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Precambrian Basement Topography using 3D Modeling of Gravity and Aeromagnetic Data in Southeastern Wisconsin and Fond Du Lac County

Project Completion Report

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Project Summary

Background /Purpose

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 in southeastern Wisconsin near the Waukesha Fault 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. Precambrian basement surface throughout Fond du Lac County is known to be undulated and this uneven basement topography controls water well yields and zones of stagnant water. Therefore, an accurate estimation of the basement topography in Fond Du Lac County is vital to determining ground water flow and quality of groundwater in this region.

Objectives

The objectives of this research are to improve the current understanding of the subsurface Precambrian basement topography in southeastern Wisconsin and in Fond Du Lac County. Results from coupled modeling of gravity and aeromagnetic data along profiles (Skalbeck et al., 2007) in this area show that the estimated bedrock surface is uneven on both sides of the Waukesha Fault. Although, this modeling greatly improved our understanding of Precambrian bedrock topography in southeast Wisconsin, detailed estimation of this surface is limited by the 10 km spacing between profiles. The 3D modeling of gravity and aeromagnetic data from this study provides an even better definition of the Precambrian bedrock surface topography and the fault geometry because the model grid density is much greater (1 km grid) relative to the profile separation. The second objective it to provide a better estimate of the uneven Precambrian basement topography that has been documented throughout Fond du Lac County (Smith, 1978; Newport, 1962). Because basement surface relief is dramatic over short lateral distances in Fond du Lac County, 3D modeling of gravity and aeromagnetic data is particularly well suited for this area. Study results yield highly constrained subsurface Precambrian elevation maps for southeastern Wisconsin and Fond du Lac County that may be valuable for refining existing numerical groundwater models.

Methods

Three dimensional (3D) models of the Precambrian basement were developed by modeling existing gravity and aeromagnetic data using computer software GMSYS-3D and Oasis Montaj. The models are constructed with 1000 m grids for each data set and each geologic unit. Initial density and magnetic susceptibility values for the layers were obtained from modeling results in southeastern Wisconsin (Skalbeck et al., 2007). Blocks were assigned constant density and magnetic susceptibility or internal variance of these physical parameters calculated by GM SYS 3D. The forward modeling option of GM-SYS 3D is used initially to calculate the model anomaly and it statistics relative to the observed anomaly. The inverse modeling option is used for the remaining model runs to adjust the geologic model surface elevation and the block density or magnetic susceptibility values o optimize the model calculated anomalies to the observed gravity and magnetic anomalies. We employed a modification of model acceptance criteria from previous studies (Skalbeck, 2001; Skalbeck et al., 2005; Skalbeck, 2007) by using percent standard deviation ([% SD]; SD/ anomaly range]). Models were judged acceptable when the % SD was below 5% for gravity, and below 10% for aeromagnetic data.

Results

The initial 3D models for southeastern Wisconsin and for Fond du Lac County using constant density and magnetic susceptibility values for the Precambrian basement with no well constraints produced unacceptable fit statistics. Subsequent model runs incorporating well constraints, variable density and magnetic susceptibility, and a surface representing mafic bodies beneath the Precambrian basement produced fit statistics for both study area models. The 3D model for southeastern Wisconsin agrees well in overall geologic structure with the modeled Precambrian basement from Skalbeck et al. (2007) but the new 3D model shows more detail. Both models show a similar trend of the Waukesha Fault; however, 3D model shows an elevated area near the southern end of the end of the Waukesha fault. The new 3D model shows slightly less variation in overall model elevations and less undulation on the up-thrown block northwest of the fault. For the Fond du Lac County model, a comparison of Precambrian basement elevations from model verification wells with elevations obtained from the 3D model shows close agreement. The mean difference between well log and 3D model elevations is 3 m in which is less than 1 % of the range. A comparison between the basement elevation map from well logs and from the 3D model combined with well log elevations illustrates that both surfaces exhibit similar overall basement structure but the new 3D model shows much greater detail. Much more undulation is present on the basement ridge located in the western portion of the study area. The largest difference between the two surfaces occurs in the northwestern and southwestern corners of the area where no well elevations exist.

Conclusions

The results of this study demonstrate that 3D modeling of existing gravity and aeromagnetic data combined with existing well log data yields a more detailed delineation of the subsurface Precambrian basement topography relative to well log data alone. The 3D model for southeastern Wisconsin is consistent with the overall structure of the Skalbeck et al. (2007) model but shows greater detail with regard to undulations in areas between the previous model profiles. The 3D model also shows the Waukesha fault more sharply defined while matching trend the previous model. This 3D model for Fond du Lac County is able to provide detail of the basement surface in areas with no well control that is consistent with gravity and aeromagnetic anomalies. The rich set of well log data that documents the basement elevation in the county allows for a highly constrained 3D model that is verified relative to a large set of well elevations. The comparison between the model calculated and well log elevations confirms that the 3D model provides reasonable prediction of the basement topography.

Introduction

This study focuses on two study areas, southeastern Wisconsin and Fond Du Lac County as shown in Figure 1. The southeastern Wisconsin study area consists of Kenosha, Milwaukee, Ozaukee, Racine, Walworth, Washington, and Waukesha Counties. This large study area encompasses 6,900 square kilometers and the entire south east corner of the state. The southeast Wisconsin area is intended to model subsurface Precambrian basement that has been offset by the Waukesha Fault and not currently reached by water wells (Figure 2).

Fond du Lac County, on the southern end of Lake Winnebago encloses the other area of study. This 1,650 square kilometer study area is underlain by Precambrian basement that is significantly undulated (Figure 2). The area is entirely dependant on groundwater wells for pubic supply and water quality in this area is strongly dependant on basement topography. The Fond du Lac County model is intended to provide an improve interpretation of this highly undulated Precambrian surface. A better understanding of the subsurface topography in both study areas may be useful for future water resource development in central and southeastern Wisconsin.

Southeastern Wisconsin

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 (Figure 2). 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 aeromagentic 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.

Fond du Lac County

Precambrian crystalline basement rocks in Fond du Lac County consist primarily of quartzite, granite. Some schist, gneiss and rhyolite as well as other metamorphic rocks may also be present. A major unconformity separates these rocks with sedimentary rocks of Cambrian, Ordovician, Silurian, and Quaternary ages. Although the surface of the Precambrian basement has a regional slope toward the east and south of about 5 m/km (25 ft/mi), the local surface in Fond du Lac County is uneven with slopes ranging from 1 to 100 m/km (few to hundreds of ft/mi) and a relief of at least 335 m (1,100 ft) (Newport, 1962).

In the City of Fond du Lac, quartzite was encountered in a well at an elevation of 3 m (10 ft) above mean sea level (amsl) while four wells within a mile encountered the quartzite at about 95 to 110 m (315 to 360 ft) amsl. Northeast of these wells, quartzite was found at 60 to 70 m (200 to 225 ft) amsl. At a location approximately 16 km (10 mi) west of the City of Fond du Lac and 3 km south of Rosendale, quartzite was encountered in a well at about 265 m (870 ft) amsl, at 244 to 255 m (800 to 835 ft) amsl in four other wells, and at 152 m (500 ft) amsl in another well (Newport, 1962).

The origin of the undulated Precambrian basement surface in Fond du Lac County is relatively unknown. Present-day Fond du Lac County is located near the convergence boundary of Archean subcontinents approximately 2200 million years ago that formed the now stable North American craton. The Marshfield terrain of Archean granite-gneiss to the south contacts the Wausau-Pembine terrain formed from and uplifted volcanic island arc to the north. A period of volcanism followed creating an area of rhyolite that underlays the western half of the county followed by period of metamorphism produced Waterloo Quartzite under the eastern half of the county. Lastly, the central-north American rift system may have affected the area around 1100 million years ago (Dutch, 1983).

Methods

The gravity and aeromagnetic data are compilations from the US Geological Survey (Daniels and Snyder, 2002; Snyder et al., 2003) for the entire state of Wisconsin. These grids were downloaded from the USGS websites. 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 1000 m 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 1000 m grid using a minimum curvature algorithm. Maps of bouguer gravity and aeromagnetic anomalies for the study areas are shown on Figure 3.

