What Lies Beneath the Iowan?
Hidden Geology of Delaware County

Figure A. Quarry east of Earlville, Iowa, late 1890s or early 1900s.
The area's Niagaran limestone was commonly quarried.

Diane D May
Geology of Iowa

Diane D May

Chad Heinzel, PhD

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Abstract

Delaware County is within a rural area in northeast Iowa. It sits on bedrock of Silurian formations of limestone and dolostone, notably including the Hopkinton formation. While formerly quarried in several locations for building stone, lime, and gravel, this activity has declined gradually since the mid 1800s as the most accessible sites have been played out. The use of water power for mills also has been abandoned. The area has fertile Iowan Surface soils and suitable climate factors therefore the major economic driver is agriculture. In addition, there is some lumber processing and a variety of smaller industrial sites, most located in Manchester, the county seat. A regional hospital and the two school districts are also major employers.

Information from well cores shows strata of sedimentary origin. However, aeromapping has shown sizable geophysical anomalies in both the magnetic and gravity readings. Further study to determine the nature of the material below and its economic implications is warranted.

Introduction

Delaware County is a typical Iowa county with extensive agriculture and low population. Its geology has been studied since the mid 1800s, however, newer geologic information hints that the rock below may be very atypical and may even contain valuable resources that could have large impacts on the county's economic future.

Delaware County is located in the Northeast quadrant of Iowa. It lies west of Dubuque (City and County) and is most easily found on a map by finding the second county west of the border between Wisconsin and Illinois. The area was opened to settlement by the Black Hawk Treaty in 1833 (Iowa History Project, 2016). Scattered settlement followed immediately, with the pace of immigration increasing rapidly with the improvement of transportation, particularly railroad service from the east. Prior to settlement the vegetation was a mixture of open grassland, wetlands, and various densities of forested ground, (See Figure B.) which covered about one third of the area that would become Delaware County (Anderson, 1996). Cameron reports nearly 100 species of trees and shrubs growing in the county, sycamore trees six feet in diameter being cut in the mid 1800s, and extensive forests in parts of the county, although most if it is second growth by the late 1800s. He laments the loss of valuable timberland being cleared to become poor farmland (Calvin & Cameron, 1898).

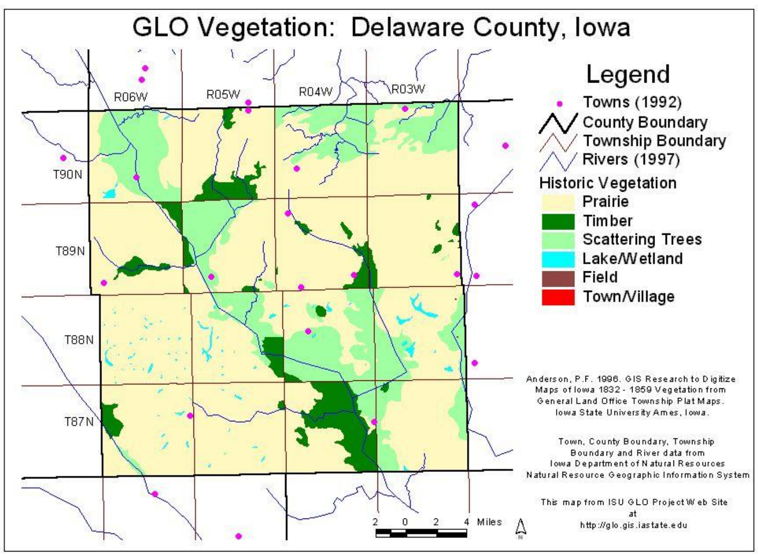

Figure B. Map of vegetation at the time of settlement (Anderson, 1996)

Oldt, in his History of Dubuque County published circa 1910, reports regular rail service to Dyersville, located at the eastern border of Delaware County beginning in 1857 (Oldt, n. d.). Delaware's population had climbed to over 8000 by 1856. (State Data Center, 2016) By 1859 a college opened in the town of Hopkinton. Later called Lenox College, it closed briefly during the Civil War when all the eligible male students enlisted in the army. The college president promptly enlisted as well to serve as their company captain. During the time the president was serving, Samuel Calvin acted as college president. Calvin studied the geology of the area and later became Iowa's State Geologist (Merry, 1914). Some of his later photographs are included here.

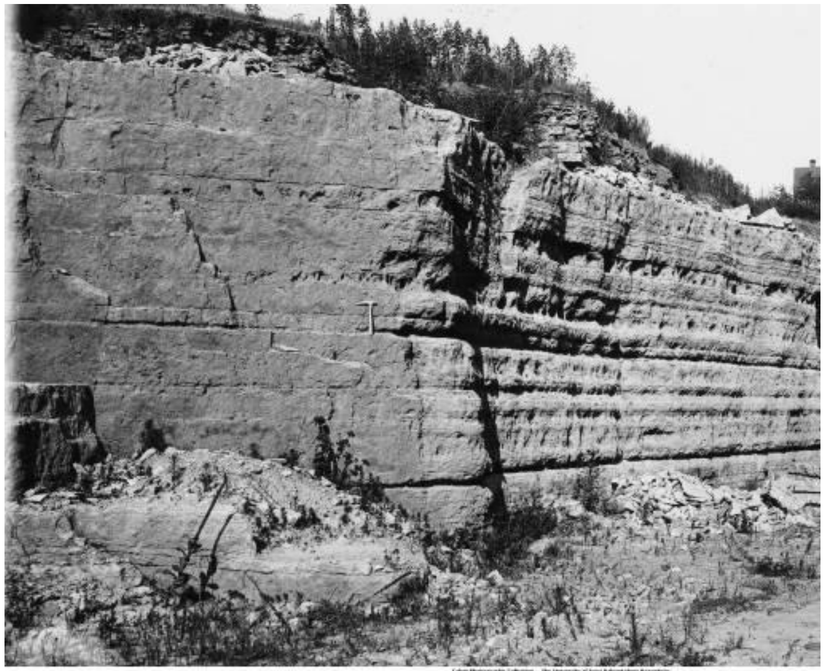

Figure C. Galena Limestone near Dubuque Iowa.
Lead deposits in these strata drove early settlement of northeast Iowa.

The population of the county peaked in the early 1900s. It declined by about two percent in the past five years to just over 17,400, approximately the number of residents in 1875. Within that population less than two percent identify themselves as belonging to a minority group and just under nine percent are in poverty. There are several small towns (populations of 100 to 800) in the county. The town of Manchester (5000 residents) includes nearly one third of the population of the county. The bulk of the population resides outside of a town. The population density of the county is lower than Iowa's average. (State Data Center, 2016). Children of the county attend one of four public school districts: West Delaware, Maquoketa Valley, Edgewood-Colesburg, or Western Dubuque. In addition, there are Catholic elementary schools in the area and one Catholic high school in Dyersville that enroll students from the county.

Many county roads are gravel and vary in quality during the year because of weather. Snow drifts occasionally render side roads temporarily impassible. The primary roads are in good condition. Due to access to Highway 13 and US 20, it takes less than an hour to reach the cities of Cedar Rapids, Dubuque, and Waterloo from Delaware County. There are two rail lines through the county, one east-west and one south to Cedar Rapids. Grain is loaded from four sites. Passenger rail service is not available (Iowa DOT, 2016).

While formerly quarried in several locations for building stone, lime, and gravel, this activity has declined gradually since the mid 1800s as the most accessible sites have been played out. (See Figures A and D.) The area has fertile Iowan Surface soils and suitable climate factors; therefore the major economic driver is agriculture. In addition there is some lumber processing and a variety of smaller industrial sites, most located in Manchester, the largest town and county seat. A regional hospital and the schools are also major employers.

Figure D. Ledge of Niagaran limestone in Loop's Quarry, Hopkinton, Iowa, late 1890s or early 1900s. The county includes many unused quarry sites.

Historically, water was employed at various sites to power mills, however this has been abandoned. (See Figure L.) Calvin lists ten water-powered mills in the county in 1897 (Calvin & Cameron, 1898). A recent plan to convert the dam at Lake Delhi to generate electricity was scrapped. Rainfall averages above 36 inches per year, which is adequate for many farm crops (US Climate Data, 2016). Water for domestic and industrial use is obtained from drilled wells ranging in depth to more than 1200 feet and accessing the Silurian and Cambrian-Ordovician Aquifers according to Iowa Geological Survey records.(2016)

Delaware County is part of the Maquoketa River drainage basin. The Maquoketa drains the area bounded by the Turkey River basin to the north and the Wapsinicon River basin to the southwest. Approximately 20 percent of county land is drained by tributaries of the Turkey in the northeast and 10 percent by the Wapsinicon. The main branch of the Maquoketa River bisects the county from northwest to southeast, running directly through Manchester. There are several large streams including Plum Creek, and a lake in Manchester. Many of the streams exhibit sharp changes in direction. The USDA Soil Conservation Service attributes this characteristic to the effect of fractured limestone bedrock on stream flow (2016). Lake Delhi, located by the town of Delhi, is a man made lake that breached in 2010 causing flooding downstream. After much community deliberation, and with state funding, the dam was rebuilt. The Lake Delhi Dam spillway was closed June 24, 2016 to allow it to refill. Both the dam and the new Whitewater Park in the river in Manchester are expected to provide a boost to the recreational options in the area and the economy.

