Groundwater Research Report
WR17R003

Mapping the base of the Cambrian aquifer through geophysical modeling of Precambrian topography, southern Wisconsin

PI: Esther K. Stewart, Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension

Co-PI: Madeline Gotkowitz, Montana Bureau of Mines and Geology, work completed while at the Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension

Project Assistants: Joseph Rasmussen, University of Wisconsin-Parkside; John Skalbeck, University of Wisconsin-Parkside; Latisha Brengman, University of Minnesota-Duluth

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Administered by:
University of Wisconsin Water Resources Institute

Funded by:
State of Wisconsin Groundwater Research and Monitoring Program

2018

This project was also supported, in part, by General Purpose Revenue funds of the State of Wisconsin to the University of Wisconsin System for the performance of research on groundwater quality and quantity. Selection of projects was conducted on a competitive basis through a joint solicitation from the University and the Wisconsin Departments of Natural Resources; Agriculture, Trade and Consumer Protection; Commerce; and advice of the Wisconsin Groundwater Research Advisory Council and with the concurrence of the Wisconsin Groundwater Coordinating Council.

Mapping the base of the Cambrian aquifer through geophysical modeling of Precambrian topography, southern Wisconsin

Project Completion Report

By

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Project Summary

Title:	Mapping the base of the Cambrian aquifer through geophysical modeling of Precambrian topography, southern Wisconsin
Project ID:	WR17R003
Co-Investigators:	Esther K. Stewart, Assistant Professor, Department of Environmental Sciences, Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension Dr. Madeline B. Gotkowitz, Professor, Department of Environmental Sciences, Wisconsin Geological and Natural History Survey, now at Montana Bureau of Mines and Geology
Project Assistants:	Joseph Rasmussen, undergraduate student hourly, Department of Geosciences, University of Wisconsin-Parkside George Segee-Wright, limited term employee, Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension
Period of Contract:	*July 1, 2017 – June 30, 2018*

Background/ need: Wisconsin's "sandstone aquifer", composed of Cambrian-age sandstone and dolomite formations, extends over most of the state, serving as the principal bedrock aquifer for large portions of southern and western Wisconsin. This aquifer also supplies groundwater to many high-capacity wells in eastern Wisconsin that extend below the Maquoketa aquitard. The lower boundary to this groundwater system is the Precambrian basement. Basement topography exerts strong control on aquifer thickness, the volume of groundwater stored in the system, and the geometry of a "no-flow" boundary to the aquifer. Accurate interpretation of the aquifer thickness supports assessment of the effects of pumping on groundwater levels and surface water features, as well as simulations of well-head protection areas. Additionally, in regions where nitrate exceedances limit the potability of shallow groundwater, efforts to find low-radium groundwater in the deeper sandstone aquifer are of increasing importance. However, published maps of the Precambrian basement rely heavily on the relatively few drill hole locations where the Precambrian surface elevation is known. The existing Precambrian topographic map of southern Wisconsin (Smith, 1978) is based on outcrop and well data but does not incorporate geologic detail evident in available gravity and aeromagnetic data.

Objectives: Produce a geologically reasonable interpretation of Precambrian basement topography across southern Wisconsin through modeling of existing gravity, aeromagnetic, and well data. Display results in map format at a minimum scale of 1:100,000. Provide map and accompanying report through the Wisconsin Geological and Natural History Survey (WGNHS) in PDF and GIS format.

Methods: Coupled 2-dimensional modeling of existing gravity and aeromagnetic data was performed using the GM-SYS 3D modeling software between July, 2017—June, 2018. Seven models were constructed: Five extend north-south and one extends east-west across Columbia County, WI. A Precambrian geologic map and cross-sections were constructed based on existing drill hole and outcrop data, and geologic units were assigned density and magnetic properties from new measurements and the literature. Petrographic and geochemical analysis of geologic units with iron formation and slate lithology constrained the Precambrian geologic map units and cross-sections. The geometry and geophysical properties of modeled geologic units were adjusted to yield acceptable fits between the observed and calculated gravity and aeromagnetic anomalies. Elevations were extracted along model profiles and incorporated with outcrop, well, and drill hole data to grid a 3-dimensional Precambrian bedrock elevation surface.

Results and Discussion: All models have acceptable fits between observed and modeled gravity and aeromagnetic anomalies. New magnetic susceptibility measurements augment published data for Wisconsin and provide model constraint specific to geologic units that underlie the study area. Petrographic and geochemical analyses of the iron formation and underlying slate constrain the detailed mineralogy of those geologic units. Drill hole, gravity, and aeromagnetic anomaly data indicate a consistent change in Precambrian rock properties across a linear, steeply-dipping, southwest-northeast-striking structure. Precambrian elevations extracted along model profiles and from Precambrian outcrop range from -165 to 448 meters relative to sea level, highest in the Baraboo Hills, and lowest in east-central Columbia County. We are working to make the updated Precambrian topographic surface digitally through the WGNHS website.

Conclusions/ Implications/ Recommendations: Coupled modeling of gravity and aeromagnetic data refines the type and distribution of Precambrian units in the subsurface of Columbia County. Significantly, modeling suggests a Precambrian fault bisects Columbia County from southwest- northeast with slightly older Precambrian units present to the north, and higher-density units present at depth mostly on the south side of the structure. This fault likely extends northeast through northwestern Dodge County and into Fond du Lac County, where it may control variation in Precambrian topography near the city of Waupun and south of Lake Winnebago. We recommend additional coupled gravity and aeromagnetic modeling to constrain Precambrian geology and topography underlying Fond du Lac and Dodge Counties. Joe Rasmussen is presently employed (July 2018- 2019) at the WGNHS to develop these models as part of his graduate work at UW-Madison.