The 3D modeling of gravity and aeromagnetic data was performed using the commercially-available modeling programs (GM-SYS 3D and Oasis Montaj by Geosoft). Each model consists of stacked data grids of 1000 x 1000 m dimension. The space between each geologic model surface grid is defined as a block that represents a geologic unit. Blocks may be assigned constant density and magnetic susceptibility or internal variance of these physical parameters calculated by GM SYS 3D. The forward modeling option of GM-SYS 3D is used initially to calculate the model anomaly and it statistics relative to the observed anomaly. The inverse modeling option is used for the remaining model runs to adjust the geologic model surface elevation (structural inversion) and the block density or magnetic susceptibility values (lateral distribution inversion) to optimize the model calculated anomalies to the observed gravity and magnetic anomalies.

The geologic model structure of the Precambrian basement surface was constrained by incorporating well log elevations data into constraint grids. One constraint grid contains a series of numerical values between zero and one that control the degree of variation in elevation of Precambrian surface at well locations. A constraint grid node value was set to zero (0) for areas with control that allows no elevation variation while grid nodes for areas without well control value are given a value of one (1) that allows elevation variation within limits specified by the modeler. The other constraint grid contains the well log elevations that serve as initial model input. The inversion runs incorporate these constraint grids and iteratively adjust the model input to optimize the model calculated anomaly to the observed gravity and magnetic anomalies.

Initial density and magnetic susceptibility data were obtained from previous modeling results of Skalbeck et al. (2007). This study relied on a state compilation (Dutch et al., 1994) and a number of local studies (Brukardt, 1983; Moll, 1987; Lahr, 1995; Sverdrup et al., 1997) A summary of density and magnetic susceptibility data is given in Table 1. Constant density and magnetic susceptibility values were assigned for the glacial deposits, Silurian-Ordovician sediments, Cambrian Mount Simon Formations, and Precambrian mafic bodies.

Well record data (location, stratigraphy, elevation) were obtained from the state compilation wiscLITH by the Wisconsin Geological and Natural History Survey (WGNHS, 2003). Well locations were projected to the nearest model grid node as required for GM SYS 3D. The 19 wells that reach Precambrian basement were used to constrain the 3D model structure for the southeastern Wisconsin study area (Table 2). For the Fond du Lac County study area, the 18 wells within 250 m of a grid node were used to constrain the 3D model (Table 3).

GM-SYS 3D calculates the standard deviation (SD) of the error between the model calculate and observed gravity and aeromagnetic anomaly grids which represents a measure of model error. We employed a modification of model acceptance criteria from previous studies (Skalbeck, 2001; Skalbeck et al., 2005; Skalbeck, 2007) by using percent standard deviation ([% SD]; SD/anomaly range]). Models were judged acceptable when the % SD was below 5 % for gravity, and below 10% for aeromagnetic data. A summary of model fit statistics is given in Table 4.

Results

Southeastern Wisconsin

The initial 3D model for southeastern Wisconsin was developed using geologic model surface grids and average values for density and magnetic susceptibility were taken from Skalbeck et al. (2007). Based on the results of Skalbeck et al. (2007), only the Precambrian basement and Precambrian mafic bodies surfaces were adjusted for this study. Constant average values for density (3.00 g/cm^3) and magnetic susceptibility (1000 x 10^{-6} cgs) for the Precambrian basement were assigned for the initial 3D model runs.

The initial forward calculation model (2.75-D with no well constraints) produced fit statistics of 20.6 % SD for gravity and 14.7 % SD for aeromagnetic which did not meet acceptable target values (Table 4). Structural inversion model runs on the Precambrian basement using well constraints and constant density and magnetic susceptibility values produced unacceptable fit statistics of 6.3 % SD for gravity and 14.6 % SD for aeromagnetics.

Model inversions for the southeastern Wisconsin model generated lateral distributions for density and magnetic susceptibility of the Precambrian basement block (Figure 4). The model inversion values for density range from 3.00 to 3.04 g/cm^3. The greatest density variation occurs northwest of the Waukesha Fault where the up-thrown block of Precambrian basement is close to the surface. The area of the down-thrown block southeast of the fault where the basement is deeper has density values close to the mean with little variability. The model inversion values for magnetic susceptibility range from -395 to 1104 x 10^{-6} cgs. The higher magnetic susceptibility values generally are located on the up-thrown block while the lower values are located on down-thrown block. Structural inversion model runs on the Precambrian basement using well constraints and variable density and magnetic susceptibility produced acceptable fit statistics of 4.5 % SD for gravity and 9.1 % SD for aeromagnetics.

Because mafic bodies were used in Skalbeck et al. (2007) to improve the model fit for the aeromagnetic data, a model surface was added to represent mafic bodies below the Precambrian basement. Since well data does not exist to provide an initial surface for mafic intrusions, a model surface was assigned an initial elevation of -10,000 m msl using initial magnetic susceptibility of 5500 x 10^{-6} cgs. A constraint grid was then constructed by assigning areas of high magnetic error from the previous model run a constraint value of one (1) to allow variance in elevation for the areas with poor fit between model and observed aeromagnetic anomalies. The structural inversion generated a mafic bodies surface with elevations ranging from (-10,000 to 4 m msl).

The final 3D model for southeastern Wisconsin incorporates a Precambrian basement surface of variable density with well constraints, variable magnetic susceptibility with well constraints, and a surface representing mafic bodies beneath the Precambrian basement. This model produced an acceptable fit statistics of 4.5 % SD for gravity 8.1 **%** SD for aeromagnetics.

The error between observed and modeled gravity and aeromagnetic data of the Precambrian basement layer for the 3D model using variable density and magnetic susceptibility is shown in Figure 5. The gravity error ranges from -2.53 to 7.20 mGal with a mean of 0.0002 mGal. The SD of the gravity error for this model is 0.94 mGal that results in an acceptable fit statistic of 4.5 % SD. The greatest gravity error is located along the western boundary of the model domain near the southern end of the Waukesha fault. This area was not part of the Skalbeck et al. (2007) study area and thus did not include initial geologic model surface elevations or structural constraint. The aeromagnetic error ranges from -523 to 835 nT with a mean of -58 nT. The SD of the aeromagnetic error for this model is 147 nT that results in an acceptable fit statistic of 8.0 % SD. The greatest aeromagnetic error is located along Waukesha fault and on the up-thrown fault block.

A comparison of the modeled Precambrian basement from Skalbeck et al. (2007) and the 3D model from this study is shown in Figure 6. Theses models show close agreement in overall geologic structure of the Precambrian basement for southeastern Wisconsin; however, the new 3D model shows more detail in the geologic structure than the previous model. Both models show a similar trend of the Waukesha Fault; however, 3D model shows an elevated area near the southern end of the end of the Waukesha fault. The new 3D model shows slightly less variation in overall model elevations and less undulation on the up-thrown block northwest of the fault.

Because the number of elevation values available for constraint of the Precambrian basement surface in southeastern Wisconsin is limited to the data from 19 wells, each available known elevation was used to constrain the 3D model. Since the constraints grid sets the model elevation equal to the well elevation, direct comparison between model elevation and well elevation for the Precambrian basement is available for southeastern Wisconsin.

Fond du Lac County

The initial 3D model structure for Fond du Lac County was developed with geologic model surface grids generated using wisLITH elevations from 83 wells. Forward calculation model runs using constant density and magnetic susceptibility values with no well constraints produced fit statistics of 20.3 % SD for gravity and 17.3 % SD for aeromagnetic which did not meet acceptable target values (Table 4). Structural inversion model runs on the Precambrian basement surface using constant density and magnetic susceptibility values with well constraints again produced forward calculation model results with unacceptable fit statistics of 9.5 % SD for gravity and 17.2 % SD for aeromagnetics.

