Wisconsin Geological
and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN–MADISON

Depth-to-bedrock mapping in Wisconsin

Final report to the Wisconsin Department of Natural Resources
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Introduction

Three types of geologic maps are commonly encountered in the upper Midwestern states. These include: 1) Bedrock geologic maps showing the lithology of igneous, metamorphic, and sedimentary rock units, 2) Quaternary Geologic maps that reflect the character and distribution of primarily Pleistocene glacial and post-glacial sediments, and 3) Depth-to-Bedrock maps, which show the thickness of any unconsolidated materials that overlie bedrock. Depth-to-bedrock maps, the subject of this report, provide an important link between the underlying geology, groundwater flow, and land use and are important in guiding activities, such as permitting, installation of utilities, bridge construction, windfarms and the land application of waste products in sensitive areas with depth-to-bedrock restrictions. An early map constructed by Trotta and Cotter (1973) illustrates that the thickness of these unconsolidated materials in Wisconsin ranges from 0 feet in areas of exposed bedrock to over 500 feet in several parts of the state (Figure 1). The thickness distribution of these deposits relates to the regional geologic history and reflects modification by glacial, alluvial, aeolian, and other processes.

Instead of representing lithologic differences or genetic origin (e.g., what process formed the materials), depth-to-bedrock maps are simple visual representations of the thickness of unconsolidated materials overlying bedrock. These maps are typically represented by contour lines or color shading that indicates specific thickness intervals, irrespective of materials present. Contour intervals represented on such maps vary widely and are based upon local conditions, data density, and other factors. Although geologic maps contain lithologic contacts that can be discovered and located precisely, depth-to-bedrock maps have no such contacts. Instead, contour lines must be interpolated based upon available data. Despite the simplicity of what they show, depth-to-bedrock maps are often more heavily used than traditional geologic maps and are therefore often more scrutinized.

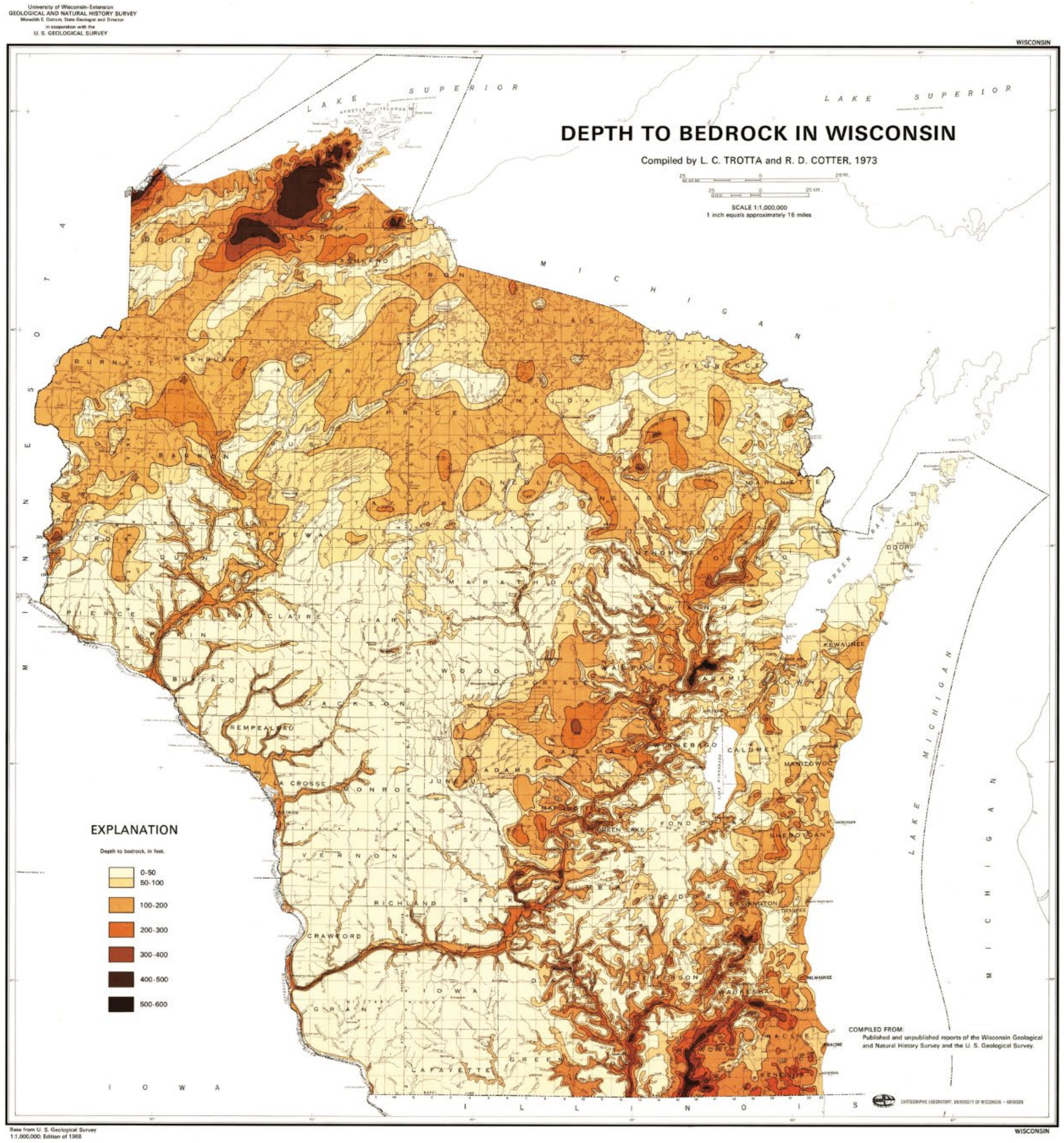


Figure 1. A state-wide depth-to-bedrock map for Wisconsin (Trotta & Cotter, 1973). Thickest unconsolidated deposits occur in areas of large river valleys, concealed paleo-valleys, and areas near Lake Superior. This product contains only 50-foot contours and displays different overall patterns than more recent, larger scale maps of many counties. This difference is not unexpected because the map was likely intended only as a state-wide educational product.

In Wisconsin, the composition and origin of materials that overlie bedrock vary widely. In the driftless region, higher elevation areas are covered by relatively thin veneers of soil, karst fills, and Pleistocene aeolian loess (wind-blown silt), whereas valleys contain alluvial sediments related to stream and slope processes. In the glaciated regions, unconsolidated sediments include glacial till (e.g., ground moraine, end moraines, drumlins), lacustrine (lake) sediments, alluvial sediments (e.g., glacial outwash, eskers, and river sediment), aeolian sediments (e.g., loess and dunes), and other materials. Creating depth-to-bedrock maps in regions with such complex landforms is neither trivial nor unimportant. In fact, producing accurate depth-to-bedrock maps in glaciated terrains, especially in rural areas with sparse data density, might be the most challenging landscape in which to accomplish this task. Maps that often accompany depth-to-bedrock maps include land surface elevation maps, as well as maps depicting bedrock surface elevation.

Who uses depth-to-bedrock maps?

Depth-to-bedrock maps are used by local and state governments, industry, and academic end-users for a wide variety of purposes. Their desired use has intensified in recent years, especially where recent changes to Wisconsin Administrative Code (Ch. NR 151, Wis. Adm. Code) in 2018 directed the Wisconsin Department of Natural Resources (WDNR) to set specific performance standards for Silurian carbonate bedrock in eastern Wisconsin to meet water quality standards in vulnerable areas (Wisconsin State Legislature, 2020). The rule's goal was to place limits on land spreading of manure on areas of thin soils over carbonate bedrock with karst characteristics. Part of the Silurian bedrock performance standard involves limitations of land spreading based upon soil depth, with specific restrictions set for depth intervals of <2 feet, 2-3, feet, 3-5 feet, and 5-20 feet.

Depth-to-bedrock maps are used by engineers and public works departments for siting pipelines and other utilities, by farmers and agronomists to inform areas of manure spreading restrictions, by regulators (county or WDNR), and by many others including hydrogeologists, builders, by DOT engineers for bridge construction, septic installers, educators, and ecologists. Depth-to-bedrock maps are an integral component in the development of groundwater susceptibility maps.

Background

The most common type of depth-to-bedrock map produced in Wisconsin is at the county level, typically on larger format maps historically printed at a 1:100,000 scale, but this also varies. Most maps are made by the Wisconsin Geological and Natural History Survey, but other groups, including the USGS and WDNR have published maps. Sometimes these are accompanied by bedrock topography maps showing the elevation of the bedrock surface or groundwater susceptibility maps. Detailed depth-to-bedrock maps are not yet available for all counties in the state, but significant progress has been made since the late 1970s. Several parts of the state have been targeted for depth-to-bedrock mapping:

1. Western and southwestern Wisconsin (Mainly Driftless Area Counties):
    - Trempealeau County – Cates (2001a)
    - Buffalo County – Cates (2001b)
    - Pepin County – Johnson (1994)
    - Pierce County – Brown (1991)

- Dunn County – Lippelt and Fekete (1988)
- Eau Claire County – Johnson (1993)
- Chippewa County – Lippelt (1988)
- Barron County – Madison et al. (1987)
- Bayfield County (northern WI) – Graham et al. (2019)
- Sauk County – Gotkowitz & Zeiler (2002)
- Iowa County – Carter and Gotkowitz (2011) (Figure 2)

2. Southeastern Wisconsin counties:

   - Composite map of 7 counties, with individual county-scale maps – Evans et al. (2004) and related county scale maps) (Figure 3)
   - Fond du Lac County – Batten (2018)
   - Dodge County – Stewart, (In Press)

3. Northeastern Wisconsin counties (in areas with Silurian bedrock):

   - Door County – Sherrill (1978)
   - A composite map of several counties – Sherrill et al. (1979)
   - Kewaunee County – Luczaj et al. (2019) (Produced for WDNR)
   - Brown County – Ongoing DNR Funded project. (Luczaj – UW-Green Bay)
   - Door County – Early phase, limited DNR funding/pending funds (Brodhagen – UW-Green Bay).

4. Some larger scale maps have been made of at the scale of townships or similar sized regions. Examples include:

   - Parsen et al. (2017) for the Town of Lincoln study in Kewaunee County
   - Town of Byron study in Fond du Lac County (Figure 4) by Bradbury & Batten (2010)
   - Geneva Lake Area study by Gotkowitz and Schoephoester, 2006)

5. Various county scale depth-to-bedrock maps published by the Wisconsin Department of Natural Resources, and hosted online by USGS (e.g., Schmidt, 1987; Figure 6a). These maps appear to have been digitized from preexisting maps, and despite their relatively recent vintage, their accuracy is not always very good.