Related Publications:

Rasmussen.J, Skalbeck, J., and Stewart, E. K., 2018, Modeling the Precambrian topography of Columbia County, Wisconsin using two-dimensional models of Gravity and Aeromagnetic data and Well Construction Reports, North Central Geological Society of America Abstracts with Program, v 50.

Rasmussen, J., Stewart, E.K., Skalbeck, J., and Gotkowitz, M., 2018, Modeling the Precambrian topography of Columbia County, Wisconsin using two-dimensional models of gravity and aeromagnetic data and well construction reports, 64TH Institute on Lake Superior Geology Proceedings, V. 64, Part 1, Program and Abstracts, p. 83-84.

Stewart, E,K, Skalbeck, J., Rasmussen, J., Gotkowitz, M., Brengman, L., and Segee-Wright, G., 2018, Developing a geologic framework for aquifer geometry through modeling of gravity and aeromagnetic data, American Water Resources Association Wisconsin Section Annual Meeting, Appleton, WI.

Key Words: aeromagnetic, gravity, modeling, Cambrian aquifer, Precambrian geology

Funding: This project was funded by the State of Wisconsin Groundwater Research and Monitoring Program through the University of Wisconsin Water Resources Institute (WRI).

Introduction

Groundwater is used almost exclusively for water supply in Columbia, Dodge, and Fond du Lac counties, Wisconsin (Figure 1). Elevated nitrate levels impair shallow groundwater quality across much of this region, with private water wells exceeding the 10 mg/L safe drinking water standard at rates of 8% in Fond du Lac, 11% in Dodge, and about 20% in Columbia County (http://wi.water.usgs.gov/gwcomp/). However, in many communities in this region, wells completed deeper in the Cambrian sandstone aquifer yield groundwater with naturally-occurring combined radium activity exceeding the drinking water standard of 5 pCi/L. In a study of saline groundwater across eastern Wisconsin, Ryling (1961) attributed elevated levels of sulfate and chloride found in Fond du Lac and Dodge Counties to the presence of "subsurface ridges" in the Precambrian basement surface. Weaver and Bahr (1991) hypothesized that these features in the subsurface form stagnation zones where the aquifer contains syndepositional connate water that is elevated in radium. Thus, accurate mapping of Precambrian basement topographic relief promises to improve understanding of the spatial distribution of radium-enriched water. In regions where nitrate exceedances limit the potability of shallow groundwater, efforts to find low-radium groundwater in the deeper sandstone aquifer are of increasing importance. Furthermore, accurate interpretation of the aquifer thickness aids in assessing effects of pumping on groundwater levels and surface water features, and it improves the accuracy of model-simulated well-head protection areas.

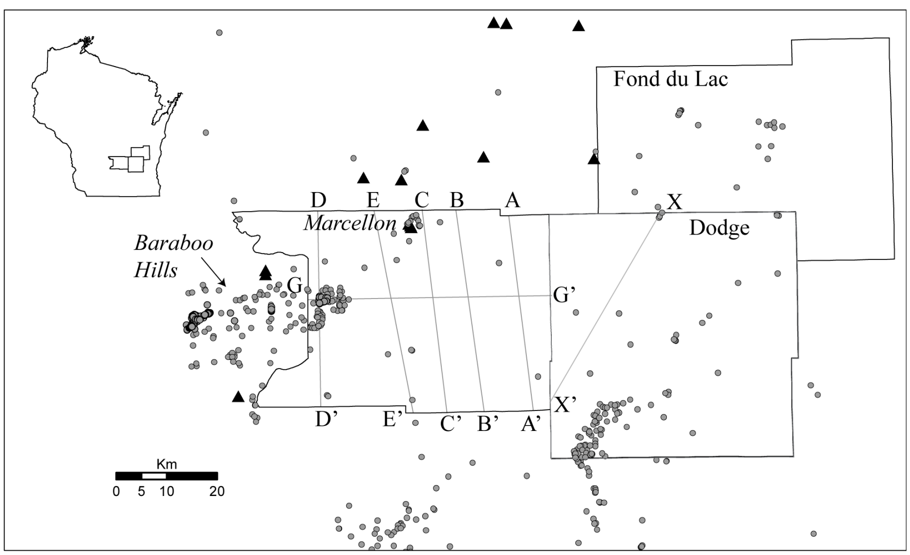

Figure 1. Inset map locates the study area within Wisconsin. A-A' through G-G' locate model profiles within Columbia County. X-X' locates the cross section shown in Figure 2. Quartzite outcrops in the area of the Baraboo Hills. Black triangles indicate 1.75 Ga igneous outcrops, including near Marcellon. Gray circles show wells and drill holes that end in Precambrian rocks.

Precambrian topography underlying the study area is controlled by Precambrian lithology and structure. The Precambrian surface here comprises ca. 1.75 billion-year old (Ga) granite, rhyolite, and diorite that are nonconformably overlain by quartzite, slate, and iron formation of the < 1.7 Ga Baraboo-interval metasediments (Smith, 1978, Stewart et al., 2018). These granites, rhyolites, and metasediments were folded into km-scale folds and faulted, perhaps during the ca. 1.63 Ga Mazatzal orogenic event and at 1.4 Ga related to emplacement of the eastern granite-rhyolite province (Figure 3; Bickford et al., 2015, Stewart et al., 2016, Schwartz et al. 2018). Locally, the metasediments were intruded probably at about 1.47 Ga during emplacement of the Wolf River batholith (Keen, 1994). Precambrian rocks were uplifted and exposed preferentially along folds and faults, and then variably eroded for some 900 million years to produce topography on the Precambrian surface. Ongoing bedrock geologic mapping in Dodge County by the WGNHS demonstrates that the overlying Cambrian Elk Mound Group sandstone infills undulations on the Precambrian surface, resulting in thickness variation of the Elk Mound Group of greater than 300 feet across a distance of less than 2 miles (Figure 2). Relief on the Precambrian surface is the dominant control on thickness variation of the overlying Cambrian sandstone in south-central Wisconsin.

