Coupled Modeling of Gravity and Aeromagnetic Data for Analysis of the Waukesha Fault, Southeastern Wisconsin

Project Completion Report

By

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Project Summary

Title: Coupled Modeling of Gravity and Aeromagnetic Data For Analysis of the Waukesha Fault, Southeastern Wisconsin

Project ID: R/UW-HDG-007 (WR03R003)

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Background/Need: Increased concerns about groundwater resources in Wisconsin have brought about the need for better understanding of the subsurface geologic structure that lead to developing conceptual hydrogeologic models for numerical simulation of groundwater flow. Models are often based on sparse data from well logs usually located large distances apart and limited in depth. Model assumptions based on limited spatial data typically requires simplification that may add uncertainty to the simulation results and the accuracy of a groundwater model. This research provides another tool for the groundwater modeler to better constrain the conceptual model of a hydrogeologic system. The area near the Waukesha Fault in southeastern Wisconsin provides an excellent research opportunity for our proposed approach because of the strong gravity and aeromagnetic anomalies associated with the fault, the apparent complexity in fault geometry, and uncertainty in Precambrian basement depth and structure.

Objectives: The objectives of this research are to improve the current understanding of the subsurface geometry (offset and fault dip) of the Waukesha Fault in southeastern Wisconsin, to improve the current understanding of the Precambrian bedrock topography of the down-thrown area southeast of the Waukesha Fault, and to demonstrate the effectiveness of coupled modeling of gravity and aeromagnetic data for delineating the hydrogeologic settings in other areas of Wisconsin. This fault appears to exhibit complex geometry that is variable along its trend. Better definition of the fault subsurface geometry obtained from this research will allow for a better understanding of the effects of this fault on the hydrogeologic system. A better-constrained estimate of the Precambrian bedrock topography will provide needed information for a regional groundwater flow model. Results from this study can be used to demonstrate the effectiveness for delineating the hydrogeologic settings in other areas of Wisconsin.

Methods: Coupled 2.75-dimensional modeling of existing gravity and aeromagnetic data was performed along seven northwest-southeast profiles, perpendicular to the trend of the Waukesha Fault and one north-south profile (Tie Line), using the commercially-available software program GM-Sys^R. Cross-sections of the geologic subsurface were constructed from existing surface and subsurface geologic information and assigned initial density and magnetic properties from literature. Adjustment to structure and properties were made to yield acceptable fits between observed and model calculated gravity and aeromagnetic anomalies. Elevations from these model sections and from well logs were used to generate a 3-dimensional representation of the top of Precambrian bedrock.

Results and Discussion: Acceptable fits between observed and model calculated gravity and aeromagnetic anomalies were obtained from the geologic models constructed for the eight profiles in the study area. A single well reaching bedrock on the down-thrown block provided excellent vertical control for initial model calibration. Profile model data yields a 3-D representation of the Precambrian bedrock top surface with elevations that range from 168 m above mean sea level (msl) on the up-thrown block to –1318 m msl on the down-thrown block. The prominent southwest-northeast trending drop in bedrock surface elevation is interpreted as the Waukesha Fault scarp.

Conclusions/ Implications/ Recommendations: The results from this study show the Waukesha Fault as a high angle normal fault dipping to the southeast. Model topography of the Precambrian bedrock surface appears complex on both sides of the fault with a maximum vertical displacement of 560 m. A reasonable estimate of top of bedrock elevations southeast of the fault has been obtained from this study. Further model refinement will be conducted to improve structure interpretations for southeast Wisconsin. Results from this study have direct application to the groundwater flow model for southeast Wisconsin (Feinstein et al., 2004). These researchers now have an additional data set for the Precambrian basement configuration that can be utilized in the flow model. Coupled modeling of gravity and aeromagnetic data can be applied to other areas in Wisconsin with groundwater management issues such as arsenic contamination and excessive drawdown.

Key Words: Aeromagnetic, Gravity, Coupled Modeling, Waukesha Fault, Precambrian Basement, Ground Water, Wisconsin

Funding: Funding was provided by the Wisconsin Groundwater Research Program through the University of Wisconsin Water Resources Institute.

Introduction

The Precambrian basement in southeastern Wisconsin consists of granite, slate, and quartzite, which dips gently to the east from the Wisconsin Dome into the Michigan Basin. The basement rocks are overlain by Cambrian and Ordovician sandstone and Ordovician and Silurian shale and dolomite. Pleistocene glacial deposits of variable thickness overlie these rocks. The northeast-trending Waukesha Fault is a prominent geologic structure in the area that has hydrogeologic significance. The fault appears to divide changes in water quality of the sandstone aquifer due to groundwater pumping. Jansen et al. (2001) found that no significant changes in total dissolved solids (TDS) occurred on the up-thrown block (northwest side) of the fault while TDS levels rose significantly on the down-thrown block (southeast side). The fault offset and geometry, however, are not well understood to date.

