual drill-holes derived from selected points along the two-dimensional gravity and magnetic models for CGA projects (Chandler, 2009 and on-file data at MGS) and for this study (Figures 3, 4, 7, 8, and 9). Rift-related rocks are color coded with yellow = Bayfield Group and equivalents, orange = Oronto Group and equivalents, light green = normally polarized volcanic rocks, and dark green = reversely polarized volcanic rocks, Pre-rift rocks are indicated in purple and magenta colors. Vertical exaggeration is 2X.

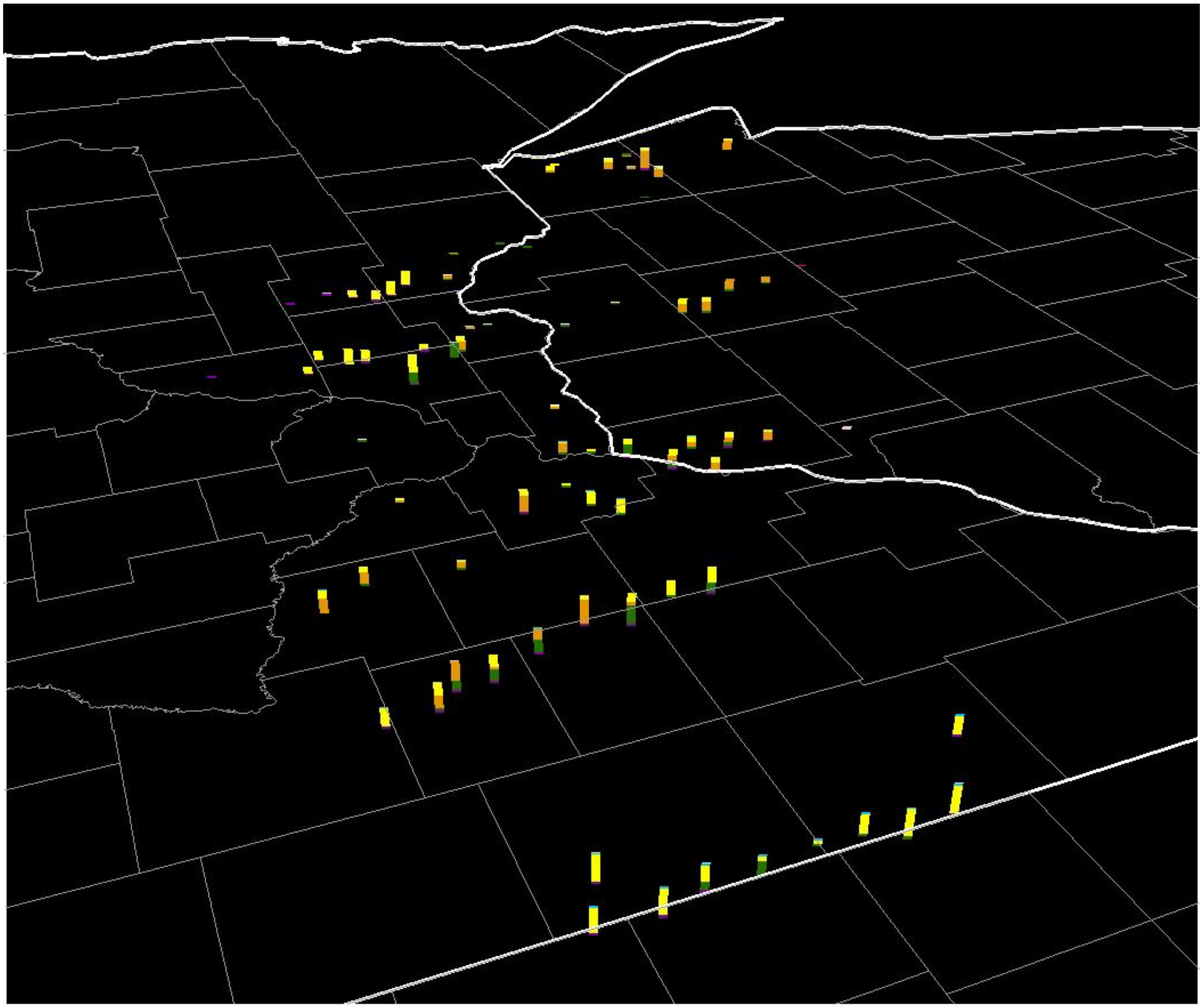

Figure 18. Seismic refraction interpretations of Mooney et al. (1970). Seismic refraction interpretations are shown as a vertical column with the following color-coding for interpreted velocities: yellow = 10,000 to 14,000 feet/sec, orange = 14,000 to 16,000 ft/ sec, green = 16,000 to 18,000 ft/sec, and magenta = >18,000 ft/sec. Vertical exaggeration is 2X.