Figure E. Iowan Drift area topography, Hazel Green Township, Iowa, June 19, 1925, located in the south part of line between sections 28 and 29 in Hazel Green township

Delaware County has extensive agriculture with more than 90 percent of the land in agricultural use (U. S. Bureau of the Census, 2016). The soils range in slope and type, however most areas are predominately various deep loams. This allows the fields to be very productive but also renders them subject to erosion (USDA Soil Conservation Service, 2016). Many sloped fields are contour farmed or terraced to reduce this. Locally, the farms around Petersburg in the northeast portion of the county have a reputation for high quality soil.

Summary of the Geology of Iowa

Bedrock

Iowa is part of the interior lowlands of North America, the physiographic province that extends from Ohio to Kansas. It consists of a stable platform of mostly Paleozoic sedimentary strata ranging in elevation from 500 to 1000 feet above sea level. It forms a large portion of the Mississippi drainage basin and roughly corresponds to the area referred to as the Midwest in economic terms (Hamblin and Howard, 1999).

The Paleozoic rock strata across the state gradually incline downward to the southwest. The Precambrian rock below is igneous and metamorphic and terminates in an unconformity. There are fault zones in the Precambrian strata that have not been active in recently, even at geologic time scales. The Paleozoic rock above that is sedimentary. From oldest to youngest the periods represented are Cambrian, Ordovician, Silurian, Devonian, Misssissippian, Pennsylvanian, Jurassic, and Cretaceous. There are unconformities between and within periods as erosional forces exceeded rock formation. The last bedrock formed in Iowa more than 100 million years ago (Anderson, 1998). Most strata are limestone; some shales and other rock types formed as well.

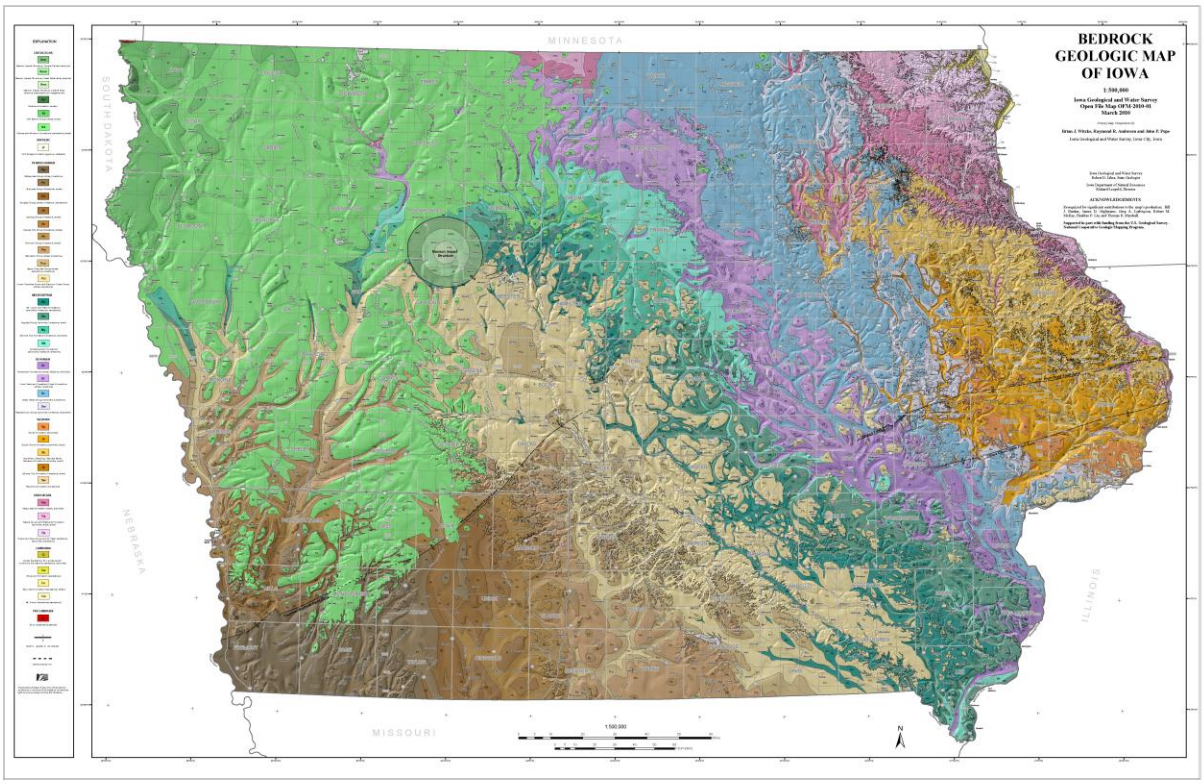

Figure F. The most current bedrock map of Iowa, showing counties overlaid. (IIHR, 2016).

The type of bedrock in Iowa goes roughly from oldest to youngest as one crosses from the northeast to the southwest. (See Figure F.) The northeast corner of the state has the oldest bedrock in a small area near the Mississippi River. These Cambrian rocks formed in shoreline or near shore environments. They are exposed on the bluffs at Lansing and by McGregor and Marquette. In contrast, the bulk of the northeast corner of Iowa has Ordovician bedrock. These rocks are packed with fossils and formed primarily in shallow seas with low oxygen content. They extend from the Mississippi to west of Decorah at the Minnesota border and narrow as they continue south into Jackson County along the river. The quarry at the Mines of Spain Preserve is a good site to observe these thick strata. Ordovician and Cambrian bedrock together correspond to the Paleozoic Plateau landform, also known as the Driftless Area. The area is cut by streams into blocky cliffs. There is little overburden (Anderson, 1998).

West and south of this area is a band of Silurian bedrock that extends from around Delaware County south and southeast to the Quad Cities neighborhood. Rock strata representative of the Silurian are exposed within Backbone State Park in Delaware County. (See Figure F.) Composed of limestone, dolostone and shales, conditions varied during the formation and later dolomitization of these sedimentary layers. Devonian bedrock underlies Iowa just west of the Silurian bedrock, extending across about one third of the state in the north and narrowing as it trends southeast toward the Mississippi. It is also primarily limestone and dolostone, which indicate a marine environment during formation. The presence of shales and gypsum in some areas provides evidence for shallow seas with little water movement (Anderson, 1998).

Figure G. Topography of "Steamboat Rock" at "Devil's Backbone" region similar to that of the driftless area, Dundee, Iowa, late 1890s or early 1900s.

The Mississippian bedrock underlies a narrow band from the area near the juncture of Interstate 35 and Highway 3 in the northwest across central Iowa to the very southeast corner of the state. Mississippian Period strata formed along marine shelves during transgression/regression (T-R) cycles of the inland sea. Various erosional forces have worn away the overlying Pennsylvanian strata to reveal it in many small isolated areas to the west of the main area of Mississippian bedrock. Bedrock that formed during the Pennsylvanian Period covers nearly the entire southern half of the state west of the Mississippian belt. Pennsylvania rock shows formation during shallow marine and non-marine conditions during repeated T-R cycles that caused the formation of huge swamps as the nearly level surface flooded easily with sea rises. These swamps deposited organic materials that became coal. At other times, there is evidence of stream channels and alluvial flats (Anderson, 1998).

A large unconformity forms the upper limit of the Pennsylvanian Period rock. It is the youngest of the Paleozoic Era strata that are found in Iowa. Aside from some small areas with Jurassic bedrock, Cretaceous Period rock covers the remaining northwest portion of the state. The Cretaceous Period in Iowa saw primarily marine conditions and the bedrock contains fossils of fish, marine reptiles, and plankton. Cretaceous bedrock also extends south into the area of Pennsylvanian rock. In addition, a small remnant of the Sioux Ridge is exposed in the far northwest of Iowa. This Precambrian quartzite rock has been dated at greater than a billion years old (Anderson, 1998).

Two sites have impact structures: a recently studied crater under Decorah and a well characterized crater surrounding Manson. Neither of these structures is evident at the surface.

