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# DRILLING OF AN AEROMAGNETIC ANOMALY IN SOUTHEASTERN SOUTH DAKOTA: RESULTS FROM ANALYSIS OF PALEOZOIC AND PRECAMBRIAN CORE

**by**

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# INTRODUCTION

## Background

An aeromagnetic survey was flown along the Missouri River from Yankton, South Dakota, to Ponca State Park, Nebraska (fig. 1), during 2002 as part of a project funded by the U.S. Army Corps of Engineers and conducted by the Archaeology Laboratory (principal investigator, Brian Molyneaux) at the University of South Dakota. The purpose of that project was to identify possible steamboat wrecks and other cultural artifacts along the river. The hope was that iron, such as that used in the steamboat boilers, would be large enough to be detected by an airborne survey.

The aeromagnetic geophysical survey is commonly used in the geosciences to investigate very old rocks in the subsurface called basement rocks. These basement rocks can be buried very deeply below land surface (thousands of feet in some cases). Despite the depth of burial, magnetic minerals, principally magnetite, present in these rocks can be detected in these surveys. Magnetic minerals in very high concentrations may constitute or otherwise be associated with economic mineral deposits. Thus, rocks that are anomalously magnetic are often of interest to the mineral extraction industry.

The Archaeology Laboratory and U.S. Army Corps of Engineers shared this new aeromagnetic data set with the Geological Survey Program, South Dakota Department of Environment and Natural Resources. Parameters of the flight, grid spacing, and elevation are presented in appendix A. A company named ENW Services of Golden, Colorado, offered to model the basement anomalies in for the Geological Survey Program. Several aeromagnetic “highs” were evident on this map (fig. 1). One of the identified anomalies, an ovoid-shaped, compound anomaly with an amplitude of >800 nT, was identified south of Elk Point, South Dakota.

## Purpose of this Study

The investigation of all subsurface rocks is important to the Geological Survey Program in order to better assess the mineral and water resources of the state. For this reason, the Geological Survey Program drilled at the Elk Point aeromagnetic anomaly (block 6 anomaly; fig. 1). Core from 411 to 1,035 feet below land surface was collected. Water samples were collected from two different bedrock units underlying the Cretaceous Dakota Formation. Some of these same rocks are utilized as aquifers in other areas of the Midwest.

Several researchers from academia and industry have shown interest in the core collected from this hole. Several core samples have been sent out for analysis (chemical, petrographic, biostratigraphic, and mineralogical). Selected information gathered by these researchers is presented in this report and all information is available to the public at the Geological Survey Program office in Vermillion, South Dakota.

## Previous Investigations

### Drilling

Knowledge of the buried basement rock in Union County, South Dakota, is mainly from oil tests (most of which were drilled in the middle of the twentieth century), but where the basement is within 500 feet of land surface, it is sometimes intersected by water wells and Geological Survey Program test holes. Additionally, the Geological Survey Program has historically drilled in various South Dakota counties to determine the source of magnetic anomalies identified in ground magnetic surveys carried out in the late 1950s.

Knowledge of buried Paleozoic rocks in eastern South Dakota is also mainly from oil tests. Several Geological Survey Program geologists through the years have logged Paleozoic rock cuttings from oil tests, attempting to correlate them with a variety of Paleozoic formations that are well studied in other areas of the Midwest. An early attempt at correlating Paleozoic units in southeastern South Dakota with those in adjacent areas of Nebraska and Iowa was made by Jorgensen (1960). Jorgensen (1960) believed the Cambrian Jordan and St. Lawrence Formations, and the Ordovician St. Peter Sandstone and Decorah and Platteville Formations were intersected in the oil tests in this region. He was only partly correct. Much more recent work by researchers in Iowa, Nebraska, and Minnesota (Witzke, 1980, 1983, 1990; Runkel and others, 1998) using considerably more data have established a revised stratigraphy of Paleozoic rocks in this region of the Midwest. Still, well-supported correlations of known formations into South Dakota are largely underplayed in published papers, due in part to the paucity of test holes intersecting Paleozoic rocks in southeastern South Dakota.

### Geophysics

Ground magnetometer, gravity, and aeromagnetic data across South Dakota were available prior to acquisition of aeromagnetic data along the Missouri River for the Archaeology Laboratory at the University of South Dakota. The ground magnetometer data were acquired mainly in the 1940s and 1950s and published by the Geological Survey Program, mostly in the form of maps (Jordan and Rothrock, 1940; Tullis, 1942; Petsch and Carlson, 1950; Petsch, 1958, 1959, 1960, 1961, 1962a, b, and 1967). South Dakota aeromagnetic and gravity maps, data that were not collected by the Geological Survey Program, are available online from the U.S. Geological Survey web site (http://pubs.usgs.gov/of/2002/ofr-02-0341/), and in print (Kucks and Hill, 2002). These data are very useful to identify large-scale basement structures, but generally cannot detect anomalies on the scale of a mile or less.

## Methods of this Study

The processed data from the aeromagnetic survey were provided to the Geological Survey Program early in 2002. Two anomalies identified by ENW Services of Golden, Colorado, were further modeled for location and depth to the source of the anomaly. Modeling of depth to an unknown source requires an assumption of certain physical properties (magnetic susceptibility is the primary one) of both the source and the surrounding rock. Based on the initial modeling of a compound dome, initial estimate of depth to bedrock (at the time this estimate gave a depth to source of approximately 410 feet), and accessibility to the site, the Geological Survey Program decided to drill the block 6 anomaly located 4 miles south of Elk Point, South Dakota (fig. 1).

The initial plan for investigating the block 6 anomaly was to mud rotary drill to basement rock, then switch to a rotary wire line coring method to core the basement rock. On May 29, 2002, drilling of test hole R2-2002-01 (NW¼ NW¼ NW¼ NE¼ sec. 13, T. 90 N., R. 50 W.) began using a mud rotary method. Drilling continued through the Dakota Formation and into the underlying Paleozoic dolostone. At a depth of 429 feet, the drill stem was pulled and a geophysical log obtained. Drilling resumed to a depth of 431 feet, where a fracture system in the dolostone was intersected, the circulation was lost, and the upper sands and gravels in the hole started to collapse. The drill stem was pulled and the hole abandoned.

On June 4, 2002, the drill rig was moved east approximately 50 feet and a second hole was started by mud rotary drilling (this hole has a dual designation of R2-2002-02/R20-2002-01, but will hereafter be referred to as R20-2002-01). The top of the Paleozoic dolostone was intersected at a depth of 409 feet. Mud rotary drilling continued to a depth of 411 feet. Casing was set to prevent caving, and rotary wire line coring commenced (fig. 2). At a depth of 446 feet, in dolostone, a water sample was taken using compressed air to lift water out of the hole. Coring stopped for the summer at a depth of 446 feet and recommenced in October. At a depth of 760 feet, a flowing sandstone formation was intersected. A second water sample was taken at the surface as water flowed from the casing top. At 898 feet, the Precambrian surface was intersected (fig. 3). Coring of the Precambrian rock (metagabbro) continued until a total depth of the hole of 1,035 feet was reached in January, 2003.