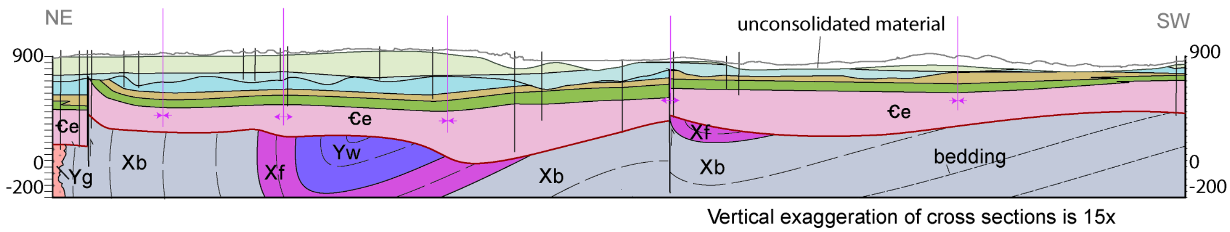

Figure 2. Cross section X-X' of bedrock geology underlying Dodge County developed as part of ongoing bedrock mapping in Dodge County by WGNHS. Figure 1 shows location. Red vertical lines indicate anticline and syncline axes. Vertical thin black lines indicate drill hole control. Thick vertical black lines indicate faults. Xb: Precambrian Baraboo Quartzite; Xf: Precambrian Freedom Formation; Yw: Precambrian Waterloo Quartzite; Yg: Precambrian granite rhyolite province; Ce: Cambrian Elk Mound Group. Younger Cambrian and Ordovician units are indicated by colored layers overlying the Elk Mound Group.

This study uses simultaneous modeling of gravity and aeromagnetic anomaly data to investigate Precambrian geology and topography underlying Columbia County. Modeling is constrained by Precambrian outcrops in the Baraboo Hills and near the town of Marcellon, in western and north-central Columbia County, respectively, as well as well and drill hole records (figure 1).

Procedures and methods

Coupled (simultaneous) forward modeling of gravity and aeromagnetic data was performed using the GM-SYS 3D modeling software. A three-dimensional model was constructed with model layers of ground surface, top of bedrock, and top of Precambrian. Two-dimensional model profiles were extracted from the three-dimensional model. Geologic cross-sections were constructed along each profile to a depth of 5,000 feet (1524 meters) below sea level based on the preliminary Precambrian geologic map of Stewart et al. (2016), aeromagnetic anomaly patterns, wells, drill holes, and outcrops. Geologic units shown in cross-section were modeled as separate bodies and assigned density and magnetic susceptibility values based on existing and new measurements (Table 1; Dutch et al., 1997, this study). Body geometry, density, and magnetic properties were iteratively adjusted to minimize the root mean square error (RMSE) between observed and calculated gravity and aeromagnetic anomalies with targets of less than 5% RMSE for gravity and less than 10% RMSE for aeromagnetic models. Elevations for the modeled top of Precambrian surface and corresponding X,Y coordinates were extracted along each model profile and incorporated with well, drill hole, and outcrop data to refine the Precambrian elevation surface. The Precambrian elevation surface along each profile was digitized by creating a distinct surface along the contact between the uppermost Precambrian body and the overlying strata. Points were digitized on a 1000 m interval on all profiles and then exported to a database containing well, drill hole, and outcrop data. The data was gridded with a 1000 m cell size using a kriging algorithm due to the clustered nature of the sample points.

To construct the models, aeromagnetic and gravity data were subset from the Wisconsin magnetic and gravity compilations (Figure 3; Daniels and Snyder, 2002, Snyder et al., 2004). The Wisconsin state-wide aeromagnetic survey was compiled from 26 separate aeromagnetic surveys by the U.S. Geological Survey in 2002. The composite survey was regridded to produce a grid cell size of 250 m using minimum curvature interpolation with a draped survey with a flight elevation of 304.8 m (1000 ft) above the surface. Gravity data was sampled from two separate surveys conducted between 1999 and 2001 by the U.S. Geological Survey and Northern Illinois University. Gravity values were reduced using the 1967 Geodetic Reference System, referenced to the IGSN-71 gravity datum, and reduced to Bouguer anomaly using a reduction density of 2.67 g/cm^3. A grid of this gravity anomaly data with a grid cell size of 250 m was created using minimum curvature interpolation. Land elevation for the ground surface model layer was sampled from 5 foot- (1.5 meter) resolution LiDAR coverage of Columbia County. Drill hole and well data was compiled from Wisconsin Geological and Natural History Survey (WGNHS) records to constrain the top of bedrock and top of Precambrian model layers. 150 well and 42 drill hole records within and adjacent to Columbia County provide Precambrian lithology and elevation. An additional 534 wells within Columbia County penetrated at least 250 feet below land surface and were completed in Cambrian sandstone. The bedrock elevation surface was taken from the Columbia County groundwater model (Gotkowitz et al., in preparation). The initial Precambrian surface was interpolated from well and drill hole records. Areas where Precambrian was at land surface were identified on the 1:100,000-scale bedrock map of the Baraboo Hills (Dalziel and Dott, 1970) and surface elevations within these areas were extracted from the LiDAR and incorporated into the Precambrian elevation surface.