Landforms

Iowa can be divided into landform regions (See Figure H.) by the composition and contours of the surface left behind by the deposition of materials and the following erosion and shifting of those materials. Some of these processes are still evident, such as along streams. The Mississippi Alluvial Plain lies along the Mississippi from the Quad Cities south and extending inland along an ancient lake. The Missouri Alluvial Plain lies along the southern two thirds of Iowa from the river to the Loess Hills to the east. The surface of these plains consists of floodplains, terraces and sand dunes that are usually dry as well as marshes, oxbow lakes and backwaters. Water acting on the plains assures that the surface materials are often well sorted. The same processes occur on a small scale in localized areas along streams throughout the state (Prior, 1976).

Another part of the state that has many wetlands is the Des Moines Lobe landform. This is the site of the most recent glaciations and shows features typical of glacial terrain, including a very level surface formed of a mixture of materials with a range of particle size and origin, and interrupted by topographic changes at the sites of moraines, kettles, and knobs. The area has many natural lakes and poorer drainage than other parts of the state. The younger surface has not allowed as long for drainage systems to form along with the associated erosional features. The soils are often mottled and dark, indications of varying drainage and accumulation of organic materials (Prior, 1976).

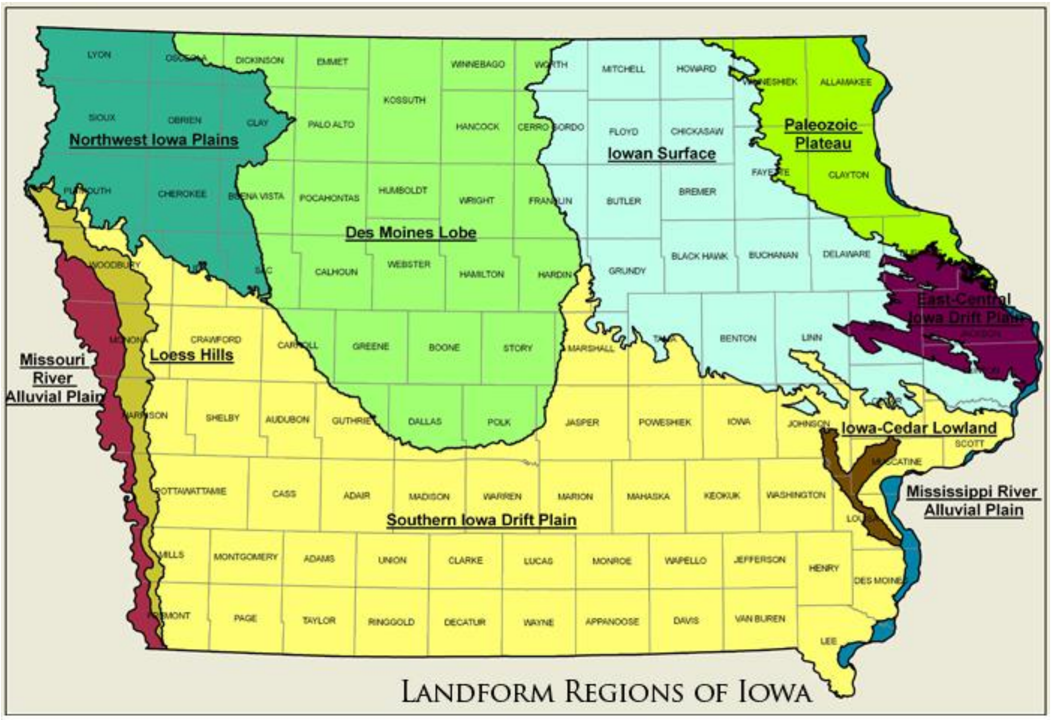

Figure H. Landform map of Iowa, showing surface types. Note Delaware County at the junction of the Iowan Surface, Paleozoic Plateau, and East Central Iowa Drift Plain (Iowa DNR, n. d.).

To the east of the Des Moines Lobe, the Iowan Surface is a gently rolling area with well established drainage systems. The materials are a mix of glacial till covered by loess and sand thought to have blown there from the glaciers to the west. There are elongated hills that rise above the surrounding area that contain thicker deposits of loess called paha. In some parts of the Iowan Surface there is shallow till and soil layers that are underlain by limestone. Karst features like sinkholes are common in these areas (Prior, 1976).

The soil layer is even thinner to the north and east on the Paleozoic Plateau. In this rugged terrain, the bedrock often forms heavily eroded outcrops and high bluffs. Between the eroded stream cuts and valleys the surface is dominated by level bedrock. There is much timber in the area as the land is less desirable for farming (Prior, 1976).

The Loess Hills are another rugged area. They formed from fine particles from glacial terrain blown east to accumulate in thick, loose layers. Erosion then cut the surface into angular steep faces that are prone to slump when precipitation lubricates the mass. Small downslope movements form “catsteps”. The steepness and high erosion rates limit agricultural use. Sharply defined on the western face, the Loess Hills gradually taper into the steeply rolling landscape of the Southern Iowa Drift Plain (Prior, 1976).

About half of Iowa is covered by the Southern Iowa Drift Plain. While the surface materials indicate the presence of glaciers, the well established drainage patterns have removed the topographic evidence glaciation. The soil layers include younger loess, thicker in the west, over paleosols, soil that formed long before the loess deposition. The paleosol is high in clay which affects water movement and soil texture. This makes the area suitable for farm ponds but also reduces the likelihood of productive wells and complicates tillage. A portion of eastern Iowa was previously classified as part of the Southern Iowa Drift Plain; however, it is now often described as a separate landform called the Southeast Iowa Drift Plain. There the terrain is rougher and streams often cut down to bedrock (Prior, 1976).

The final landform is the Northwest Iowa Plains. It is higher in elevation and has less precipitation than other areas in the state, affecting which crops are grown. Its lack of timber also helps to make it appear as a transition zone to the high plains of the Dakotas. It has established drainage patterns on a gently rolling landscape of till and soil as the Iowan Surface does. The Northwest Iowa Plains differ from the Iowan in its deeper till and loess cover and lack of paleosol. Also, rock outcrops are limited to some Cretaceous formations along the Missouri and small areas where the Sioux Quartzite, the oldest bedrock in Iowa, is exposed (Prior, 1976).

Mineral Resources in Iowa

The nearest coal mines to Delaware County are near the border of Scott and Muscatine counties where Pennsylvanian formations are found (Iowa DNR, 2016b). Lead and zinc were mined in Dubuque County and across the Mississippi in Jo Daviess County Illinois and the southwestern counties of Wisconsin. Gypsum is mined in north central Iowa near Fort Dodge where conditions favored the formation of evaporates (USGS, 2016). Stone for aggregates, agricultural use and building have been mined or, in the case of sand and gravel, dug from pits, all over the state. Interesting fossils are found at many sites throughout the state. A particularly active site and accessible is at Graf, Dubuque County (Jean Prior, personal communication, July 7, 2016).

Summary of the Geology of Delaware County, Iowa

Geology of the Bedrock

Delaware County sits on bedrock of Silurian formations of limestone and dolostone, notably including the Hopkinton formation. A resistant ridge of that formation makes up the backbone for which Backbone State Park is named. The formations in this area developed under seas after a period of regression and erosion that left an unconformity at the surface of the Ordovician formations below. The sea level changed during the Silurian deposition, possibly due to global cooling that bound the water into glaciers. The dolomitization of the limestone likely occurred at the shoreline near sea level, where fresh water rich in magnesium mixed with the brine, replacing part of the calcium in the minerals (Anderson, 1998).

Information from well cores shows strata of sedimentary origin far below 1000 feet from the surface (Iowa Geological Survey, 2016). However, aeromapping has shown sizable geophysical anomalies in both the magnetic and gravity readings. These are being studied further to determine the nature of the material below.

Fossils

Fossils confirm the changing level of the sea during the formation of the different rock units. They are primarily of types that occur in normally saline, oxygen rich, marine shelf environments. Algae and linqulid fossils identify the shallow seas during deposition of the Maquoketa and Mosalem formations. In contrast, an inferred depth of 30-100 feet is found during parts of the Hopkinton and Tete des Morts strata formation from the included coral-stromatoporoid (sponge relatives) communities. The presence of brachiopods indicates deeper waters during much of the Hopkinton and Scotch Grove deposition. Other fossils are found in Silurian rock, including gastropods, trilobites and crinoids. The Upper Silurian includes carbonate mounds comprised of skeletal debris and carbonate rich muds. The Gower Formation is part of this time frame and includes the long-quarried Anamosa Stone (Anderson, 1998).

I have collected *Pentamerus* “pig toe” fossils from a construction site just inside the Delaware County border in Dyersville. There the exposed rock was composed almost entirely of fossils.

