COUPLED MODELING OF GRAVITY AND AEROMAGNETIC DATA TO ESTIMATE SUBSURFACE BASEMENT TOPOGRAPHY IN SOUTHEASTERN WISCONSIN

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ABSTRACT

We used coupled modeling of gravity and aeromagnetic data to estimate subsurface structure along seven northwest–southeast profiles perpendicular to the Waukesha Fault and one north–south profile (tie line). Study results showed the Waukesha Fault as a high-angle normal fault dipping southeast and having maximum vertical displacement of 560 m. The depth to Precambrian crystalline basement rock southeast of the fault (downthrown block) exceeds the total depth of water wells, with one exception, because of normal vertical displacement. Delineating the basement elevations in this area has implications for addressing geologic and groundwater-resource issues in southeastern Wisconsin. Data from well records constrained basement elevations for the profile parts northwest of the fault on the upthrown block and elevations of the top of the Cambrian Mount Simon Formation on the downthrown block. Only the southernmost profile contained data to constrain the basement elevations on the downthrown block; this profile was used to calibrate density and magnetic susceptibility values for the study. We used basement elevations from the profile models and well records to create a three-dimensional representation of the Precambrian basement surface, which appears complex on both sides of the fault. Comparison of the Precambrian basement surface from this study with a surface based on well record data alone illustrates the benefit of incorporating data from potential fields modeling for the delineation of subsurface structure.

INTRODUCTION

The lithologic units of the Precambrian basement in southeastern Wisconsin consist of granite, slate, and quartzite, which dip gently to the east from the Wisconsin Dome into the Michigan Basin. Mafic intrusions crosscut some of these units. The basement rocks are overlain by Cambrian and Ordovician sandstone and Ordovician and Silurian shale and dolomite. Pleistocene deposits of various thicknesses overlie these rocks. The northeast–trending Waukesha Fault, a prominent geologic structure in the area, has hydrogeologic significance. Jansen and others (2001) determined that the fault appears to be a dividing line for water quality of the sandstone aquifer. They found that levels of total dissolved solids generally increased to the east and with depth, but that no significant changes occurred on the upthrown (northwest) block of the fault; levels of total dissolved solids rose significantly on the downthrown (southeast) block. The fault offset and geometry 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 40º E with an apparent high-angle southeast dip and normal displacement (Sverdrup and others, 1997). Sufficient well record data exist for the upthrown block to determine that the depth to the Precambrian basement ranges from approximately 250 to 600 m below ground surface (Smith, 1978; Feinstein and others, 2004); however, depth to basement on the downthrown block of this normal fault is not well established because of the lack of deep water wells. Thwaites (1940, 1957) inferred the depth to the Precambrian basement in this area as greater than 800 m, with maximum vertical displacement of 450 m across the fault. Eaton and others (1999) presented a contour map of the Precambrian basement surface for southeastern Wisconsin that showed approximately 300 m of vertical offset across the fault. Their map includes the depth to Precambrian basement on the downthrown side of the fault based on a single well record (Nicholas and others, 1987).

Geophysical investigations have added other estimates of the subsurface geometry in the area. A gravity survey in Waukesha County by Brukardt (1983) provided the basis for a Bouguer anomaly map over the fault that was interpreted as a high-angle (70º)

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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. Model results suggested normal offset of the downthrown fault block, ranging from 900 to 1,200 m, and the fault dip toward the southeast ranged from 20° to vertical. Lahr (1995) predicted 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 on the downthrown block 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 85º to 22º for the southern and northern transects, respectively. Sverdrup and others (1997) noted a steep gravity gradient coincident with the northeast-trending fault; gravity values on the upthrown fault block were approximately 10 mGal higher than values on the downthrown block. Gravity models along two profiles across the fault suggested a maximum vertical offset of 500 to 600 m and fault dip to the southeast of 80º for the southern profile and 10º to 20º for the northern profile. Eaton and others (1999) modeled the elevation of the magnetic basement in southeastern Wisconsin in an attempt to supplement scarce well data and concluded that the non-unique solution presented interpretation problems. Preliminary analysis of the Precambrian basement from aeromagnetic data (Mudrey and others, 2001) indicated this area is underlain by a complex Precambrian structural terrane and suggested the prominent northeast-trending aeromagnetic anomaly that corresponds to the Waukesha Fault defines a basement terrane boundary. Results of a detailed east–west gravity profile across the Waukesha Fault by Baxter and others (2002) yielded model estimates of vertical displacement of the Precambrian basement, ranging from 260 m to greater than 600 m, and fault geometry that varied significantly along strike.

Our study is the first to investigate the Precambrian basement topography adjacent to the Waukesha Fault using coupled (simultaneous) modeling of gravity and magnetic data, which minimizes the non-uniqueness problem inherent in potential fields modeling. In addition, we incorporated lithologic data from a single well record (Nicholas and others, 1987), which provided the depth to Precambrian basement on the downthrown side of the fault. The extensive lithologic data from the Wisconsin Geological and Natural History Survey wiscLITH database (2004) provided constraint on the subsurface structure.