Model inversions were performed next to generate variable density and magnetic susceptibility lateral distributions for the Precambrian basement block of the Fond du Lac 3D model (Figure 7). The model inversion produced density values ranging from 2.98 to 3.07 g/cm^3. The higher density values are located in the southwestern and southeastern corners of the study area where the basement consists of rhyolite and quartzite rocks while the lower values occur in the northwestern corner and central portion of the study area where granite basement is found. The model inversion produced magnetic susceptibility values that range from -554 to 886 x 10^{-6} cgs. The higher magnetic susceptibility values are located in the western portion of the county that correspond with rhyolite and granitic basement rocks while the lower values occur in the central and eastern portion of the county where the basement consists of quartzite. Structural inversion model runs on the Precambrian basement surface using well constraints and variable density and magnetic susceptibility produced forward calculation model results with an acceptable fit statistic of 2.4 % SD for gravity but an unacceptable fit statistic of 11.3 % SD for aeromagnetics.

To improve the model fit for the aeromagnetic data, a model surface was added to represent mafic bodies below the Precambrian basement. Since well data does not exist to provide an initial surface for mafic intrusions, a model surface was assigned an initial elevation of -10,000 m msl using initial magnetic susceptibility of 5500 x 10^{-6} cgs. A constraint grid was then constructed by assigning areas of high magnetic error from the previous model run a constraint value of one (1) to allow variance in elevation for the areas with poor fit between model and observed aeromagnetic anomalies. The structural inversion generated a mafic bodies surface with elevations ranging from -10,000 to -202 m msl).

The final 3D model for Fond du Lac County incorporates a basement surface of variable density with well constraints, variable magnetic susceptibility with well constraints, and a surface representing mafic bodies beneath the Precambrian basement. This model produced the forward calculation model result with an acceptable fit statistic of 10.0 **%** SD for aeromagnetics.

The error between observed and modeled gravity and aeromagnetic data from the 3D model of the Precambrian basement layer for the Fond du Lac County is shown in Figure 8. The gravity error ranges from -2.58 to 4.29 mGal with a mean of 0.0002 mGal. The SD of gravity error for this model is 0.87 mGal that results in an acceptable fit statistic of 2.4 % SD (Table 4). The greatest gravity error is located along the western boundary of the model where only two wells exist to constrain the model. The aeromagnetic error ranges from -232 to 470 nT with a mean of -58 nT. The SD of the aeromagnetic error for this model is 110 nT that results in a fit statistic of 10.0 % SD (Table 4). The greatest aeromagnetic error is also located along western and southern boundaries of the model where well control is limited.

Table 5 provides a comparison of Precambrian basement elevations from wells with elevations obtained from the 3D model. Elevations from 65 wells projected to the nearest model node are compared with the 3D model elevations from the corresponding node. It is important to note that these 65 wells have been projected greater than 250 m to the nearest model node. This comparison shows that the 3D model yields basement elevations that closely match the elevations from well logs. The minimum elevations (-93 vs -117 m msl) and maximum elevations (265 vs 274 m msl) are close with the 3D elevations capturing a slightly wider range

(391 m). The mean difference between well log and 3D model elevations is 3 m in which is less than 1 % of the range.

Elevations from the final 3D model were combined with elevations from 18 constraint wells (Table 2) and 65 evaluation wells to generate a 3D representation of the Precambrian basement surface for Fond du Lac County. Figure 9 presents a comparison of Precambrian basement elevation for Fond du Lac County generated from well log elevations only and from the 3D model combined with well log elevations. Although both surfaces exhibit similar overall basement structure, the new 3D model shows much greater detail. Much greater undulation is present on the basement ridge located in the western portion of the study area. The greatest difference between the two surfaces occurs in the northwestern and southwestern corners of the area where no well elevations exist.

Discussion and Conclusions

The results of this study demonstrate that 3D modeling of existing gravity and aeromagnetic data combined with existing well log data yields a more detailed delineation of the subsurface Precambrian basement topography relative to well log data alone. Beginning the 3D modeling of gravity and aeromagnetic data in southeastern Wisconsin provided the opportunity to become familiar with a newly released commercial software package applied to a study area with an existing highly constrained geophysical model with solidly tested physical input parameters. This 3D model is consistent with the overall structure of the Skalbeck et al. (2007) model but shows greater detail with regard to undulations in areas between the previous model profiles. The 3D model also shows the Waukesha fault more sharply defined while matching trend the previous model.

The study has also provided greater detail of the subsurface Precambrian basement surface in Fond du Lac County relative to previous studies. The experience gained from the modeling work in southeastern Wisconsin was critical given the highly undulated topography of the Precambrian basement surface in Fond du Lac County. As with southeastern Wisconsin, the 3D model for Fond du Lac County shows much greater detail of the undulated Precambrian basement topography relative to well data only. This 3D model is able to provide detail of the basement surface in areas with no well data control that is consistent with gravity and aeromagnetic anomalies. The rich set of well log data that documents the elevation of the basement in the county allows for a highly constrained 3D model that is verified relative to a large set (65) of well elevations. The comparison between the model calculated and well log elevations confirms that the 3D model provides reasonable prediction of the basement topography.

The study was not able to produce an acceptable coupled (simultaneous) model of the gravity and aeromagnetic data as anticipated. Computation time for the coupled models for this study were long (> 24 hours) and resulting structures were not reasonable. Future research on coupled modeling may yield reasonable results; however, the methodology used for this study (modeling gravity followed by modeling aeromagnetic data) produce high quality results.

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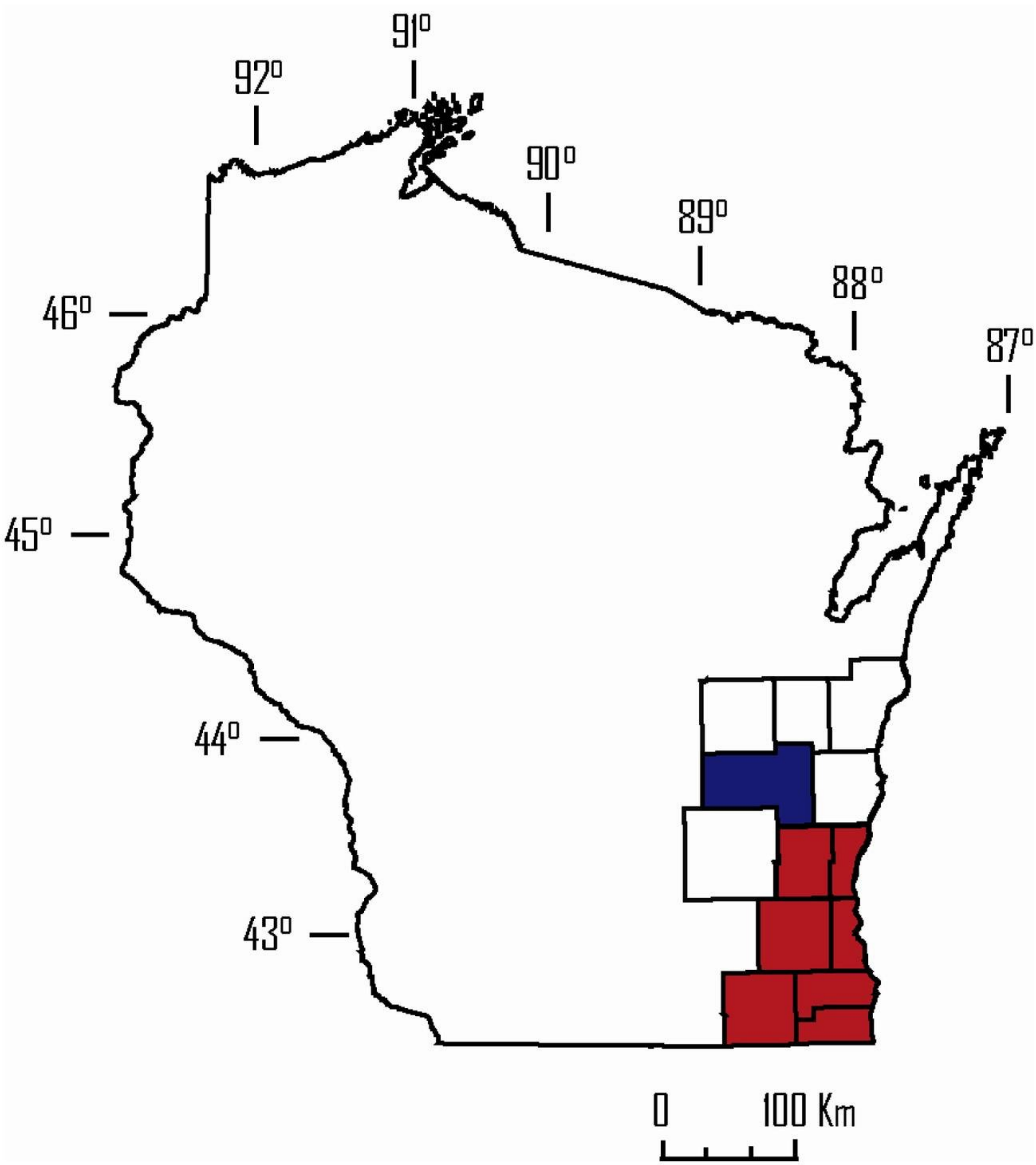