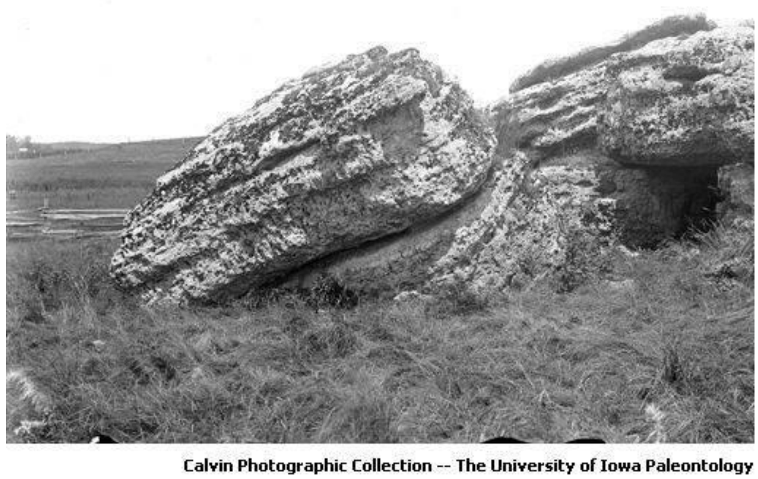

Figure I. Masses in situ on plain underlain by Buchanan gravels, Manchester, Iowa, late 1890s or early 1900s, showing boulders on soil surface, common to Iowan surface.

Landforms

Delaware County’s bedrock is mostly overlain by the Iowan Surface, which is characterized by glacial till and loam soils with some areas of thin loess. Cuts in the Iowan Surface often reveal a stone line where the till and loam cover meet. This is not present in the long low ridge formations called paha. In paha the till is covered by paleosol, and above that, loess. Paha are concentrated near the southern border of the Iowan Surface (Prior, 1976) and so are not common in the county. The Iowan Surface is thought to be the result of erosion of Kansan glacial till and deposits of Wisconsin eluvium, although other processes have been suggested (Troeger, 1983). Glacial erratics once found throughout the area have been used as building stone or moved to facilitate farming. (See Figure I.)

Calvin Photographic Collection -- The University of Iowa Paleontology

Figure J. Monadnock east of Almoral, Iowa, late 1890s or early 1900s.

To the casual viewer, much of the county follows the typical Iowan Surface pattern. The rises are low and it is difficult to follow the slope of the gently rolling fields. This can leave one with the impression that streams are not flowing downhill. However, the drainage is well established and in many places has cut to the limestone bedrock. Early settlers described the streams of the western part of the county as beginning in sloughs. This aspect of the waterways has been changed by tiling of fields to improve drainage and increase the number of tillable acres. Monadnocks, resistant outcrops of the bedrock (Parker, 1997), are often marked by trees that have grown up where tillage is not possible. (See Figure J.)

In the southern and eastern edges of the county the Iowan Surface gives way to the East Central Iowa Drift Plain. This area differs from the Southern Iowa Drift Plain in that the terrain is more rugged and the rivers have cut down to bedrock (Anderson, 1998). (See Figure K.)

Figure K. Beds of passage, Iowa, late 1890s or early 1900s, Niagaran limestone and Maquoketa shale. The stream cuts along a fracture in the limestone bedrock.

Natural Resources of Delaware County Iowa

Delaware County’s natural resources include soils, lumber, gravel, sand, and rock, and possible metal ores in deep deposits. The area was identified as a suitable location for wind power and a number of wind turbines have been installed in the past few years. Water-for crops, human use, electric generation, industry, and recreation-is readily available, though there are significant concerns about surface contamination from agricultural, industrial, and human sources. Nitrates are water soluble and can leach from fields, lawns and golf courses to contaminate streams and groundwater. Shallow wells in Delaware County often have elevated levels of nitrates which can cause health issues, particularly in infants. Most homes and farms outside of towns have their own well (Iowa DNR, 2016). Deeper wells that access the Cambrian-Ordovician Aquifer in communities to the east (Dyersville and Farley) are showing elevated levels of radium, a possible health hazard. This may be a problem if similar wells are installed in Delaware County. The former water power facilities on the Maquoketa and its tributaries are no longer in use and there are no current plans to reestablish the use of that resource. (See Figure L.)

Figure L. The Old Mill, J.O. Strong, Propr., on a branch of Elk Creek, Iowa, late 1890s or early 1900s.

Overall the precipitation level is a benefit for crops and other uses. However, heavy precipitation can lead to localized flooding and crop damage. Although erosion is a concern, farming practices that reduce erosion are employed on a large proportion of the farmland. These include maintaining organic matter on the soil surface, no-till planting, strip cropping, and terracing. Crop rotation is also employed; however, many fields are planted into corn, the most profitable crop, in successive years. This could jeopardize soil fertility and increase the need for pest control.

As livestock numbers on many farms have decreased, less acreage is devoted to pasture and hay crops, which can contribute to erosion. Animal feeding operations also increase the likelihood of manure contamination of water resources. The location of large livestock operations in the county are limited by rules requiring that they be placed away from sinkholes. Much of the county is considered karst terrain as the limestone and dolostone bedrock is near the surface. Known sinkholes are common in the northeast corner of the county, particularly near White Pine Hollow State Park. There are other sinkhole sites scattered throughout the county, becoming less common to the southwest (Iowa DNR, 2016a). The Iowa Geological Survey lists three areas with large numbers of sinkholes: in outcrops of the Galena Group carbonates, in Devonian carbonates in the counties north of Cedar Falls to the Minnesota border, and at the erosional edge of Silurian formations including parts of Dubuque and Clayton Counties (2016). The edge of the Silurian formation extends into Delaware County.

Geology and the Anomaly at Manchester, Iowa

If you are not familiar with Iowa's geology, Delaware County could be considered boring. It does not have the picturesque bluffs of the Mississippi River counties nearby, nor does it have the seemingly endless expanses of fertile soil that Iowa's midlands are known for. And, while the impressive strata of Backbone State Park are close by, most of the local high school students have already made multiple visits to the park.

So, instead I chose to concentrate on an unseen quirk of the county for my project. A significant geophysical anomaly lies beneath Delaware County and forms the southernmost and largest of a series of such anomalies that extend into Minnesota. (See Figures M and N.) These areas are not associated with the linear geophysical differences that are part of the Midcontinent Rift that cuts an arc diagonally through north central to southwest Iowa. Rather, they hint at deep rock formations that differ in composition from the sedimentary strata above. Such high gravity and magnetic readings are often associated with mineral ores (Gubbins & Herrero-Bervera, 2007), so the location may be of interest to geologists and mining concerns as well.

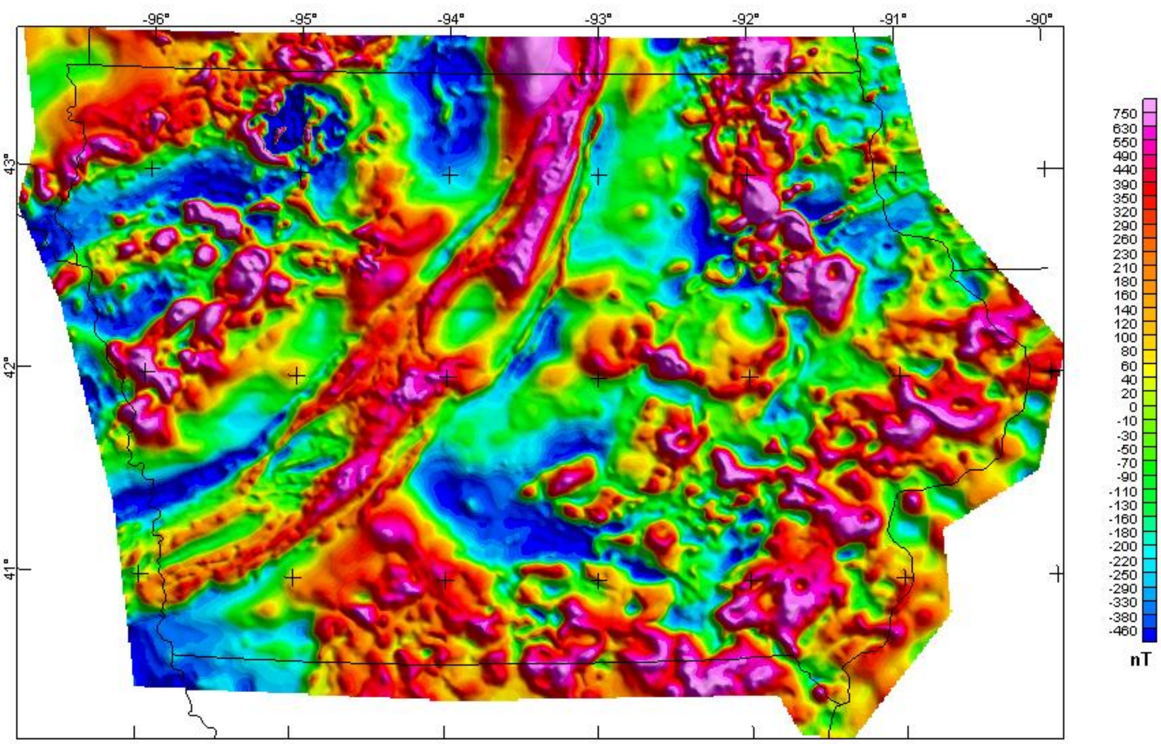

Figure M. Iowa Composite Magnetic Anomaly Map (NE illumination) at simulated flight altitude of 305 m (1,000 ft) above ground, showing the Midcontinent Rift and northeast Iowa magnetic anomalies (USGS, 2013b)

The results of recent geophysical mapping of northeast Iowa anomalies were compared to well-characterized sites with similar patterns of gravity and magnetic anomalies in Ontario, Labrador, and Finland. The authors of a recent report proposed that the anomalies either represent mafic plutons that contain a center portion of less magnet rock or mafic plutons with centers that have reversed magnetism. The second model is more likely to explain the conditions in the Manchester anomaly. Most less-magnetic rock also has lower density and therefore would show gravity readings near normal for the region (USGS, n. d.). However, the site of the Manchester anomaly (See Figure N.) has high gravity readings across the site. (Drenth, B. J., Anderson, R. R., Schultz, K. J., Cannon, W. F., Feinberg, J. M., & Chandler, V. W. 2015).