METHODS

We used existing gravity, aeromagnetic, elevation, density, magnetic susceptibility, and well record data to construct models along seven northwest–southeast profiles spaced 10 km apart across the Waukesha Fault and one north–south profile that serves as a “tie line” for the other profiles (fig. 1B). The gravity and aeromagnetic data are from compilations by the U.S. Geological Survey (fig. 1C and 1D; Daniels and Snyder, 2002) for the entire state of Wisconsin. They reduced the observed gravity values in relation to the IGSN-71 datum to the Bouguer anomaly using the 1967 gravity formula and a reduction density of 2.67 g/cm^3; they then converted the data to a 1 km grid using minimum curvature techniques. Daniels and Snyder (2002) compiled the Wisconsin aeromagnetic map from 26 surveys with relative uniformity of flight-line spacing (0.5 mi or less) and processed the data to simulate flight altitude of 1,000 ft (305 m) above ground surface. They converted the data to a 250 m grid using a minimum curvature algorithm; we downloaded their grids and sampled along the study profiles at 500 m intervals.

We obtained ground-surface elevations along profiles at 500 m intervals from U.S. Geological Survey 7.5-minute series topographic maps. Well record data were obtained from the Wisconsin Geological and Natural History Survey (via the U.S. Geological Survey) as a digital database that was compiled for constructing the regional groundwater flow model of southeastern Wisconsin (Feinstein and others, 2004). Well records from a total of 41 wells that reach the Precambrian basement or the overlying Cambrian Mount Simon Formation were used in this study (table 1; fig. 1B) for vertical control of model blocks. Wells were projected perpendicular to the nearest profile. The log from a single U.S. Geological Survey test well in Zion, Illinois (Nicholas and others, 1987), includes the only depth to the Precambrian basement on the downthrown block of the Waukesha Fault, providing constraint on the subsurface structure along the southernmost profile (profile A–A'). Thus, the model for profile A–A' was constructed first to select appropriate density and magnetic susceptibility information for the study area. Initial density and magnetic susceptibility data were obtained from a state compilation (Dutch and others, 1994) and a number of local studies (Brukardt, 1983; Moll, 1987; Lahr, 1995; Sverdrup and others, 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' because the depth to the Precambrian basement is known on both sides of the