Figure 1. Location map showing study areas. Southeastern Wisconsin study area is shown in red. Fond du Lac County is shown in blue.

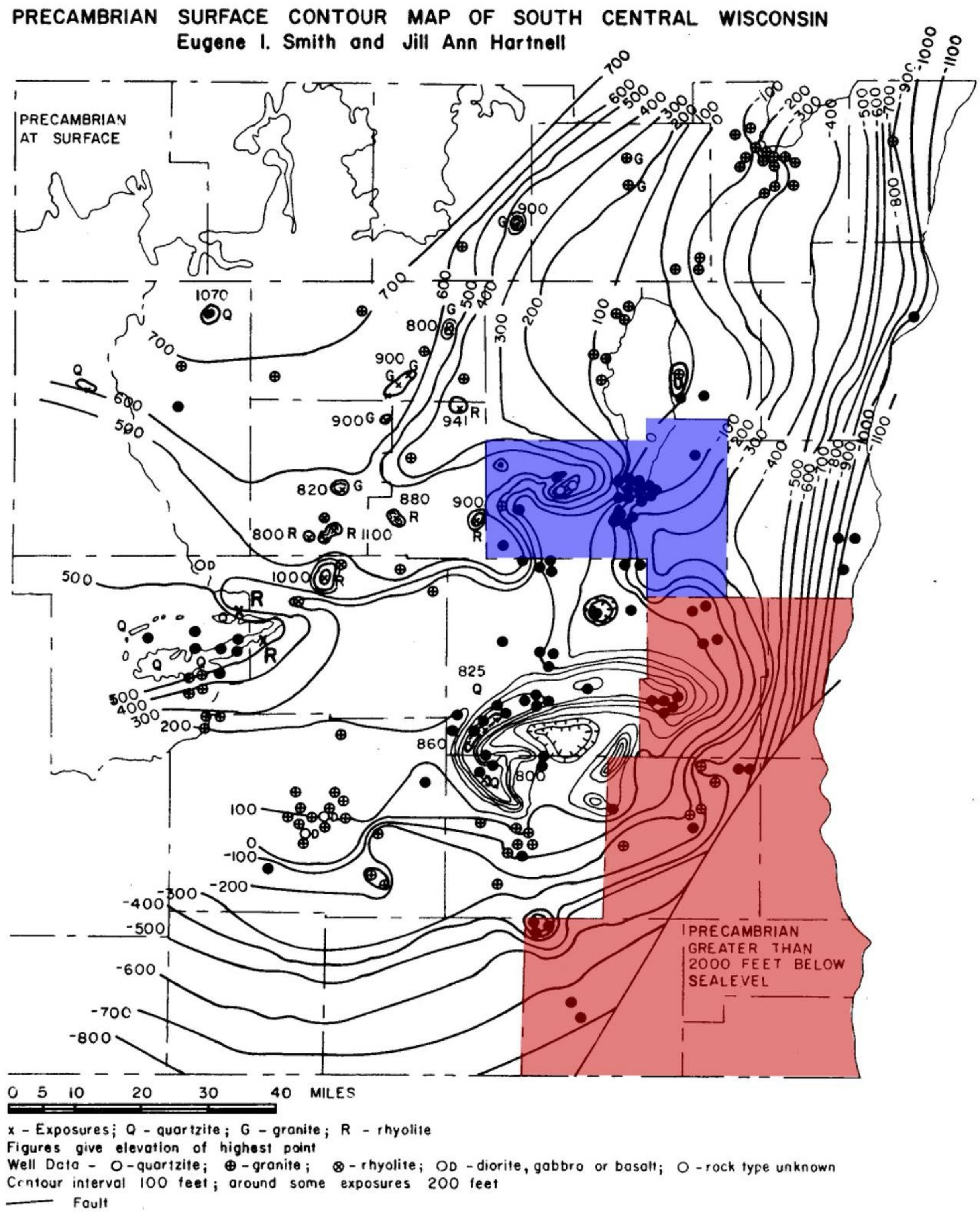

Figure 2: Map showing elevation of Precambrian basement in Wisconsin (modified from Smith, 1978). Southeastern Wisconsin study area shown in red. Fond du Lac County shown in blue.

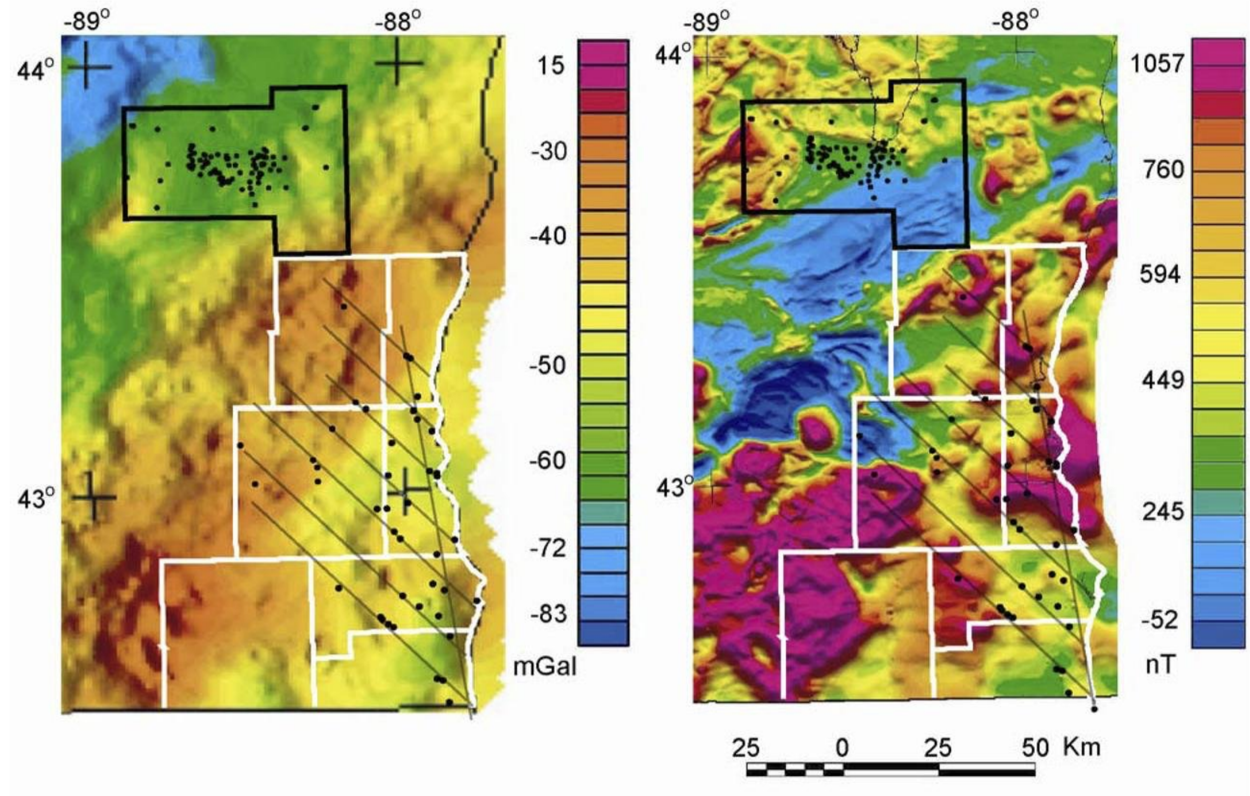

Figure 3: Gravity and aeromagnetic anomaly maps of study areas (Modified from Daniels and Snyder, 2002; Snyder et al, 2003). Southeastern Wisconsin study area is outlined in white, Fond du Lac County is outlined in black. Wells used in the study are indicated by black dots, profile locations from 2 ¾ D study (Skalbeck, et al., 2007) are shown by grey lines.