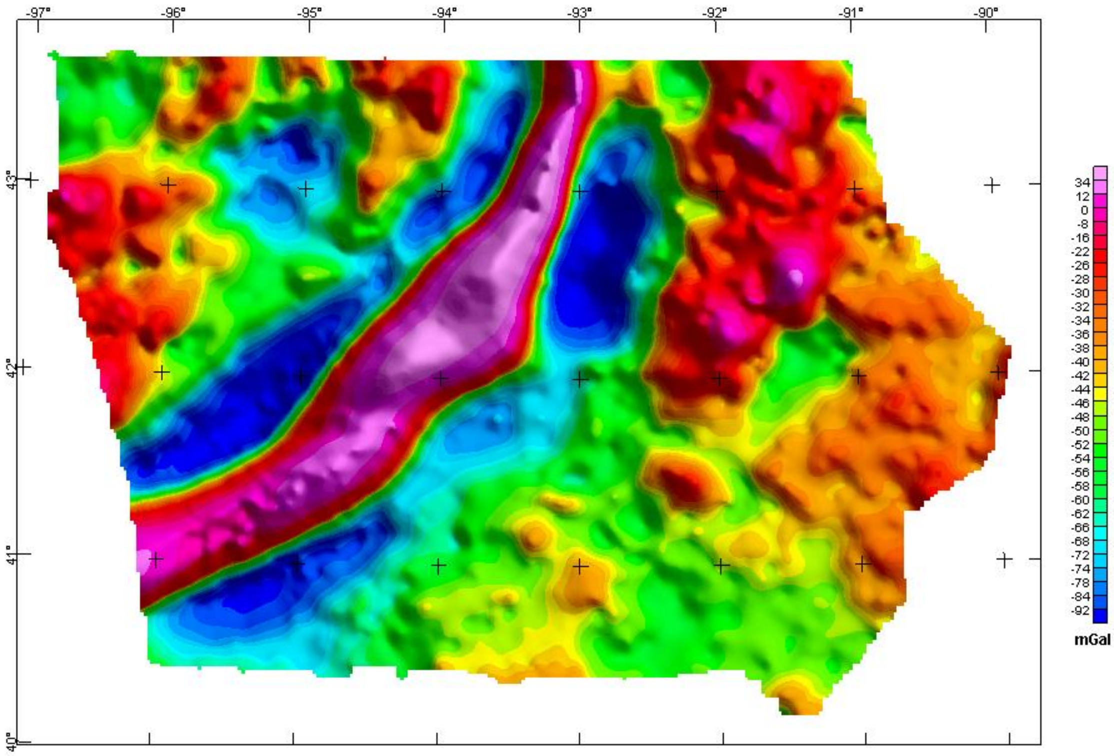

Figure N. Iowa Complete Bouguer Gravity Anomaly Map,
showing gravity differences (USGS, 2013a)

The few deep drill cores within the northeast Iowa anomalies indicate that the intrusive complex lies below more than 200 meters of sedimentary rock. There may still be mining interest. Ores rich in nickel, copper, platinum and other related metals are found in sites with similar geophysical readings in Labrador and the Lake Superior region. Scarcity and improved mining techniques may make these deeper sites economically feasible for mining (Drenth, B. J., Anderson, R. R., Schultz, K. J., Cannon, W. F., Feinberg, J. M., & Chandler, V. W. 2015).

The Appendices contains a lesson plan and other information to familiarize high school students with magnetic mapping.

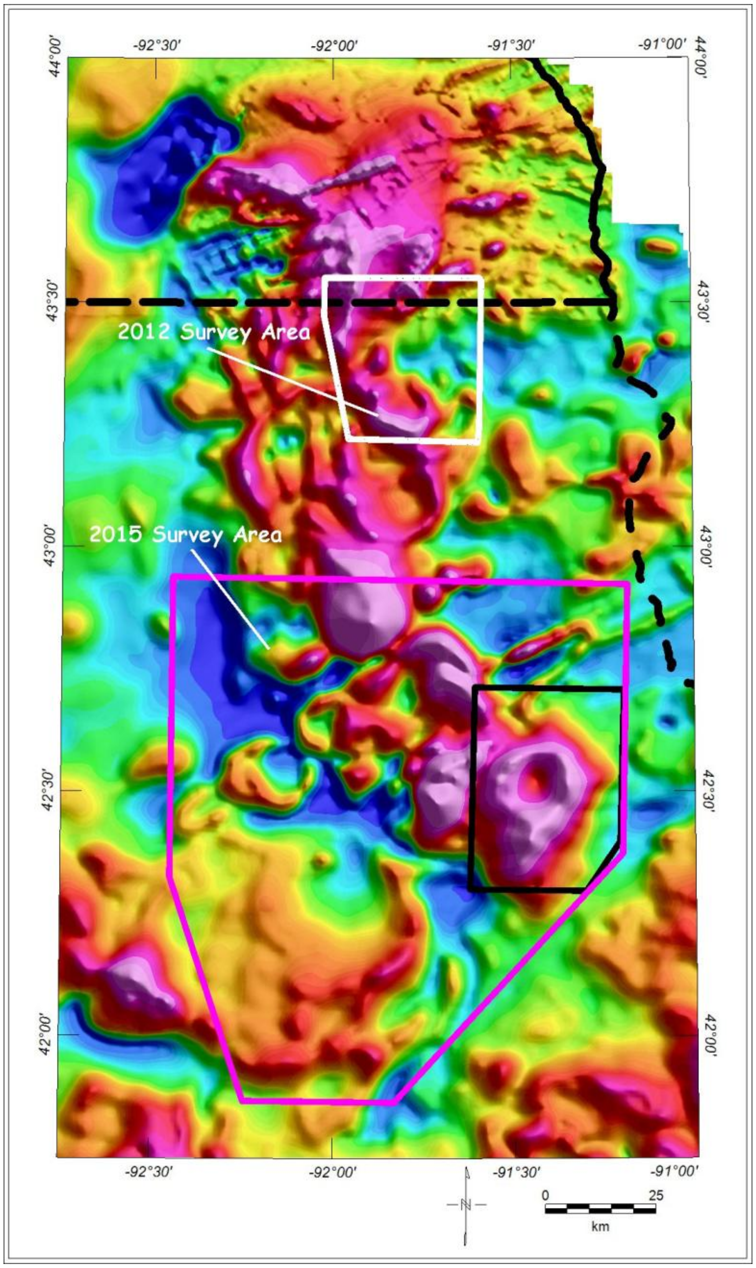

Figure O. Detail of the Iowa Composite Magnetic Anomaly Map showing recent study area. The black outline encloses most of Delaware County. The town of Manchester lies within the circular structure there. The white outline encloses the area around Decorah.
(Ray Anderson, personal communication, 2016)

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Photo Sources

All photos in the figures are taken by Samuel Calvin and can be found in the digital library of the University of Iowa Collection. Retrieved 19 June from the following pages.

Figure A. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/163/rec/21

Figure C. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/95/rec/52

Figure D. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/139/rec/13

Figure E. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/285/rec/24

Figure G. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/167/rec/11

Figure I. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/186/rec/12

Figure J. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/193/rec/13

Figure K. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/115/rec/1

Figure L. http://digital.lib.uiowa.edu/cdm/singleitem/collection/calvin/id/157/rec/6

Appendix A

Geophysical Anomaly Lesson Plan

By Diane D May

Iowa Core Science Standard-HS-ESS3-1: Students who demonstrate understanding can Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity.