The only significant surface exposure at the Waukesha Stone and Lime Quarry in Waukesha reveals the fault strikes N 70^{o} E and an apparent high angle southeast dip and with normal displacement (Svedrup et al., 1997). Sufficient well data exists on the up-thrown block to delineate the Precambrian basement with depths ranging from approximately 250 to 600 m below ground surface (Smith, 1978; Feinstein et al., 2004); however, depth to basement on the down-thrown block of this normal fault is not well established due to the lack of deep water wells. Thwaites (1940, 1957) inferred the depth to Precambrian basement in this area at greater than 800 m with maximum vertical displacement of 450 m across the fault.

Geophysical investigations have added additional estimates of the subsurface geometry in the area. A gravity survey in Waukesha County by Brukardt (1983) produced a Bouguer anomaly over the fault that was interpreted as the result of a high angle (70^{o}) normal fault dipping to southeast, with vertical displacement of at least 300 m. Moll (1987) performed an investigation of the Waukesha Fault that included 2.5-dimensional models of one north-south and two east-west profiles of ground magnetic data across the fault. Model results suggest offset of the down-thrown fault block ranging from 900 to 1200 m and the fault dip toward the southeast ranging from 20^{o} to vertical. Lahr (1995) predicts depth to Precambrian rock by modeling gravity along two transects crossing the fault using basement density varying from 2.6 g/cm^3 to 3.3 g/cm^3. For a density of 2.9 g/cm^3, depth to basement was modeled at 905 m (vertical displacement of 500 m) and at 1,140 m (vertical displacement of 680 m) with fault dip to the southeast of 85^{o} to 22^{o} for the southern and northern transects, respectively. Sverdrup et al. (1997) noted a steep gravity gradient coincident with the northeast-trending fault with gravity values on the up-thrown fault block that are approximately 10 mgal higher than values on the down-thrown block. Gravity models along two profiles across the fault suggest maximum vertical offset of 500 to 600 m and fault dip to the southeast of 80^{o} for the southern profile and 10^{o} to 20^{o} for the northern profile. Results of a detailed east-west gravity profile across the Waukesha Fault by Baxter et al. (2002) yield model estimates of vertical displacement of Precambrian basement ranging from 260 to >600 m (several thousand feet) and fault geometry that varies significantly along strike. Preliminary analysis of the Precambrian basement from aeromagnetic data (Mudrey et al., 2001b) indicates this area is underlain by a complex Precambrian structural terrane and suggests that the prominent northeast trending aeromagnetic anomaly corresponds to the Waukesha fault defines a basement terrane boundary.

This study is the first to investigate the Waukesha Fault and Precambrian basement topography using coupled (simultaneous) modeling of both gravity and magnetic data, which minimizes the non-uniqueness problem inherent in potential fields modeling. Additionally, this study is the first to include lithology data from a single well log (Nicholas et al., 1987) that provides the depth to Precambrian bedrock on the down-thrown side of the fault. Also, the extensive lithology data from well logs used in the USGS regional groundwater model (Feinstein et al., 2004) provides excellent constraint on the subsurface structure.

Procedures and Methods

Existing gravity, aeromagnetic, elevation, density and magnetic susceptibility, and well log data were used to construct models along seven northwest-southeast profiles across the Waukesha Fault and one north-south profile that serves as "Tie Line" for the other profiles (Figure 1). The gravity and aeromagnetic data are compilations from the US Geological Survey [USGS] (Daniels and Snyder, 2002) for the entire state of Wisconsin. The observed gravity values, relative to the IGSN-71 datum, were reduced to the Bouguer anomaly using the 1967 gravity formula and a reduction density of 2.67 g/cc. The data were converted to a 1-km grid using minimum curvature techniques. The Wisconsin aeromagnetic map was compiled from 26 separate surveys with relative uniformity of flight line spacing of 1/2 mile or less and processed to simulate flight altitude of 1000 ft (305 m) about ground. The data were converted to a 250-m grid using a minimum curvature algorithm. These grids were downloaded from the USGS Web site (http://pubs.usgs.gov/of/2002/of02-493/) and sampled along the study profiles at 500 m intervals.