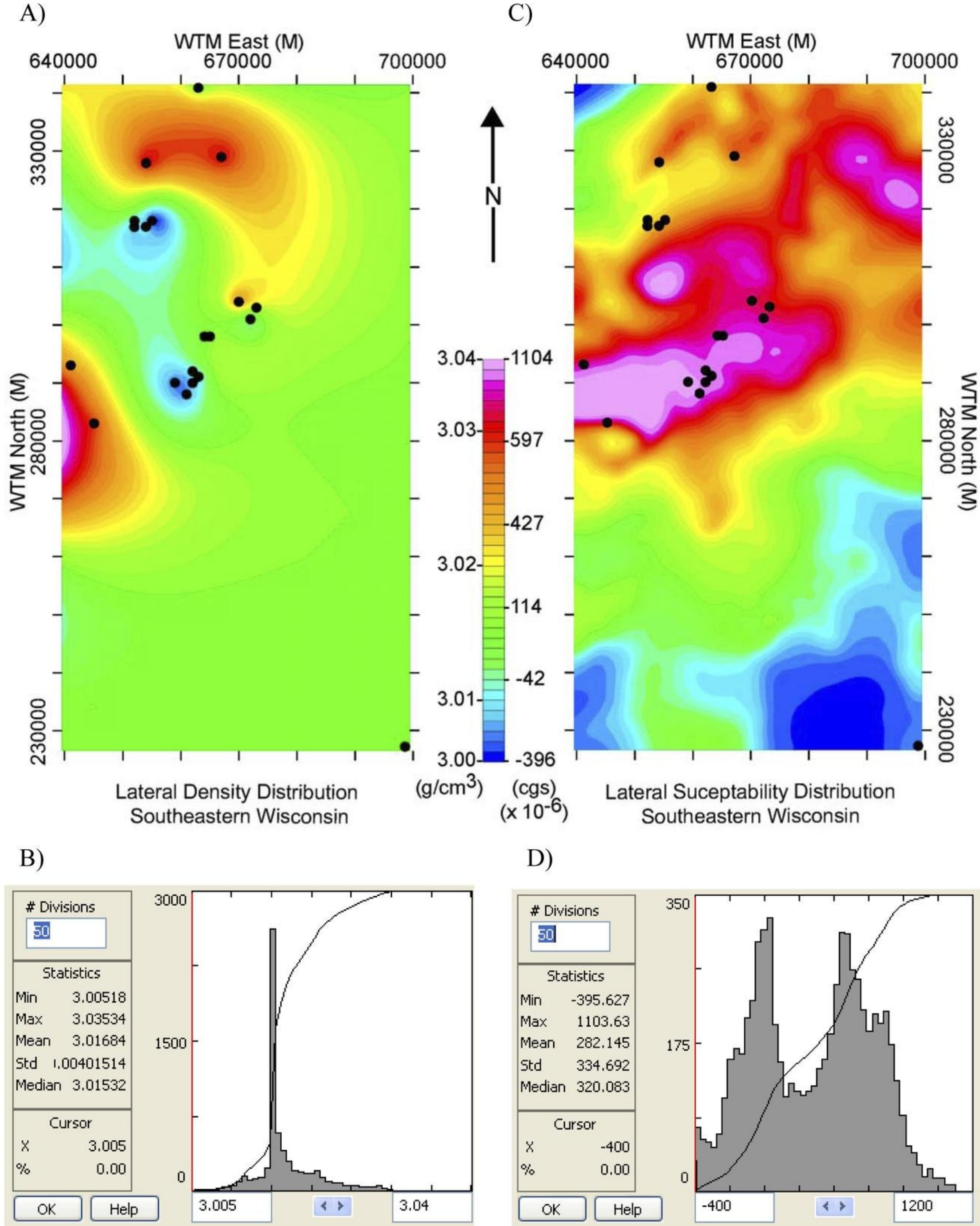

Figure 4: Model properties of Precambrian basement for southeastern Wisconsin. A) Lateral density distribution. B) Histogram of lateral density distribution. C) Lateral magnetic susceptibility distribution. D) Histogram of lateral magnetic susceptibility distribution. Closed circles indicate constraint well locations.

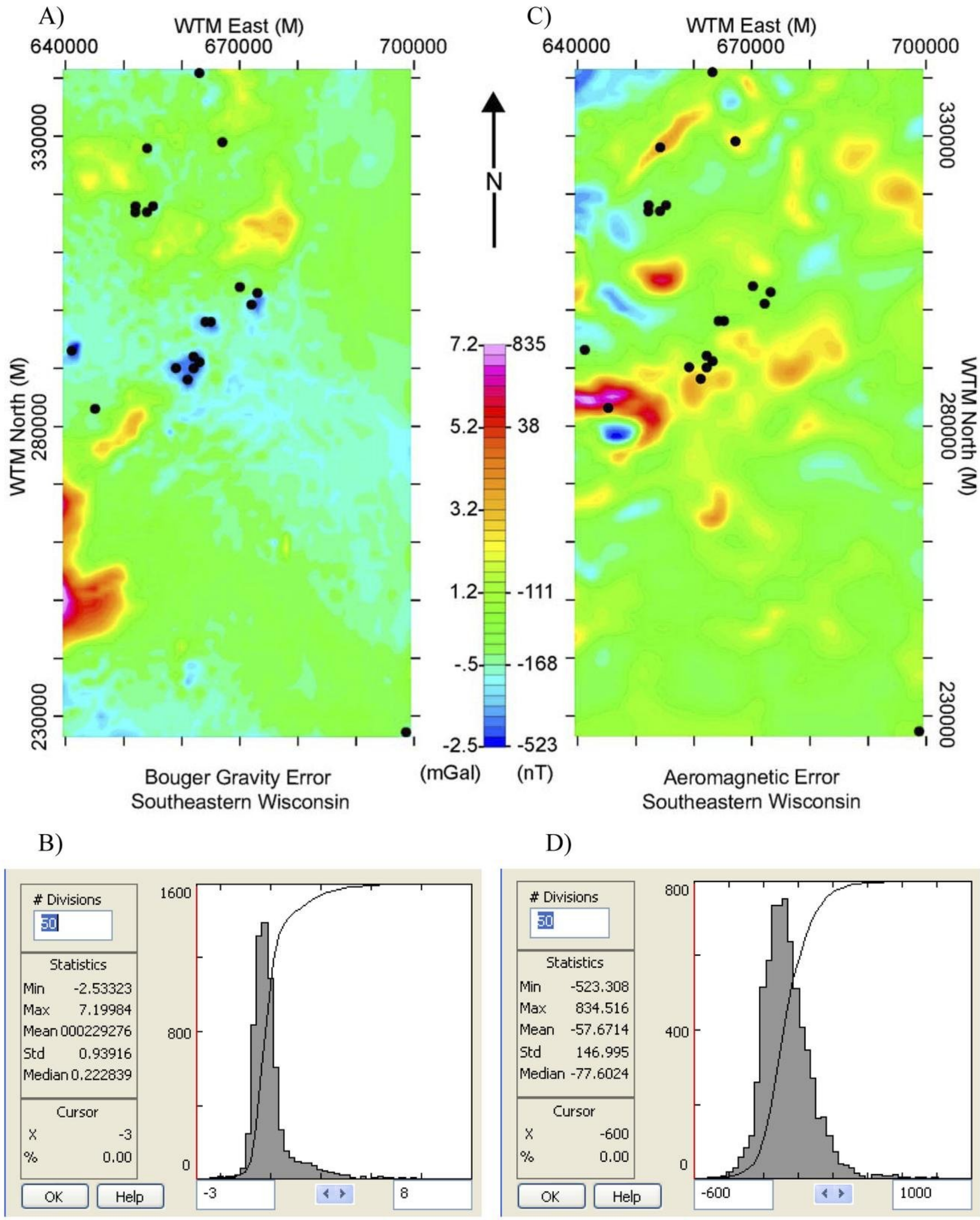

Figure 5. Error between observed and modeled gravity and aeromagnetic anomalies of the Precambrian basement for southeastern Wisconsin. A) Bouguer Gravity Error distribution. B) Histogram of Bouguer Gravity Error. C) Aeromagnetic Error distribution. D) Histogram of Aeromagnetic Error. Closed circles indicate constraint well locations.