A geophysical log of this hole, consisting of single point resistivity, natural gamma, and spontaneous potential, was run from 1,035 feet to the bottom of the casing at 411 feet. Geophysical logs record rock and fluid properties of the bore hole. Single point resistivity logs measure the resistance of the rocks to an electrical current and provide information on lithology. These logs are also affected by porosity of the rock and salinity of the ground water (Keys, 1990). In test hole R20-2002-01, the Precambrian metagabbro has the highest resistivity followed by the dolostones and sandstones. The shales have the lowest resistivity.

Natural gamma logs measure the naturally-occurring gamma radiation of the rocks. The radioisotopes that are the primary gamma emitters are potassium 40, uranium 238, and thorium 232 (Keys, 1990). Shales usually have the highest gamma radiation counts due to their clay content, and organic-rich shales generally have higher counts than other shales (Keys, 1990) because organic layers often absorb uranium (Ehrenberg and Svånå, 2001). Sandstones, dolostones, and siltstones have generally lower gamma radiation counts than shales. In test hole R20-2002-01, the dolostones and sandstones have very low gamma radiation counts.

Spontaneous potential logs record the voltages (potentials) that develop at the contacts between different rock units, particularly between shales or clay beds and sandstone aquifers, and are also affected by the difference in salinity between the bore-hole fluid and the formational fluid (Keys, 1990).

## RESULTS FROM ANALYSIS OF THE PALEOZOIC ROCKS

Results from test hole R20-2002-01 provide further information on depth to the Paleozoic surface and depth to the Precambrian basement in Union County, South Dakota, and a revised model of the aeromagnetic data (fig. 1). Test hole R20-2002-01 is currently the northwesternmost control point for the correlation of Ordovician and Cambrian Formations in the region south-southeast of the Sioux Ridge. Structure contour maps of both the Paleozoic and Precambrian surfaces, which include this new information, are presented in figs. 4 and 5.

Paleozoic rocks directly underlie the Dakota Formation in the area of study (NW¼ NW¼ NW¼ NE¼ sec. 13, T. 90 N., R. 50 W.). The contact between the Dakota Formation and the underlying Paleozoic rocks lies at a depth of 412 feet in the first test hole (R2-2002-01), and 409 feet in the second test hole (R20-2002-01). A geophysical log showing single point resistivity and natural gamma through the Paleozoic rocks and into the Precambrian in test hole R20-2002-01 is presented in figure 6. Spontaneous potential data are not presented in this report, but are available on request at the Geological Survey Program.

Paleozoic rocks younger than Devonian are not present in southeastern South Dakota, although Mississippian rocks have been identified in test holes in northeastern Nebraska and western Iowa (Bunker and others, 1988).

### Devonian Strata

A 35.5-foot thickness of dolostone and limestone of probable Devonian age are present in Geological Survey Program test hole R20-2002-01 (fig. 3). This age estimate is based on an external brachiopod mold of an indeterminate cyrtinid of the family Cyrtinidae (at a depth of 430.1 feet). This family of brachiopod existed from the Silurian through the Triassic, and this particular brachiopod mold (fig. 7) resembles some Devonian forms (B. Witzke, Iowa Geological Survey, oral commun., 2003).

This Devonian(?) carbonate unit is gray and vuggy. Pyrite and dolomite crystals partially fill some vugs, whereas other vugs are filled with a greenish “clay,” possibly insoluble residue of the rock itself. Greenish silica mud is found in layers a few inches thick in this unit (an X-ray diffraction analysis is available at the Geological Survey Program). Thin sandy and shaly zones also occur and commonly show fine laminations. Styolites are present. Cavities greater than 4 inches in diameter, based on a caliper log from Geological Survey Program test hole R20-2002-01, are developed locally.

Devonian strata are not present in the Camp Quest core near LeMars, Iowa (table 1), but are present in other parts of western Iowa (Bunker and others, 1988), including the Quimby test hole (NE¼ sec. 34, T. 90 N., R. 41 W.) in Cherokee County, Iowa (Van Schmus and others, 1989), and in parts of northeastern Nebraska (Doerr No. 1 Boler, table 1; Bunker and others, 1988; Carlson, 1970).

## Ordovician Strata

Over 250 feet of Ordovician strata were intersected in test hole R20-2002-01 (fig. 3). The identified units, from top to base, are the Wise Lake Formation, Dunleith Formation, and Decorah Shale of the Galena Group, Platteville Formation, Glenwood Formation, and St. Peter Sandstone. The greatest thickness (almost 200 feet) is represented by Galena Group rocks. A detailed stratigraphic column of the Ordovician section of the R20-2002-01 core and its correlation with cores from Iowa and Kansas is presented in appendix B, courtesy of Brian Witzke (Iowa Geological Survey).

Not present in the R20-2002-01 core are the Lower Ordovician Prairie Du Chien Group (Shakopee and Oneota Formations). Prairie Du Chien Group rocks are present, however, in much of western Iowa (it is absent in the Camp Quest core, table 1, app. B) and eastern Nebraska (Bunker and others, 1988).

### Galena Group

Regionally, the Upper Ordovician Galena Group consists of several formations. From top to base, these are the Dubuque Formation, Wise Lake Formation, Dunleith Formation, and Decorah Shale. In Iowa, the Dubuque and Wise Lake Formations are generally fossiliferous and noncherty, whereas the Dunleith Formation is generally fossiliferous and cherty (Witzke, 1990). Underlying these carbonate units is the Decorah Shale, which covers a large region of the mid-continent (Bunker and others, 1988). The Decorah Shale thins significantly with distance from the Transcontinental Arch (the Sioux Ridge in South Dakota) and becomes more carbonate-rich (Witzke, 1980). This regional variation suggests that the Transcontinental Arch is the source area for the Decorah Shale (Witzke, 1980).

In test hole R20-2002-01, Dubuque Formation rocks are not present. The upper 27.5 feet of Galena Group rocks in test hole R20-2002-01 are gray, vuggy dolostones with some cavities greater than a few inches in diameter. These rocks probably belong to the Wise Lake Formation (B. Witzke, Iowa Geological Survey, written commun., 2003; app. B). Chert-filled vugs are rare. Vugs partially filled with pyrite and ankerite crystals are common. Some vugs are partially filled with clay, which in some cases is silty or sandy. The cavities and vug filling suggest the development of Devonian karst. Significant cavity zones are likely developed through this formation, as circulation of drilling mud was lost in this formation and was never recovered.