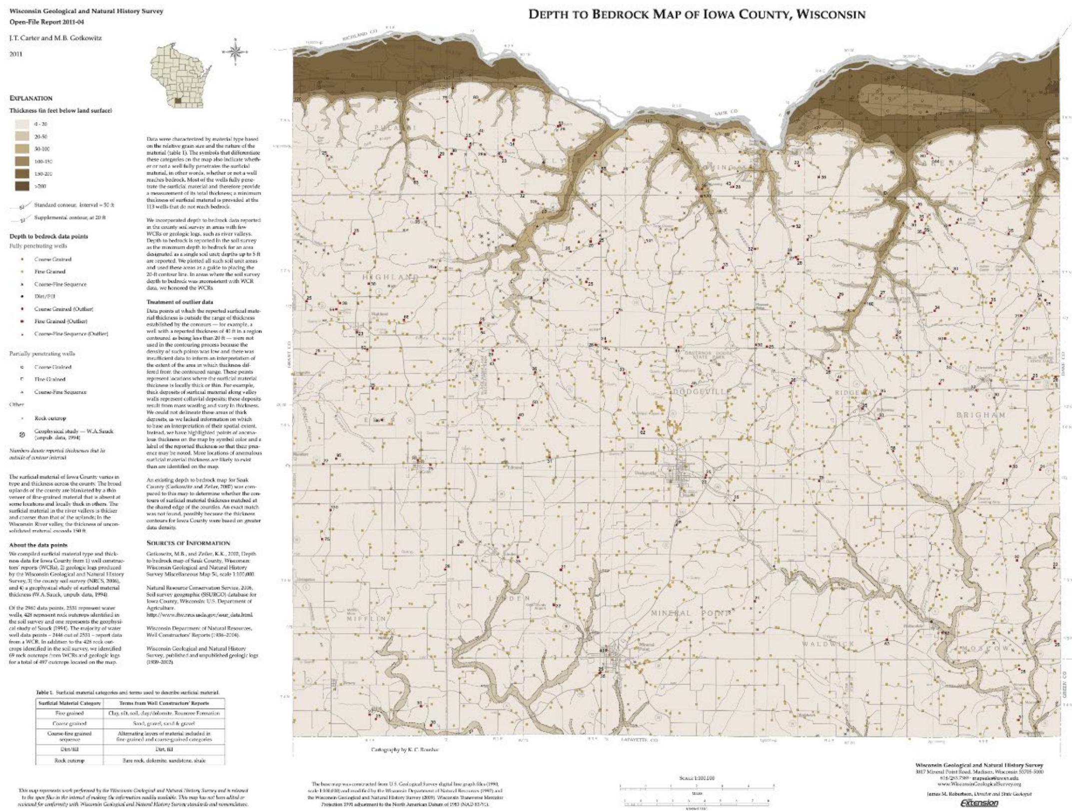


Figure 2. A regional Depth-to-Bedrock Map for Iowa County, Wisconsin by Carter and Gotkowitz (2011)

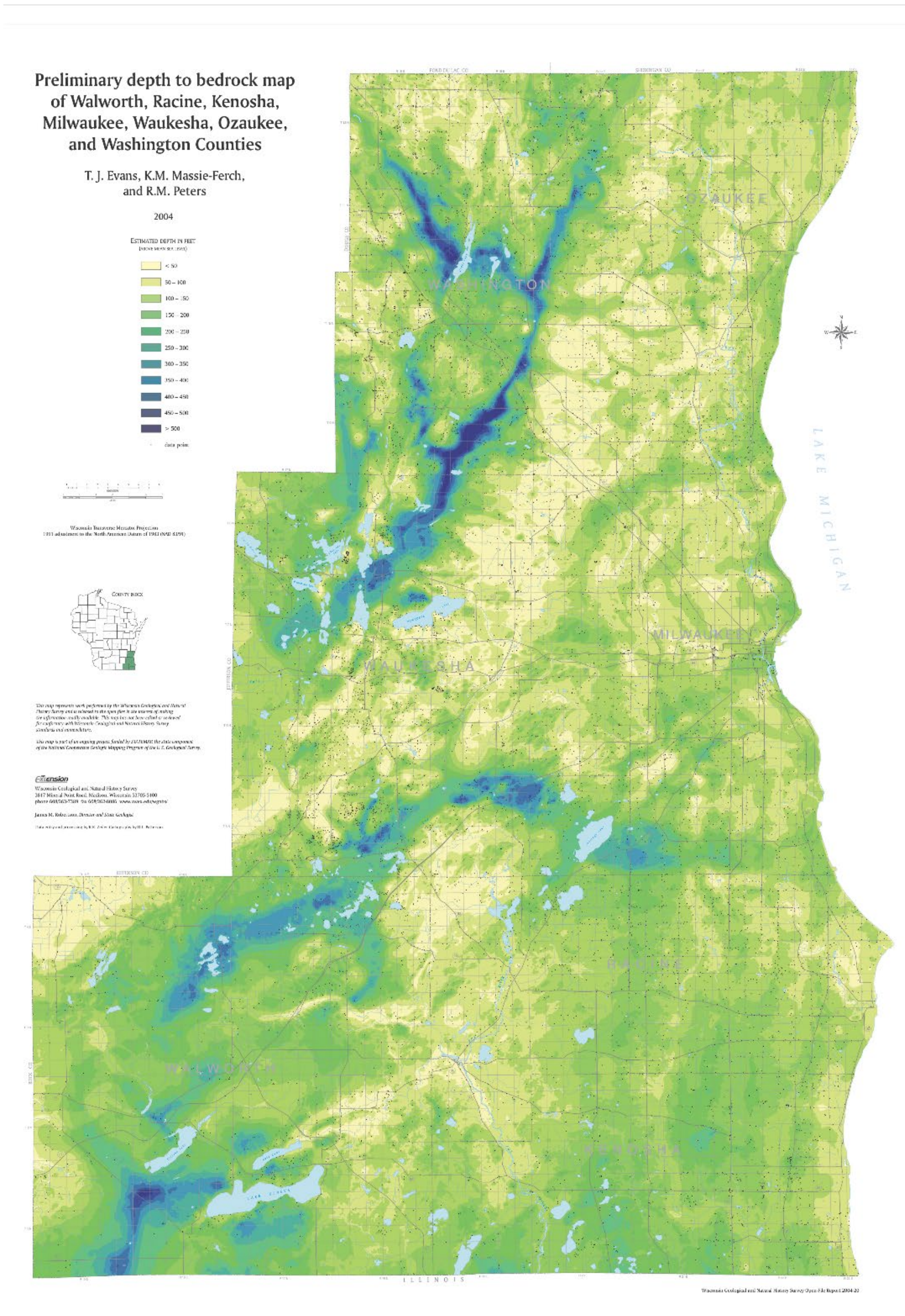


Figure 3. A regional Depth-to-Bedrock Map consisting of several counties for southeastern Wisconsin produced by Evans et al. (2004).

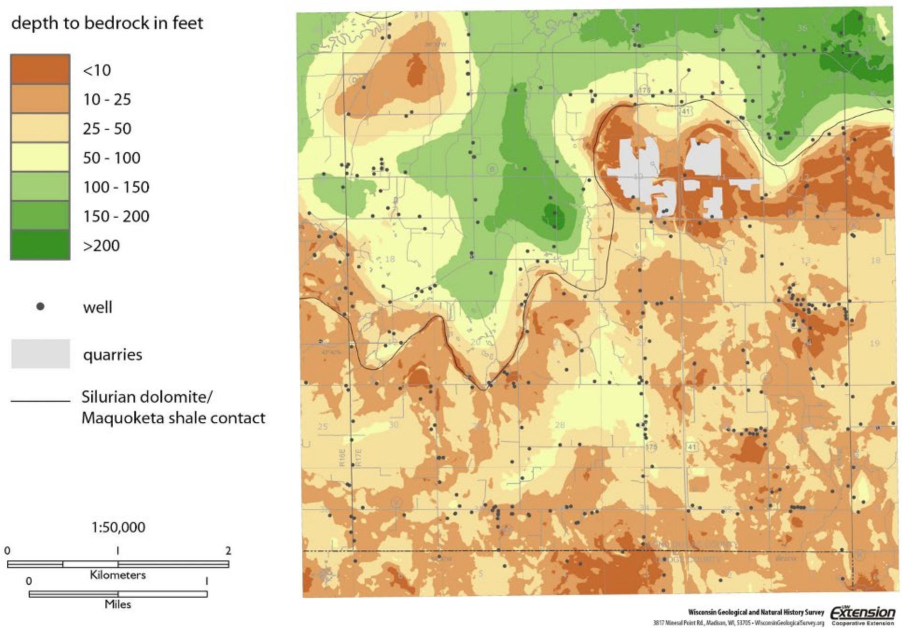
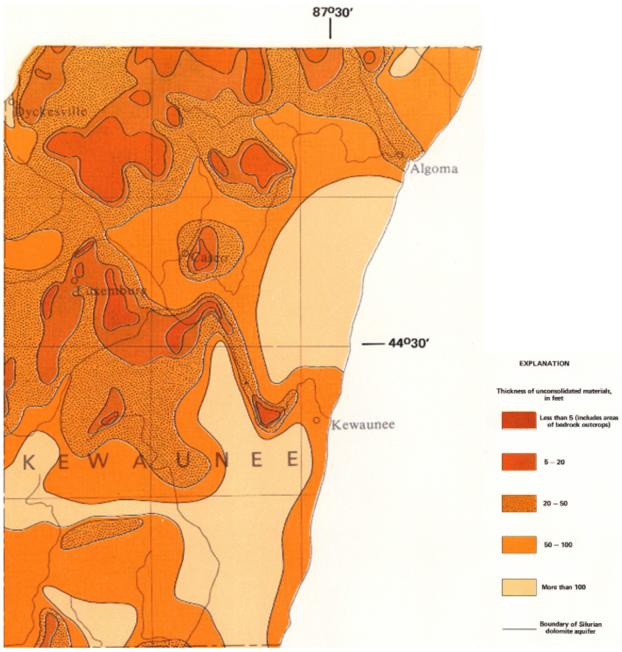


Figure 4. Example of a Depth-to-Bedrock Map constructed for the Town of Byron in Fond du Lac County, Wisconsin (Bradbury and Batten, 2010).

Multiple maps for the same area – An Example of Confusion

Unfortunately, some areas suffer from a form of "version confusion", and county personnel are eager to avoid such confusion. This is especially true in areas in which local ordinances have prompted urgent attention related to land spreading of manure and other waste products. One example of this is for Kewaunee County. Land use ordinances restricting manure usage began as early as 2014. At least four maps exist that cover Kewaunee County, and they differ significantly, but most appear to contain data essentially from 1979 or earlier. Kewaunee County is also one of the few counties in eastern Wisconsin that has not recently been mapped under the USGS Statemap Program, so an up-to-date geologic map, with an accompanying depth-to-bedrock map is not available. The first detailed map for the county was a color depth-to-bedrock map for the Silurian of eastern Wisconsin that was published by Sherrill (1979) (Figure 5a). This closely resembles a black and white traced map of unknown origin (Figure 5b) that was widely circulated and was the map upon which the aforementioned Kewaunee County ordinances were developed (Davina Bonness, 2016, personal communication).



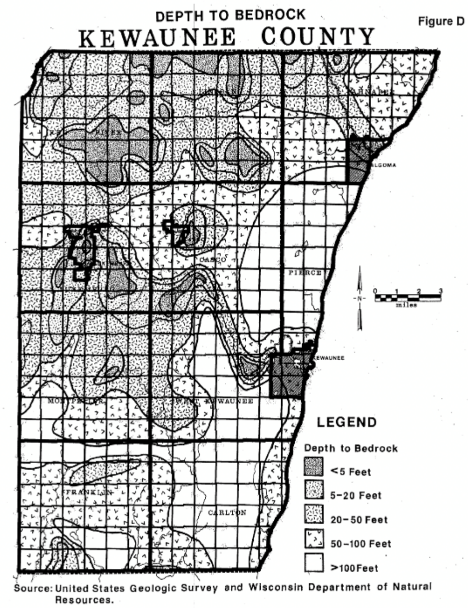


Figure 5a. Left: A portion of regional Depth-to-Bedrock Map for the Silurian of eastern Wisconsin produced by Sherrill (1979). Map shows Kewaunee County, Wisconsin.
Figure 5b. Right: A Depth-to-Bedrock Map for Kewaunee County that was used as the basis of a county-wide land spreading ordinance in 2014. The origin of the map is likely a traced version of Sherrill's 1979 map.

A newer color depth-to-bedrock map for Kewaunee County was published by Schmidt (1987) and again by the USGS (2007) (Figure 6a). These appear to have been drafted from the same map by Sherrill (1979), and may have introduced some potential errors or modifications. An additional map was recently published by Clayton (2013) as part of a WGNHS bulletin on the Pleistocene Geology of Kewaunee County (Figure 6b). This map was published as a figure to illustrate the nature of the glacial sediments described in the report and not to provide a tool for land use decisions. Although the Clayton (2013) map figure appears reasonably detailed and the relatively recent publication date suggests improved accuracy over Sherrill (1979), in some areas the precise origin, methods, data vintage, and accuracy of the more recent map are not described. Many parts of the Clayton (2013) map differ substantially from other maps in use, however it is difficult to evaluate the origin or significance of these differences. Although the more recent publication date implies the Clayton (2013) map incorporates more data, in reality, it is unlikely that all available well construction reports were used in the construction of this map (they had yet to be located) and this mapping effort did not utilize all available data for Kewaunee County. This map might be reasonably accurate for the county, but it did not provide enough detail or a geodatabase that can serve as a foundation for future data regarding the bedrock surface nor was it intended to be used for any purpose other than to support the geologic interpretation.