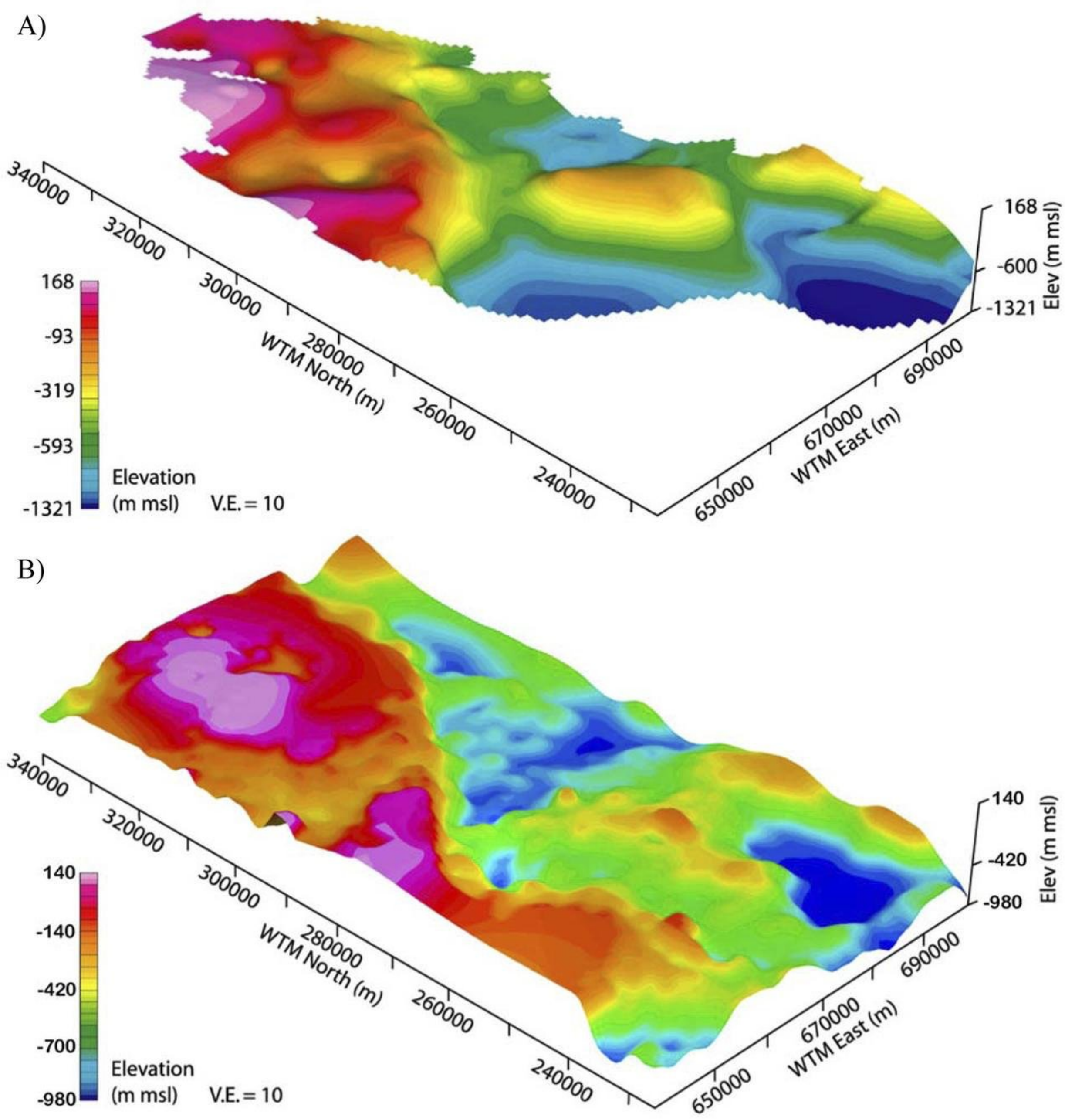

Figure 6. Comparison of Precambrian basement topography for southeastern Wisconsin.
A) Based on 2 ¾ D profile models and well log elevations (Skalbeck et al., 2007).
B) Based on 3D model and well log elevations.