One soft, shaly zone at approximately 470 feet that looked similar to altered volcanic ash (bentonite) was analyzed by X-ray diffraction. The results showed the presence of quartz and dolomite, and possible presence of fluorapatite and illite. A clay analysis was not performed on this sample from this zone, thus, it is still speculative as to whether some volcanic ash could be mixed in with the shale at this depth.

The Dunleith Formation directly underlies the Wise Lake Formation in test hole R20-2002-01. The total thickness of the Dunleith Formation in this hole is 57.7 feet. The upper 48 feet of this formation is a pinkish to gray, fossiliferous, cherty dolostone. Pyrite is common along fractures. Shell fragments are particularly evident in the cherty zones. One fossil, oriented parallel to the long axis of this core, almost 1 foot in length and up to about 0.75 inch in diameter has been tentatively identified as a bryozoan. Sandy and shaly lenses also occur. The lower 9.7 feet of this formation is dolomite-cemented sandstone that grades to a sandy dolostone at the base. The sand grains are mainly subrounded to rounded, range from coarse- to fine-grained, and are almost all quartz.

Generally, the thickness of the Galena Group dolostone increases to the south into Nebraska (compare the drill holes R20-2002-01, Sioux Valley No. 1 Lafleur, and Doerr No. 1 Boler in table 1), and to the east and south across Iowa (B. Witzke, Iowa Geological Survey, written commun., 2003; Witzke, 1990; Bunker and others, 1988; app. B). However, it is significantly truncated by erosion in the Camp Quest hole just across the border of South Dakota near LeMars, Iowa (table 1; app. B).

On the geophysical log (fig. 6), the Devonian and Ordovician carbonates have similar single point resistivity and natural gamma signatures, having generally high resistivity and low natural gamma. However, the Wise Lake Formation appears to have considerably more variable resistivity and natural gamma signatures than the overlying and underlying formations.

The Decorah Shale underlies the Dunleith Formation in test hole R20-2002-01 (fig. 3), and is approximately 112 feet thick, the greatest thickness of the formation known in the region. In this core, the Decorah Shale is mainly a finely laminated, dolomitic, gray-green shale, with thin sandy lenses and dolostone layers. Locally, nondolomitic, fossiliferous, and bioturbated zones occur. The dolostone layers are commonly vuggy. Phosphatic grains are dispersed through this unit. Graptolites are found near the base of the Decorah Shale in this core in a unit that has been identified by Brian Witzke (app. B) as the Spechts Ferry Shale Member of the Decorah Shale. Pyrite occurs as crystals in vugs, as thin, concentrated layers, and as partial fill in worm burrows. Dolomite crystals are also common in vugs. The lower few feet of Decorah Shale in this test hole is identified as the Carimona Member (B. Witzke, Iowa Geological Survey, written commun., 2003; app. B).

On the geophysical log, the Decorah Shale has a distinctively different signature from the overlying carbonates. The Decorah Shale has a high natural gamma and a relatively low resistivity signature (fig. 6).

The Decorah Shale appears to thin to the east. East of test hole R20-2002-01, in the Sioux Valley No. 1 Lafleur oil test (table 1), the Decorah-Platteville-Glenwood together are about 100 feet thick. In northwestern Iowa, the Decorah Shale is about 95 to 100 feet thick (Camp Quest core, table 1), and is only about 60 feet in the M.G. Eischeid No. 1 drill hole in Carroll County, west-central Iowa (Witzke, 1990). However, the Decorah Shale does not appear to thin immediately southward. South of test hole R20-2002-01, in Dakota County, northeastern Nebraska, the Decorah Shale-Platteville-Glenwood is about 150 feet thick (Doerr No. 1 Boler test hole, table 1).

## Platteville Formation

The Upper Ordovician Platteville Formation underlies the Galena Group rocks in test hole R20-2002-01, where it is approximately 17 feet thick (fig. 3). In this test hole, it is a thin, brown, organic-rich, generally finely laminated shaly dolostone that is about 14 feet thick with zones of well-preserved worm burrows. Hardground features are common in the upper portion and phosphatic grains are present in the lower portion of this formation. On the geophysical log, this formation looks similar to the Decorah Shale, but has a relatively lower natural gamma, and generally higher resistivity signature than the Decorah Shale (fig. 6).

## Glenwood Formation

The Upper Ordovician Glenwood Formation is about 12 feet thick and underlies the Platteville Formation in test hole R20-2002-01 (fig. 3). It is a moderately fissile, gray-green shale that is locally dolomitic with a few disseminated phosphatic grains throughout the sequence. Bioturbation is also evident in this sequence. The upper Glenwood Formation contact is gradational with the overlying Platteville Formation.

This formation has a slightly higher gamma signature than the Platteville Formation and a significantly higher gamma signature than the underlying St. Peter Sandstone. On the single-point resistivity log, the Glenwood Formation has a lower signature than both the overlying Platteville Formation and underlying St. Peter Sandstone (fig. 6).

## St. Peter Sandstone

The Middle to Upper Ordovician St. Peter Sandstone is the basal formation of the Tippicanoe Sequence that is separated from the Sauk Sequence rocks (such as the Upper Cambrian rocks described below) by an erosional surface (Bunker and others, 1988).

In test hole R20-2002-01 (fig. 3), the St. Peter Sandstone is typically gray to white, fine- to medium-grained, well sorted, and mature. It is generally poorly consolidated to unconsolidated except for the upper 5 feet and the lower 3 feet, which are well cemented. Minor, inches thick, black, organic-rich layers and pink sandstone layers are present in the St. Peter Sandstone in test hole R20-2002-01. Phosphatic nodules are common in the upper cemented portion and reach 5 millimeters in diameter.

On the geophysical log, the St. Peter Sandstone has a generally higher resistivity signature as compared to the shale-dominated formations, which is typical of sandstones. However, this formation has a variable natural gamma signature (fig. 6). A relatively low natural gamma signature would be expected in a mature sandstone, but the organic-rich layers present in the St. Peter Sandstone have high natural gamma values, resulting in a widely varying natural gamma signal through this formation.

In South Dakota, the thickness of the St. Peter Sandstone varies from 28 feet in test hole R20-2002-01 to 40 feet in Sioux Valley No. 1 Lafleur oil test (table 1). A similar thickness of this unit is found in northeastern Nebraska (Doerr No. 1 Boler test hole, table 1), and northwestern Iowa (Camp Quest core, table 1).