Ground surface elevations along profiles were obtained at 500 m intervals from USGS 7.5 minute series topographic maps. Well log data was obtained from the Wisconsin Geological and Natural History Survey (via the USGS) as a digital database that was compiled for constructing the regional groundwater flow model of southeastern Wisconsin (Feinstein et al., 2004). A total of 42 wells that reach Precambrian bedrock or the overlying Cambrian Mount Simon Formation were used in this study (Figure 1) for vertical control of model blocks. A single well log (Zion; Nicholas et al., 1987) includes the only depth to Precambrian bedrock on the down-thrown block of the Waukesha Fault providing excellent constraint on the subsurface structure along the southernmost profile (Profile A-A'). Thus, the model for Profile A-A' was constructed first in order to select appropriate density and magnetic susceptibility for the study area. Initial density and magnetic susceptibility data were obtained from a state compilation (Dutch et al., 1994) and a number of local studies (Brukardt, 1983; Moll, 1987; Lahr, 1995; Svedrup et al, 1997). Model block density and magnetic susceptibility values were adjusted to obtain the best fits between observed and calculated gravity and aeromagnetic anomalies along Profile A-A' since depth to Precambrian bedrock is known on both sides of the fault. A summary of study and published density and magnetic susceptibility data is given in Table 1.

Coupled 2.75-D forward modeling of gravity and aeromagnetic data was performed using the commercially available modeling program (GM-Sys^{R} by Northwest Geophysical Associates) based on Talwani et al. (1959) and Talwani and Heirtzler (1964). Model block polygons were constructed to represent the subsurface geologic units along each profile. Model block strike lengths were extended 10 km perpendicular to the profile. Density and magnetic properties within a given model block were assumed constant. Iterative adjustments to geologic block

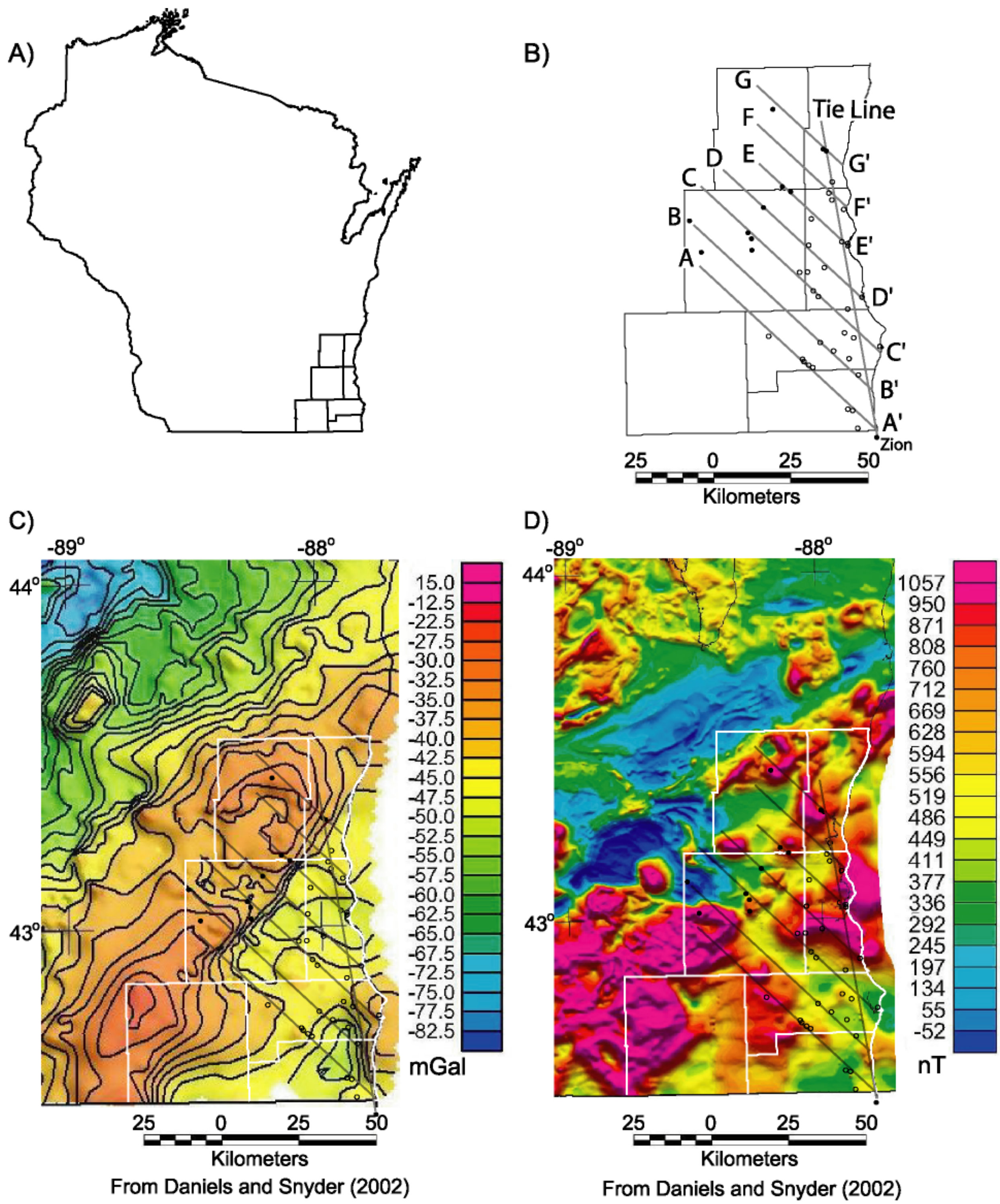

Figure 1. A) Study area location in southeast Wisconsin shown by seven county boundaries. B) Model profile lines and well locations used for vertical control; solid dots indicate wells that reach Precambrian bedrock, open circles indicate wells that reach Cambrian Mount Simon Formation. Complete Bouguer Anomaly map (C) and aeromagnetic map (D) show data used for model profiles along with county boundaries, profile lines, and well locations.