Iowa Core 21st Century Skills-21.9-12.TL.3: Apply digital tools to gather, evaluate, and use information.

Related Standards: HS-ESS1-6, HS-PS2-5, HS-PS2-4, 21.9-12.ES.1

Ties to Additional Subjects: History, Economics, Engineering, Environmental Science, Agriculture, Radon Readings

Teacher Instructions

Class Time: 90 minutes

Grouping: Students will work in lab groups of 2-4 students.

Enrichment: This lesson can be extended to student online research, GPS, GIS and drone technology, contacting researchers for questions, etc.

Formative Assessment: The teacher will observe student participation in the lab work and discussion. The teacher will question individuals during the process. Maps will be reviewed for completeness and accuracy, with opportunities to improve it as needed.

Summative Assessment: Vocabulary and concepts from the lesson are included on the unit test.

Supplies:

For class-thin plywood simulated land with 3-4 samples under it that would affect a compass (ex: iron, magnet, electrical device), matching samples and other samples, including local rock, for student testing, online Iowa map of magnet anomalies

For each lab group: smart phone with compass application, magnet, printed magnetic field lines, computer access, and student instructions

Procedures: Prior to Class

1. Prepare the simulated land prior to class time so that students cannot see what has been placed under the plywood. Locate it away from objects that will affect the magnetic field. Locate visible samples in a nearby location.
2. Ascertain that each group will have access to a working smart phone.
3. Check the availability of the website needed to answer the questions.
4. Assemble supplies for each lab group.

During Class

5. Project magnetic anomaly map of Iowa and bring it to students' attention.
6. Have them locate Delaware County on the map and check the key for what the colors mean.
7. Break the students into groups and facilitate their progress through the student instructions.
8. Rotate groups through using the simulated land, preferably limiting groups from observing other groups' results until all groups have tried the simulation.
9. Lead a discussion comparing results and implications of finding a magnetic anomaly in the area, tying their ideas to the Iowa map.
10. If there is sufficient time bring in historical, economic, and environmental, etc. aspects.

Geophysical Anomaly Student Instructions

A. Search for the following phrase "magnetic anomalies for geology and resources" to find a pdf of two articles published by Springer. Use the articles to answer the following questions with your group.

1. Define the term anomaly.

2. What are maps of magnetic anomalies used for?

3. Why are they commonly used instead of other methods?

4. Name four elements that are associated with magnetic anomalies.

5. What areas of the world are shown in the example maps?

6. Compare the magnetic map of Iceland with a “normal” map of the island. How are they similar? How are they different?

7. What was the author’s purpose in including the map of Iceland?

8. How does aeromagnetic anomaly mapping support plate tectonic theory?

B. If you do not know already, find out how to use a compass application for your group’s phone and how it works. What does the arrow point to?

C. Using a magnet placed in the center of the printout with arcs on it, see how the compass arrow on the phone behaves when you move it around the magnet. What do the lines on the paper represent? Describe the behavior of the compass.

D. Try moving the phone near other objects or substances in the room. This should not be done near known magnets. List three and tell the corresponding behavior of the phone compass.

E. Move the compass in a grid pattern over the simulated land. Draw a map on the attached paper, showing the magnetic anomalies. Remember that the compass should be affected by the same forces from the earth within this small area, so changes in magnetic field are probably caused by buried elements.

F. Compare the mapped areas of anomaly to the element samples on the other table. Describe your ideas about what buried elements are under the simulated land.

G. How could finding certain elements be important to Delaware County? Predict possible positive and negative effects for such findings.

Extension Questions: (Answer on the back of the map if you have time.)

1. What is the land in Delaware County primarily used for?
2. What resources are (or were in the past) taken from the ground here?
3. If a company proposed opening a large mine in the area, which of your group members would be in favor of it? Which against? Tell why you each feel the way you do.

Appendix B
This is a PDF of the article that students will access online. (Gubbins & Herrero-Bervera, 2007)

For example, the anisotropy of anhysteretic remanent magnetization (AARM) (see *Magnetization, anhysteretic remanent (ARM)*, *q.v.*) is a method unaffected by paramagnetic constituents. In many cases, a reasonable approximation of single mineral anisotropies can increasingly be obtained. These methods will continue to provide exciting opportunities to advance the state of research relating magnetic fabrics and rock fabrics.

Peter D. Weiler

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Cross-references

Magnetic Susceptibility, Anisotropy
Magnetization, Anhysteretic Remanent (ARM)

MAGNETIC ANOMALIES FOR GEOLOGY AND RESOURCES

Magnetic anomalies and geological mapping

Knowledge of the geology of a region is the scientific basis for resource exploration (petroleum, solid minerals, groundwater) the world over. Among the variety of rock types to be found in the Earth's crust, many exhibit magnetic properties, whether a magnetization induced by the present-day geomagnetic field, or a remanent magnetization acquired at some time in the geological past, or a combination of both. Mapping the patterns of magnetic anomalies attributable to rock magnetism has proved to be a very effective way of reconnoitering large areas of geology at low cost per unit area. The fact that most sedimentary rocks and surface-cover formations (including water) are effectively nonmagnetic means that the observed anomalies are attributable to the underlying igneous and metamorphic rocks (the so-called "magnetic basement"), even where they are concealed from direct observation at the surface. Anomalies arising from the magnetic basement are only diminished in amplitude and extended in wavelength through the extra vertical distance between source and magnetometer imposed by the nonmagnetic sediment layers. Thus *aeromagnetic surveys* (*q.v.*) are able to indicate the distribution of bedrock lithologies and structures virtually everywhere. Interpretation of magnetic anomaly patterns can then lead to maps of (hidden) geology that give direction to the exploration process (Figure M1/Plate 7b). In igneous and metamorphic ("hard rock") terranes, outlines of local areas promising for the occurrence of ore bodies can be delineated for closer follow-up studies. In the case of petroleum exploration, interpretation of the structure of the underlying basement can help understanding of basin development and help locate areas for (costly) seismic studies and drilling. Similar economies in the exploration process can be made through exploitation of aeromagnetic surveys in the systematic mapping of potential groundwater resources, of particular importance in the arid and semiarid areas of the world.

Mineral exploration

The amplitude, shape, and internal texture of magnetic anomalies may be used to indicate the likelihood of finding of certain ore types. Initially, aeromagnetic measurements were used in direct prospecting for magnetic iron ores and in the indirect detection of certain classes of magmatic-hosted Ni-deposits, kimberlite pipes for diamonds, and so forth. Hydrothermally altered areas in magnetic environments are often detectable as low magnetic zones and may be prospective for Au and Pb. The largest concentrated source of magnetic anomaly in terms of magnetic moment is the Kursk low-grade magnetic iron–quartzite ore formation in Ukraine that can be measured even at satellite altitudes. Most of the major satellite anomalies are, however, attributable to entire provinces of relatively magnetic rocks, such as Northern Fennoscandia, of which the Kiruna magmatic iron ore is but a tiny part.

Most ore deposits within the crystalline basement are, either in themselves or through their host rocks, accompanied by magnetic

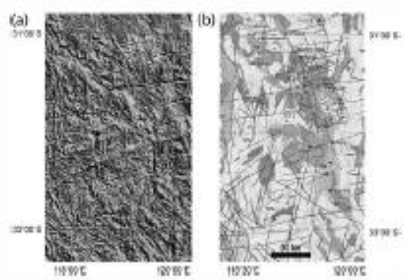

Figure M1/Plate 7b (a) Magnetic anomaly patterns over part of Western Australia recorded in various aeromagnetic surveys. (b) Geological interpretation of the data shown in (a). (Courtesy of Geoscience Australia and the Geological Survey of Western Australia).

anomalies. These anomalies are often used further in the closer evaluation of the extent and geometry of a deposit and in assessing the mineral potential of other comparable geological formations. At the reconnaissance stage of mineral assessment, area selection and prospecting—particularly of soil-covered areas of crystalline basement—geological mapping can be driven in large part by interpretation of detailed aeromagnetic anomaly maps. These provide, in a cost-effective and environmentally friendly way, a reliable picture of the underlying subsurface, including the location and extent of geological units and their lithology, structure, and deformation.

Continental and oceanic anomaly mapping

Given that most countries have a national program of mineral resource management, the foundation of which is the geological mapping program at an appropriate scale (say 1:1000 000), ambitious national programs of aeromagnetic anomaly mapping have been instigated generally to supplement and accelerate geological mapping (for example Canada, Australia, former Soviet Union, the Nordic countries). National aeromagnetic anomaly maps, together with gravity anomaly maps, have therefore become prominent in the geophysical support of geological reconnaissance. Given that gamma-ray spectrometer surveys are now usually flown simultaneously with aeromagnetic surveys at little additional cost, they form a third common type of geophysical support for geological mapping.