Three split-core samples were collected from the St. Peter Sandstone (at 685.5 to 685.7 feet, 694.5 to 694.9 feet, and 696.35 to 696.6 feet) by Brian Witzke (Iowa Geological Survey) for conodont biostratigraphy (fig. 3). To date, specimens of *Phragmodus* cf. *flexuosus* and *Erismodus* have been identified in one sample (685.5-685.7), and *Erismodus* and *Oneotodus* in another (694.5-694.7).

## Cambrian Strata

Almost 200 feet of Upper Cambrian strata were intersected in test hole R20-2002-01. The identified formations are, from top to base, the Davis Formation, Wonewoc Sandstone, Bonneterre-Eau Claire Formations, and the Mt. Simon Sandstone. Not present in test hole R20-2002-01 are rocks of the Jordan and St. Lawrence Formations, although rocks of the St. Lawrence Formation may be presence in Sioux Valley No. 1 Lafleur oil test (see the Davis Formation section below). The Jordan and/or St. Lawrence Formations are present in western Iowa (table 1) and eastern Nebraska (Bunker and others, 1988).

A total of 12 samples containing either trilobite or brachiopod fossil fragments were collected from the Davis and Bonneterre-Eau Claire Formations (fig. 3) with the help of Anthony Runkel (Minnesota Geological Survey) and sent to A.R. Palmer (Institute for Cambrian Studies, Boulder, Colorado) for identification. The results of the biostratigraphic analysis (table 2) support the formation calls presented in this report.

### Davis Formation

The Upper Cambrian Davis Formation is recognized in the subsurface of western Iowa, northeastern Nebraska, and northwestern Missouri. The Davis Formation is, in part, equivalent to the sandstone-dominated Lone Rock/Franconia Formations in eastern Iowa and southeastern Minnesota (Runkel and others, 1998). In Iowa, the Davis and Lone Rock Formations typically consist of siltstone, shale, glauconite sand, and variable amounts of dolostone (Bunker and others, 1988; Witzke, 1990).

In southeastern Union County, the Davis Formation is mainly green-gray, dolomitic shale with thin (typically no more than inches thick), shaly dolostone layers and minor sandy lenses. Local zones of glauconite sand are also present. Possible bentonitic clay layers occur at approximately 714 and 716 feet. Some dolostone layers are fragmented. The geophysical log signature through the Davis Formation reflects the variable lithologies. The uppermost part of this formation has high resistivity and variable natural gamma signatures (fig. 6), likely reflecting a higher carbonate content through this interval. With depth, the resistivity drops to low values and the natural gamma increases significantly (fig. 6), suggesting a significant decrease in carbonate content and increase in shale content.

The Davis Formation appears to thicken to the south and east in Union County. In test hole R20-2002-01, this unit is 53 feet thick; in the Sioux Valley No. 1 Lafleur oil test, it is 95 feet thick (table 1). However, the 95 feet of Davis Formation in the Sioux Valley No. 1 Lafleur oil test may include St. Lawrence Formation in its upper part, based on the presence of the St. Lawrence Formation in Iowa cores, such as the nearby Camp Quest core (table 1). It is also possible that the thinner sequence of Davis Formation in test hole R20-2002-01 is due to erosion prior to deposition of the Middle to Upper Ordovician St. Peter Sandstone (A. Runkel, Minnesota Geological Survey, written commun., 2005).

Six samples containing possible trilobite fragments were collected from the Davis Formation (fig. 3) by Anthony Runkel (Minnesota Geological Survey) for biostratigraphic analyses by A.R. Palmer (Institute for Cambrian Studies, Boulder, Colorado). Specimens of *Dikelocephalus* cf. *D. minnesotensis* Owen at 706 feet, Dikelcephalid (genus and species indeterminate) at 725 feet, and *Wilbernia* cf. *W.* pero (Walcott) at 741 feet were identified (table 2). Results of Palmer's work confirm that this formation is clearly Upper Cambrian (middle to upper Sunwaptan Stage), Sauk III subsequence (Runkel and others, 1998).

## Wonewoc Sandstone

The Upper Cambrian Wonewoc Sandstone is a laterally continuous formation that extends across much of the mid-continent; it is equivalent to the Ironton and Galesville Sandstones of Minnesota, Wisconsin, and Illinois (Runkel and others, 1998). It was deposited in the Hollandale embayment during the Late Cambrian in energetic offshore to nearshore marine environments. This formation typically consists of a fine- to very coarse-grained quartzose sandstone, but dolostone, shale, and feldspathic or glauconitic sandstone also occur. The Wisconsin Arch and Dome are the probable regional sources for the clastic sediments of the Wonewoc Sandstone, (Runkel and others, 1998).

In southeastern South Dakota, the Wonewoc Sandstone consists of white, brown, and gray, fine- to medium-grained, well-sorted, relatively mature quartzose sandstone. The upper and lower thirds of this unit are well cemented, but the central part is poorly consolidated to unconsolidated. The geophysical log signature through this formation reflects the lithologic variations well (fig. 6). Overall, the resistivity signature of the Wonewoc Sandstone is relatively high and the natural gamma low. However, the upper part of the formation has a higher resistivity signature than any other part of the formation, suggesting this well-cemented interval is carbonate cemented. In the basal part of this formation, the natural gamma increases moderately, an increase that is carried into the underlying formation.

The Wonewoc Sandstone appears to increase in thickness to the south and east. It is 47 feet thick in test hole R20-2002-01 and 64 feet thick in the Sioux Valley No. 1 Lafleur oil test (table 1). In both test hole R20-2002-01 and the Sioux Valley No. 1 Lafleur oil test, this formation had a potentiometric surface that was above the land surface, which resulted in a flow of water out of the top of the core rod.

## Bonneterre and Eau Claire Formations

Both the Bonneterre and Eau Claire Formations are recognized in Iowa and Minnesota. However, in northeastern Nebraska and northwestern Iowa, only the Bonneterre is generally recognized (Runkel and others, 1998). These two formations are essentially time-equivalent, but the Eau Claire Formation is typically sandstone-dominated whereas the Bonneterre Formation is carbonate- and shale-dominated (Runkel and others, 1998).

The Bonneterre Formation rocks could have been deposited in a shallow marine or carbonate-rich tidal flat environment (Mossler, 1992) where sedimentation rates were very low. However, recent work suggests that the carbonates and sandstones of the Bonneterre/Eau Claire were deposited offshore above storm wave base but below fair weather wave base (A. Runkel, Minnesota Geological Survey, written commun., 2005). In either case, low rates of sedimentation are necessary for the formation of glauconite (Ojakangas and Matsch, 1982). Clastic sources for the Hollandale Embayment sediments at this time were mainly the Wisconsin Dome and Canadian Shield (Bunker and others, 1988). The Bonneterre Formation occurs a considerable distance to the west and south of these clastic sources, whereas the Eau Claire Formation is exclusively recognized proximal to these source areas.