Table 1. Density and susceptibility values

		Density (g/cm3)			Susceptibility (x 10^{-6} cgs)			
Geologic Unit	Symbol	Dutch (1995)	Skalbeck (2007)	This Study	Dutch (1995)	Moll (1987)	Skalbeck (2007)	This Study
Quaternary	Q	1.8	1.7-1.9	1.7	N/A	N/A	0	0
Paleozoic	Pz	2.19-2.86	2.45-2.82	2.4	16-125	0	75-100	100
Waterloo Quartzite	YW	2.64-2.81	N/A	2.7	67	N/A	N/A	70
Freedom Formation	XF	2.68	N/A	2.8	N/A	N/A	N/A	5300
Baraboo Quartzite	XB	2.62-2.72	N/A	2.7	86	N/A	N/A	90
Montello	XG	2.64	N/A	2.5	490	200	N/A	150
Marcellan	XR	2.45-2.83	N/A	2.5	142-3489	N/A	N/A	3280
Felsic Intrusion	Yf	2.67	2.67-3.02	2.67	65-2430	6000	3000	6000
Mafic Intrustion	Ym	2.70-3.06	3.00-3.2	3.2	91-2713	6000	1000	1500
Magnetite Rich	Ymg	N/A	N/A	2.67	N/A	N/A	N/A	12000
Fault Zone	FZ	N/A	N/A	varies	N/A	N/A	100-1000	varies
Undiff Quartzite	XYQu	2.55-2.72	2.77-3.02	2.7	44-462	N/A	N/A	100

Table 2: Model best fit statistics

	Complete Bouguer Residual Gravity					Residual Aeromagnetics				
Profile	Min (mGal)	Max (mGal)	Anomaly (mGal)	Profile Error (mGal)	%RMSE	Min (nT)	Max (nT)	Anomaly (nT)	Profile Error (nT)	%RMSE
A-A`	-64.7	-54.4	10.3	0.163	1.59	-163.1	935.4	1098.5	39.833	3.63
B-B`	-82.1	-52.6	29.4	0.726	2.47	-59.0	942.7	1001.7	26.512	2.65
C-C`	-80.4	-47.6	32.9	0.454	1.38	147.9	673.6	525.7	11.449	2.18
D-D`	-79.6	-46.7	32.9	0.510	1.55	229.2	744.6	515.4	6.703	1.30
E-E`	-74.0	-54.5	19.5	0.307	1.58	150.7	1388.6	1237.9	60.866	4.92
G-G`	-73.2	-58.1	15.1	0.451	2.99	296.9	869.4	572.6	55.783	9.74
Target Value for %RMSE					5.0					10.0

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

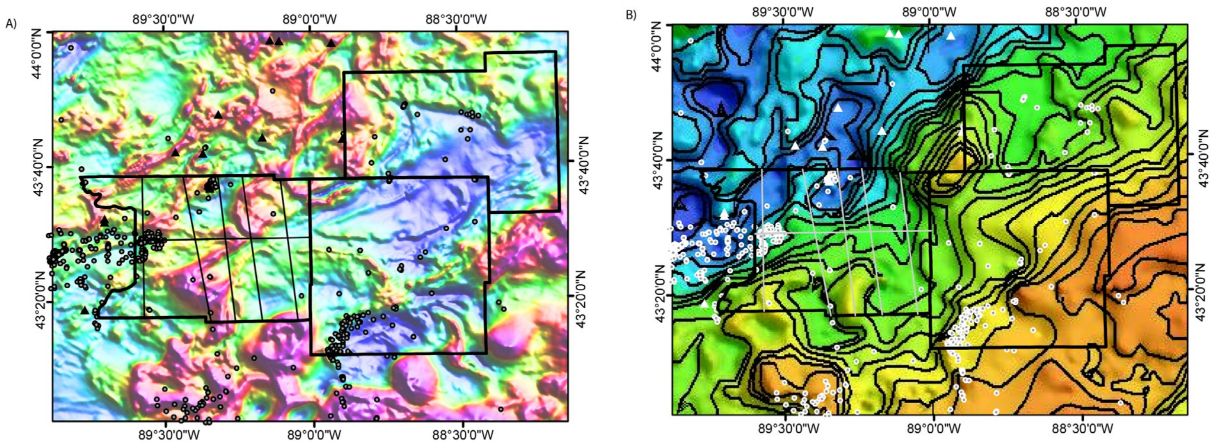

Figure 3. A) Reduced to pole aeromagnetic anomaly map calculated using the following parameters: Lat: 43.48; Long: -89.02; Altitude: 300 m; Field Strength: 56733.7; Inclination: 71.7; Declination: 358.5. B) Gravity anomaly map from Daniels and Snyder (2002). County outline, wells, drill holes, outcrops, and profile lines as in Figure 1. Warm colors are greater anomaly values and cool colors are smaller values.

New magnetic susceptibility measurements, petrographic observations, and geochemical analyses collected as part of this study constrained both the physical properties used as model input and the geologic interpretation of the relative age and lateral distribution of geologic units. These measurements focused on the iron formation and underlying slate (Freedom Formation and Seeley Slate) and the 1.75 Ga igneous rocks because these units are characterized by the broadest range in susceptibility values. Measurements were collected using a TerraPlus KT10 handheld magnetic susceptibility tool. Additional remnant magnetism and magnetic susceptibility measurements of the iron formation and slate were collected at the UW-Milwaukee Paleomagnetic Laboratory on a 2G Enterprises super conducting rock magnetometer and molspin minispin magnetometer, respectively.

Due to the significance of the iron formation in interpreting structural features expressed in aeromagnetic data in the Baraboo area (Stewart et al. 2018), we examined the Freedom Formation in detail using petrography and in situ geochemical techniques. Our goal was to establish the relationship between the Freedom Formation recovered in drill core from the Baraboo Hills ca. 1903 for mineral exploration (core name H122, WGNHS unique well ID 57001945) and a newly discovered iron-rich metasedimentary unit recovered in drill core from Dodge County as part of an ongoing, STATEMAP-funded bedrock mapping project by the WGNHS (core name Slinger; WGNHS unique well ID 14001388; Lamb and Stewart, 2016). To this end we compared mineralogic similarities of 23 samples of the Freedom Formation and underlying Seeley Slate from the Cahoon and Slinger cores, and quantified major element distributions in fine-grained samples using standard petrographic methods, scanning electron microscopy (SEM), and electron probe micro analyzer techniques (EPMA) to aid in mineral identification.