Over 70% of the Earth is covered by oceans. The geology here is totally obscured, even over the continental shelves. Until the advent of systematic ocean exploration in the second half of the 20th century, little was known of the geological evolution of the deep oceans. The patterns of magnetic anomaly stripes discovered, paralleling the mid-ocean ridges (Figure M2/Plate 9e from Verhoef *et al.*, 1996), became one of the leading lines of evidence in support of continental drift and, eventually, global tectonics (see *Vine–Matthews–Morley hypothesis*). This revelation must count as one of the most profound advances in our understanding of the Earth's history and its mode of development.

Being of igneous origin, the rocks of the oceanic crust solidify and cool at the mid-ocean ridge while inheriting a magnetic field direction from the erstwhile geomagnetic field. Repeated reversals of that field are recorded symmetrically either side of the ocean-spreading axis as new crust is relentlessly added, a few centimeters per year, at the axis itself. While people's interest in mineral resources of the deep ocean is still limited, understanding the previous locations of the continents, particularly during the past 200 Ma for which ocean floor can still be found, is central to our understanding of geological processes in this period. The sedimentary rocks laid down on the passive continental margins now separated by "new" oceans host a great deal of the world's hydrocarbon reserves.

Ocean crust is eventually recycled into the Earth's mantle via subduction zones with the result that ocean crust *in situ* older than about 200 Ma is no longer to be found. Evidence of the earlier 95% of geological history is therefore confined to the continents. Here a great deal of geological complexity is revealed (Figure M3/Plate 7d; Zonenshain *et al.*, 1991), reflecting repeated orogenesis (mountain building) and metamorphism since the time of the oldest known rocks, dating from the Archean. The patterns of repeated continental collisions and separations evident from more recent geology can be extrapolated into this past. However, poor rock exposure in most of the oldest, worn-down areas of the world (Precambrian shields) hampers their geological exploration. Aeromagnetic surveys assist markedly here, though understanding at the scale of whole continents often necessitates maps extending across many national frontiers, as well as across oceans where present continents were formally juxtaposed.

What holds for investigations into geology and resources over regions or areas quite locally (say, scale 1:250000, a scale typical for geological reconnaissance) also holds for national compilations of larger countries (say scale 1:1000 000) and at continental scale (1:5 million or 1:10 million). Magnetic anomaly mapping is arguably even more useful at such scales since it represents unequivocal physical data coverage, part of a nation's (or a continent's) geoscience data-infrastructure. The view it offers to the geological foundations of continents is therefore of prime importance to improved understanding of global geology. Repeated cycles of continental collision, coalescence, and rifting-apart have led to the present-day arrangement of the igneous and metamorphic rocks of the continental crust, as revealed in continental scale images of magnetic anomalies, such as Australia (Figure M4/Plate 7a; Milligan and Tarlowski, 1999).

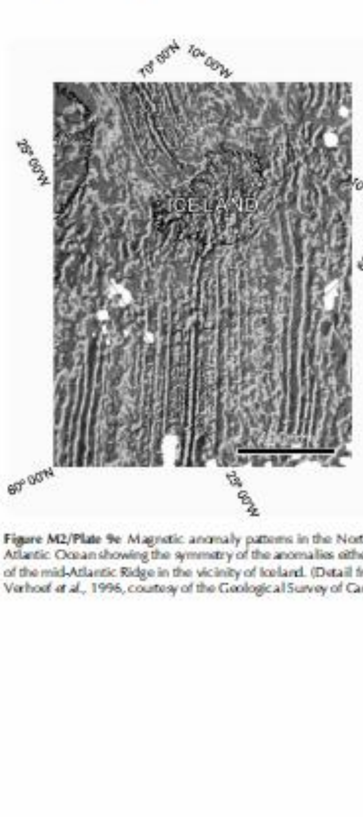

Figure M2/Plate 9e Magnetic anomaly patterns in the North Atlantic Ocean showing the symmetry of the anomalies either side of the mid-Atlantic Ridge in the vicinity of Iceland. (Detail from Verhoef *et al.*, 1996, courtesy of the Geological Survey of Canada).

Continental and global compilations of magnetic anomalies

(Aero-)magnetic surveys usually record only the total strength of the magnetic field at any given point, thus avoiding the need for any precision orientation of the magnetometer. After suitable corrections have been applied for temporal field variations during the weeks or months of a survey, subtraction of the long wavelength (more than several hundred kilometers) components of the field leaves local anomalous values that should be comparable from one survey to another. Thus it is possible—though, in practice, challenging—to link many hundreds of surveys together to make national or continental scale coverages (Tarlowski *et al.*, 1996; Fairhead *et al.*, 1997).

The long wavelength components of magnetic anomalies must be defined in an internationally coherent way, for which purpose the *IGRF* (*q.v.*) was designed and is periodically updated by IAGA. Anomaly definitions still vary greatly between surveys for various

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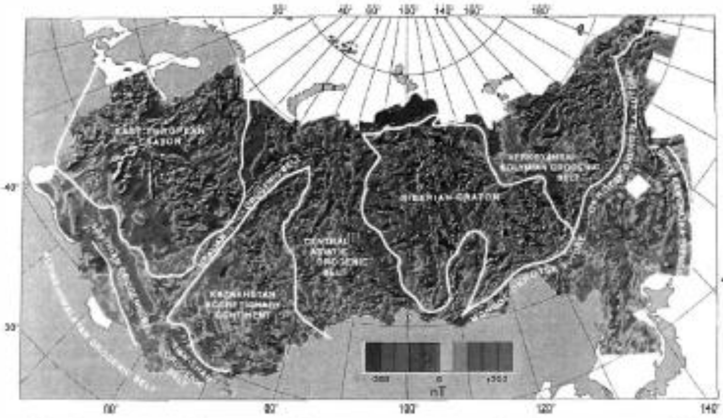

Figure M3/Plate 7d Magnetic anomaly patterns recorded in aeromagnetic surveys over the former Soviet Union with the outlines of some major tectonic domains added. Russia. (From Zonenshain *et al.*, 1991, courtesy of the American Geophysical Union).

Figure M4/Plate 7a *Magnetic Anomaly Map of Australia*, 3rd edn (Milligan and Tarlowski, 1999). (Courtesy of Geoscience Australia).

reasons and, in addition to consistent use of the IGRF, national and international cooperation is required to link and level together the variety of magnetic surveys to a common level. Magnetic anomaly data exist over most of the Earth's surface, mostly a patchwork of airborne surveys on land and marine traverses at sea (Reeves *et al.*, 1998). In 2003, IAGA appointed a Task Group to oversee the compilation of such a global magnetic anomaly map (www.ngdc.noaa.gov/IAGA/vmod/TaskGroupWDMAM-04July12s.pdf) that endeavors to complete its work in time for the 2007 IUGG General Assembly.

Magnetic mineralogy

The physical link between geological formations and their magnetic anomalies is the magnetic properties of rocks (Clark and Emerson, 1999). These are often measured, for example, in connection with Ocean Drilling Program (ODP) analyses, paleomagnetic studies, geological mapping, and mineral prospecting. ODP data provide local information at widespread oceanic locations giving a global coverage. International paleomagnetic databases represent the remanent magnetic properties acquired in the geological past (see *Paleomagnetism*). Magnetomineralogical studies reveal that by far the most common magnetic source mineral of Precambrian shield areas is magnetite. So far, the largest national campaign of magnetic property mapping was that carried out in the former Soviet Union. The results were presented as analog maps. Most of the world's resource of digital petrophysical data for the continents was collected in the Fennoscandian Shield by the Nordic countries (Korhonen *et al.*, 2002a,b). Even so, these data represent only a small part of the crystalline basement of NW Europe. More, similar data sets are required if we are to understand how well this information represents crustal rocks more globally.