In Geological Survey Program test hole R20-2002-01, the Bonneterre-Eau Claire sequence is 81 feet thick. The upper 23 feet (figs. 3 and 6) consists of dark- to medium-gray shale with significant sandstone- and dolostone-rich layers. It is fossiliferous with fossils mainly of inarticulate brachiopods. Pyritic zones and glauconite-rich zones occur locally. Ferroan sphalerite crystals are rare but do occur along with dolomite and pyrite in some vugs. From about 815 feet to 822 feet, the shale becomes lighter in color and more green-gray.

This upper 23 feet may better correlate with the Eau Claire Formation rather than the Bonneterre Formation. The geophysical log signature of this upper sequence has a relatively low resistivity and high natural gamma compared to the lower 58 feet (fig. 6), mainly reflecting the lower volume of dolostone and higher volume of shale here than in the underlying strata. The biostratigraphic sample taken from this interval (R20-2002-01-816, table 2) was likely not a fossil and no time-stratigraphic information from it was gained.

The lower 58 feet of this sequence (figs. 3 and 6) is mainly dolostone with numerous glauconite-rich sand layers. Shale layers are also common starting at 834 feet. As in the upper 23 feet, fossiliferous zones are common. Thin pyritic zones occur in this sequence as well. Pyrite and dolomite occur in vugs, as well as ferroan sphalerite, although rarely. This interval is likely the Bonneterre Formation.

Five samples from the lower 58 feet of the Bonneterre-Eau Claire strata were collected for biostratigraphic analysis (R20-2002-01-820, -821, and -822a, b, and c; table 2). The “820,” “821,” and “822” indicate sample depths in feet. The three R20-2002-01-822 samples yielded trilobite fossil fragments identified as *Aphelaspis sp*., which places these Upper Cambrian rocks in the early Steptoean Stage, Sauk II subsequence. This places the Sauk II-Sauk III boundary (which occurred in the late Steptoean) somewhere between 741 feet in the Davis Formation and 822 feet in the Bonneterre Formation. In Iowa and northeastern Nebraska, this boundary lies within the Wonewoc Sandstone (Runkel and others, 1998). Thus, the biostratigraphic data presented in table 2 are consistent with published data.

The Bonneterre-Eau Claire Formations together are significantly thicker in test hole R20-2002-01 than in the Sioux Valley No. 1 Lafleur oil test (81 and 43 feet, respectively). However, most of the Paleozoic rocks thin to the north and west from Iowa and Nebraska into southeastern South Dakota, so the significantly greater thickness of the Bonneterre-Eau Claire Formations in test hole R20-2002-01 relative to the same sequence of strata in the Sioux Valley No. 1 Lafleur oil test is somewhat contradictory. As the thickness of the overlying Wonewoc Sandstone in the Sioux Valley No. 1 Lafleur oil test is about 20 feet thicker than in test hole R20-2002-01, it is possible that a sandy Eau Claire Formation(?) was mistaken for the lower, well-cemented portion of the Wonewoc Sandstone in drill cuttings in this oil test. Thus, the varying thicknesses of the Wonewoc Sandstone and Bonneterre-Eau Claire Formations between test hole R20-2002-01 and the Sioux Valley No. 1 Lafleur oil test, which are only about 7 miles apart, could in part be accounted for by an incorrect interpretation of the depth of the contact between these formations in the latter hole (the depths of the contacts are reported in McCormick and Hammond, 2004). Based on Marv Carlson's notes (M. Carlson, Nebraska Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln, written commun., 2002), the contact between the Wonewoc Sandstone and the Bonneterre-Eau Claire Formations in the Sioux Valley No. 1 Lafleur oil test could be as high as about 935 feet (instead of 964 feet), resulting in a thickness of the Wonewoc Sandstone of 35 feet, rather than 64 feet, and a total thickness of the Bonneterre-Eau Claire Formations of 72 feet, rather than 43 feet. Unfortunately, there is no geophysical log from the Sioux Valley No. 1 Lafleur oil test to refine the interpretations of depths of formation contacts.

## Mt. Simon Sandstone

The Upper Cambrian Mt. Simon Sandstone is widely distributed throughout the mid-continent. It typically directly overlies Precambrian basement rocks (Witzke, 1990; Mossler, 1992), and reaches thicknesses greater than 1,000 feet in Indiana, Michigan, Illinois, and eastern Iowa, but dramatically thins to the west (Witzke, 1990). This formation consists of sandstone with minor interbedded shale. The sandstone is variable in its mineralogy and grain size, but is typically a white to gray, medium- to fine-grained, mature quartz sandstone (Uribe, 1994). It is thought to have been deposited in a braided stream to shallow marine environment (Mossler, 1992).

In test hole R20-2002-01, the Mt. Simon Sandstone consists of 9 feet of varicolored quartz-rich sand that directly overlies a saprolite (fig. 3) developed on the Precambrian surface. The sandstone is moderately sorted and relatively mature. It is quartz-dominated and typically fine- to medium-grained, but thin, fine-grained gravel lenses (up to 1-inch thick) are also present. This unit ranges from strongly cemented to poorly cemented. Ferroan oolites are present within the poorly cemented upper portion of the sand. Similar oolites have been noted in south-central Minnesota, where they are believed to have formed in nearshore environments (Mossler, 1992).

The geophysical log of the Mt. Simon Sandstone shows a typical sandstone signature of low natural gamma and moderate single point resistivity (fig. 6).

In the Sioux Valley No. 1 Lafleur oil test, 8 feet of quartz-rich pink, red-brown, and white sand overlies Precambrian granite (McCormick and Hammond, 2004). The upper pink to red-brown sand in this oil test is believed to be Mt. Simon strata. The lower white sand could be Mt. Simon Sandstone or may have formed locally by chemical weathering of the granite surface.

The thin, pink sandstone layers in the Mt. Simon Sandstone in southeastern South Dakota apparently have not been described within this formation in other areas of the mid-continent. It is possible that the pink sandstone originated from the Sioux Quartzite Ridge, which was probably locally emergent along the Transcontinental Arch in the Late Cambrian. Through petrographic studies, some lithic sand grains of the Mt. Simon Sandstone in southeastern Minnesota have been traced to the Sioux Quartzite (Uribe, 1994), but a pink color has not been described in the literature.

## RESULTS FROM ANALYSIS OF THE PRECAMBRIAN ROCKS

### Saprolite

At a depth of 898 feet, a 9.8-foot thick unit of very sticky, reddish-brown clay was intersected. Millimeter-sized micaceous flakes and pockets of reddish-brown, crumbly, granulated, highly weathered rock are present within this clay.