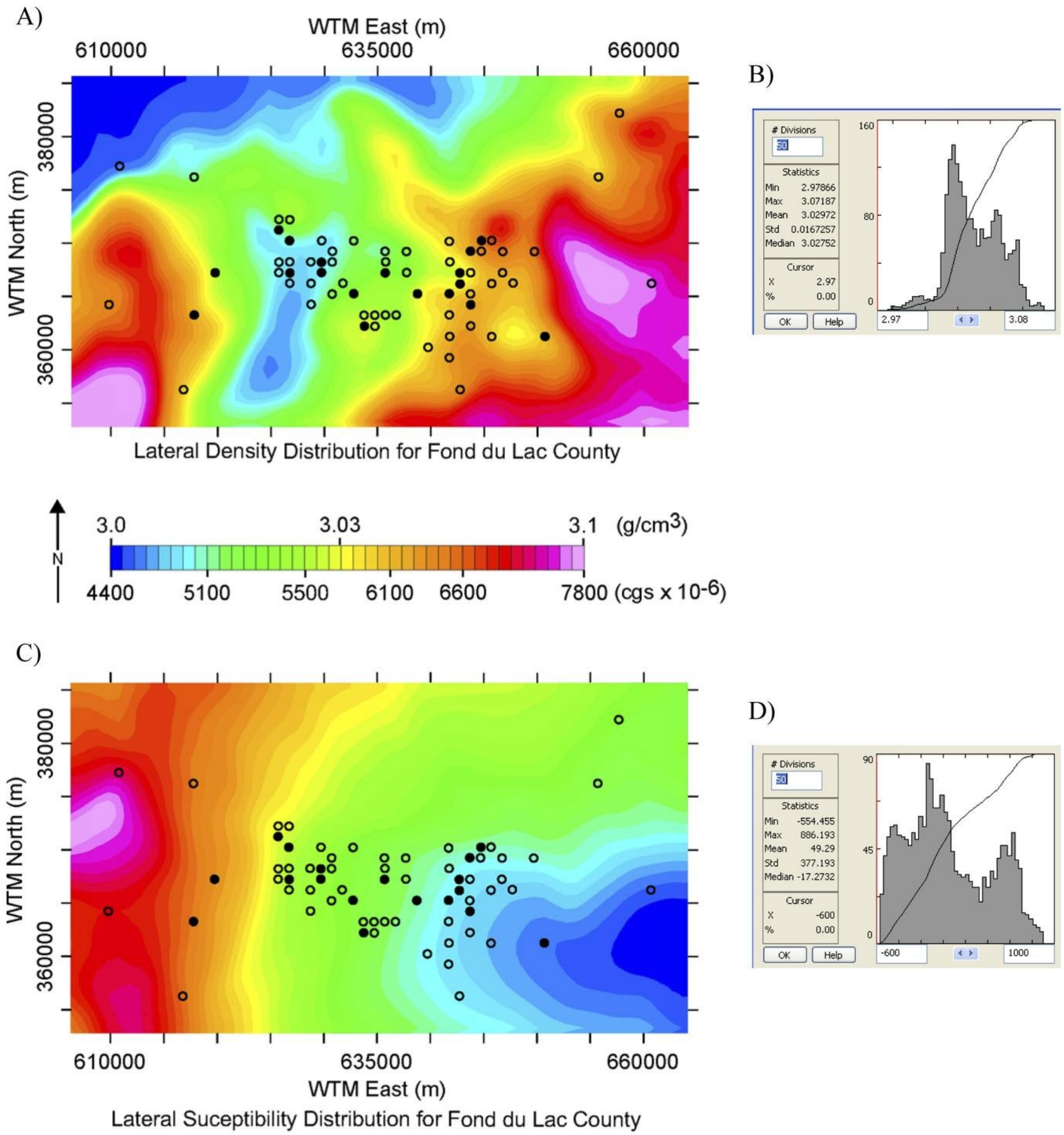

Figure 7. Model properties of Precambrian basement for Fond du Lac County. A) Lateral density distribution. B) Histogram of lateral density distribution. C) Lateral magnetic susceptibility distribution. D) Histogram of lateral magnetic susceptibility distribution. Closed circles indicate constraint well locations, opencircles indicate model verification well locations.

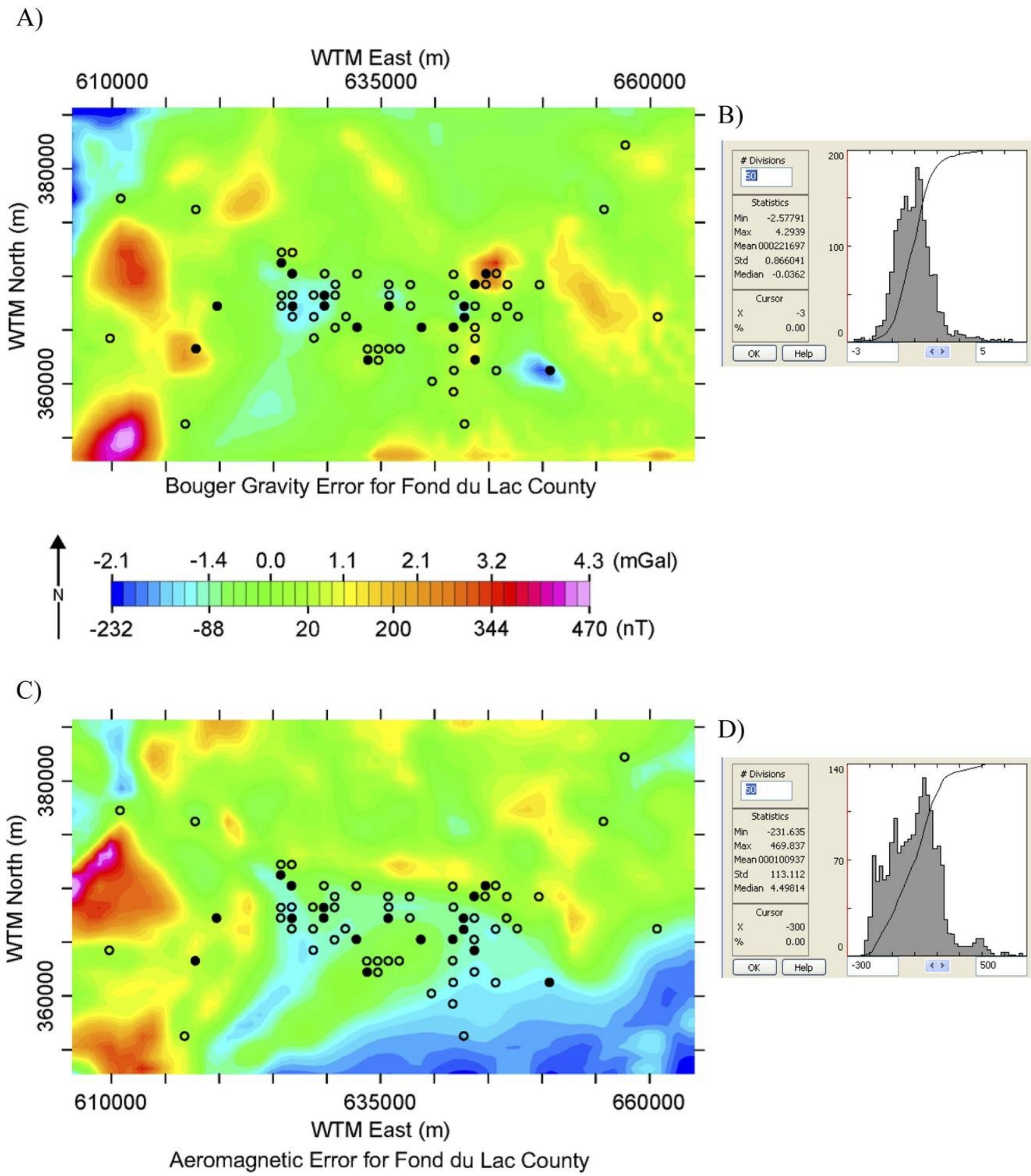

Figure 8. Error between observed and modeled gravity and aeromagnetic anomalies of the Precambrian basement for Fond du Lac County. A) Bouguer Gravity Error distribution. B) Histogram of Bouguer Gravity Error. C) Aeromagnetic Error distribution. D) Histogram of Aeromagnetic error. Closed circles indicate constraint well locations, open circles indicate model verification well locations.