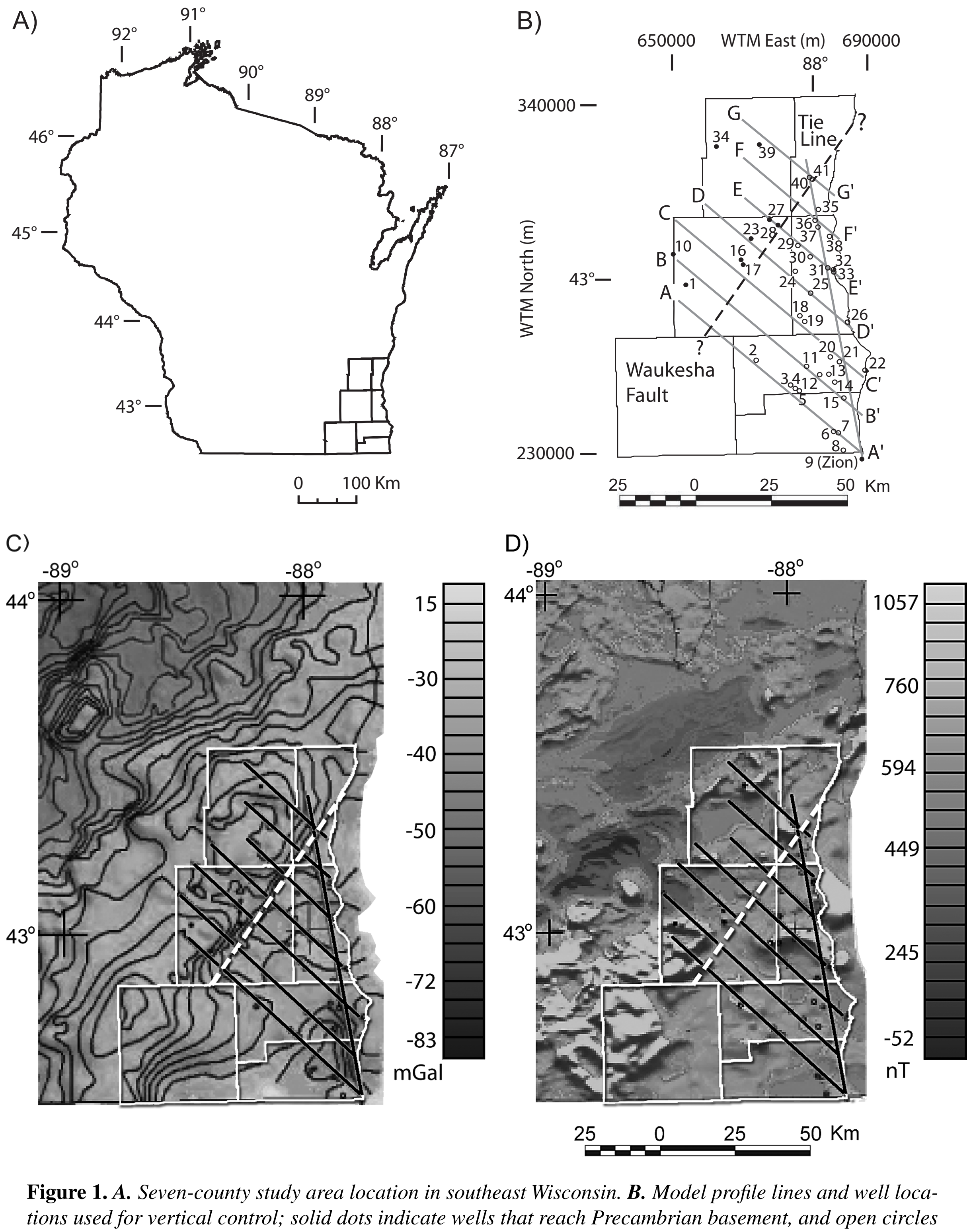


Figure 1. ***A.*** *Seven-county study area location in southeast Wisconsin.* ***B.*** *Model profile lines and well locations used for vertical control; solid dots indicate wells that reach Precambrian basement, and open circles indicate wells that reach Cambrian Mount Simon Formation. Dashed line is Waukesha Fault. See table 1 for data associated with numbered locations. Complete Bouguer anomaly map* ***(C)*** *and residual aeromagnetic map* ***(D)*** *show data used for model profiles along with county boundaries, profile lines, and well locations. Bouguer anomaly and residual aeromagnetic maps were modified from Daniels and Snyder (2002).*

Table 1. Well data (from Wisconsin Geological and Natural History Survey, 2004) used for vertical control in 2.75-dimensional forward models. NA: no data available.

Number on fig. 1	Profile line	wiscLITH well record	WTM-E[1] (m)	WTM-N[2] (m)	Surface elevation (m above mean sea level)	Glacial deposits bottom depth (m)	Mount Simon Fm. top depth (m)	Basement top depth (m)
1	A–A'	680862	644686	283489	263	96	223	331
2	A–A'	520351	666144	256748	252	30	334	
3	A–A'	520066	677062	248743	260	79	349	
4	A–A'	520376	678789	247635	248	49	343	
5	A–A'	520349	680091	246803	241	40	340	
6	A–A'	300274	691246	233692	223	52	401	
7	A–A'	300012	692748	233254	210	44	389	
8	A–A'	300301	694479	227429	220	54	438	
9	A–A'	Zion	698600	227300	180	36	500	1,047
10	B–B'	680020	640886	293445	269	52	223	235
11	B–B'	520354	682491	254858	217	40	352	
12	B–B'	520359	686799	252190	242	32	395	
13	B–B'	520017	692035	249808	220	48	453	
14	B–B'	520005	691689	249752	223	43	448	
15	B–B'	300006	694629	244471	195	30	366	
16	C–C'	680028	659494	289673	274	15	276	363
17	C–C'	680865	660658	287722	272	18	250	346
18	C–C'	410548	680300	271306	241	42	409	
19	C–C'	410400	681872	269383	233	42	373	
20	C–C'	520053	690244	257953	229	33	381	
21	C–C'	520350	693131	256262	220	40	355	
22	C–C'	520023	701819	253473	181	21	479	
23	D–D'	680180	664463	297673	287	9	287	393
24	D–D'	410321	678828	285770	223	23	314	
25	D–D'	410440	683864	278631	242	58	345	
26	D–D'	410332	695943	269224	206	58	404	
27	E–E'	670909	670428	304391	266	8	332	419
28	E–E'	680004	673081	302714	268	8	297	415
29	E–E'	410482	679709	293899	223	41	335	
30	E–E'	410286	683629	290350	238	46	415	
31	E–E'	410057	689358	286899	179	67	393	
32	E–E'	410052	690980	286141	178	58	372	
33	E–E'	410299	691189	285441	178	63	369	
34	F–F'	670920	654139	328150	303	17	NA	218
35	F–F'	460073	686386	305867	204	58	387	
36	F–F'	410431	685240	302265	205	163	384	
37	F–F'	410007	686259	300074	212	30	383	
38	F–F'	410341	689914	296861	196	56	395	
39	G–G'	670009	667386	325522	277	58	NA	284
40	G–G'	460016	683534	315985	242	4	343 (E)[3]	
41	G–G'	460018	684347	315744	239	13	343 (E)[3]	

[1] Wisconsin Transverse Mercator East

[2] Wisconsin Transverse Mercator North

[3] Wells only reach the top of the Eau Claire

fault. A summary of this study's and published density and magnetic susceptibility data is given in table 2.

Coupled 2.75-dimensional forward modeling of gravity and aeromagnetic data was performed using the commercially available modeling program GM-Sys® (by Northwest Geophysical Associates) based on Talwani and others (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 configuration, density, and magnetic properties were made to minimize the root mean square error (RMSE) between observed and calculated gravity and aeromagnetic anomalies. Because GM-Sys calculates the modeled gravity and aeromagnetic anomalies simultaneously in real time, the modeler endeavors to achieve the smallest RMSE possible for both techniques by adjusting block shapes after settling on acceptable density and magnetic properties.

Experience from previous coupled modeling of aeromagnetic and gravity data (Skalbeck, 2001; Skalbeck and others, 2005) suggested that models were judged acceptable when the percentage of RMSE (%RMSE [RMSE/anomaly range]) was below 5 percent for gravity and below 10 percent for aeromagnetic data. A summary of model best-fit statistics for each profile is given in table 3.