The contact between the base of the Mt. Simon Sandstone and this clay is sharp. This sharp contact is reflected in the geophysical log. Below the Mt. Simon Sandstone-clay contact, resistivity drops and the natural gamma rises abruptly (fig. 6). The contact between this clay and the underlying weathered, but competent basement rock is gradational over approximately the lower 15 centimeters. On the geophysical log, resistivity increases gradually from the clay-basement contact (907.8 feet) to a depth of 917 feet (figs. 3 and 6), and the natural gamma stays at about the same level through the entire thickness of the clay and weathered Precambrian basement rock (to a depth of 917 feet; figs. 3 and 6). This suggests that although the physical contact between the saprolite and the weathered basement is sharp, the chemical nature of the contact is gradational from the base of the clay through the weathered Precambrian rock.

This sticky, reddish-brown clay is interpreted here to be a saprolite, which by strict definition, forms in place by chemical weathering of igneous or metamorphic rock. It is possible, perhaps probable, that this clay has in part undergone local transport, but it is doubtful that the transport was on the scale of miles because the aeromagnetic anomaly, of which the underlying basement rock is assumed to be the source, is only about 2 miles in longest dimension (fig. 8). The areal restriction of the metagabbro suggests a restricted source from which the clay developed. Further support for a local source for the clay is that the basement rock surrounding the metagabbro appears to be granitic (as indicated by the Precambrian granite intersected in the Sioux Valley No. 1 Lafleur oil test; McCormick and Hammond, 2004), and the weathered surface of the granite typically consists of sand in this region, not clay (McCormick and Hammond, 2004).

Although the alteration of the Precambrian surface in test hole R20-2002-01 is interpreted here as a saprolite, it should be noted that alteration of the Precambrian surface in some parts of North America have been attributed to thermal alteration by deep, migrating brines (Ziegler and Longstaffe, 2000). It is thought that these brines may be responsible for Mississippi Valley type lead-zinc mineralization of Paleozoic rocks, as well as hydrocarbon accumulations, dolomitization, paleomagnetic disturbances, and high paleotemperatures in the mid-continent. Alteration in these areas occurs in both the Precambrian and Paleozoic rocks at the contact. Minerals associated with these fluids include potassium-rich feldspar, illite, and chlorite (Ziegler and Longstaffe, 2000). The possibility that the Precambrian alteration in test hole R20-2002-01 is hydrothermal cannot be ruled out. However, unlike that observed in hydrothermally altered rocks, the altered Precambrian rocks in this study do not appear to contain significant authigenic potassium-rich feldspar, nor do the Paleozoic rocks at the contact with the Precambrian surface appear significantly altered.

In Wisconsin, Cummings and Scrivner (1980) report a saprolite that developed on felsic crystalline Precambrian rock. This particular saprolite constitutes a gray-green, clay-rich zone at least 6.6 feet, and possibly 11.5 feet thick that directly underlies the Mt. Simon Sandstone. Obvious similarities exist between the saprolite in test hole R20-2002-01 and that described by Cummings and Scrivner (1980), though the Wisconsin saprolite may have a more gradational physical contact with the underlying Precambrian rock. A detailed study was conducted on this Wisconsin saprolite and compared to saprolites reported at the same stratigraphic level (that is, on top of the Precambrian surface and below the Mt. Simon Sandstone) in Minnesota. Cummings and Scrivner (1980) concluded that the saprolite formed prior to deposition of the Mt. Simon Sandstone. An investigation of paleogeography and inferred climate in the Precambrian and into the Early Cambrian led Cummings and Scrivner (1980) to conclude that the saprolite formed during the Precambrian which is consistent with the interpretation of saprolites underlying the Mt. Simon Sandstone in the Minnesota River Valley in Minnesota.

No such detailed work has been carried out to date on the saprolite in test hole R20-2002-01. However, the occurrence of the saprolite in test hole R20-2002-01 at the same stratigraphic level as that of the Wisconsin saprolite and those of the Minnesota River Valley in Minnesota suggests that the saprolite in test hole R20-2002-01 also developed during the Precambrian.

## Precambrian Metagabbro

### Weathered Basement Rock

Strongly weathered, but relatively competent, strongly foliated, Precambrian basement rock was intersected at a depth of 907.8 feet. At this depth, the basement rock consists mainly of alteration minerals of chlorite and hematite. With depth through this weathered zone (from 907.8

to 917 feet), the degree of chemical alteration of the rock gradually decreases as reflected on the resistivity log (fig. 6). Across this interval, the natural gamma signature remains fairly constant, reflecting the significant quantity of clay minerals within the rock throughout this zone. From 917 feet downward, the basement rock changes from weakly altered to unaltered, and the geophysical log reflects this; below 917 feet the resistivity sharply increases to the highest measured levels in the core and the natural gamma drops sharply to low values (fig. 6).

Thin veins (of feldspar and quartz?) in the upper portion of the core run at a wide variety of angles to the foliation, but most commonly subhorizontally, suggesting that they post-date metamorphism and may be part of the chemical alteration/weathering event.

### Unweathered Basement Rock

The unweathered basement rock is a metamorphosed gabbro. It is a strongly foliated rock in which the mafic bands consist mainly of amphibole with lesser amounts of biotite, and the felsic bands consist mainly of feldspar with some quartz. In hand sample, pyrite can reach up to 10 percent or more of the rock, but only in thin bands along foliation. Veins mainly of alkali feldspar and quartz typically run parallel or subparallel to foliation and are recrystallized suggesting an episode of veining prior to metamorphism.

## GENERALIZED THIN SECTION DESCRIPTIONS

Three thin sections of metagabbro from the R20-2002-01 core were made courtesy of Sam Treves (Department of Geosciences, University of Nebraska–Lincoln). Texturally, these samples are strongly foliated. In thin section, amphibole is the main constituent of the rock. Although variable, generally the proportions of minerals in each of the thin sections examined are 45-50 percent amphibole and 7-15 percent biotite, such that amphibole and biotite together make up about 50 percent to more than 60 percent of the rock; 10-15 percent feldspar and 5-10 percent quartz, such that feldspar and quartz together make up about 20-30 percent of the rock; 5-7 percent apatite; and 3-5 percent opaque minerals. A reflected light examination of these sections was not made because they had cover plates. However, based on a petrographic examination by WMC Exploration Inc., Denver, Colorado, the opaque minerals can consist of variable amounts of ilmenite, magnetite, pyrite, chalcopyrite, and pyrrhotite.

The amphibole, probably hornblende, is pleochroic; some grains form triple junctions with other amphibole grains. Apatite inclusions are common within the amphibole. In some areas, opaque grains can be seen to line up along amphibole grain boundaries. Biotite typically occurs parallel to the long axis of the amphibole. Biotite can occur with amphibole or in biotite-rich bands. Within the biotite-rich bands, biotite grains are not exactly parallel to each other, but rather are at a slight angle, forming almost a herring-bone pattern. Quartz and feldspar commonly show undulatory extinction and triple junctions.