Results and discussion

Five north-south and one east-west coupled models of gravity and aeromagnetic data were completed as part of this study. Each model achieved a percent RMSE (RMSE/anomaly range) well below the acceptable thresholds of less than 5% for gravity and less than 10% for aeromagnetic data (Table 2). Modeling, together with petrographic and geochemical analyses of the iron formation, refine the preliminary Precambrian geologic map of Stewart et al. (2016) thereby constraining the distribution of Precambrian lithology and structure that influences Precambrian topography beneath the study area.

Petrographic and geochemical analyses indicate iron formation is associated with quartzite and slate in Dodge County, similar to the stratigraphy known from the Baraboo Hills. Modeling supports the presence of a Precambrian fault bisecting Columbia County from southwest- northeast with slightly older Precambrian units present to the north, and higher-density units present at depth mostly on the south side of the structure. Select model profiles and a discussion of iron formation petrography and geochemistry are presented in detail, below.

Models of select profiles

Profiles D-D' and E-E' are described below to illustrate the geologic and geophysical interpretations that are the basis for modeling Precambrian topography in the study area (Figures 4-5). The upper third of each figure shows aeromagnetic values, the middle third shows gravity anomaly values, and the lower third shows the modeled geologic cross-section. Observed gravity and aeromagnetic values are indicated by the thick, black curve; modeled values by the thin black curve; and difference between calculated and observed values is shown by the red line with deviation from horizontal representing model error.

Profile D-D' crosses the Baraboo Hills, where Precambrian basement is exposed at land surface in western Columbia County (figures 1, 4). This profile achieves a good model fit of 1.30 %RMSE for aeromagnetic and 1.55 %RMSE for gravity data (Table 2). Outcrop, drill hole, and well data provide abundant, independent geologic control in the vicinity of the Baraboo Hills. Independent control does not exist for the northern profile extent and is sparse in the south. Density and susceptibility values for glacial, Paleozoic, and Precambrian units are shown in Table 1.

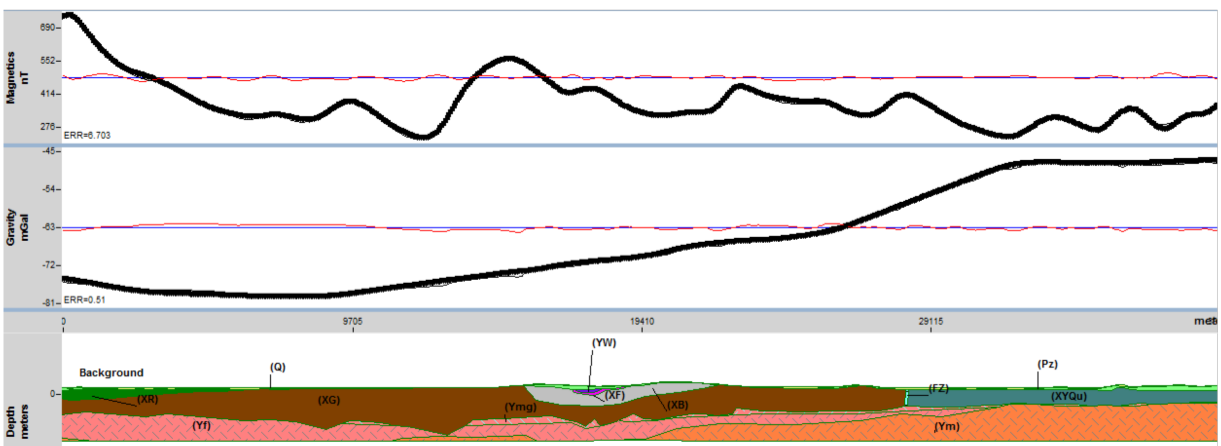

Figure 4. Coupled gravity and aeromagnetic anomaly model D-D' for Western Columbia County. No vertical exaggeration

The northern part of profile D-D' indicates a southward-thinning wedge of 1.75 Ga rhyolite overlying 1.75 Ga granite. Rhyolites outcrop near the towns of Marcellon and Endeavor with magnetic susceptibility values ranging from 3279 to 668 µCGS (41200 to 8390 SI), and most values above 1591 µCGS (20000 SI). We use a value from the high end of this range in the modeling (Table 1).

Rhyolite and diorite outcrops near the Baraboo Hills at the Lower Narrows and near the village of Denzer with magnetic susceptibility values between 7 – 1074 µCGS (90 – 13500 SI) and most values below 1 µCGS (79580 SI). The Baraboo Quartzite and Seeley Slate, Freedom Formation iron formation, and Dake Quartzite overlie the 1.75 Ga igneous rocks and are folded into the Baraboo syncline. Wells, drill holes, and outcrop constrain Precambrian unit contacts in this area. Our modeling suggests the Baraboo quartzite thins from 1.5 km (5,000 feet), where it is calculated from outcrop near Devil's Lake, to ~ 500 meters (~ 1640 feet) along profile D-D'. South of the Baraboo syncline a high-angle, northeast-trending fault juxtaposes quartzite to the south against 1.75 Ga granite to the north. The steep dip indicates the structure is likely a strike-slip fault. Gravity and aeromagnetic data suggest the presence of high-density mafic and associated felsic intrusive material at depth. A magnetite-rich cap is modeled to locally overlie the felsic intrusion as a thin layer. The intrusions are interpreted to be related to the 1.4 Ga eastern granite rhyolite province. Mafic dikes are observed in outcrop associated with both the 1.75 Ga granites and rhyolites (Smith, 1978) and the 1.47 Ga Wolf River Batholith (Kean 1994), and mafic underplating and intrusions are predicted for the eastern granite rhyolite province (Bickford et al., 2015). Samples of the felsic intrusion exist in the form of water well drill cuttings collected from high capacity several tens of miles from the profile. Magnetite-rich material was recovered from a well that intersects section E-E'.