RESULTS AND DISCUSSION

2.75-dimensional models of selected profiles

Some mafic bodies that were not documented in the well record data used in this study were included in the geologic model for the profiles to match observed aeromagnetic anomalies. Initial models were constructed without these bodies, but no reasonable combination of physical properties and model configuration could be found to simultaneously match gravity and aeromagnetic data. Moll (1987) included subsurface mafic bodies to yield reasonable model anomalies for profiles across the Waukesha Fault, and Sverdrup and others (1997) had included gabbro in models to account for gravity and magnetic highs attributed to mafic rock at depth. We found that mafic bodies were needed in this study to achieve acceptable fit between model and observed anomalies.

Due to the higher density and magnetic susceptibility values and to the greater volume of the model blocks representing Precambrian basement and mafic bodies in relation to overlying sedimentary and glacial deposits, the crystalline rocks contribute most of the model anomalies. Qualitative sensitivity analysis indicated that the Precambrian basement and mafic bodies significantly influence the gravity and aeromagnetic anomalies. Adjustments in physical property values and model configuration of the crystalline model

Table 2. Density and magnetic susceptibility data from previous work and this study; cgs: centimeter-gram-second; NA: not available or applicable.

		Density (g/cm^3)					Magnetic susceptibility (x 10^{-6}cgs)		
Geologic unit	Model symbol	Brukardt (1983)	Dutch and others (1994)	Lahr (1995)	Sverdrup and others (1997)	This study	Dutch (1994)	Moll[1] (1987)	This study
Lake Michigan		NA	NA	NA	1.00	1.00	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
Maquoketa		2.70	2.54 – 2.74	2.63	NA	2.63	79 – 108	0	100
Sinnipee		NA	2.51 – 2.84	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
Trempealeau		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
Mount Simon		2.67	2.58	2.45	2.60	2.58	16 – 125	0	100
Precambrian basement		3.00	2.63 – 2.74	2.60 – 3.30	2.69	2.77 – 3.02	44 – 3489	200	1000
Mafic bodies[2]		NA	NA	2.71 – 3.04	3.00	3.00 – 3.05	91 – 2713	6000	3000
Fault zone		NA	NA	NA	NA	2.22 – 2.82	NA	NA	100 – 1000

[1] Moll (1987) modeled sedimentary formations as a single unit.

[2] Remanent magnetism properties include magnetic intensity 2000 x 10^{-6}cgs

Table 3. Model best fit statistics for Waukesha Fault area, southeastern Wisconsin. RMSE: root mean square error; %RMSE: RMSE/anomaly; mGal: milligal; nT: nanoTesla.

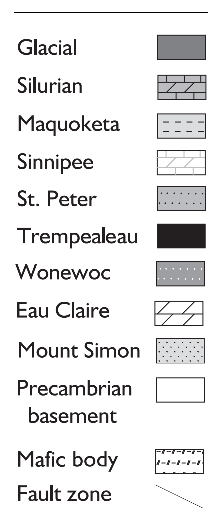
	Complete Bouguer residual gravity				Residual aeromagnetics			
Profile	Range (mGal)	Anomaly (mGal)	RMSE (mGal)	%RMSE	Range (nT)	Anomaly (nT)	RMSE (nT)	%RMSE
Line A–A'	-31.9 – -52.1	20.2	0.69	3.4	354–1742.8	1389	127.6	9.2
Line B–B'	-32.8 – -49.7	16.9	0.36	2.1	-94–1675	1769	106.7	6.0
Line C–C'	-39.3 – -49.1	9.8	0.23	2.3	71–951	880	55.5	6.3
Line D-D'	-37.0 – -48.1	11.1	0.52	4.7	264–1229	965	94.1	9.8
Line E–E'	-35.5 – -50.5	15.0	0.49	3.3	445–1341	896	73.0	8.1
Line F–F'	-32.5 – -44.9	12.4	0.42	3.4	338–1040	702	54.8	7.8
Line G–G'	-31.8 – -45.4	13.6	0.33	2.4	426–1141	715	69.5	9.7
Tie line	-35.6 – -50.3	14.7	0.39	2.7	391–1107.2	716	67.8	9.5
Target value for %RMSE				5.0				10.0