The results from Fennoscandia show that, when plotted on a diagram of induced magnetization against density (Figure M5a) the samples form two populations, A and B. Population A represents the paramagnetic range of susceptibilities defined by Curie's law. Compositional variation of Fe- and Mn-oxides correlates with density, the denser, more basic (mafic) rock lithologies being more magnetic than acid (silicic) ones by up to an order of magnitude. This population is only capable of causing anomalies less than about 25 nT, however. A second population of rocks (B), mostly acid in chemistry, represents the ferrimagnetic range of susceptibilities, mainly due to variations in the abundance and grain size of magnetite. This population is two

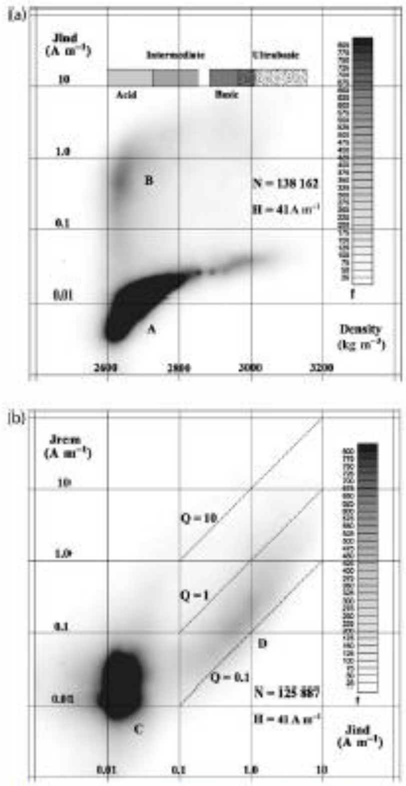

Figure M5 (a) Bulk density and induced magnetization in the Fennoscandian Shield (redrawn from Korhonen *et al.* 2002a). The lower population (A) contains the majority of rock samples, and represents the paramagnetic range of susceptibilities defined by Curie's law. A second population of rocks (B), mostly acid in chemistry, represents the ferrimagnetic range of susceptibilities, due mainly to variations in the abundance and grain size of magnetite. This population is two orders of magnitude more magnetic than the average of the first population (A). (b) Induced and remanent magnetization in the Fennoscandian Shield (redrawn from Korhonen *et al.*, 2002b). For the relatively few rock samples (D) that depart from a low level of magnetization (C), the Q-ratio is mostly less than 1.0, indicating the predominance of induced magnetization over remanent. A few exceptions are, however, highly magnetic. (Courtesy of Geological Surveys of Finland, Norway, and Sweden and the Ministry of Natural Resources of the Russian Federation).

orders of magnitude more magnetic than the average of the first population (A). Population B rocks represent most sources of local, induced magnetic anomalies. Average susceptibilities vary typically from 0.04 to 0.02 SI units for these ferrimagnetic geological formations, but much variation is found from one formation to another.

Another important parameter is the relative proportion of ferrimagnetic (population B) rocks to the effectively "nonmagnetic" paramagnetic (population A) rocks in any given area. For example, it is only a few percent in the magnetic "low" of central Fennoscandia but almost 100% in the northern Fennoscandian "high." Overall in Fennoscandia the average value is about 25%. In oceanic areas, by contrast, it approaches 100%.

Spatial contrasts in magnetic rock properties that give rise to the local magnetic anomalies encountered in mineral exploration are attributable to such factors as (a) the aforementioned bimodal nature of magnetic mineralogy (populations A and B), (b) the effects of magnetic mineralogy and grain size, (c) the history of magnetization and demagnetization, and (d) the variation between induced and remanent magnetization. These are related in turn to geological causes such as initial rock lithology, chemical composition, oxygen fugacity, and metamorphic history.

The ratio of remanent to induced magnetization varies typically from 0.1 to 20, corresponding to rocks containing coarse-grained fresh magnetite (most susceptible to induced magnetization) via altered and fine-grained magnetites to pyrrhotite (with a very stable remanent magnetization). Figure M5b shows the results for induced and remanent magnetization from the Fennoscandian Shield. For the relatively few rock samples (population D) that depart from a low level of magnetization (population C), the *Q*-ratio is mostly less than 1.0, indicating the predominance of induced magnetization over remanent as a source of magnetic anomalies. A few exceptions are, however, highly magnetic (above 1.0 A m^{-1}). For increasingly large source bodies, variations in the direction of all local remanent magnetizations cause the net remanent magnetization to sum up more slowly than the consistently oriented induced magnetization. Hence the effects of remanent magnetization are relatively more important in magnetic anomalies measured close to source bodies (such as on the ground) than farther away (from an aircraft or satellite). This effect is even more noticeable at magnetizations above 1 A m^{-1}, where *Q*-values tend to approach or even exceed 1.0 (Figure M5b).

Colin Reeves and Juha V. Korhonen

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Cross-references

Aeromagnetic Surveying
IGRF, International Geomagnetic Reference Field
Paleomagnetism
Vine–Matthews–Morley Hypothesis

MAGNETIC ANOMALIES, LONG WAVELENGTH

Long-wavelength anomalies are static or slowly varying features of the geomagnetic field, and originate largely within the lithosphere. These anomalies stand in contrast to the rapidly time varying features characteristic of even longer wavelengths, which originate within the outer core. An inflection point, or change of slope, in the geomagnetic power spectrum (Figure M6) can be seen at degree 13 and is a manifestation of the relatively sharp transition from core-dominated processes to lithospheric-dominated processes. Long-wavelength anomalies (Figure M7a/Plate 5c) are most easily recognized from near-Earth satellites at altitudes of 350–750 km, and these altitudes define the shortest wavelengths traditionally associated with such geomagnetic features. The lithospheric origin of these features was firmly established by comparison with the marine magnetic record of seafloor spreading in the North Atlantic (LaBrecque and Raymond, 1985). Virtually identical features have now been recognized in satellite magnetic field records from POGO (1967–1971), Magsat (1979–1980), Ørsted (1999–), and CHAMP (2000–). Long-wavelength anomalies were first recognized by Cain and coworkers in about 1970 on the basis of total field residuals of POGO data.

Although electrical conductivity contrasts (Grammatica and Tarits, 2002) and motional induction of oceanic currents (Vivier *et al.*, 2004) can produce quasistatic long-wavelength anomalies, the largest contributors to long-wavelength anomalies are induced (M_i) and remanent (M_r) magnetization in the Earth's crust. Contributions from the uppermost mantle may also be of importance, at depths where temperatures do not exceed the Curie temperature (T_c) of the relevant magnetic mineral. The earth's main field (H) is the inducing magnetic field responsible for induced magnetization of lithospheric materials. $M_i = kH$ expresses the linear relationship between the inducing field and induced magnetization, true for small changes in the inducing field. k is the volume magnetic susceptibility, treated here as a dimensionless scalar quantity, and reflects the ease with which a material is magnetized. If M does not return to zero in the absence of H, the resulting magnetic field is said to be remanent or permanent. Thus $M = M_i + M_r$, and the relative strength of the two contributions is referred to as the Koenigsberger ratio or $Q = M_r/M_i$.

Inversions of long-wavelength anomaly observations into lithospheric source functions, for example magnetic crustal thickness

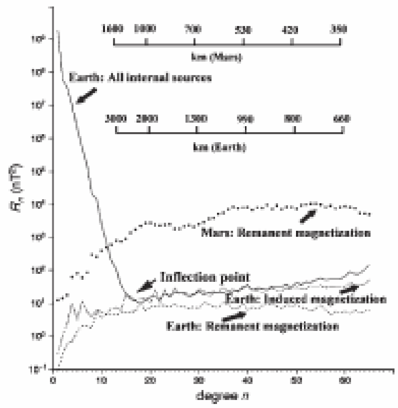

Figure M6 Comparison of the Lowes–Mauersberger (R_n) spectra at the surface of the Earth and Mars for a variety of internal fields. The inflection point in the terrestrial power spectra represents the sharp transition from core processes at low n to lithospheric processes at higher n. R_n is the mean square amplitude of the magnetic field over a sphere produced by harmonics of degree n. The terrestrial spectrum of all internal sources comes from Sabaka *et al.* (2004), the Martian remanent spectrum is derived from Langlais *et al.* (2004), the terrestrial induced spectrum is derived from Fox Maule *et al.* (2005), and the terrestrial remanent magnetization spectrum (of the oceans, and hence a minimum value) was derived from Dyment and Arkani-Hamed (1998).

(Figure M7b/Plate 5d) are subject to many caveats. Simple solutions are preferred, which also agree with other independently determined lithospheric properties. Specific caveats with respect to inversions of these magnetic field observations are that (1) direct inversion, in the absence of priors, can uniquely determine only an integrated magnetization contrast, (2) a remarkably diverse assemblage of magnetic annihilators (Maus and Haak, 2003) exist, which produce vanishingly small magnetic fields above the surface, and (3) the longest wavelength lithospheric magnetic signals are obscured by overlap with the core and it is formally impossible to separate them.

Unresolved research questions include (1) the continuing difficulty of signal separation, especially with respect to external fields (Sabaka *et al.*, 2004), and the particular problem of resolving north–south features from polar-orbiting satellites, (2) the relative importance of magnetic crustal thickness variations and magnetic susceptibility variations in producing long-wavelength anomalies, (3) the relative proportions of induced and remanent magnetization in the continents and oceans, (4) the mismatch between the observed long-wavelength fields at satellite altitude, and surface fields upward continued to satellite altitude, (5) the separation of long-wavelength anomalies caused by motional induction of large-scale ocean currents, (6) the isolation and relative importance of shorter wavelength anomalies (between 660 and 100 km wavelength), and finally (7) the origin of the order of magnitude difference between the observed lithospheric magnetic fields of the Earth and Mars.

Michael E. Purucker

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