Profile E-E' trends northwest-southeast across west-central Columbia County. This profile achieved a good model fit of 4.92 %RMSE for aeromagnetic data and 1.58 %RMSE for gravity (Table 2). The north part of the profile crosses near the town of Marcellon, where 1.46 Ga rhyolite outcrops. Otherwise, there is sparse well control for the model. Refer to Table 1 for modeled gravity and susceptibility values.

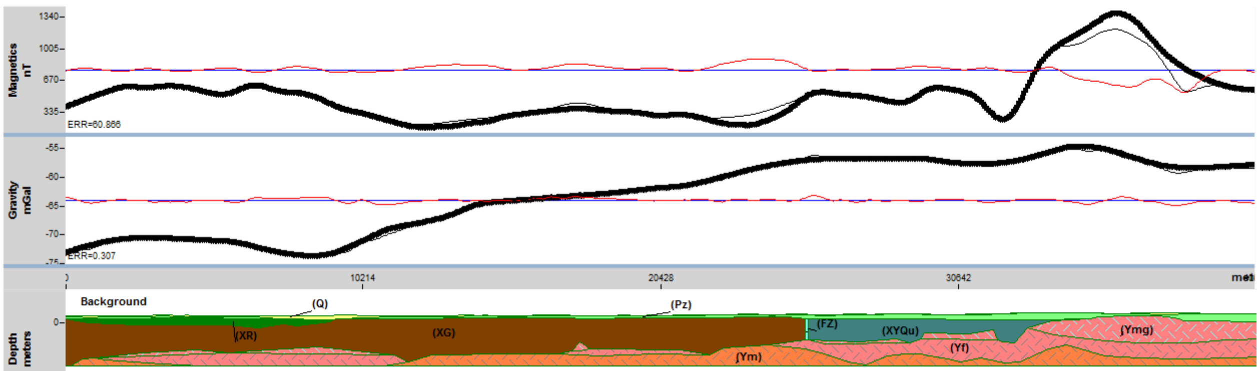

Figure 5. Coupled gravity and aeromagnetic anomaly model E-E' for West-central Columbia County. No vertical exaggeration.

Similar to D-D', profile E-E' indicates a wedge of 1.75 Ga rhyolite overlying 1.75 Ga granite. This 1.75 Ga basement is juxtaposed against quartzite by the same vertical fault modeled in profile D-D'. Similar to D-D', mafic and felsic material, likely related to the eastern granite rhyolite province, intrude the quartzite and 1.75 Ga basement. The magnetite-rich layer is most significant south of the fault. Drill cuttings from a well that intersects the south side of this profile (well 11000777, Poynette Village Test Hole for well #4) recovered dark-colored, fine-grained slatey material that is strongly attracted to a magnet. This material may represent metamorphosed iron formation or iron-rich slate. Alteration may be caused by contact metamorphism or interaction with hydrothermal fluids related to emplacement of the eastern granite rhyolite province. Additional thin section work would permit better lithologic characterization of this material. Petrography and geochemistry of iron formation from the Baraboo Hills, Sauk and Columbia Counties, and an iron-rich metasediment recovered in drill core from Dodge County indicate the presence of iron formation associated with quartzite across the study area (see below).

Iron formation petrography and geochemistry

The Freedom Formation iron formation preserved in historic drill core (the Cahoon core) comprises a mix of carbonates, silicates, and Fe-oxides. The Freedom Formation is underlain by slate with a clear detrital origin, which transitions up into a mixed carbonate-silicate facies iron formation, overlain by an upper hematite-rich chemical sedimentary unit, capped by a hematite-cemented, poorly sorted detrital quartzite. The units of interest to this study include those rich in iron-silicate and carbonate minerals. Figure 6a shows transmitted light images of carbonate iron formation (Cahoon H122-583). Individual grains form a “granular” texture, where space between grains (called granules) fills in with cement (Figure 6A, representative sample H122-583). Compositionally, granules consist of iron- and magnesium-rich silicate minerals (Figure 6B, representative sample H122-583), namely chamosite and stilpnomelane, while surrounding cement consists of carbonate minerals. The granular texture is not prevalent throughout the stratigraphic section, and only represents a thickness less than 20 cm. The main texture of the iron formation is mm- to cm-scale planar to wavy banding. Mineralogically, the banded units of the iron formation consist of chamosite, stilpnomelane, quartz, magnetite, hematite, dolomite, and siderite, with interbedded intervals of clastic minerals (detrital quartz and clays) (Figure 6C, D, M1, representative sample H122-585). Quantitative high-spatial resolution element maps obtained using the EPMA at low (8) keV (in collaboration Dr. John Fournelle and Dr. Aurelian Moy at the University of Wisconsin – Madison) document complex micron-scale silicate mineral reactions between chamosite and stilpnomelane of ranging composition (Figure 6E, representative sample H122-585), and carbonate minerals including dolomite and siderite (Figure 4D, representative sample H122-585).