One of the light-colored veins that occur along foliation and appear to have been emplaced prior to metamorphism was also examined in one of the thin sections. The vein generally consists of quartz with lesser amounts of feldspar. Quartz grains reach 1 centimeter in size and typically show undulating extinction; other small, granulated, recrystallized quartz veinlets crosscut the main vein. The feldspar occurs with quartz along the outer portion of the vein. Sericite alteration of feldspar is apparent in some grains.

GEOCHEMISTRY

Three samples of metagabbro were analyzed courtesy of WMC Exploration Inc., Denver, Colorado (table 3). The data show a general decrease in silica and slight increase in calcium, magnesium, and iron with depth in the sampled part of the metagabbro (table 3). Metal content of these samples are below values of economic interest, although platinum (Pt) is notably present and increases from 25 to 40 parts per billion with depth in the sampled portion of the core (table 3). However, results obtained from a private consultant (R. Blair, Denver, Colorado, written commun., 2004) of an analysis run at the same analytical laboratory on a sample from 980.1 to 980.3 feet show the amount of Pt to be less than 0.005 parts per million (<5 parts per billion).

Cross-Iddings-Pirsson-Washington (CIPW) normative mineral calculations on each of the geochemical samples were carried out by Sam Treves (Department of Geosciences, University of Nebraska–Lincoln), using a $Fe_2O_3/FeO$ ratio of 0.2 (Middlemost, 1989) and Minpet software. Results (table 4) show a general decrease in normative quartz and feldspar, and an increase in normative pyroxene and calcium content of the feldspar with depth in the upper part of the metagabbro reflecting the geochemical trends with depth (table 3).

NEODYMIUM MODEL AGE AND ZIRCON AGE DATE

A 1.5-foot long split-core sample (from a depth of 980 to 981.5 feet) was sent to W.R. (Randy) Van Schmus at the Department of Geology, University of Kansas, for possible age dating. He calculated a neodymium model age (TDM) of 2.17 $\pm \approx$ 0.1 Ga and has obtained a preliminary zircon date of 1.74 Ga (Van Schmus, 2005). The older TDM age suggests that the mafic magma probably contained material from older sources (W.R. Van Schmus, Department of Geology, University of Kansas, written commun., 2005). Further analyses are in progress. Both the TDM and the preliminary zircon age are older than the rubidium-strontium (Rb-Sr) potassium feldspar age of 1.46 Ga for the Precambrian basement rock in the Sioux Valley No. 1 Lafleur oil test, although this Rb-Sr age is considered to be a minimum age (Goldich and others, 1966; Sims and others, 1991).

## WATER CHEMISTRY RESULTS

Water samples (table 5) were taken from two different Paleozoic formations intersected in test hole R20-2002-01. The first sample was taken when the test hole was at a depth of 446 feet in the karst developed in the Wise Lake Formation dolostone (fig. 3). At that time, depth to water in the test hole was 15.2 feet and the average pumping rate was 36 gallons per minute using an air-lift purging method. No trace metal analyses were performed on this sample, but results of the analysis for common inorganic parameters show that the water from this depth is harder than that of two major aquifers in Union County (the Missouri aquifer and the Dakota Formation aquifer), and sulfate is significantly higher (table 5). Total dissolved solids in this water sample are also higher, but the iron content is lower than that of the Missouri and Dakota Formation aquifers. Regardless, where parameter concentrations have a corresponding South Dakota drinking water standard, the sample was under the upper limit (table 5).

A hydraulic connection between the Dakota Formation and the underlying dolostone at 446 feet cannot be proven, although it is possible. Dakota Formation sandstone (with thin shale interbeds) directly overlies vuggy dolostone at a depth of 409 feet (fig. 3). However, if the vugs in the dolostone are not connected, there will be limited hydraulic connection between the sandstone and the dolostone.

The second water sample was taken when the test hole was at a depth of 765 feet in the Wonewoc Sandstone (fig. 3). At this depth, the water was under sufficient natural pressure to cause water to flow out of the top of the core rod onto the land surface, so no pumping was required. The average flow rate during sampling was approximately 25 gallons per minute. Both common inorganics and trace metals were measured. Most of the major parameters have similar values to that of the sample taken at 446 feet in the dolostone. However, this deeper water sample is generally more saline, harder, and has a higher sulfate concentration. All measured parameters are within the South Dakota drinking water standards except for one: gross alpha. Gross alpha is high in this deeper water sample (16 picocuries per liter [pCi/L]), and in fact is slightly higher than the allowable limit in South Dakota (15 pCi/L). Radium 226, radium 228, and uranium are all at measurable levels in this sample. This water cannot be considered potable based on the present South Dakota drinking water standards.

## AEROMAGNETIC DATA AND MODELING RESULTS

The aeromagnetic survey along the Missouri River from Yankton, South Dakota, to Ponca State Park, Nebraska, was flown by Terraquest Ltd., which is based in Mississauga, Ontario, Canada. Details of the survey itself are presented in appendix A. The aeromagnetic data were modeled by Ron Bell of ENW Services, Geophysics & GIS, Golden, Colorado. Mr. Bell remodeled the block 6 aeromagnetic data for the Geological Survey Program (fig. 8) after the actual depth to the Precambrian metagabbro (907.8 feet below land surface) was known.

The commercial software package MAGIX (interpex Ltd.) was used to model the total field magnetic (TFM) data. Several lines through the block 6 anomaly were modeled. Line 5 (shown in fig. 8) traverses closest to test hole R20-2002-01, which provides the control on the depth to the Precambrian surface. The TFM data used for the model profiles were extracted from a grid. The model profile data for line 5 were extracted along a north-south traverse placed on the approximate long axis of the anomalous feature. Details of the modeling procedure are outlined in appendix A.

Mr. Bell's modeling suggests the source of the block 6 anomaly is a body that is elongated in the north-northeast-south-southwest direction and has some apparent structure (fig. 8), and that the surface of this anomaly is undulating (fig. 9), although this is not a unique solution. A more complex model with lateral variations in magnetic susceptibility can yield a flat upper surface. The 2.5-dimensional model (fig. 10) shows the north and south edges of the body to be sharp and well defined, and the source body appears to dip to the northwest.