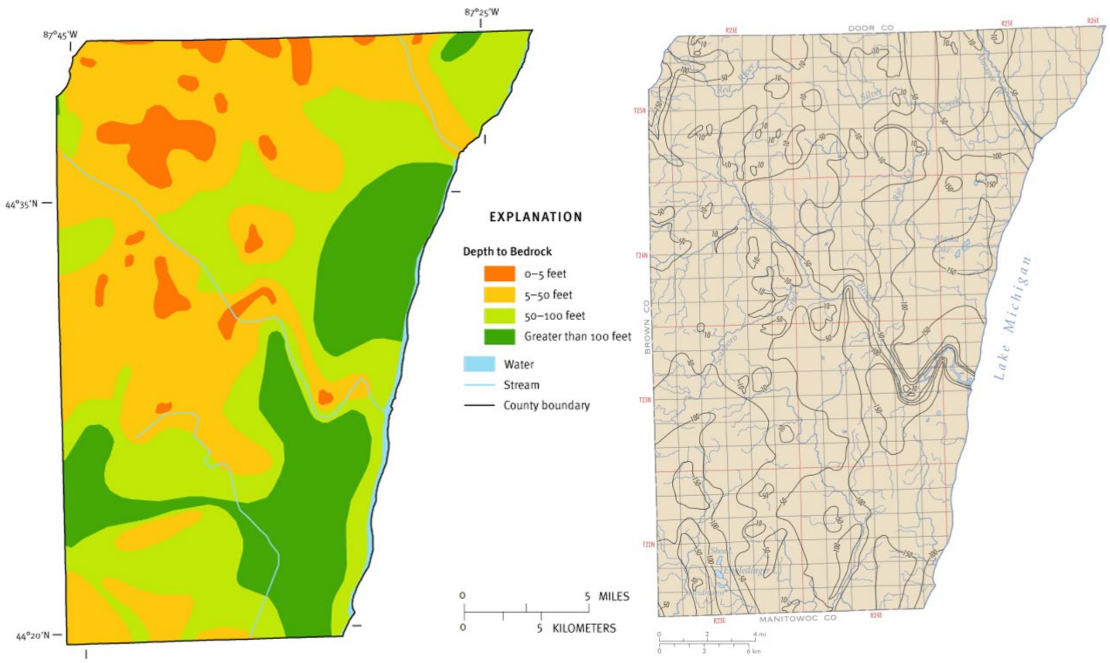


Figure 6a. Left: Depth-to-bedrock Map for Kewaunee County, Wisconsin by Schmidt (1987). Right: Depth-to-bedrock Map for Kewaunee County, Wisconsin by Clayton (2013) as a subordinate figure in a Pleistocene geology publication

Due to inaccuracies in the existing maps, coupled with the urgent need for a modern depth-to-bedrock map for Kewaunee County to assist field scale mapping investigations, the Wisconsin Department of Natural Resources commissioned a study in 2018 to produce a county-wide depth-to-bedrock map and accompanying GIS geodatabase that could be built upon for future mapping efforts (Figure 7; Luczaj et al., 2019).

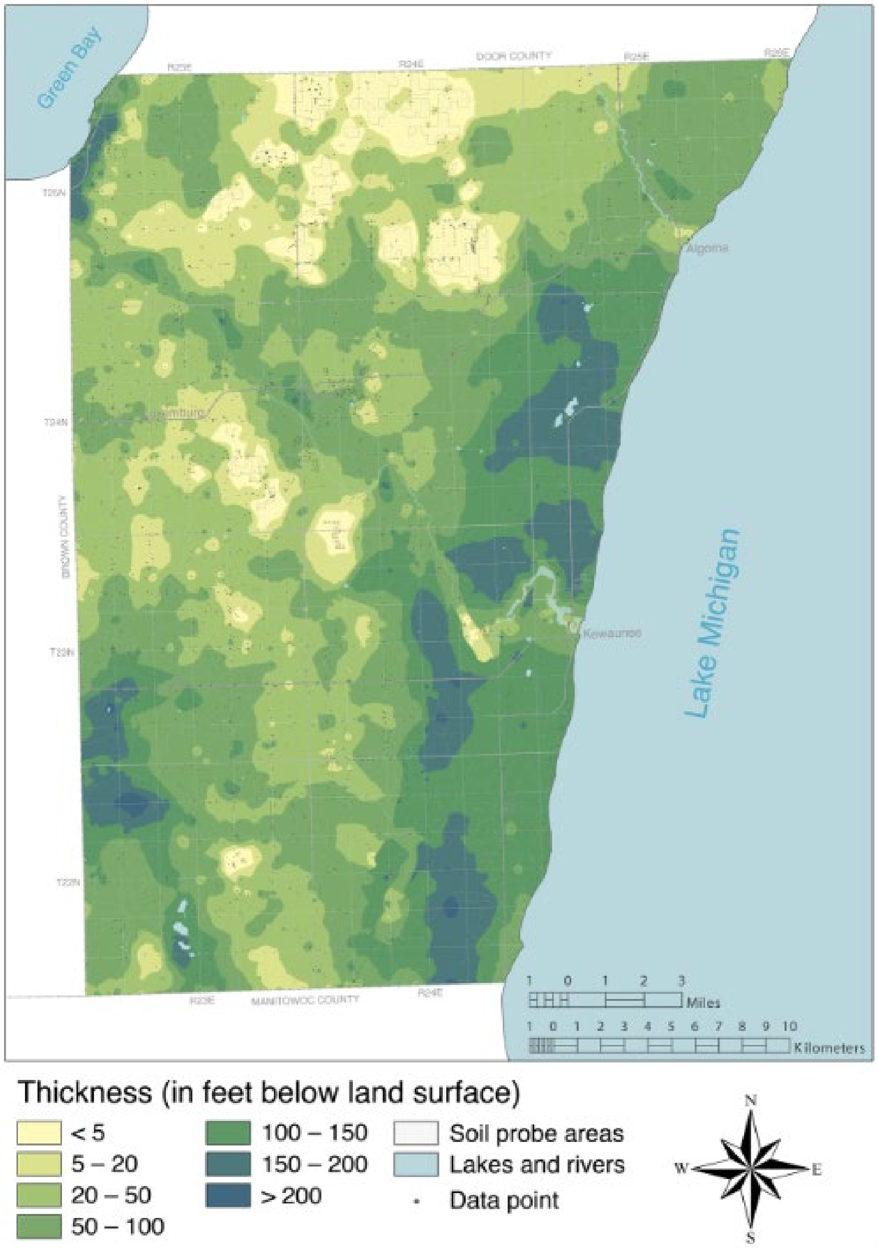


Figure 7. The most recent Depth-to-Bedrock Map for Kewaunee County, Wisconsin produced by Luczaj et al. (2019) for the WDNR. Color scheme follows that used by WGNHS maps for southeastern Wisconsin.

Literature Review

Although depth-to-bedrock maps are one of the most important and most commonly used decisions support tools for land use planning, the number of publications describing methods, techniques, and common issues for making depth-to-bedrock maps are fewer than expected. Making these maps is challenging since depth-to-bedrock is an integration of erosional and depositional processes of both the bedrock and the overlying sediment. The following papers provide some of that background. Traditional bedrock mapping techniques are discussed in Gao and others (2006), Hickin and Kerr (2005), Lively and others (2006) and Berg, R. and Kempton, J. (1988). These papers focus on using borings as the basic data and provide flow charts to analyze and synthesize borehole data. A more sophisticated approach is found in Chung and Rogers (2012). They make use of geologic zones that aid in interpretation. The introduction of geologic zoning allows the mapmaker to account for the different geologic processes and how they might have acted differently in the different zones. Their example looks at mapping in uplands and river valleys. Another trend in depth-to-bedrock maps is to use principal component analysis and machine learning. This allows for more automation by incorporating more variables, more flexibly, into the analysis than is possible with traditional interpolation schemes. Examples are discussed in Yan and others (2020), Shangguan and others (2017), and Boer and others (1996). The last category of publications are geophysical methods used to produce depth-to-bedrock data. Geophysics can provide more data than drilling and so can address the issue of low bedrock depth-data density. Surface geophysics examples are shown in Doolittle and others (2009), Sass (2007), Richard and others (2007), and Ahmed and Carpenter (2003). Airborne Electromagnetics, a method that can provide depth-to-bedrock data over large areas quickly, are discussed in Anschutz and others (2017) and in Christensen and others (2015).

Overview of Mapping Process

Creation of depth-to-bedrock maps involves multiple steps. These include 1. Assembly of available data sources, 2. Review and organization of data sources into geodatabases, 3. Interpretation and synthesis of available data, 4. Application of cartographic standards so map is accessible and accurately portrays the ideas and data intended by the map maker. Steps 1 to 3 are repeated until a consistent interpretation of the data is found. For example, there may be little data available in a critical area. In that case, additional data should be collected that best meets the ultimate goals of the map. Drilling or coring will provide the best depth data and includes the overlying sediments while geophysics might provide a continuous profile of depths along a transect. A second example might be the geologic log for a well that was deepened sometime after it was first completed. The WCRs for deepened wells often either erroneously imply bedrock begins at land surface or the data entry begins at the original total depth of the well. Automated geology picks for unconsolidated materials vs. bedrock for these situations often result in errors. Another issue that creates the need for iteration is that some data points are clearly inaccurate and need to be removed from the interpretation. For example, WCRs that are not properly located often need to be removed or properly located. These mislocated data points do not fit the rest of the data. They are outliers and when the log is reviewed, the error in the location or depth pick is apparent. In addition to honoring the data, the interpretation needs to incorporate geologic principles to guide interpretation in areas with either faulty data or in areas

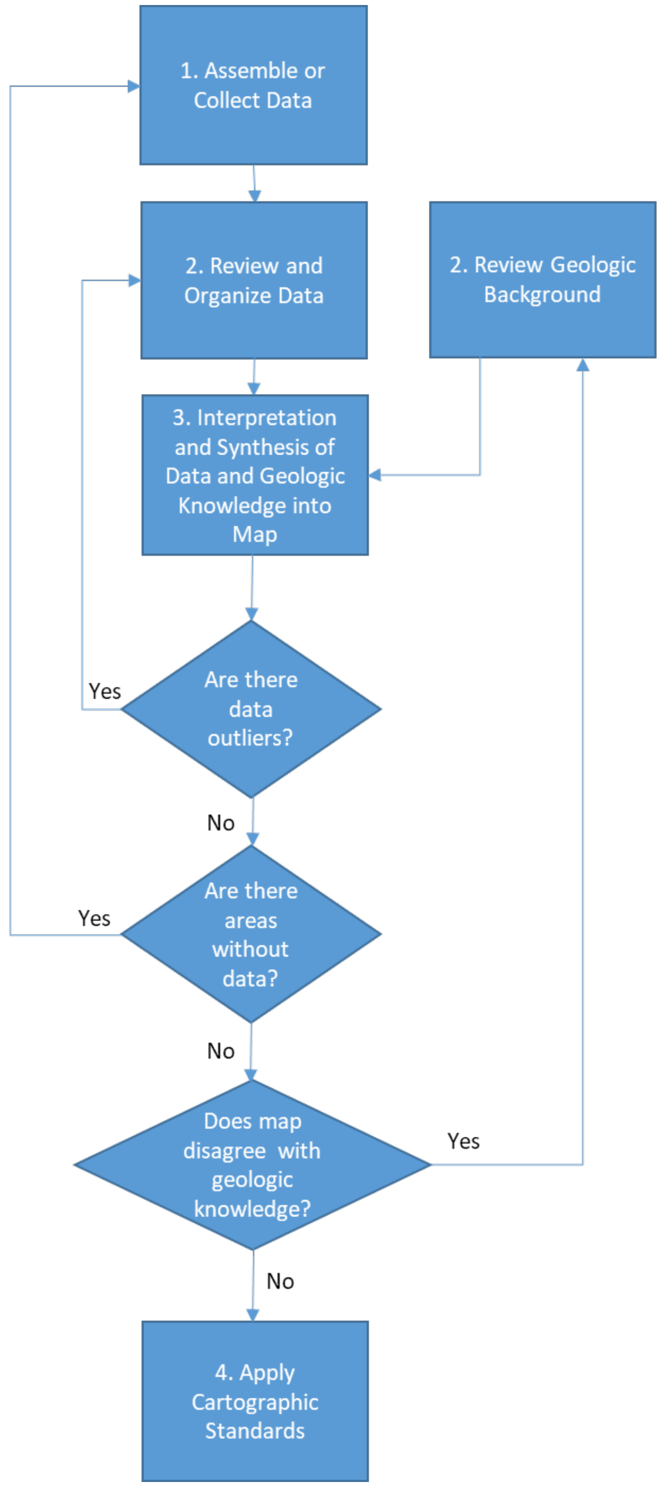


Figure 8. Flow chart of depth-to-bedrock mapping.

with little data, a common issue in depth-to-bedrock mapping. Step 4 should include a peer review to ensure map readability and provide a check on the interpretation and synthesis. Peer review could also occur during Step 3 after several iterations have been completed. Figure 8 summarizes the mapping process.