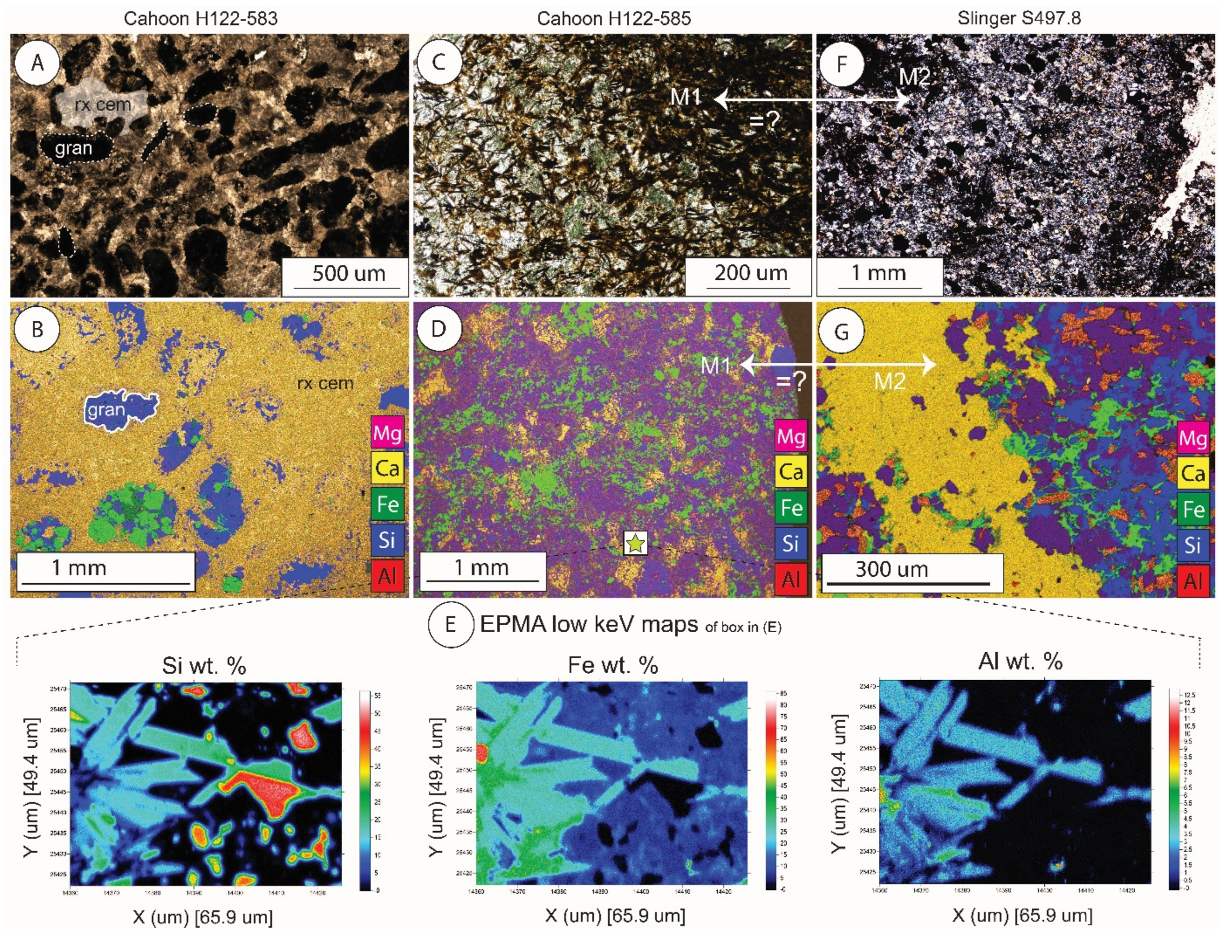

Figure 6. Petrographic, scanning electron imaging, and electron probe microanalyzer maps of representative Freedom Formation samples from the Cahoon and Slinger cores. (A) Cross-polarized light image of granular textures within the Freedom Formation (Cahoon core H122, depth 583’). Gran = granule, rx cement = recrystallized cement. (B) Composite qualitative element maps of sample in (A) obtained using SEM. Colors listed indicate element. Gran = granule, rx cement = recrystallized cement. (C) Plane polarized light image of fine-grained iron- and magnesium-rich silicate minerals within the Freedom Formation (Cahoon core H122, depth 585’). M1 indicates mineral assemblage 1 identified using SEM and EPMA. (D) Composite qualitative element maps of sample in (C) obtained using SEM. Colors

listed indicate element. Star represents location and scale of quantitative EPMA maps in (E) Representative quantitative element maps (low keV) obtained from sample Cahoon H122-585. Only three of 9 element maps shown (Si, Fe, Al). (F) Cross-polarized light image of banded sample, putative Freedom Formation (Slinger core, depth 497.8'). M2 indicates mineral assemblage 2 identified using SEM and EPMA. (G) Composite qualitative element maps of sample in (F) obtained using SEM. Colors listed indicate element.

With mineral compositions for the well-preserved Cahoon core, we determined the genetic relationship of the Freedom Formation preserved in the Cahoon core to the iron-rich putative iron formation identified in the Slinger core. Within the Slinger core, mineral assemblages include iron-oxides, quartz, and iron- and magnesium-rich silicates as well as prevalent carbonate veins and detrital minerals (Figure 6F, M2, representative sample S497.8). The Slinger mineral assemblage (M2) closely resembles the mineralogy of the Cahoon samples (M1), indicating a potential shared origin. Mineral assemblages such as those found in Slinger 497.8 often occur in iron-rich chemical sedimentary rocks with varied clastic contamination. Based on comparison of detailed quantitative element mapping and EPMA point analyses of minerals within the silicate-rich banded horizons of the Cahoon cores to similar units in the Slinger cores, we conclude that the iron-rich units of the Slinger core represent the Freedom Formation equivalent.