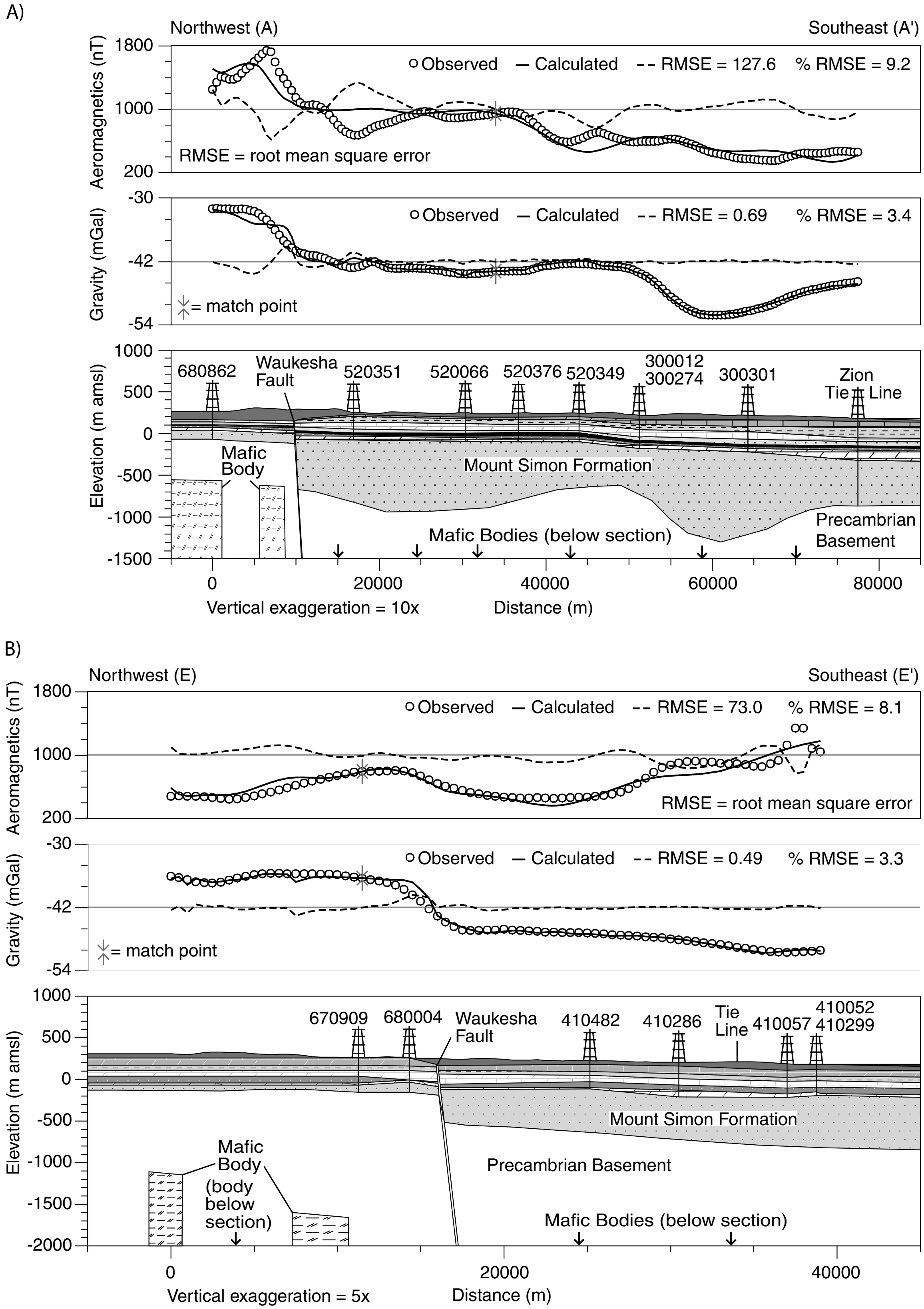
blocks have significantly greater effect on model anomalies than changes with the sedimentary and glacial deposits model blocks.

Figure 2 shows two of the eight modeled profiles (profiles A–A' and E–E'). Note the difference in scale and vertical exaggeration between the two profiles. Profile A–A' (fig. 2A) crosses the Waukesha Fault at the southernmost extent of the study area and represents the best constrained model. Good model fits for gravity (%RMSE = 3.4) and aeromagnetic data (%RMSE = 9.2) were obtained for this profile. Excellent vertical geologic control data were provided from nine wells, including the only well (Zion) within the study area that reaches the Precambrian basement on the downthrown (southeast) block of the fault. The Waukesha Fault is represented as a 100 m wide zone that dips 60º toward the southeast. The part of the fault adjacent to sedimentary units has a density of 2.22 g/cm^3 and magnetic susceptibility of 100 x 10^{-6} centimeter-gram-second (cgs); the part adjacent to Precambrian basement units has a density of 2.82 g/cm^3 and magnetic susceptibility of 1,000 x 10^{-6} cgs (table 2). Modeling results from Skalbeck (2001) suggested that rocks within major fault zones may have altered density and magnetic properties relative to the host rocks. 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 0 x 10^{-6} cgs. The density and susceptibility values for glacial, sedimentary, and Precambrian basement and mafic intrusive units are also provided in table 2.

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 upthrown fault block, but the bottom of this unit (top of Precambrian basement) is estimated from the model results on the downthrown block. Depth to the Precambri-

▶ **Figure 2.** ***A.*** *Profile A–A', showing 2.75-dimensional model for southern extent of study area.* ***B.*** *Profile E–E', showing 2.75-dimensional model for northern part of study area. The upper section of each profile shows the aeromagnetic data; the center section, the gravity data. In each section, open circles represent the observed data; the solid line indicates the model-calculated anomaly. The dashed line represents the deviation between the observed and calculated data, and distance from the horizontal gray line indicates greater error. Cumulative error of the model is indicated by the RMSE value. The lower section of each profile illustrates the geologic model; the horizontal distance is relative to the northwest end of the profile, and elevation is above or below mean sea level. Geologic unit categories were modified from the groundwater model layers used by Feinstein and others (2004). nT: nanoTesla.*