Depth-to-Bedrock Data

Depth-to-bedrock data are necessary to create depth-to-bedrock maps. Identifying sources of those data and compiling the data into a database are the first steps towards creating a map. There are many different types and sources of depth-to-bedrock data. These can be divided into direct and inferred measurements. Direct measurements include those where the bedrock is physically encountered. The depth encountered during drilling of a well or by pushing a tile probe to refusal are considered direct measurements. Depths determined using inferred methods use differences in material properties between the overlying soil and bedrock. These differences might be the ability to conduct electricity or heat and transmit radar or seismic waves. In this case, depth-to-bedrock is inferred from the measurements. Often these measurements require mathematical analyses to determine depth-to-bedrock. Since they are indirect, they often require ground-truthing or comparison with direct measurements to provide validation of the measurements. Other considerations for depth-to-bedrock data are their availability, cost, density and coverage over the area of interest, depth accuracy, applicable depth range, permissions if proprietary, and location and elevation accuracy.

These data by themselves are unlikely to produce a good depth-to-bedrock map. They need to be placed into geographical and geologic context. Use of digital elevation models, air photos, and geologic maps are essential for understanding the depth-to-bedrock data and assessing its validity. High resolution digital elevation models, such as those created from LIDAR, allow the depth-to-bedrock data to be located and related to topography. Geologic maps showing bedrock and quaternary maps showing the overlying sediments provide geologic context. If the geologic framework and processes (mainly depositional and erosional) documented in geologic maps are disregarded, it is more likely that erroneous depth-to-bedrock interpretations will be the result. Air photos provide additional context. They often indicate land use that can be correlated to depth-to-bedrock. For example, forested areas in Calumet County often have shallow depth-to-bedrock. Areas where bedrock is at landsurface can also be located with air photos, for example quarries and road cuts.

The following list of depth-to-bedrock data is meant to give a sense of the various sources, their utility, strengths, and weaknesses.

1. Well Construction Reports

In Wisconsin, the most common and available depth-to-bedrock data are found in well construction reports. These data often provide a starting point for depth-to-bedrock mapping. They have the benefit of being the primary source historically and provide a bridge to modern mapping. They exist in two formats. The first format consists of newer WCRs submitted by well drillers to the WDNR where they are entered into a digital database. Recently the adoption of GPS makes the location of newer WCRs more accurate than those collected more than ten years ago. The second format consists of scanned logs. These logs are available from the WGNHS and are older, typically for wells drilled from the late 1800s to 1987. The data from these logs is not in digital format and must be transcribed from the scan to a database. The location information for these logs is in PLSS and not as accurate as that available from GPS. The older WCRS are available from the WGNHS on request. The newer WCRs are available for download from the WDNR

Figure 9. Example of a Well Construction Report (WCR)

(https://dnr.wi.gov/WellConstructionSearch/#!/PublicSearch/Index). These data all need to be checked for accuracy. The quality of the data in WCRs varies widely with era and the driller recording the data. Location and geologic interpretation errors are common. For example, logs might have a granite above glacial till or be located in the middle of a lake in a different county. Figure 9 is an example of an older WCR.

2. Exposed Rock and Outcrops

Figure 10. Area of with exposed bedrock indicated by stars.

Exposed rock is perhaps the clearest direct indication of shallow bedrock, and information about rock exposure is available from multiple sources. Bedrock exposures can be located and identified by walking fields, searching for outcrops along road cuts, or occasionally from air photos. Bedrock quarries are typically situated in areas of shallow bedrock. Road cuts often indicate shallow rock since soil would be sloped back and vegetated while rock would be left bare and as a vertical face. Road cuts and quarries have an additional advantage of providing a direct view of variability in the shallow bedrock surface and the fracture connectivity of the underlying bedrock. Discussions with local land owners will often provide locations of shallow or exposed bedrock. In addition, since exposed rock is used in state and county statutes to limit land use, outcrops are often recorded and the data maintained by county conservation departments. Finally, bedrock outcrops are often indicated on geologic maps and included in the supporting materials.

Examination of air photos, LiDAR, and similar imagery provide additional context for bedrock exposures observed on the landscape or documented in county databases or on geologic maps. Although bedrock crops out as isolated pinnacles in many areas of Wisconsin, exposed rock often indicates a larger area of shallow depth-to-bedrock, especially in glaciated areas. The observation of exposed bedrock can be coupled with detailed elevation images from LIDAR and air photos to estimate the extent of shallow rock. Figure 10 shows an area of shallow rock with multiple exposures. Photographs from Google's street view provide an additional resource for identifying bedrock along road cuts, complementary to driving the roads. In addition, shallow bedrock is often apparent from color changes in vegetation and land surface texture apparent on air photos. The vegetation is lighter colored in areas of shallow bedrock and greener in areas with deeper depth-to-bedrock. Solution-enlarged fracture traces are also evident as linear green vegetation patterns in air photos. Figures 11a and b show the fracture traces in areas of shallow bedrock. Finally, if available, the primary data used to create an existing geologic map should be used to identify outcrops. If a scanned and georectified map is used to identify exposed rock, it is important to verify those locations against air photos and LIDAR, because maps commonly simplify and generalize individual features.

Figure 11a. Vegetation growing in fracture traces. The mound is likely made of rocks placed over a sinkhole (Photo: John Luczaj). Figure 11b. An airphoto of vegetation growing in fracture traces.

3. Infield Probe Depth Measurements

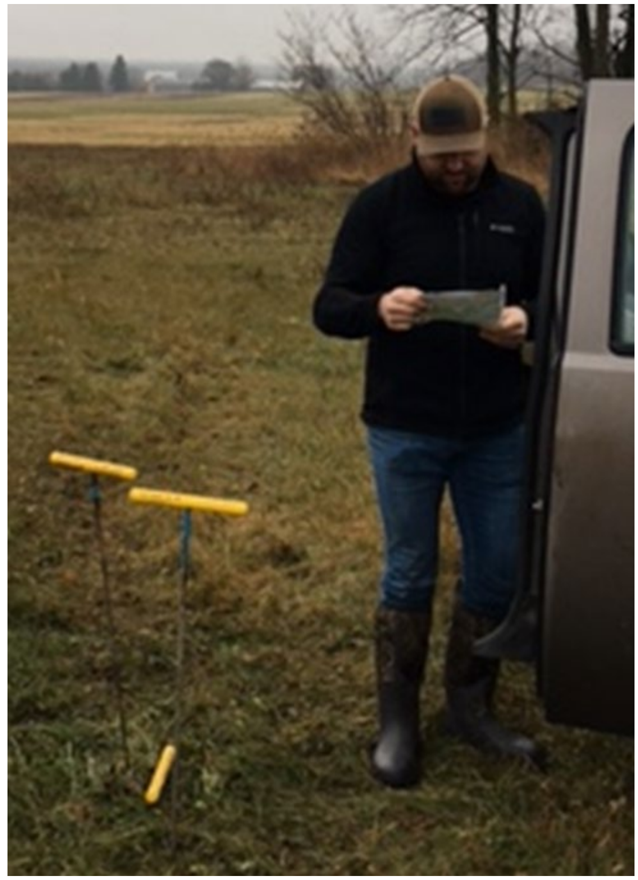


Figure 12. Three push probes in area of shallow bedrock. The central probe is pushed into a vertical fracture. (Photo: David Hart).

Infield depth measurements are collected as part of a nutrient management plan and submitted to the counties. These direct measurements are collected with a hand probe or skid steer with a probe on the bucket. Bedrock depth is indicated by refusal of the probe to penetrate further. These methods are lower cost, easily implemented with some training, and can be used in areas with difficult access. Their simplicity is also an advantage since the results are easily understood and so more likely to be accepted. However, these methods are only applicable to depths of less than five feet. Other methods must be used to measure greater depths to bedrock. Accurate depth measurements depend on the user differentiating between stiffer soil horizons such as cobble and boulders, indurated gravels, and the plow pan. For this reason, the measurements might under-estimate bedrock depths. These methods are also point measurements and if the bedrock surface is varying more than expected, it may be difficult to establish a depth-to-bedrock contour. Figure 12 illustrates this issue with three 48-inch length hand probes. The probes on the left and right encounter bedrock at depths of less than one foot. The middle probe is located in a fracture and does not encounter bedrock, even at its full depth of 48 inches. These methods are physically taxing and may cause repetitive stress injuries if thousands of points are collected by a single individual.

4. NRCS Shallow Soils Data

As part of their soil survey data, the NRCS includes lithic soils and depth to those soils. These data are easily acquired and can be useful as initial estimates of depth-to-bedrock. Furthermore, the data were collected over the last 100 years during soil surveys by a soil scientist and are generally of high quality. However, these soils might not represent bedrock. The data were not collected for the purposes of determining depth-to-bedrock but to represent lithic soils. For that reason, these data should be used with caution and corroborated with other data. The data can be found at: USDA NRCS Geospatial Data Gateway https://gdg.sc.egov.usda.gov/GDGOrder.aspx.

5. Land Surface Topography and Air Photos

In additional to providing elevations to aid in depth interpretations, the land surface topography might also indicate bedrock depths, especially shallow depths. Small scarps are readily evident in LIDAR and show areas of bedrock highs that are in turn often areas of shallow bedrock. These can be coupled with air photos to identify dryer, less green vegetation that represents shallow soils and linear bedrock fractures represented by more green vegetation in a linear orientation. The absolute elevation can be used to identify other regions with similar shallow bedrock. Dhuey Hill, located in northwestern Kewaunee County (Figure 1 in Parsen and others, 2017) is an example of how shallow bedrock is correlated to topography. It is shown in Figure 13.

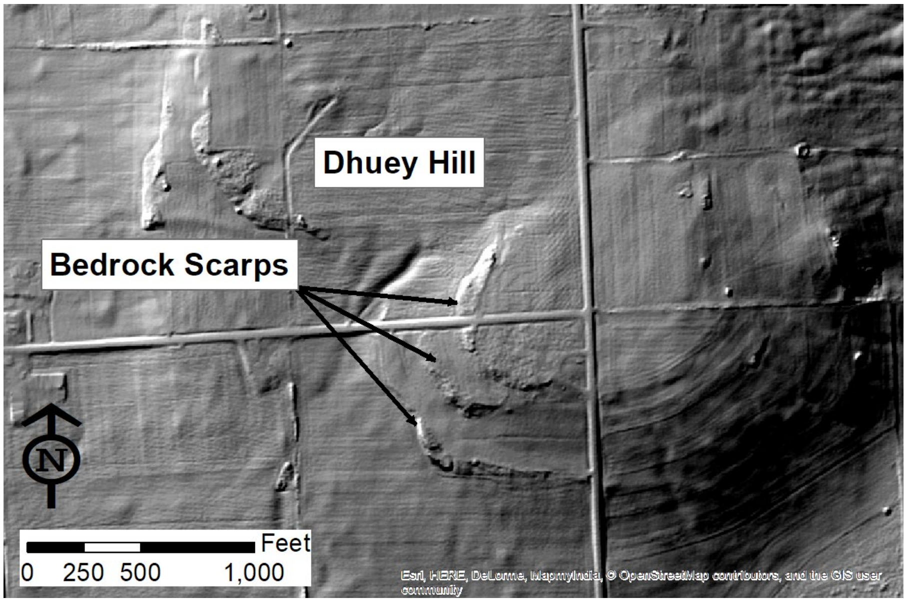


Figure 13. An example of three scarps indicting shallow bedrock.