configuration, density, and magnetic properties were made to minimize the root mean square error (RMSE) between observed and calculated gravity and aeromagnetic anomalies. By experience from previous coupled modeling of aeromagnetic and gravity data (Skalbeck, 2001), models were judged acceptable when the percent RMSE (%RMSE; [RMSE/anomaly range]) was below 5% for gravity, and below 10% for aeromagnetic data. A summary of model best fit statistics for each profile is given in Table 2.

Table 1. Published and model density and magnetic susceptibilty data for Waukesha Fault area, southeastern Wisconsin

	Density (g/cm^3)					Magnetic Susceptibility ($x10^{-6}$ cgs)		
Geologic Unit	Brukardt 1983	Dutch et al.,1994	Lahr 1995	Sverdrup et al., 1997	This Study	Dutch 1994	Moll* 1987	This Study
Lk. Michigan	NA	NA	NA	1.00	1.80	NA	NA	0
Glacial	1.80	1.80	1.80	1.80	1.80	NA	NA	0
Silurian	2.70	2.29 - 2.86	2.77	2.67	2.77	49 - 76	0	75
Maquokata	2.70	2.54 - 2.74	2.63	NA	2.63	79 -108	0	100
Sinnipee	NA	2.51 - 284	2.72	NA	2.72	80 - 113	0	100
St. Peter	2.67	2.19 - 2.66	2.33	2.60	2.45	32 -126	0	100
Trempelau	2.67	2.82	2.45	NA	2.82	16 - 125	0	100
Wonewoc	2.67	NA	NA	NA	2.67	NA	0	100
Eau Claire	2.67	2.67	2.45	NA	2.67	16 - 125	0	100
Mt. Simon	2.67	2.58	2.45	2.60	2.58	16 - 125	0	100
Precambrian	3.00	2.63 - 2.74	2.60 - 3.30	2.69	2.77-3.02	44-3489	200	1000
Mafic Instrus.	NA	NA	2.71-3.04	3.00	3.02-3.09	91-2703	6000	3000-7000
Fault Zone	NA	NA	NA	NA	2.22-2.82	NA	NA	100-1000

NA: Not available or applicable
*Moll (1987) modeled sedimentary formations as a single unit

Results and Discussion

Example profile models are shown in Figures 2 and 3. Note the difference in scale and vertical exaggeration between the two figures. The elevations for the model top of Precambrian bedrock were extracted at 500 m intervals from the model profiles and associated with the appropriate map coordinates. These elevations were converted to a 1000 m grid using minimum curvature techniques to create the model surface map of Precambrian bedrock shown in Figure 4.

Table 2. Model best fit statistics for Waukesha Fault area, southeastern Wisconsin

Profile	Complete Bouguer Residual Gravity Range (mGal)		Anomaly (mGal)	RMSE (mGal)	%RMSE	Residual Aeromagnetics Range (nT)		Anomaly (nT)	RMSE (nT)	%RMSE
Line A-A'	-31.9	-52.1	20.2	0.68	3.3	354	1743	1389	114.3	8.2
Line B-B'	-32.8	-49.7	16.9	0.82	4.9	-94	1675	1769	140.4	7.9
Line C-C'	-39.3	-49.1	9.8	0.48	4.9	71	951	933	83.1	9.4
Line D-D'	-37.0	-48.1	11.1	0.51	4.6	264	1229	1511	89.8	9.3
Line E-E'	-35.5	-50.5	15.0	0.66	4.4	445	1341	896	77.5	8.6
Line F-F'	-32.5	-44.9	12.4	0.58	4.7	338	1040	702	68.3	9.7
Line G-G'	-31.8	-45.4	13.6	0.65	4.8	426	1141	715	71.1	9.9
Tie Line	-35.6	-50.3	14.7	0.65	4.4	391	1107	716	65.2	9.1
Target Value for % RMSE					5.0					10.0