A)
Northwest (A)
Southeast (A')
Aeromagnetics (nT)
1800
1000
200
Observed
Calculated
RMSE = 127.6
% RMSE = 9.2
RMSE = root mean square error
Gravity (mGal)
-30
-42
-54
Observed
Calculated
RMSE = 0.69
% RMSE = 3.4
= match point
Elevation (m amsl)
1000
500
0
-500
-1000
-1500
680862
Waukesha Fault
520351
520066
520376
520349
300012
300274
300301
Zion Tie Line
Mafic Body
Mount Simon Formation
Precambrian Basement
Mafic Bodies (below section)
0
20000
40000
60000
80000
Vertical exaggeration = 10x
Distance (m)
B)
Northwest (E)
Southeast (E')
Aeromagnetics (nT)
1800
1000
200
Observed
Calculated
RMSE = 73.0
% RMSE = 8.1
RMSE = root mean square error
Gravity (mGal)
-30
-42
-54
Observed
Calculated
RMSE = 0.49
% RMSE = 3.3
= match point
Elevation (m amsl)
1000
500
0
-500
-1000
-1500
-2000
670909
680004
Waukesha Fault
410482
410286
Tie Line
410057
410052
410299
Mount Simon Formation
Mafic Body (body below section)
Precambrian Basement
Mafic Bodies (below section)
0
20000
40000
Vertical exaggeration = 5x
Distance (m)

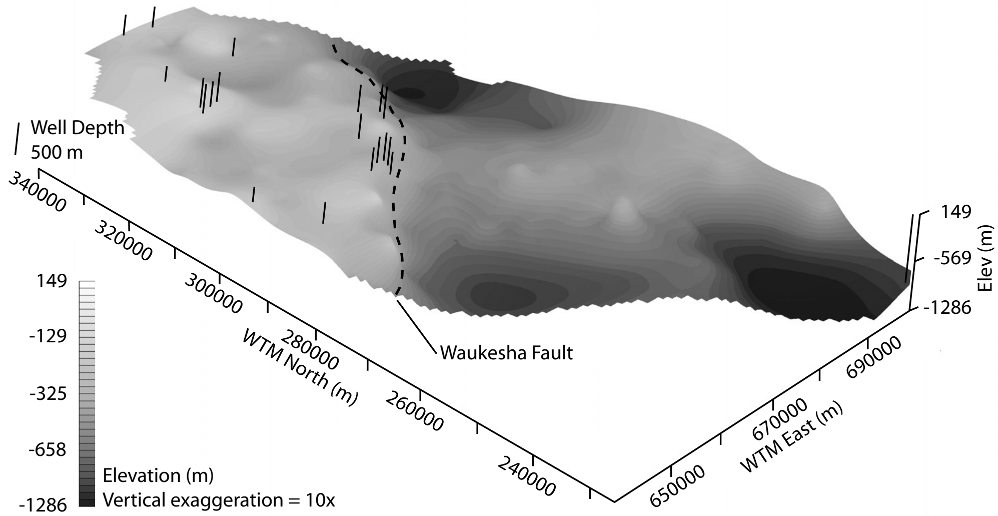


Figure 3. *Precambrian basement elevation surface obtained from model profile and well record elevations. View from southwest (S 45°E) at 30° above horizon. Wells represented by vertical bars; length of bars indicates depth to basement. Elevations are above or below mean sea level.*

an basement on the upthrown block was documented at 331 m below ground surface (bgs) in wiscLITH well record 680862 and was modeled at approximately 890 m on the downthrown block adjacent to the fault. This model yielded a normal vertical displacement of approximately 560 m; most of the displacement was within the Cambrian Mount Simon Formation. Well data indicated vertical displacement of 120 to 130 m for the Cambrian Eau Claire, Wonewoc, and Trempealeau Formations and 30 m for the Ordovician Sinnipee and St. Peter Formations. The maximum depth to basement within the study area was modeled at 1,520 m bgs along this profile near wiscLITH well 300301. The model indicates a significant depression in the basement surface; this area has local relief of 470 m, in contrast to the documented depth at the Zion well and of 660 m for the modeled ridge beneath wiscLITH well 300274. A second depression between wiscLITH wells 520351 and 520066, modeled with a maximum depth of 1,200 m bgs, shows relief of 270 to 315 m for the fault and model ridge, respectively. Two mafic bodies with densities of 3.01 g/cm^3, magnetic susceptibility of 3,000 x 10^{-6} cgs, and remanent magnetism with reverse polarity (declination = 270°, inclination = -45°, intensity of 2,000 x 10^{-6} cgs) were modeled on the upthrown fault block at depths of 900 and 1,000 m bgs. Six mafic bodies on the downthrown fault block (not shown in fig. 2A because of the depth) were modeled at depths of 4,000 to 5,000 m with the same magnetic properties, but with densities of 3.00 to 3.03 g/cm^3.