6. Surface Geophysics

Depth-to-bedrock can be mapped using surface geophysics. There are many methods available to acquire these data. Commonly used methods include electrical resistivity imaging, ground conductivity meters, ground penetrating radar, seismic refraction, multichannel analysis of surface waves, seismic horizontal to vertical spectral ratio, and gravity. These methods can be applied in locations where depths are unknown and where access is difficult such as in wetlands or steep slopes. They are often able to produce large amounts of data to cover large areas. However, they require significant training to acquire reliable data and even more training to design and interpret geophysical surveys. As a result, qualified personnel who can collect and analyze geophysical depths to bedrock might be limited. Some methods perform better in specific environments than others. For example, multiple-coil ground conductivity meters work best when there is a contrast between the electrical conductivity of the overlying soils and

Figure 14. A DualEM ground conductivity meter in use. This unit records both data and location at the same time. (Photo: David Hart.

bedrock. In eastern Wisconsin, the Kewaunee and Holy Hill Formations are orders of magnitude more conductive than the underlying dolomite bedrock making ground conductivity meters a viable geophysical method in that location. Different equipment and methods perform better for different depths as well. For example, a low power electrical resistivity imaging unit will not be able to produce enough current to image more than 50 feet depth. Likewise, a low frequency ground penetrating radar antenna, e.g., 50 MHz, will be unable to image shallow bedrock depths of less than several feet since the wavelength is greater than the depths of interest. Geophysical methods are indirect measurements and so generally provide approximate depths. For this reason they should be corroborated by other independent and direct methods such as drilling or hand probing.

7. Airborne Electromagnetics

Figure 15. Area to be covered by AEM flights over the Silurian dolomite.

Airborne electromagnetics (AEM) has tremendous potential to aid in creating depth-to-bedrock maps. These surveys use the same physical principles as ground conductivity meters mentioned above and shown in Figure 14 and provide an indirect measurement of depth-to-bedrock. In these systems, one coil induces current in the subsurface while another measures the induced current. Better conductors are indicated by more induced current. If the system uses several different frequencies for frequency domain electromagnetics or multiple time windows for time domain electromagnetics, then multiple layers can be resolved. If there is significant contrast between the overlying soils and bedrock with sufficient soil thickness, then these methods can provide estimates of depth-to-bedrock. It is expected that these data can be used for additional interpretations such as mapping fault offsets or saline waters in deep aquifers. These systems have been used with success in Nebraska and Denmark (Eastern Nebraska Water Resources

Assessment; Barford and others, 2016). At this time, AEM is not widely available in Wisconsin and its efficacy to image depth-to-bedrock in Wisconsin has not been tested. However, a pilot study is currently underway that will support depth-to-bedrock estimates over the Silurian dolomite in eastern Wisconsin. These data will cover several thousand linear miles of flights at ½ mile intervals across area of interest shown in Figures 15. The data density along the flight lines will be around one sample every 100 feet. These data, coupled with WCRs and other direct data, should dramatically increase the data density for much improved depth-to-bedrock maps. Collection of these data has a large up-front cost but the cost per area is much lower than other methods. This method is limited in that it is unlikely to resolve depths of less than five feet and may have difficulty accurately resolving a sharp conductor transition at the soil/bedrock interface. The interface may be "smeared" over several feet or more.

8. Engineering and Study Borings and Core

Figure 16. WGNHS core drill rig in operation.

Depth-to-bedrock is an important measurement for foundations of engineered structures such as roads, bridges, buildings, manure lagoons, windmills, and pipelines. The depths are measured using drill rigs, percussion hammer drilling, and coring. These methods are direct indications of depth-to-bedrock. Coring provides the most definitive indicator of bedrock since the core is retrieved and can be observed. Bedrock depth is identified in the other methods by a distinct change in drilling. Either the bit refuses to advance farther or drilling slows and bedrock drill cuttings are brought to the surface. Drilling to refusal might underestimate depths if excessively hard indurated soils or boulders are encountered. Soil samples are often collected during drilling and coring. The soil samples can informs the geophysical interpretation or hydraulic properties of soils. These data would be the highest quality of all the methods. This is because engineers or geoscientists collect the data or provide oversite during data collection and the data must meet high standards since they are used for construction or research. As a result, depth and location accuracy, detailed soil descriptions, and details of the drilling method and conditions are available. These depth-to-bedrock data are available from multiple sources including the DOT, WDNR, and the WGNHS. The DOT maintains records of borings and core drilled for road and bridge construction. These data have very high locational and elevation data with high quality geologic description but the data is unlikely to be in a convenient electronic format. The WDNR maintains records of borings completed for several programs. Activities at a CAFO such as building manure storage require borings to be completed and submitted to the WDNR before construction is begun. Another WDNR source would be from the Bureau for Remediation and Redevelopment's Tracking System (BRRTS). The user could search this database for sites in the area of interest and review the reports for depth-to-bedrock information. Last, the WGNHS and university and college researchers conduct groundwater and geologic studies. Data from the drilling supporting those studies can be found in the project reports, bulletins, technical reports, and the researchers' project files. Figure 16 shows a core drill rig at a field site.

Methods, Tools, and Considerations for Creating a Map

The following discussion describes some of the tools and best practices used to create depth-to-bedrock maps here in Wisconsin. It is meant to address common issues and help guide the mapmaker through the multiple decisions made during creation of depth-to-bedrock maps.

Use GIS databases

A database that is designed for use in a GIS software application is called a geodatabase. The advantage of using a geodatabase to store data is that the structure of the geodatabase allows for increased functionality by allowing the creation of relationships between the spatial data (points, lines, polygons) and any data tables containing associated data. There are also performance improvements in speed, built-in and customizable functionality, customizable structure, portability, and versioning. ESRI ArcGIS allows the creation and population of different types of geodatabases, but some of those databases are proprietary, and some data are not easily transferred to other GIS applications. The open-source application QGIS is a powerful GIS with many comparable geoprocessing tools, and current versions of QGIS can access data inside ESRI geodatabases.

Visualization of data and surfaces

A tool to visualize geographical data is essential. This tool could be GIS software such as QGIS or ArcMap. It could also have a more geologic focus such as RockWorks or Petrel. The Geostatistical wizard in ArcGIS Desktop and ArcGIS Pro is a collection of tools for analyzing your data points statistically, spatially, or visually. Many of the tools are common statistical methods for evaluating the distribution of data points. Most use graphical displays to display data points to a calculated trend. There are many options for display and comparison, but the goal is the same, to identify and examine outliers in the data that may influence interpolation or interpretation.

More information about the Geostatistical Wizard tools in ArcGIS Desktop or ArcGIS Pro is available here:

DESKTOP: https://desktop.arcgis.com/en/arcmap/latest/extensions/geostatistical-analyst/a-quick-tour-of-geostatistical-analyst.htm

ArcGIS Pro: https://pro.arcgis.com/en/pro-app/latest/help/analysis/geostatistical-analyst/get-started-with-geostatistical-analyst-in-arcgis-pro.htm

The 3D applications like ESRI ArcScene and the 3D Window in ArcGIS Pro can be used to find outliers visually. Statistical outliers are often visual outliers as well, and when displaying point data in 3D it is sometimes obvious which points are the outliers. Both applications allow for the editing of data in the 3D environment. By changing vertical exaggeration, changing symbology, turning data layers on/off, rotating the data, querying the attribute table to select desired/undesired data, changing transparency of data, the user can often see erroneous points relative to the rest of the data set.

Interpreting slope into the subsurface

Where bedrock is exposed at the land surface, the top-of-bedrock surface often sticks out above the surrounding land surface and dips steeply into the overlying sediments that surround the bedrock knob or pinnacle. This geometry creates issues for interpolation schemes that rely on low density data points like wells, because such interpolations typically underestimate the topography and slope of the bedrock surface. Interpreting the slope of a geologic formation or top-of-bedrock surface into the subsurface involves creating data (lines and points) to continue the observed slope into the subsurface. The slope of a buried bedrock unit can be extrapolated by analyzing the slope of that same geologic formation where it has been exposed to subaerial erosion, calculating the mean slope (degrees or percent, but be consistent), and creating concentric contour lines adjacent to some known or approximate bedrock depth. The steps to create the depth to bedrock surface are to (1) Create an initial surface without the bedrock pinnacle or knob; (2) Create a series of concentric contours around the pinnacle or knob that have the same slope as the pinnacle surface; (3) Delete contours that extend below the initial bedrock surface; and (4) Recreate the bedrock surface using the original boring data and the contours above the initial surface. The process is illustrated in Figure 17.

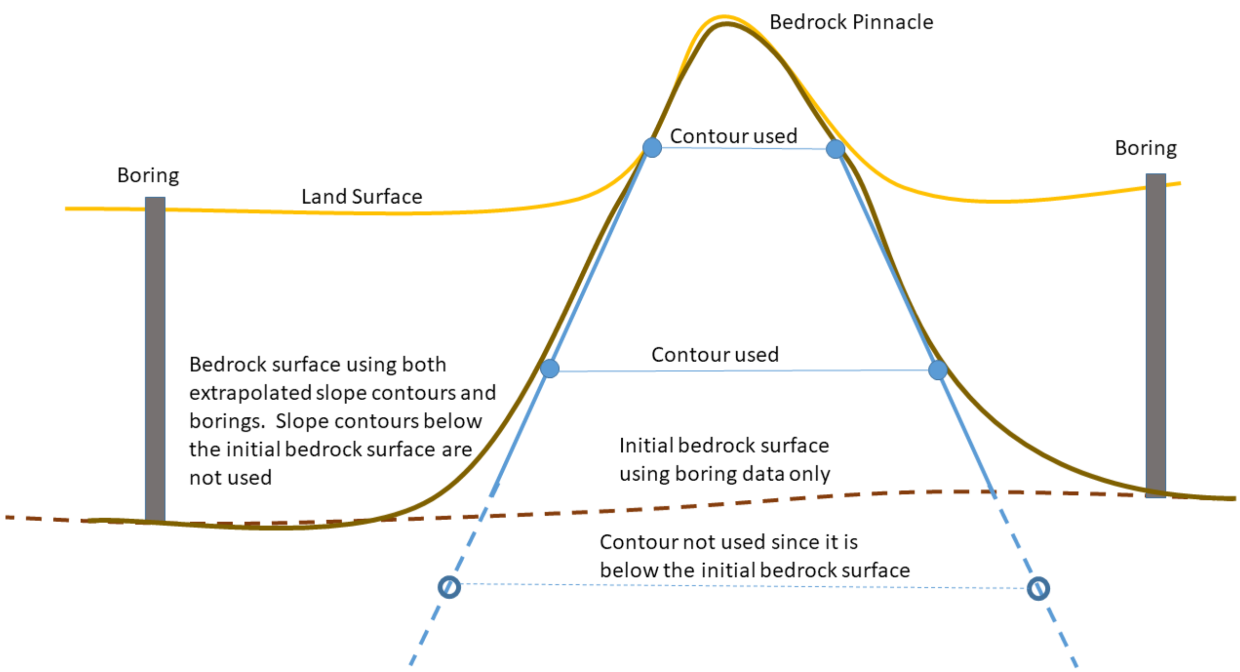


Figure 17. Cartoon of slope extrapolation method to create bedrock surface around bedrock pinnacles.

Integration of Geologic mapping

It is crucial to integrate geologic mapping when interpreting depth-to-bedrock. Any available geologic maps should be examined closely when mapping the depth or elevation of bedrock. Geologic maps are produced with much consideration given to the dynamics of the landscape, the transport and processes of deposition, and the displacement of materials by weathering and erosion. Geologic maps describe the chemical composition, texture, physical properties, and distribution of the bedrock formations. By examining the bedrock and quaternary geologic maps, an author can test hypotheses about controls on the bedrock surface and make interpretations about the depth or elevation of bedrock, which may in part be influenced by the specific geologic formations on the map.