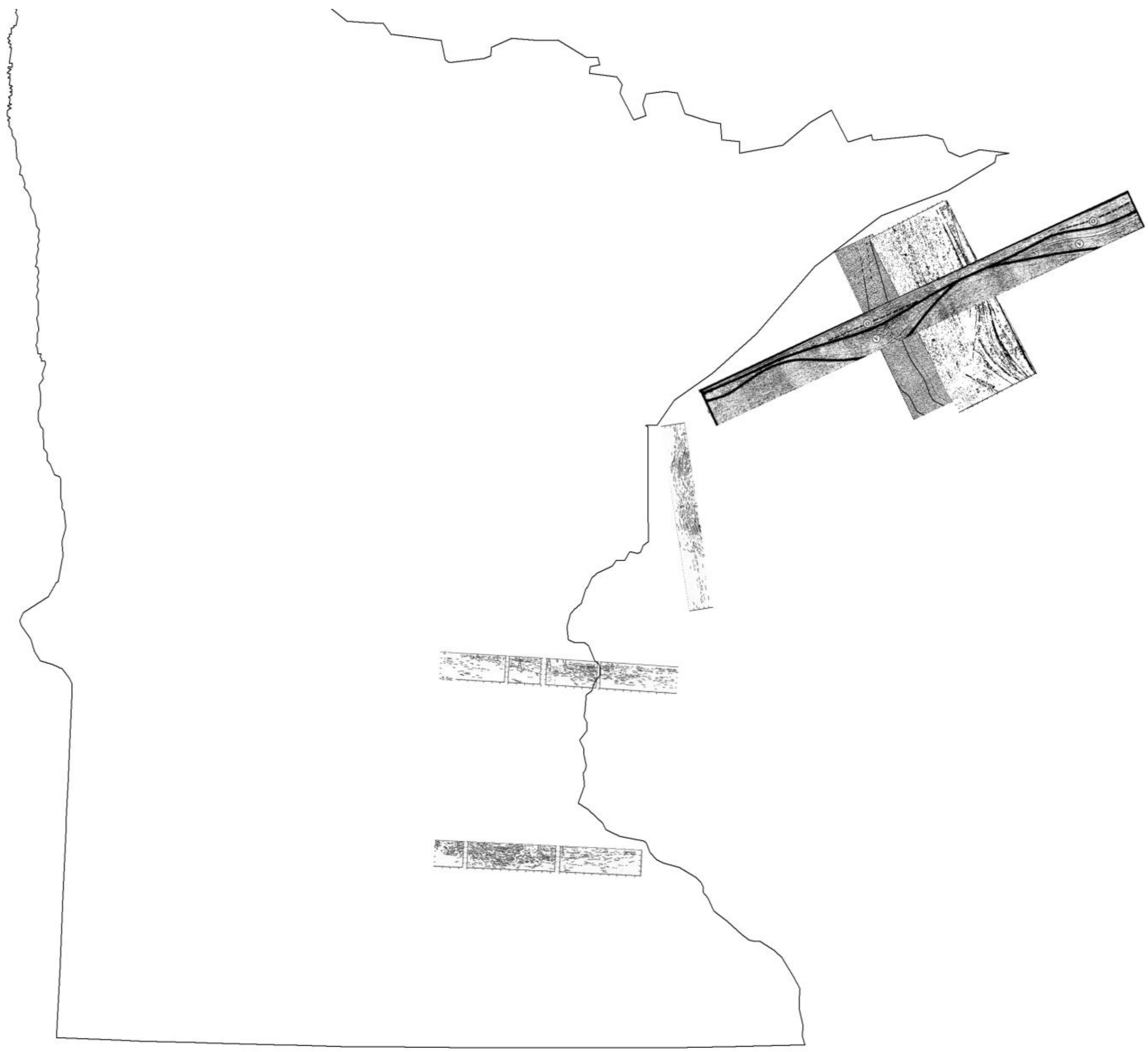

Figure 19. Geo-referenced sections showing seismic interpretations. Sections geo-referenced at end points only, so a straight line is assumed. Interpretations are from Chandler et al. (1989), Cannon et al., (1989), Allen (1994), and Allen et al. (1997).