Profile E–E' (fig. 2B) crosses the northern part of the Waukesha Fault, where a good fit for gravity (%RMSE = 3.3) and for aeromagnetic data (%RMSE = 8.1) was obtained for this model. Data from seven wells provided vertical geologic control for the profile. Two wells on the upthrown fault block document the depth to Precambrian basement at 415 and 419 m bgs, but the four wells on the downthrown fault block do not reach the basement. Model results yielded normal vertical displacement of 340 m of the Precambrian basement. Unlike the undulating surface modeled in profile A–A', the modeled basement surface in profile E–E' gently slopes to the east. The depth to basement adjacent to the fault is modeled at 765 m bgs and at 1,000 m bgs beneath wiscLITH well 410299, which is approximately 20,000 m southeast of the fault. Two mafic bodies with densities of 3.00 and 3.01 g/cm^3, magnetic susceptibility of 3,000 x 10^{-6} cgs, and reverse polarity remanent magnetism (declination = 270°, inclination = -45°, intensity of 2,000 x 10^{-6} cgs) were modeled on the upthrown fault block at depths of 1,400 and 1,900 m bgs. Another mafic body on the upthrown fault block was modeled at a depth of 3,000 m (not shown in fig. 3B because of the depth) with the same magnetic properties, but with density of 3.02 g/cm^3. On the downthrown block, two mafic bodies were modeled at depths of 3,000 and 4,000 m (not shown in fig. 3B because of the depth) with the same magnetic properties, but with densities of 3.01 and 3.02 g/cm^3.

Table 4. Well data used for Precambrian basement elevation surface.

wiscLITH well record	WTM-E[1] (m)	WTM-N[2] (m)	Surface elevation (m above mean sea level)	Basement top depth (m)	Basement top elevation (m above or below mean sea level)
Wells used for vertical control on profiles and for basement surface elevation					
680862	644686	283489	263	331	-68
Zion	698600	227300	180	1047	-867
680020	640886	293445	269	235	34
680028	659494	289673	274	363	-89
680865	660658	287722	272	346	-74
680180	664463	297673	287	393	-106
670909	670428	304391	266	419	-153
680004	673081	302714	268	415	-147
670920	654139	328150	303	218	85
670009	667386	325522	277	284	-7
Wells used for basement surface elevation					
680027	661765	291564	259	401	-142
680723	663014	290982	324	431	-106
680758	671878	300936	344	489	-145
680888	664846	298300	364	467	-102
681233	662342	290038	336	438	-102
670006	653879	317482	473	390	84
670008	663293	340505	292	318	-25
670012	651668	316710	594	450	144
670013	652244	317752	597	453	145
670034	655188	317877	604	455	149

[1] Wisconsin Transverse Mercator East
[2] Wisconsin Transverse Mercator North

Precambrian basement topography

Figure 3 illustrates the model top of the Precambrian basement elevation obtained from the 2.75-dimensional coupled model of gravity and aeromagnetic elevations along eight profiles, extracted at 500 m intervals, and elevations from 20 wells (table 4). The top of basement elevations ranges from 149 m above mean sea level in the northern part of the study area (Wisconsin Transverse Mercator [WTM] North 320000 m, WTM East 650000 m) to 1,286 m below mean sea level in the southeast part of the study area (WTM North 240000 m, WTM East 690000 m). We interpreted the prominent southwest–northeast trending drop in basement surface elevation 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 basement surface shows some moderate undulations on the upthrown block and major undulations on the downthrown block. An elevated area was modeled on the downthrown block centered near WTM North 250000 m and WTM East 660000 m. This may represent a small upthrown fault sub-block within the primary downthrown block or may be a result of deep erosion of two nearly parallel valleys.

For comparison, figure 4A shows the Precambrian basement elevation surface from this study as a contour map; figure 4B is the contour map from Eaton and others (1999) based on well record data. Delineation of the Waukesha Fault and the surface of the upthrown (northwest) fault block are similar. The lack of detail for the downthrown (southeast) fault block surface is obvious in the Eaton and others (1999) map because the surface is based on a single elevation point from the Zion well. Our map illustrates the additional resolution of the Precambrian basement surface for the downthrown block that has been added on the basis of the coupled modeling of gravity and aeromagnetic data. Because the Precambrian basement serves as the base of the overlying