Bedrock depth vs. bedrock elevation

What's the difference? The fundamental difference between bedrock depth and bedrock elevation is that bedrock depth is relative to land surface and bedrock elevation is relative to mean sea level. Depth is a relative measurement where land surface is your reference. In Wisconsin, land surface is often a rolling, undulating, and inconsistent three-dimensional surface. Land surface is not a good reference. Elevation (or altitude) is a relative measurement of your height above some known reference elevation surface, usually mean sea level.

Bedrock depth mapping is easy if you have a dense data set, collected by a direct and dependable means to measure bedrock depth (push-rod, geoprobe, drill rig, etc.), and the positions and attributes of the data set were accurately recorded. But our reality involves interpolating bedrock depth over large land areas, using just well records and outcrops, and this method produces a poor result if the interpreter does not consider how and where the unlithified materials (sand, clay, gravel, stones, boulders, etc.) are located, and how they got there.

When you consider the repeated glaciation, glacial outburst flooding, enormous glacial lakes, in addition to the lakes, streams, and rivers in Wisconsin that have been eroding, accumulating and transporting unlithified materials for hundreds of millions of years, these processes cannot be ignored when creating a bedrock depth map. Bedrock depth is often a direct result of these geomorphological processes. Quaternary geologic maps outline and describe these types of unlithified deposits and landforms, and explain their genesis. By categorizing groups of deposits and landforms, the map author can formulate and test hypotheses about depth and geology, and apply a depth interpretation to group(s) of deposits and landforms.

Bedrock geology is crucial for mapping bedrock depth. The Paleozoic rock formations in Wisconsin were generally deposited in a series of alternating limestone and sandstone layers, where the limestones are typically the harder, more resistant rock and the sandstones are typically the softer and more easily eroded lithology. Knowing where there is sandstone under the land surface and where there is limestone/dolomite under the land surface allows the author to separate interpretation of the typical bedrock depths above these different formations. For example, almost everywhere in Wisconsin where there is Paleozoic rock, if there is shallow bedrock it is typically limestone or dolomite at land surface. By mapping the bedrock, the relationships between the local bedrock formations, bedrock depth over those formations, and the effects of the local aerial, fluvial, and glacial erosion, become apparent.

Bedrock elevation mapping requires that your data have elevation values instead of depth. It's simple to calculate the elevation of bedrock at a single point when you know the elevation at land surface and the depth of the bedrock at that point. Existing bedrock elevation contours are also easily integrated. But depth contours require a different approach to integrate. Depth contours are continuous measures of depth relative to land surface. The contours must be converted to discreet points to obtain elevations for each point on the land surface, from which you subtract your bedrock depth to derive bedrock elevation.

When mapping bedrock elevation, utilizing bedrock and Quaternary geologic mapping can reveal the relationship between the bedrock elevation, the bedrock formations, the Quaternary deposits, and the erosion in the subsurface. The Paleozoic geology in Wisconsin is a series of alternating carbonate, shale, and sandstone layers, where the carbonate is typically the more resistant cap rock and the sandstone and shale are the less resistant underlying and eroding formations. Figure 18 shows two examples of this with the Silurian dolomite forming an escarpment in eastern Wisconsin and the Ordovician-age Prairie du Chien dolomite forming another escarpment to the west.

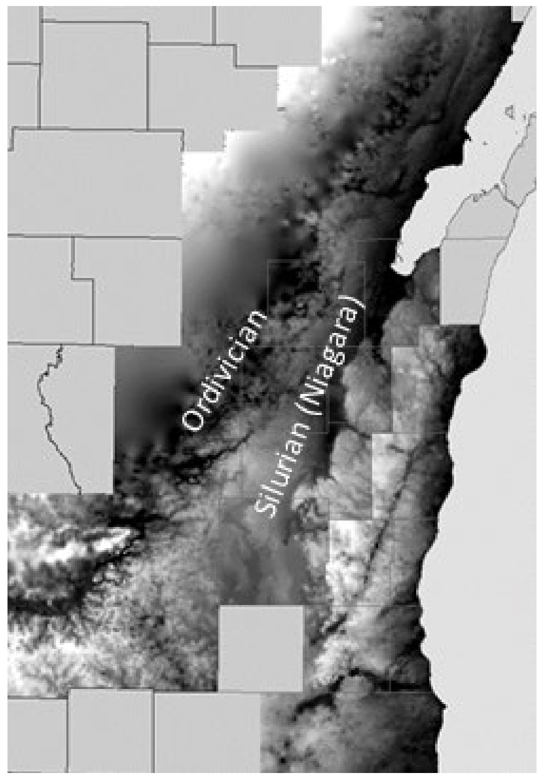


Figure 18. Eastern WI bedrock elevation and the Silurian (Niagara) and Ordovician-age Prairie du Chien escarpments.

Hand and machine contouring considerations

Whether the contours are hand drawn or computer generated, contour lines are "isolines", meaning the value of the variable being mapped is constant along each individual contour line. Computer generated contours are usually produced from a raster file, and the quality and character of computer-generated contours depends on the input data distribution, the noise and error in the signal, the chosen contour interval, the base contour, the statistical distribution of the values of the raster, and the interpolation method used to produce the raster that was the source of the contours.

Hand drawn contours are a human product, and the output depends on the interpretation of the author. An author's interpretation is dependent on their experience. Have they ever drawn a contour map before? It depends on the author's training. If they have made contour maps before, what phenomena were they contouring? It depends on their expertise. Do they have experience compiling many different maps and data sets at many different scales, within a GIS or on paper? Two very experienced contour map authors may each produce similar maps at the statewide scale, but the same two authors may have differing interpretations at the 1:50,000 or 1:24,000 especially if primary data is spatially sparse.

Instead of choosing either hand-drawn or machine-generated contours, the two methods should be merged. “Hand contouring” often takes place in the dynamic scale GIS environment, an impossibility on paper. In the GIS, the freedom of the flexibility of scale often leads to over-complication or over-simplification of the phenomena being contour mapped. In dynamic scale environment, it is best practice to choose and communicate a static “workspace scale” when contouring data. Setting a static scale for contouring in the GIS enables the author to maintain consistent level of detail, or resolution, while contouring.

Resolution of data and map

Just as a map has scale, the data compiled to make that map has scale. If you collect or digitize data at some set spatial interval, that interval limits the scale at which the data should be displayed. As a general rule, a map scale (for example, 1:24,000) should not be larger than the scale of the data used to create the map (for example, 1:100,000). To elaborate, if a 40-acre parcel has only one data point with bedrock depth information, it is inappropriate to construct a map showing depth to bedrock for those 40 acres based on that one data point. Similarly, it’s inappropriate to display dense data collected on a large scale (1:2,000) at a statewide level (1:1,000,000).

When we are considering the scale of the point data, it is a simple calculation to derive a “points per unit area” quotient to determine data scale. However, the spatial distribution of point data may vary greatly across your map area, which means your data scale will vary over the map area, but ultimately the scale of the point data is dependent on the coarsest spatial distribution of that point data.

But how does one quantify the resolution of a hand drawn line? Without a set sample spacing, the scale at which one feels confident to map a specific level of detail is subjective, and data dependent. Whether you use paper or a computer, it is up to the map author to explain the data capture (scaled maps of sample data distribution, scaled maps of different interpolations and/or contour maps, etc.) and the procedure they followed to create the contour data (the scale at which the data was contoured, any additional data such as geologic maps, depth to bedrock maps, bedrock elevation maps, outcrops, etc.) that influenced their interpretation.

Given all these variables, what is the best method to inform the reader of the data scale used to make a map? The best method of informing the map reader is to include both a visual explanation (a map of the data) and a written explanation. When producing an explanatory map of the data, there are two different scale formats to deliver maps, a static scale (this could be paper or digital) or a dynamic scale (exclusive to digital maps). Regardless of the format, displaying the data inputs on a static scale map product may answer many of the questions the map reader may have about how the data scale has affected the interpretation. In the static scale example for the Town of Lincoln (Parsen et al., 2017) shown in Figure 19 below, the authors chose to display the data inputs for the map product on a separate map for the sake of map readability.

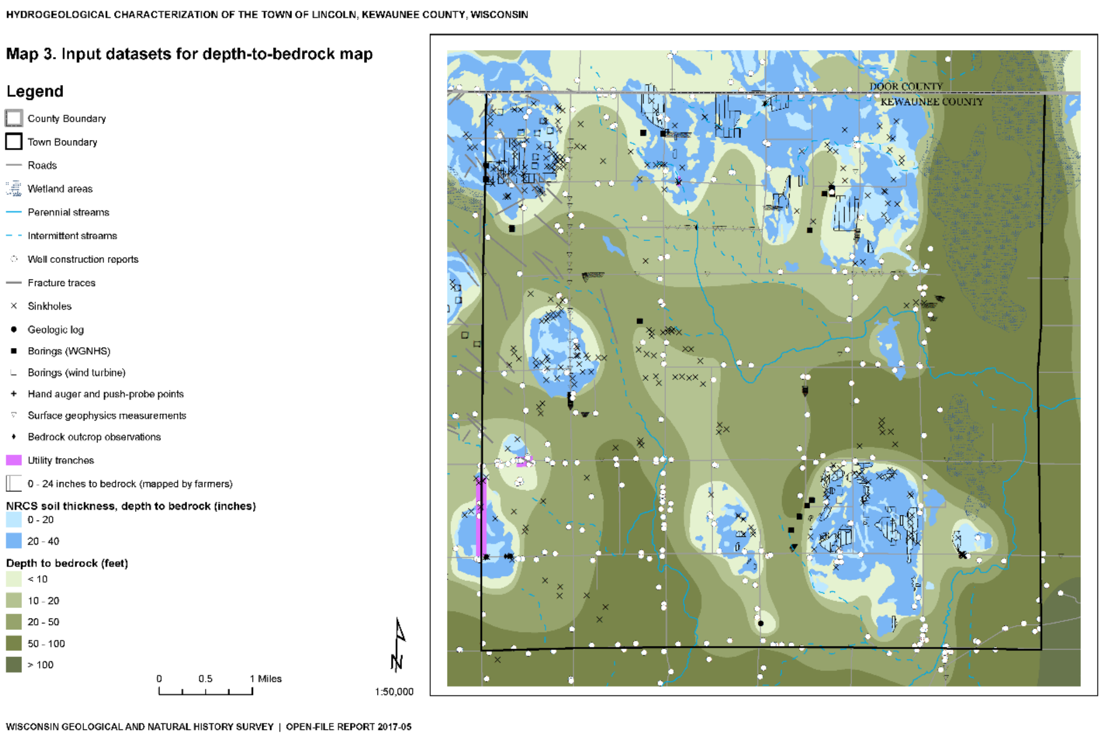


Figure 19. Example of map with input data shown (Parsen et al., 2017).

In a dynamic scale (digital) version of a map product, the data inputs can be displayed in separate layers that can be toggled on or off by the reader, or the data can be limited to display at a set scale (only when zoomed in beyond 1:50,000, only when zoomed out past 1:24,000, or some combination). Google Maps, Bing Maps, and Here Maps are good examples of maps with dynamic scales. In each of those dynamic scale web map applications, the further you are “zoomed in”, more detailed data replaces the coarser data displayed when “zoomed out”, or at small scale. The advantage of this flexibility is when the user “zooms in”, the underlying primary and secondary data for a depth to bedrock or bedrock elevation map can be displayed at an appropriate map scale.

In a static scale map, the display of thousands of data points on the map could interfere or obscure the readability of the map. Unless the data points are sparse, it is often advised to include a separate map plate that includes the input data so the reader can see for themselves the inputs that resulted in the final map. This approach provides the opportunity for a deeper understanding of the map output and interpretation. Alternatively, regions with very dense data could be illustrated as transparent stippled areas that would not obscure the underlying map (e.g., Figure 7).