RMSE: Root mean square error % RMSE: RMSE/Anomaly mGal: Milligal nT: Nanotesla

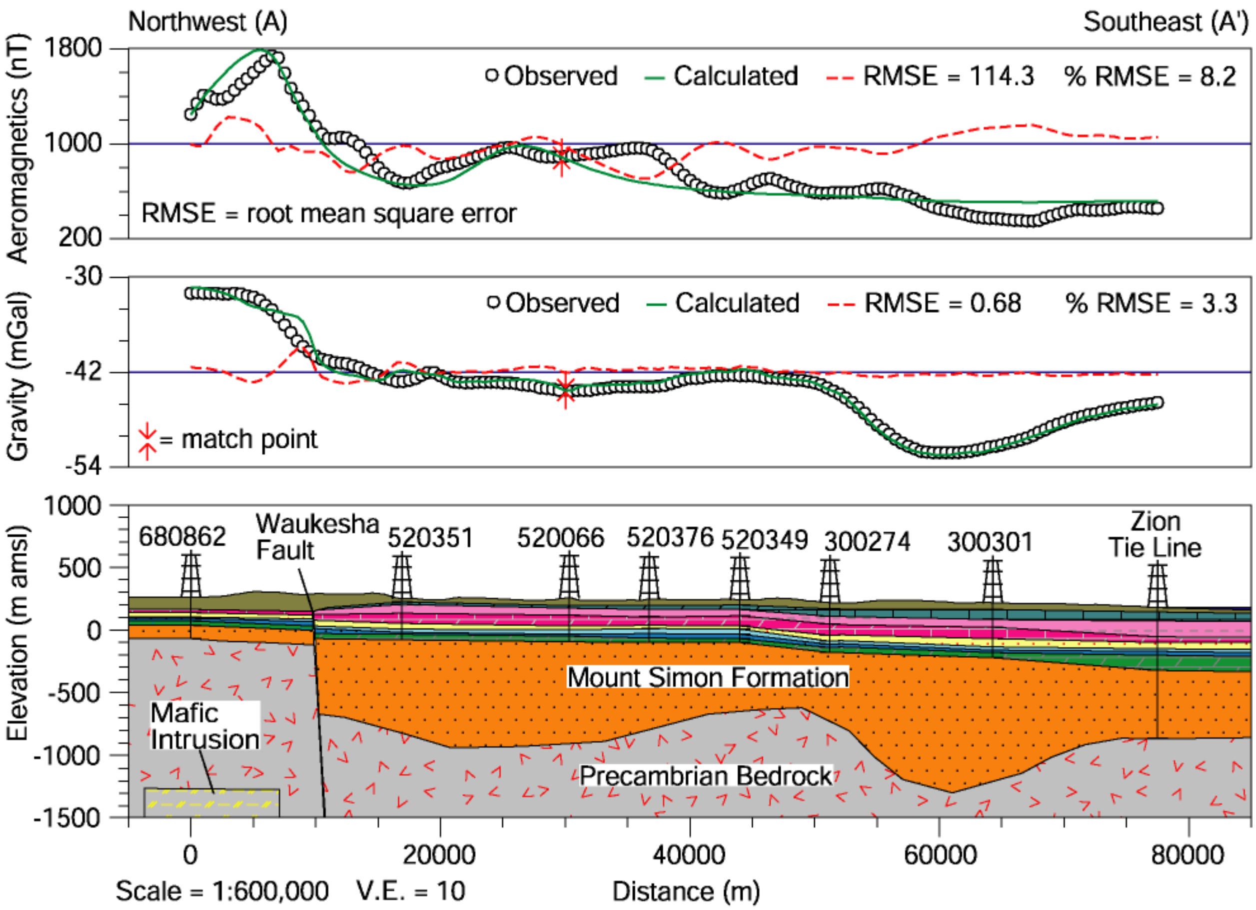

Figure 2. Profile A-A’ showing 2.75-dimensional model for southern extent of study area.