Precambrian bedrock topography

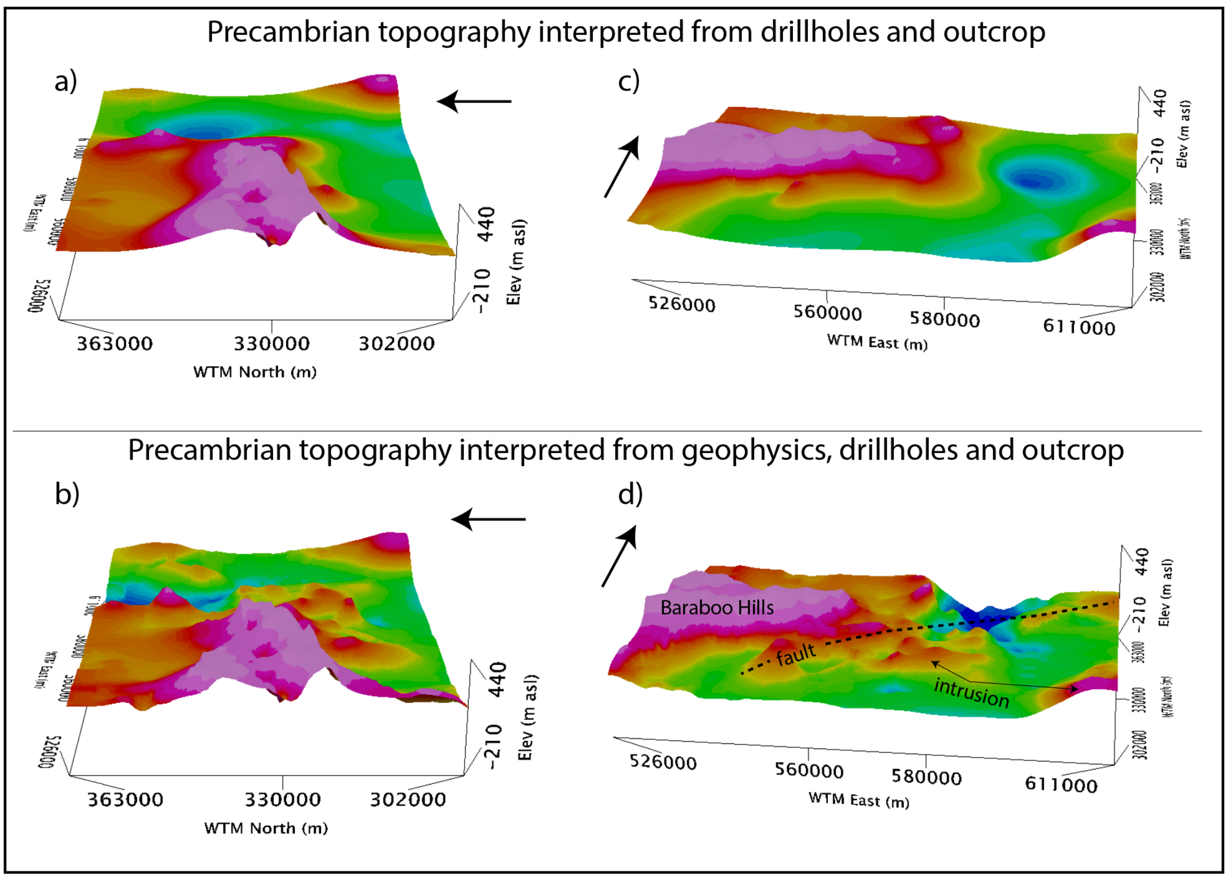

Figure 7. Precambrian topographic surface interpreted from drill holes and outcrop only (7a, 7c) and after incorporating coupled gravity and aeromagnetic anomaly models (7b, 7d). View is to the east (A, B) and north-northeast (C,D). Arrows indicate north.

Figure 7 compares the Precambrian topographic surface interpreted based on drill holes and outcrops only (Figure 7a) to the same surface interpreted from coupled gravity and aeromagnetic anomaly modeling (geophysics), drillholes, and outcrops(Figure 7b). Several significant differences are apparent. Incorporation of geophysical data improves the resolution and decreases the elevation of the Precambrian surface underlying northwest Columbia County, from the north limb of the Baraboo Hills northwards. The southwest—northeast—trending fault is expressed in the Precambrian surface topography as a linear, discontinuous topographic high. Underlying central Columbia County and just south of this structure, granite and altered, fine-grained, magnetic rock recovered from three nearby wells (11000677- Arlington Experimental Farm well #9; 13000123- De Forest Oil Test Hole; 11000777- Poynette Village Test Hole for well #4) are expressed as elevated areas on the Precambrian surface (Figure 7d). The deep, isolated basin shown on the Precambrian surface interpreted from wells and outcrop only underlying northeast Columbia County (figure 7a, c) is modified into an elongate southwest-northeast-trending trough (Figure 7b, d). We are working to make this updated Precambrian surface available for download through WGNHS.

Conclusions and recommendations

Incorporation of geophysical data improves resolution of the Precambrian surface and understanding of the Precambrian lithology and structure underlying Columbia County. Coupled modeling of gravity and aeromagnetic data support the presence of a significant Precambrian structure bisecting Columbia County. This structure extends from Sauk City through the northeast corner of Columbia County. It is interpreted as an oblique strike-slip fault that uplifts and juxtaposes slightly older 1.75 Ga igneous rocks and overlying metasediments to the north against metasediment to the south. Intrusions related to the eastern granite rhyolite province are present preferentially along and south of this structure. Precambrian surface topography is elevated along and north of the structure, particularly where quartzite outcrops in the Baraboo Hills. A topographically low area is present where a large eastern granite-rhyolite intrusion is interpreted to intrude along and north of the fault. Precambrian geology is most complex in this area, suggesting that associated Precambrian topography may be varied. This fault is a significant structure and a good candidate for Paleozoic reactivation. Therefore, it may have influenced fractures, cementation, and depositional facies of overlying Paleozoic units in addition to impacting Precambrian topography.

These results indicate that coupled modeling of gravity and aeromagnetic data is a useful method for developing topographic models of the Precambrian surface in the study setting. We recommend the method be extended to Dodge and Fond du Lac Counties. Towards this end, Mr. Rasmussen will continue coupled geophysical modeling of Precambrian basement, south-central Wisconsin through his graduate work at UW Madison Geosciences Department and the Wisconsin Geological and Natural History Survey. Our objective is to generate a geologically reasonable interpretation of Precambrian basement topography across the tri-county area.

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