Interpolation

Simply put, interpolation methods predict the value of some variable(s) at unsampled sites using data from point observations within the same spatial region. (Burrough and McDonnell, 1998). An interpolation creates a continuous raster output with values in all cells, and those values are usually based on the summation of the mean data point values over a given distance, direction, or number of nearby points (deterministic method) or on some statistical method based on geostatistics.

The interpolation tools are generally divided into deterministic and geostatistical methods. The deterministic interpolation methods assign values to locations based on the surrounding measured values and on specified mathematical formulas that determine the smoothness of the resulting surface. The deterministic methods include IDW (inverse distance weighting), Natural Neighbor, Trend, and Spline (ESRI, 2021).

The geostatistical methods are based on statistical models that include autocorrelation (the statistical relationship among the measured points). Because of this, geostatistical techniques not only have the capability of producing a prediction surface but also provide some measure of the certainty or accuracy of the predictions. Kriging is a geostatistical method of interpolation (ESRI, 2021). The general conclusions are that geostatistical methods are generally superior when there are sufficient data to estimate a variogram because, unlike deterministic interpolators, such methods do not treat noise as part of the signal (Burrough and McDonnell, 1998).

How do I know which is the best interpolation method for making a depth-to-bedrock or bedrock elevation raster? None of the interpolation methods were designed specifically to predict bedrock elevation or depth-to-bedrock. Unfortunately, very few Earth science processes are understood well enough to permit the applications of deterministic models. Though we know physics and chemistry of many fundamental processes, the variables of interest (in this case depth to bedrock) are the result of a vast number of processes which we cannot describe quantitatively (Burrough and McDonnell, 1998). Figure 20 is a comparison of three deterministic interpolation schemes (nearest neighbor, spline, and inverse distance weighted) and a geostatistical method (kriging) using hand probe data in an area of shallow depth to bedrock. Red is shallow and green is deeper depth to bedrock. The nearest neighbor and inverse distance weighting interpolations are similar because the methods are similar. The spline interpolation, while also similar, has created a shallow region at the west edge of the model where no data exists. Finally, the kriged surface does not seem to match the data well. This lack of fit is due to use of the default parameters for the geostatistical model. Kriging requires that the geostatistical parameters such as sill, lag, and nugget be varied to reduce misfit. For this reason, we recommend that when using kriging, multiple models be run and those that better fit the data and geology be accepted.

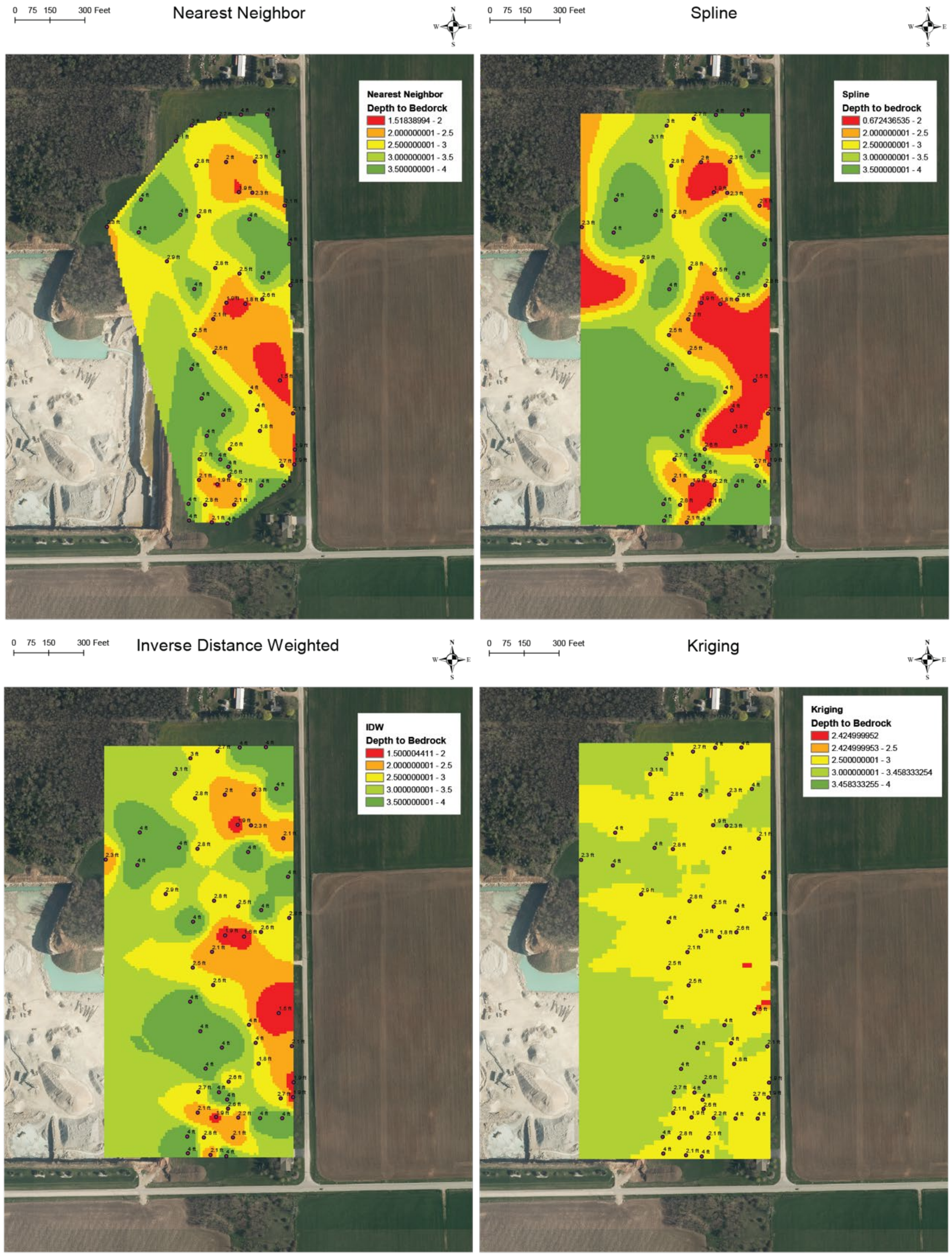


Figure 20. Examples of widely variable results from different contouring methods produced using ArcMap. Agricultural field is located in an area of thin soils (<4 feet). Images courtesy of Nick Peltier (Brown County).

The accepted approach to interpolation is 3 steps:

1) data analysis
2) data modelling
3) evaluation of results

The “data analysis” step involves the quality assurance and quality control tasks like identifying, examining, and editing outliers and errors. These data analysis tasks can often spill over into the modelling and evaluation of the results steps in the approach.

“Data modelling” and “evaluation of results” are somewhat integrated. The accepted approach to these two steps is called validation. Validation requires a complete data set be split into a “training” data portion, and a “testing” data portion, in some adequate ratio (example: 75% training data and 25% testing data) that still allows for the construction of a dependable model. The training portion of the data is used to create the model and optimize the parameters of the interpolator, and the testing data is used to validate the predicted values at the test data locations.

Although validation is the accepted approach for measuring the predictions of the interpolator, the WCR point data in Wisconsin is not spatially dense enough to split the data into “training” and “testing” data sets without degrading the quality of the interpolator output significantly. In counties that have relatively dense WCR data, the data is not dense enough to build a high-resolution bedrock surface for any of those counties using WCRs alone. In Wisconsin, there exist large data gaps of bedrock depth/elevation in areas like wetlands, lakes, undeveloped and agricultural lands, state, federal and municipal lands, and municipalities with just a few high-capacity wells for public water supplies. In large areas of the state where no wells have been drilled for the purpose of obtaining potable water, there is likely no point data informing bedrock depth or elevation, unless exposed bedrock is present.

The spatial interpolation methods, including geostatistics, have been developed for and applied to various disciplines. They are data-specific or even variable-specific. Many factors including sample size, sampling design and data properties affect the estimations of the methods. There are no consistent findings about how these factors affect the performance of the spatial interpolators. Therefore, it is difficult to select an appropriate spatial interpolation method for a given input dataset (Li and Heap, 2008).

There exists no interpolation method that incorporates geology, geomorphology, and topographic position, alongside the primary data to produce an output. Assessing the quality of results without including those known variables into the modelling approach ignores the fundamental problem of employing statistical modelling on multiple variables over space and time. This issue of error is further discussed below in the section on map uncertainty.

Zoning different geologic settings:

One approach that has shown promise is to divide the landscape into “zones” in GIS, based on geomorphology and the subsurface bedrock geology. By examining the interrelationship between the geologic bedrock formations, the geomorphological setting/features, the primary data, and any secondary data and existing maps, a more accurate interpretation can become clearer regardless of geography. By treating these zones separately, additional primary and secondary data indicating depth or elevation over large geographic areas can be incorporated into the interpolation, improving the accuracy of the output without the need for more WCRs.

For instance, in an area that has been glaciated there may be many glacial features composed of unlithified materials (i.e., clay, sand, gravel, boulders, etc.) like eskers, drumlins, moraines, kames, etc. By segregating these features from the rest of the map area, the author can treat the features as a group, or split them into subgroups by feature type. By categorizing these features the author can apply an interpretation of bedrock depth in those areas individually or as a group(s). The same can be said of river valleys or flood plains. By delineating the flood plains within a river system, and segregating them from the rest of the map area, the flood plains, and the bottoms of the river valleys, can be interpreted separately from the other zones in the map area.

Geologic zones can be created from the bedrock formations as well, if they have been mapped. The physical properties of a rock formation may make them more or less resistant to erosion than the overlying or underlying rock formations. If the rock formation of interest is easily erodible, perhaps the depth to bedrock in that geologic zone may be relatively deep. Where there is a more resistant rock formation, it may tend to crop out relative to the other rock formations in the map area. Again, dividing the map area into geologic zones creates the option to treat each zone according to any observed relationship between geologic formations and geomorphic landforms or patterns of erosion.

Uncertainty in Depth-to-bedrock and bedrock elevation maps

What is uncertainty and why is it important for decision making?

Depth-to-bedrock maps provide a representation of the thickness of unconsolidated sediments of an area. Errors in data, gaps in available data, and poor interpretation all create mismatch or differences between mapped depths and actual depths. Since we can't know the actual depth at all locations, we can only estimate the mismatch. These estimations of the mismatch is the uncertainty of the map.

Effective communication of uncertainty aids the decision making process (Fischhoff and Davis, 2014). In the context of depth-to-bedrock maps, decision makers may, for example, use those maps to impose site-specific restrictions on manure-spreading. Locations where the map over-estimates bedrock depth may suffer from increased risk of groundwater contamination by manure-contaminated surface water, while locations where the map under-estimates bedrock depth may result in over regulation that is detrimental to local farmers. Effective communication of uncertainty of depth-to-bedrock maps should allow decision makers to narrow down those locations that would benefit from site-specific evaluation of bedrock depth.

Uncertainty related to understanding bedrock depths can be broken down into uncertainty about (1) the accuracy of the numerical data including depths and locations; (2) the availability or lack of data; and (3) interpretation of the data. These categories roughly mirror Van der Bles et al. (2019) use of “facts, numbers, and hypotheses”. Figure 21 illustrates these three uncertainties.

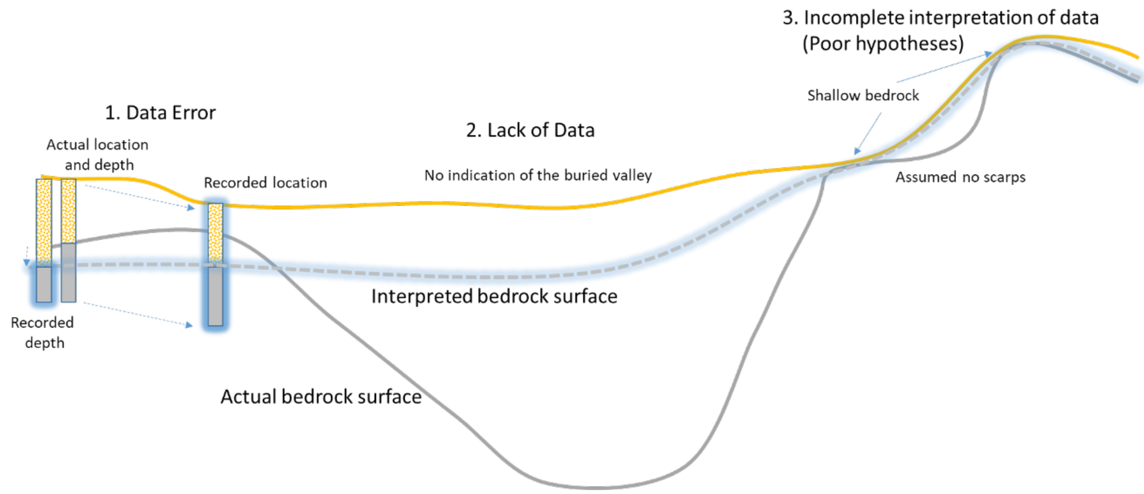


Figure 21. Illustration of the three different causes of uncertainty in depth-to-bedrock maps, 1. Data error, 2. Lack of Data, and 3. Incomplete Interpretation.