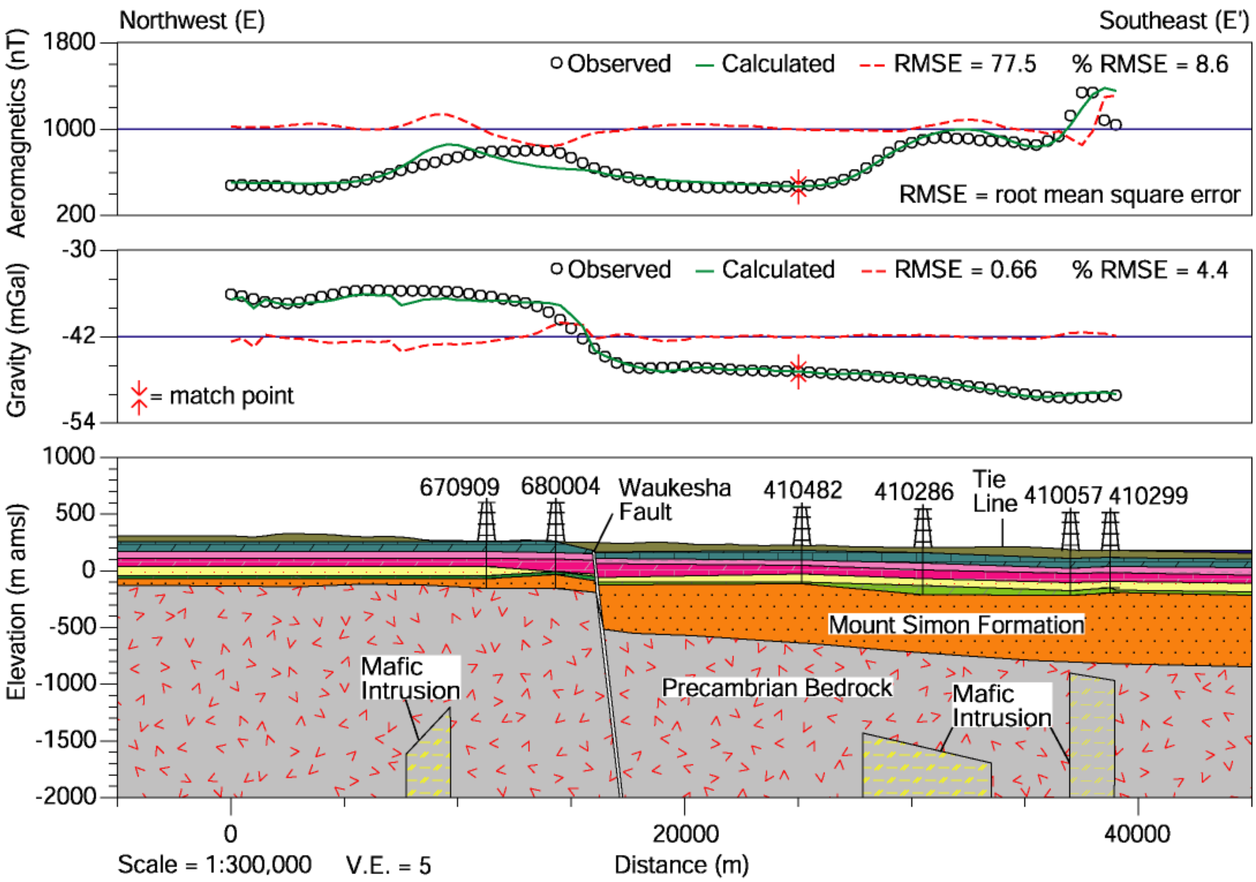

Figure 3. Profile E-E' showing 2.75-dimensional model for northern portion of study area.

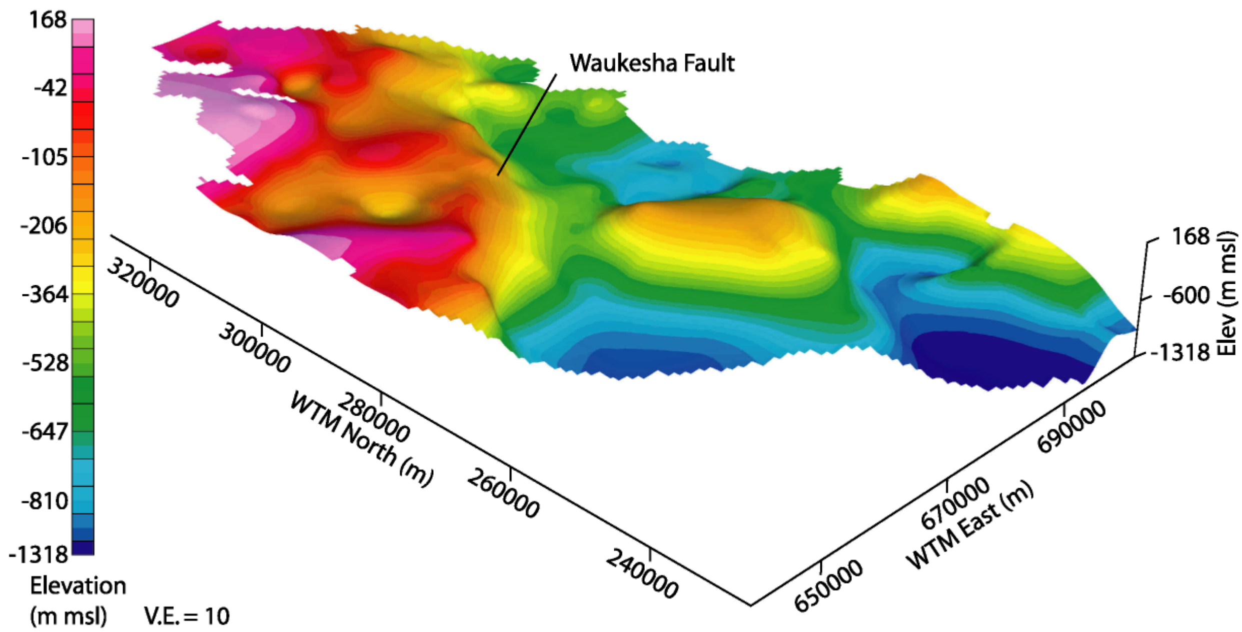

Figure 4. Precambrian bedrock topography obtained from model profile data throughout study area and well log data on up-thrown (northwest) block of Waukesha Fault. View from southwest.