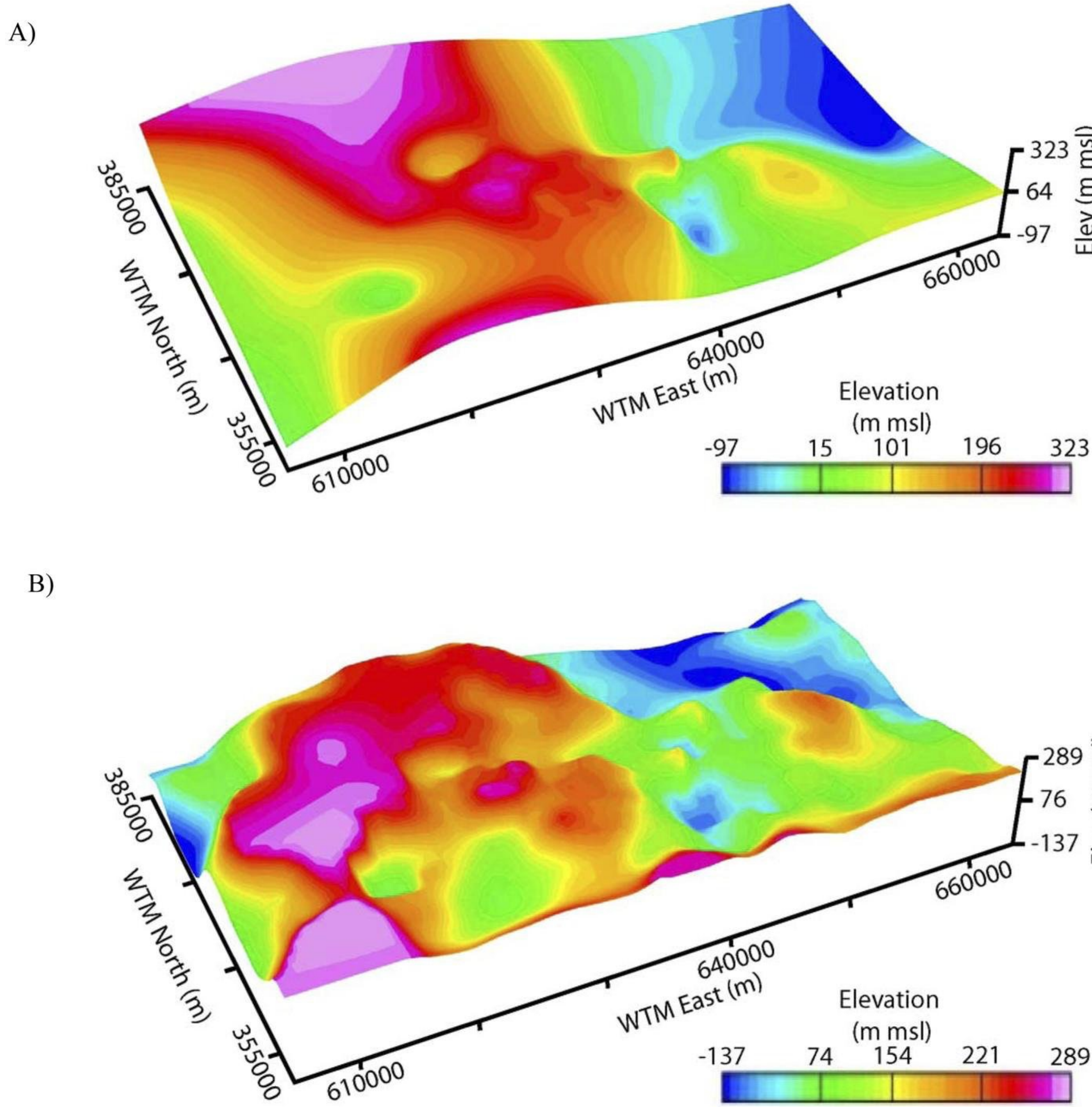

Figure 9: Comparison of Precambrian basement topography for Fond du Lac County. A) Based on well log elevations only. B) Based on 3D model and well log elevations.

Table 1. Density and magnetic susceptibilty data for 3D models.

Geologic Model Unit	Density (g/cm^3) Southeastern WI	Fond du Lac	Skalbeck et al., 2007
Glacial	1.80	1.80	1.80
Silurian-Cambrian Sediments	2.67	2.67	2.45 - 2.77*
Mount Simon Formation	2.58	2.58	2.58
Precambrian Basement	3.00 - 3.04	2.98 - 3.07	2.77 - 3.02
Precambrian Mafic Bodies	3.00 - 3.04	2.98 - 3.07	3.00 - 3.05

Geologic Model Unit	Magnetic Susceptibility ($x10^{-6}$ cgs) Southeastern WI	Fond du Lac	Skalbeck et al., 2007
Glacial	0	0	0
Silurian-Cambrian Sediments	100	100	100
Mount Simon Formation	100	NA	100
Precambrian Basement	-396 - 1104	-554 - 886	1000
Precambrian Mafic Bodies	5500	5500	3000 - 7000

*Values input for individual sedimentary formations
NA: Not available or applicable
Negative magnetic susceptibility values resulting from model inversion interpreted as reversed magnetization

Table 2. Well data used for structural constraint in 3D model for southeastern Wisconsin.

State Well ID	WTM-E (m)	WTM-N (m)	Surface Top Elevation (m amsl)	Sediments Top Elevation (m amsl)	Mount Simon Top Elevation (m amsl)	Basement Top Elevation (m amsl)
670006	653879	317482	306	287	85	84
670008	663293	340505	293	263	-24	-25
670009	667386	328823	276	218	-7	-7
670012	651668	316710	306	286	145	144
670013	652244	317752	308	297	146	145
670034	655188	317877	306	260	150	149
670909	670428	304391	266	259	-66	-153
670920	654139	328151	303	287	86	85
680004	673082	302714	268	259	-30	-147
680020	640886	293445	269	261	47	34
680027	661765	291564	259	207	-6	-142
680028	659494	289674	274	259	-1	-88
680180	664464	297673	287	272	1	-106
680723	663014	290982	258	249	-1	-106
680758	671878	300936	273	255	-27	-145
680862	644686	283489	263	245	41	-68
680865	660659	287723	272	253	22	-74
680888	664846	298300	290	280	-8	-102
681233	662342	290038	267	258	-4	-102

Notes:

WTM-E: Wisconsin Transmercator-East
WTM-N: Wisconsin Transmercator-North
m: meters
m amsl: meters above mean sea level

Source: Wisconsin Geologic and Natural History Survey, 2003, wiscLITH: A digital lithologic and stratigraphic database of Wisconsin Geology, Open-File Report 2003-05, version 2.0.

Table 3. Well data used for structural constraint in 3D model for Fond du Lac County.

State Well ID	WTM-E (m)	WTM-N (m)	Surface Top Elevation (m amsl)	Sediments Top Elevation (m amsl)	Basement Top Elevation (m amsl)
200389	625794	371241	277	272	174
200828	626776	370314	282	277	225
200841	629714	368326	285	275	256
200865	650627	361279	297	274	130
200866	642778	367222	237	229	170
200660	638674	365186	254	240	115
200847	635816	367149	280	259	210
200860	633882	362300	276	271	214
200868	642791	366418	239	223	157
200854	632596	365129	276	274	220
200835	626840	367092	291	283	262
200367	643513	364232	252	205	-30
200664	643500	369262	229	206	29
200375	641775	365064	255	219	-7
200039	644896	370430	229	209	-11
200849	629732	367519	278	276	244
200839	619978	367399	302	292	234
200022	617979	363129	304	300	44

Notes:
WTM-E: Wisconsin Transmercator-East
WTM-N: Wisconsin Transmercator-North
m: meters
m amsl: meters above mean sea level

Source: Wisconsin Geologic and Natural History Survey, 2003, wiscLITH: A digital lithologic and stratigraphic database of Wisconsin Geology, Open-File Report 2003-05, version 2.0.

Table 4. Model fit statistics for southeastern Wisconsin and Fond du Lac County.

Southeastern Wisconsin

Model Run	Density (g/cm^3)	Residual Bouguer Anomaly (mGal)	SD (mGal)	Gravity % SD	Basement Mag. Suscep. ($x10^{-6}$ cgs)	Residual Aeromagnetics Anomaly (nT)	SD (nT)	% SD
2.75-D (No WC)	3.00	21.0	4.33	20.6				
Constant Density (WC)	3.00	21.0	1.32	6.3				
Variable Denisty (WC)	3.00-3.04	21.0	0.94	4.5				
Target Gravity Error				5.0				
2.75-D Surface (No WC)					1000	1847	270.8	14.7
Constant Basement Mag. Suscep. (WC)					1000	1847	270.1	14.6
Variable Basement Mag. Suscep. (WC)					-396 - 1104	1847	169.0	9.1
Variable Basement Mag. Suscep. with mafic bodies (5500)*					-396 - 1104	1847	147.0	8.0
Target Magnetic Susceptibility								10.0

Fond Du Lac County

Model Run	Density (g/cm^3)	Residual Bouguer Anomaly (mGal)	SD (mGal)	Gravity % SD	Basement Mag. Suscep. ($x10^{-6}$ cgs)	Residual Aeromagnetics Anomaly (nT)	SD (nT)	% SD
Well Surface (No WC)	3.00	35.7	7.25	20.3				
Constant Density (WC)	3.00	35.7	3.39	9.5				
Variable Denisty (WC)	2.98-3.07	35.7	0.87	2.4				
Target Denisty				5.0				
Well Surface					1000	1001	172.6	17.2
Constant Basement Mag. Suscep. (WC)					1000	1001	172.0	17.2
Variable Basement Mag. Suscep. (WC)					-554 - 886	1001	113.0	11.3
Variable Basement Mag. Suscep. With mafic bodies (5500)*					-554 - 886	1001	100.0	10.0
Target Magnetic Susceptibility Error								10.0

Notes:

SD: Standard Deviation % SD: Standard Deviation / Anomaly mGal: Milligal nT: Nanotesla
WC: Well constraints

*Mafic bodies assigned constant magnetic susceptibility of 5500 x 10^{-6} cgs, well constaints on basement

Table 5. Comparison of well to model basement elevations for Fond du Lac County.

	Well Log Elevations (m amsl)	3D Model Elevations (m amsl)	Difference in Elevations (m)
Minimum	-93	-117	
Maximum	265	274	
Mean	116	119	-3
Standard Devation	115	101	38
Number of elevations	65	65	65