1. Numerical data such as depth-to-bedrock in a drilling log or the elevation of a boring all have associated error. For example, the accuracy of the reported depths from the well construction reports is generally not better than several feet and are rarely reported to a precisions of less than a foot. The reported depths also depend on the definition of bedrock. For example, is bedrock defined as the top of solid bedrock, the top of weathered bedrock, or an electrical resistivity value? How is the top of bedrock defined in a location that is underlain by a deep but narrow crack in the bedrock? Depth-to-bedrock values can be directly observed as the depth-to-bedrock recorded by well drillers on well construction reports, or arrived at indirectly from, for example, interpretation of geophysical data or interpolation between values recorded in well construction reports, but all have some error.
2. Lack of available data will also result in mismatch between the actual and mapped depths. For example, buried valleys without any surface expression or depth-to-bedrock data will not be identified or mapped. This aliasing or lack of data will result in a smoother interpretation of the bedrock surface than is actually present.
3. Finally, incomplete or poor interpretations of the data will result in mismatch. These understandings, more formally scientific hypotheses, involve peoples’ ideas of how the world works. For example, a hypothesis applied to depth-to-bedrock is that softer, more readily eroded bedrock lithologies like shale and sandstone are more deeply buried beneath unconsolidated material than resistant lithologies like dolomite or quartzite.

Since scientific hypotheses are working assumptions about the way the world works that are not directly observable (Van der Bles et al., 2019), they often require experience and judgement to be properly applied. Figures 22 to 24 show three different interpretations of the same data (Stewart, In Press), by computer interpolation, contours drawn near the beginning of the mapping effort, and contours drawn at the end of the mapping effort.

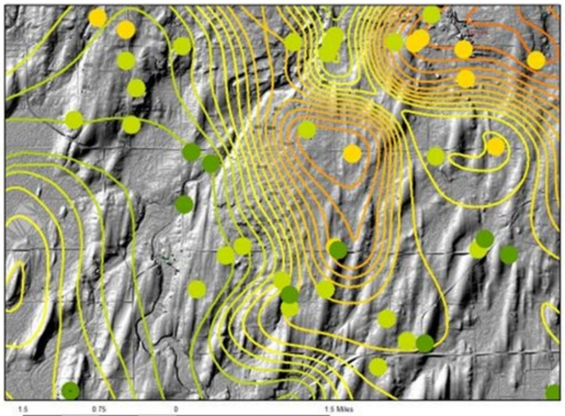


Figure 22. Bedrock surface determined by using computer interpolation without control points.

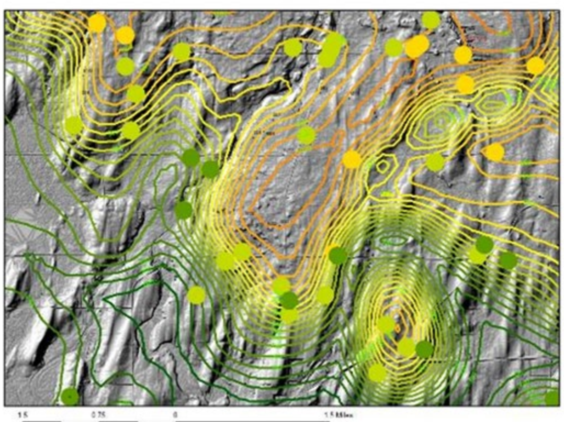


Figure 23. Initial bedrock surface interpreted near beginning of mapping effort.

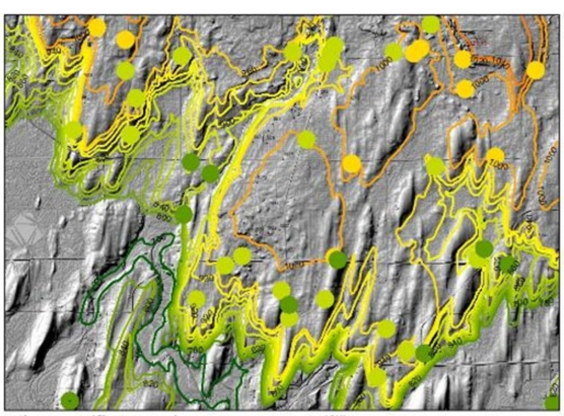


Figure 24. Final bedrock surface interpreted at the end of the mapping effort. It incorporates more hypotheses about factors that influence the bedrock surface.

The result of these three sources of uncertainty is that depth-to-bedrock maps are a synthesis of data and hypotheses about the way bedrock depth varies across an area. They are a model, a simplified representation; they are not a shrunken version of reality.

How is uncertainty measured?

Of the three different types of uncertainty discussed above, only the uncertainty due the accuracy of the data can be estimated, *a priori*. Uncertainty due to lack of data resulting in missed features and variability and uncertainty due to incomplete and poor hypotheses can't be known since we don't know what we don't know. One way the error could be estimated is by setting aside a portion of the data as mentioned above and comparing that to the interpreted depth surface as discussed in the section above discussing interpolation. For example, a percentage of the WCRs in the map area could be excluded from interpretation of bedrock depths. Once the map is completed, the bedrock depths recorded in the withheld WCRs could be compared against the bedrock depth shown on the map at each well's location. Similarly, uncertainty of bedrock depths interpreted from geophysical data could be evaluated through comparison to a set of withheld wells within the survey area. However, the low density of depth-to-bedrock data nearly always forces the mapmaker to use all available data and so it is not possible to test the depth-to-bedrock surfaces to determine the misfit and estimate uncertainty. Use of jackknife or bootstrap methods where multiple subsets of the data are used for creating the bedrock surface and others for comparison could be applied. The process would need to be automated to be useful for the multiple interpretations using the multiple subsets and so would disallow in-depth interpretation by the mapmaker. Stewart (in press) presents a depth-to-bedrock map for Dodge County that is derived from subtracting a bedrock elevation map from LIDAR land surface elevation. This map includes a comparison of the depths-to-bedrock of the interpreted map at each well location to the depth-to-bedrock value recorded in the corresponding WCRs. Although the differences between the interpreted surface and WCRs are residuals that are due to the analysis process, they are informative when compared to the top bedrock lithology: Greater magnitude in the differences between the interpreted surface and WCRs are associated with softer lithology of the Maquoketa shale and (to a lesser extent) Cambrian sandstone units. The few other available published studies of uncertainty in bedrock depth interpretations tend to be site-specific and method-specific (e.g., Gomes et al., 2017; Christensen et al., 2015; Gasson et al., 2015; Zhou et al., 2000).

Precision and accuracy

In the context of depth-to-bedrock maps, precision refers to the contour interval of the map: A map with a one-foot contour interval is more precise than a map with a 50-foot contour interval. Accuracy refers to how close the range of bedrock depths defined by the map contours is to the actual bedrock depth at a specific location. Maps can be precise and accurate, precise and inaccurate, imprecise and accurate, or imprecise and inaccurate (Table 1).

Table 1: examples of precision and accuracy as applied to depth-to-bedrock maps

Precision & accuracy	Bedrock depth indicated by contour interval at specific location	Actual bedrock depth at specific location
Precise, accurate	5 to 6 feet	5.5 feet
Precise, inaccurate	5 to 6 feet	20 feet
Imprecise, accurate	0 to 50 feet	15 feet
Imprecise, inaccurate	0 to 50 feet	150 feet

Distribution of data and map accuracy

Interpretation of depth-to-bedrock maps is complicated by uneven data distribution. In Wisconsin, water wells represent the most significant source of bedrock depth information. However, wells are unevenly distributed across a map area, and focused where people build houses or install irrigation wells. This leads to data gaps in marshes, agricultural fields, surfaces with steep slopes, and sometimes bedrock plateaus or drumlins. Furthermore, wells are often spaced several miles apart, resulting in a data density and data resolution that is below the resolution of bedrock depths stipulated in land use regulations. Maps are more accurate in locations with higher data density. The resolution of the data (both in terms of distribution and uncertainty of individual data points) must be above the desired resolution of the land use decision-maker. For example, the ability to constrain 3-foot bedrock depth from 20-foot bedrock depth is poor in areas with little well or other data constraint. Similarly, even in places of high data density, it may be impossible to differentiate 3- vs. 5-foot bedrock depths if each individual data point can only resolve bedrock depth on the order of 5- or 10-foot increments.

How can uncertainty be displayed on a map?

Recent science communication research has focused on effective methods for communicating uncertainty (e.g., van der Bles et al., 2019, 2020; Fischhoff and Davis, 2014). Effective communication depends on an understanding of the relevant uncertainties that are important for decision making, characterizing those uncertainties, and constructing effective methods for graphical or verbal communication.

Map uncertainty is typically displayed on a map in terms of map scale, contour interval, line type, and display of data points on the map. Map uncertainty may also be communicated in the text that accompanies the map. National map accuracy standards published by the U.S. Geological Survey provide guidance on appropriate map scales for desired levels of map accuracy (USGS, 1999). However, map scale is becoming less meaningful in the digital age when map users can easily zoom into specific locations at very large scales. Contour interval communicates uncertainty, with smaller contour intervals indicating smaller uncertainty that allows for greater precision of the map. Different line style is sometimes used to communicate uncertainty, with a progression from smaller to larger uncertainty corresponding to solid, dashed and dotted lines. The display of data points used to interpret a map is one final way for communicating map uncertainty because it allows the map user to evaluate those locations where the map interpretation is based on lots of data (presumably more accurate) vs. those areas with little or no data and corresponding larger uncertainty.

The above are traditional means used by map makers to communicate uncertainty. If the need to more accurately communicate map uncertainty grows, other methods may be used. For example, along with the interpreted depths to bedrock, a separate map could show the uncertainty of the depths, perhaps as a color flood indicating the potential error as ± depth. The method used to provide the numerical estimates of the uncertainty would need to be described.

Summary of map uncertainty

The information shown on maps has associated uncertainty that should be considered in decision making. Uncertainty is most often communicated on maps via map scale, contour interval, data distribution, and line style. Map users should not use the map to make decisions that require better precision than the map scale or contour interval displays. In most cases, maps are best suited for identifying those areas to focus site-specific investigation of depth-to-bedrock.

Conclusions

Depth-to-bedrock maps are used for many societal needs, including informing land use decisions, designing infrastructure, and applying rules designed to protect groundwater. Inaccurate maps may cause the rules to be improperly applied increasing health risks or creating economic hardship. An inaccurate map may increase the cost of infrastructure by creating the need for additional site characterization. Given the need and utility of depth-to-bedrock maps, the lack of scholarship and publications surrounding them is surprising. In addition, these maps are often given the least attention in a mapping project.

This report is an effort to address the need for more accurate depth-to bedrock maps. Mapping of depth-to-bedrock can be improved by applying following the process and using the tools discussed above. The process allows for multiple iterations, with each iteration improving the map accuracy by eliminating bad data and incorporating geologic knowledge.

Depth-to-bedrock mapping will continue to improve as new data, new tools, and better interpretations become available. Recent innovations include airborne EM data, slope extrapolation, and use of bedrock geology to inform the depth-to-bedrock mapping. These innovations will reduce map uncertainty and improve accuracy. Finally, nurturing a community of geoscientists who can review and understand the issues surrounding depth-to-bedrock mapping is essential to continued improvement of these maps.

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