2.75-Dimensional Models of Selected Profiles

Of the eight profiles modeled in this study, Profiles A-A' and E-E' are described here to highlight key features within the study area. The upper portion of each figure shows the aeromagnetic data while the center section shows the gravity data. In both sections, open circles represent the observed data while the solid green line indicates the model-calculated anomaly. The dashed red line represents the deviation between the observed and calculated data with distance from the horizontal blue line indicates greater model error. The cumulative error is indicated by the RMSE value. The lower section illustrates the geologic model where the horizontal distance in meters is relative to the northwest end of the profile and elevation in meters is relative to mean sea level (msl). Qualitative sensitivity analysis indicates that Precambrian bedrock and mafic intrusive bodies significantly influence the RMSE for both gravity and aeromagnetic data.

Profile A-A' crosses the Waukesha Fault at the southernmost extent of the study area and represents the best-constrained model. Excellent model fits for gravity (%RMSE = 3.3) and aeromagnetic data (%RMSE = 8.2) were obtained for this profile. Excellent vertical geologic control data are provided from eight wells including the only well (Zion) within the study area that reaches the Precambrian bedrock on the down-thrown (southeast) block of the fault. The Waukesha fault is represented as a 100 m wide zone that dips 60^o toward the southeast. The portion of the fault adjacent to sedimentary units has a density of 2.22 g/cm^3 and magnetic susceptibility of $100x10^{-6}$ cgs while the portion adjacent to Precambrian bedrock units has a density of 2.82 g/cm^3 and magnetic susceptibility of $1000x10^{-6}$ cgs (Table 1). This model configuration of the fault is maintained consistently throughout the study area. Lake Michigan does not appear on either of the profiles but was modeled using density of 1.0 g/cm^3 and magnetic susceptibility of $0x10^{-6}$ cgs. The density and susceptibility values for glacial, sedimentary, and Precambrian bedrock and mafic intrusive units are also provided in Table 1.

Depth control on both blocks of the fault is good for the glacial unit through the Eau Claire Formation. The Mount Simon Formation is well constrained on the up-thrown fault block but the bottom of this unit (top of Precambrian bedrock) is estimated from the model results on the down-thrown block. Depth to Precambrian bedrock on the up-thrown block is documented at 331 m below ground surface (bgs) in Well 680862 and is modeled at around 890 m on the down-thrown block adjacent to the fault. This model yields a normal vertical displacement of approximately 560 m with most of the displacement occurring within the Cambrian Mount Simon Formation. Well data indicate vertical displacement of 120 to 130 m for the Cambrian Eau Claire, Wonewoc and Trempleau Formations and 30 m for the Silurian Sinnipee and Saint Peter Formations. The maximum depth to bedrock within the study area is modeled at 1520 m bgs along this profile near Well 300301. The model indicates a significant depression in the bedrock surface in this area with local relief of 470 m with respect to the documented depth at the Zion Well and of 660 m relative to the modeled ridge beneath Well 300274. A second depression between Wells 520351 and 520066 modeled with maximum depth of 1200 m bgs shows relief of 270 to 315 m relative to the fault and model ridge, respectively. A mafic intrusion with density of 3.01 g/cm^3 and magnetic susceptibility of $7000x10^{-6}$ cgs is modeled beneath Well 680862 at a depth of 1520 m bgs. A second mafic intrusion between Wells 520351 and 520066 (not seen in Figure 3 because of the depth) is modeled at a depth of 4000 m with density of 3.03 g/cm^3 and magnetic susceptibility of 6000x10^{-6} cgs.

Profile E-E' crosses the northern portion Waukesha Fault where a good fit for gravity (%RMSE = 4.4) and a good fit for aeromagnetic data (%RMSE = 8.6) were obtained for this model. Data from six wells provide good vertical geologic control for the profile. Two wells on the up-thrown fault block document the depth to Precambrian bedrock at 415 and 419 m bgs but no wells exist on the down-thrown fault block. Model results yield normal vertical displacement of 340 m of the Precambrian bedrock. Unlike the undulating surface modeled in Profile A-A', the modeled bedrock surface in Profile E-E' gently slopes to the east. The depth to bedrock adjacent to the fault is modeled at 765 m bgs and at 1000 m bgs beneath Well 410299, at a distance approximately 20,000 m to the southeast. One mafic intrusion with density of 3.01 g/cm^3 and magnetic susceptibility of 5000x10^{-6} cgs is modeled beneath Well 67090 at a depth of 1465 m bgs on the up-thrown fault block. On the down-thrown block, a mafic intrusion is modeled below Well 410286 at a depth of 1635 m with density of 3.00 g/cm^3 and magnetic susceptibility of 4000x10^{-6} cgs and another is modeled between Wells 410057 and 410299 at a depth of 1075 m with density of 3.00 g/cm^3 and magnetic susceptibility of 7000x10^{-6} cgs.