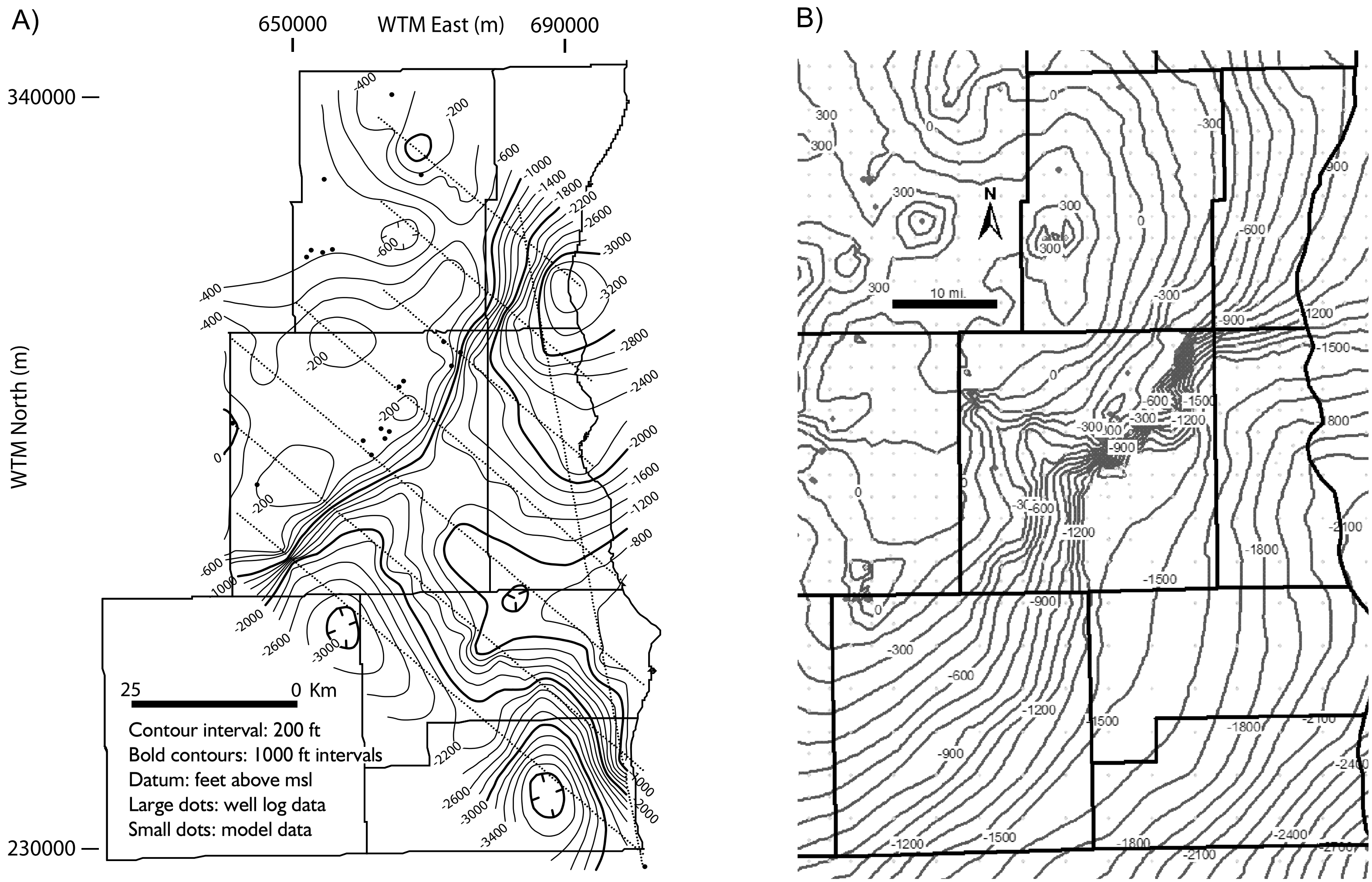


Figure 4. *Contour maps of Precambrian basement elevation surface from **(A)** this study and **(B)** modified from Eaton and others (1999). (Elevations on our map [A] are shown in feet instead of meters to facilitate comparison with the previously published map [B] and are above or below mean sea level.)*

Mount Simon Formation, which is the lower part of an important sandstone aquifer system in southeast Wisconsin, the added detail of the basement surface from this study could provide critical information for future study of this system.

CONCLUSIONS

The Waukesha Fault was modeled in this study as a high-angle normal fault dipping to the southeast; however, the gravity error associated with the location of the fault suggests that a shallower dip angle is possible. Model topography of the Precambrian basement elevation surface appears undulated on both sides of the fault, with more relief on the downthrown fault block. Reasonable estimates of the elevations of the top of the basement southeast of the fault have been obtained from this study. The well record data used in this study support the model results of Sverdrup and others (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 Sverdrup and others (1997) results of between 500 and 600 m of vertical displacement. Although the Waukesha Fault was modeled as a geologic unit with constant dip of 60° for each of the profile models, the Precambrian basement model topography gradient on the downthrown fault block along some profile models appears to gradually shallow. Thus, the model structure could alternatively be interpreted as a listric-type fault.

Coupled modeling of gravity and aeromagnetic data provides non-unique solutions because 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 basement, and increasing the depth to basement could produce a computed field similar to the previous configuration. Input of published density and magnetic susceptibility data and subsurface geology from well records greatly constrains possible interpretations of the subsurface structure in southeast Wisconsin; however, other interpretations of the structure do exist.

Results from this study provide an excellent data set for the Precambrian basement configuration. Researchers working on groundwater-management issues (such as arsenic contamination, excessive drawdown, increasing salinity, and so forth) in southeast Wisconsin may find the results of this study useful. In addition, these results may be of interest to researchers working on structural and tectonic models for the region. Coupled modeling of gravity and aeromagnetic data can be applied to other 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 from well records, but have not been able to construct a reasonable three-dimensional model of this surface due to the paucity of point data. Because of the excellent statewide compilation of gravity and aeromagnetic data for Wisconsin, a well constrained three-dimensional model of Precambrian basement topography is obtainable not only for the Fond du Lac area, but for almost anywhere in the state.

ACKNOWLEDGMENTS

Funding was provided by the Wisconsin Groundwater Research Program through the University of Wisconsin Water Resources Institute, grant number R/UW-HDG-007 (WR03R003). We give special thanks to David J. Hart of the Wisconsin Geological and Natural History for providing the suggestion to pursue the study and Daniel T. Feinstein of the U.S. Geological Survey for providing the well record database and many helpful discussions. Thanks also to undergraduate students Jamie Lambert, Adrian Koski, and Stephan Kurdas for their important contributions. Lastly, we appreciate the helpful comments and suggested changes of the reviewers William Kean, David J. Hart, David L. LePain, and Thomas J. Evans.

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