Precambrian Bedrock Topography

Figure 4 illustrates the model top of Precambrian bedrock obtained from 2.75-dimensional coupled model gravity and aeromagnetic data along eight profiles (seven northwest-southeast and one north-south) and data from 19 well logs on up-thrown (northwest) block of Waukesha Fault. Top of bedrock elevations range from 168 m above mean sea level (msl) in the northern portion of the study area (WTM North 320000 m, WTM East 650000 m) to –1318 m msl in the southeast portion of the study area (WTM North 240000 m, WTM East 690000 m). The prominent southwest-northeast trending drop in bedrock surface elevation is interpreted as the Waukesha Fault scarp dipping steeply toward the southeast. The model suggests that the trend of the scarp is primarily linear with some minor curvature along strike. The model bedrock surface shows some moderate undulations on the up-thrown block and major undulations on the down-thrown block. An elevated area is modeled on the down-thrown block centered near WTM North 250000 m and WTM East 660000 m. This may represent a small up-thrown block within the down-thrown block or may result from deep erosion of two nearly parallel valleys.

Conclusions and Recommendations

The results from this study show the Waukesha Fault as a high-angle normal fault dipping to the southeast. Model topography of the Precambrian bedrock surface appears complex on both sides of the fault. A reasonable estimate of top of bedrock elevations southeast of the fault has been obtained from this study. Well log data used in this study support the model results of Svedrup et al. (1997) showing vertical displacement of 30 m in Silurian rocks. Our model results for maximum vertical displacement of the Precambrian basement of 560 m along Profile A-A' are also in close agreement with Svedrup et al. (1997) results of between 500 and 600 m. Although the Waukesha Fault was modeled as a geologic unit with constant dip of 60^o for each of the profile models, the Precambrian bedrock model topography gradient on the down-thrown fault block along some profile models appears gradually shallow. Thus, the model structure could alternatively be interpreted as a listric-type fault. Further model refinement will be conducted to investigate this alternative interpretation.

Coupled modeling of gravity and aeromagnetic data provides non-unique solutions since numerous different model geometries and assigned density and magnetic properties can produce fields that closely match the observed anomalies. For example, decreasing the model's density contrast between sedimentary rock and crystalline bedrock, and increasing the depth to bedrock could both produce a computed field similar to the previous configuration. Input of published density and magnetic susceptibility data and subsurface geology from well logs greatly constrains possible interpretations of the subsurface structure in southeast Wisconsin; however, other interpretations of the structure do exist. We intend to continue research on this study area to refine the results. We will conduct sensitivity analysis using reverse modeling to optimize model density and magnetic susceptibility values. We will evaluate the effects of incorporating remanent magnetic data in model blocks on reproducing observed aeromagnetic anomalies.

Results from this study have direct application to the groundwater flow model for southeast Wisconsin (Feinstein et al., 2004). These researchers now have an additional data set for the Precambrian basement configuration that can be utilized in the flow model. Additionally, others working on groundwater management issues (e.g., arsenic contamination, excessive drawdown, increasing salinity, etc.) in southeast Wisconsin may find the results of this study useful. Coupled modeling of gravity and aeromagnetic data can be applied to many other groundwater research topics across Wisconsin. For example, researchers have long known of the undulating nature of the top of Precambrian basement in the Fond du Lac area based on well log records but have not been able to construct a reasonable 3-dimensional model of this surface due to the paucity of point data. Because of the excellent state-wide compilation of gravity and aeromagnetic data for Wisconsin, a well-constrained 3-dimensional model of basement topography is obtainable not only for the Fond du Lac area but for most anywhere in the state. Additionally, the authors of GM-Sys^{R} (Northwest Geophysical Associates) have recently released GMSys-3D^{R}, which is capable of fully 3-dimensional coupled modeling of gravity and aeromagnetic data. Fully 3-dimensional coupled modeling has the capability of more accurately depicting the variation and irregularity of subsurface structures.

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Appendix A

Conference Presentation:

> PRELIMINARY RESULTS FROM COUPLED MODELING OF GRAVITY AND AEROMAGNETIC DATA IN THE WAUKESHA FAULT AREA OF SOUTHEASTERN WISCONSIN John D. Skalbeck, James N. Couch, Dennis M. Roy, Department of Geosciences, University of Wisconsin-Parkside, 900 Wood Road, Kenosha, WI 53141, presented at American Geophysical Union Fall Meeting 2003 in San Francisco, California, on December 11, 2003.