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**Table 1. A generalized correlation of Devonian through Cambrian formations between selected South Dakota, Iowa, and Nebraska test holes**

| Core hole | SDGS R20-2002-01 | Sioux Valley No. 1 Lafleur | Doerr No. 1 Boler[1] | Camp Quest Core[2] |
|---|---|---|---|---|
| **Nearest town** | Elk Point, SD | Richland, SD | Dakota County, NE | LeMars, IA |
| **Legal location** | NW¼ NW¼ NW¼ NE¼ sec. 13, T. 90 N., R. 50 W. | SW¼ NE¼ NW¼ SW¼ sec. 18, T. 80 N., R. 48 W. | SE¼ NE¼ sec. 11, T. 28 N., R. 7 E. | SW¼ sec. 2, T. 92 N., R. 45 W. |
| **Devonian strata** | Present, but unknown formation. Mainly gray to tan, vuggy dolostone and limestone, ~ 35.5 feet thick | Possibly present up to 120 feet thick (M. Carlson, unpublished lithologic log) | Present, unknown formation underlying Mississippian strata. Mainly tan to gray dolostone, ~ 170 feet thick | Not present |
| **Ordovician strata:** | | | | |
| **a) Galena Group: Wise Lake Fm Dunleith Fm Decorah Shale** | a) Wise Lake Fm (27.5 ft), Dunleith Fm (57.7 ft), and Decorah Shale (112 ft) are all present | a,b,c) Upper dolostone (~155 ft), Decorah Shale, Platteville and Glenwood Formations (together ~100 ft) | a) Upper dolostone (185 ft) and underlying Decorah Shale (probably includes the Platteville and Glenwood Formations (149 ft) | a) Dunleith Formation (29 ft) and Decorah Shale (95 ft) |
| **b) Platteville Fm** | b) ~ 17 feet thick | | b) not identified | b) ~ 26 feet thick |
| **c) Glenwood Fm** | c) ~ 12 feet thick | | c) not identified | c) ~ 28 feet thick |
| **d) St. Peter Sandstone** | d) ~ 28 feet thick | d) ~ 40 feet thick | d) ~ 36 feet | d) ~ 36 feet thick |
| **e) Other formations** | e) none present | e) none present | e) Arbuckle Formation | e) none present |
| **Cambrian strata:** | | | | |
| **a) St. Lawrence Fm** | a) not present | a) not present? | Not intersected, hole terminated in Arbuckle Formation | a) ~ 43 feet thick |
| **b) Lone Rock/Davis Fm** | b) Davis Formation (53 ft) | b) Davis Formation (95 ft) | | b,c) Lone Rock (and Wonewoc?) Formation (145 ft) |
| **c) Wonewoc Sandstone** | c) ~ 47 feet thick | c) ~ 64 feet thick | | |
| **d) Eau Claire Fm** | d) ~ 23 feet thick (?) | d, e) ~ 43 feet thick | | d) ~ 50 feet thick |
| **e) Bonneterrre Fm** | e) ~ 58 feet thick | | | e) not present |
| **f) Mt. Simon Sandstone** | f) ~ 9 feet thick | f) ~ 8 feet thick | | f) ~ 42 feet thick |

[1] Lithologic log provided by the Nebraska Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.
[2] Lithologic log provided by the Iowa Geological Survey, Iowa Department of Natural Resources.

**Table 2. Results from biostratigraphic analyses of trilobite and brachiopod fragments in Cambrian strata**

| Sample[1] | Hand sample description | Identification[2] | Faunal zone/Stage |
|---|---|---|---|
| R20-2002-01-706 | Trilobite fragment in shale | Piece of a pygidium; *Dikelocephalus* cf. *D. minnesotensis* Owen | *Dikelocephalus* Zone of the upper Sunwaptan Stage |
| R20-2002-01-719 | Trilobite fragment in shale | Indeterminate trilobite thoracic segment | |
| R20-2002-01-725 | Trilobite fragment in shale | Piece of a pygidium; Dikelcephalid; genus and species indeterminate, but not *Dikelocephalus* | Probably still in the upper part of the Sunwaptan Stage |
| R20-2002-01-741 | Trilobite fragment in shale | Cranidium; *Wilbernia* cf. *W*. pero (Walcott) | Widespread genus in the middle Sunwaptan Stage |
| R20-2002-01-742 | Trilobite fragment in shale | Cranidium, deformed; *Wilbernia*? sp. | |
| R20-2002-01-745 | Trilobite fragment in shale | Indeterminate trilobite free cheek | |
| R20-2002-01-816 | Trilobite fragment in shale | Sedimentary artifact? | |
| R20-2002-01-820 | Possible acrotretid brachiopod | Piece containing pedicle valve of an acrotretid brachiopod; not stratigraphically distinctive | |
| R20-2002-01-821 | Possible acrotretid brachiopod | Piece containing pedicle valve of an acrotretid brachiopod; not stratigraphically distinctive | |
| R20-2002-01-822a, b, c | Trilobites in dolostone/grainstone | Cranidia; *Aphelaspis* sp. | Early Steptoean. The Sauk II/III boundary occurs uphole |

[1] The sample identification consists of two, and in one case, three parts. The first part, R20-2002-01, is a unique identifier for the test hole from which the samples were collected and is the same for all entries in this table. The second part (i.e., 706 or 820) indicates the depth below land surface from which the sample was collected. The third part pertains only to the last entry in the table (a, b, c) and indicates that three samples were collected from the same depth of 822 feet

[2] The analyses were carried out by A.R. Palmer, Institute for Cambrian Studies, Boulder, Colorado

**Table 3. Oxide and element geochemistry of the Precambrian metagabbro intersected in test hole R20-2002-01**

| Oxide[1] (wt. %) | R20-2002-01 919 ft | R20-2002-01 940 ft | R20-2002-01 947 ft |
|---|---|---|---|
| **$Al_2O_3$** | 12.52 | 11.5 | 11.37 |
| **BaO** | 0.06 | 0.08 | 0.08 |
| **CaO** | 7.75 | 8.12 | 8.45 |
| **$Cr_2O_3$** | <0.01 | <0.01 | <0.01 |
| **$Fe_2O_3$**[2] | 17.01 | 19.24 | 19.47 |
| **$K_2O$** | 1.33 | 1.65 | 1.63 |
| **MgO** | 3.7 | 4.02 | 4.35 |
| **MnO** | 0.25 | 0.28 | 0.29 |
| **$Na_2O$** | 2.6 | 2.08 | 1.92 |
| **$P_2O_5$** | 1.24 | 1.45 | 1.95 |
| **$SiO_2$** | 47.12 | 45.24 | 43.62 |
| **SrO** | 0.03 | 0.03 | 0.02 |
| **$TiO_2$** | 3.02 | 3.4 | 3.61 |
| **LOI** | 1.08 | 0.56 | 0.83 |
| **TOTAL** | 97.71 | 97.65 | 97.59 |
| **Element**[1] | | | |
| **Ag** (ppm[3]) | 0.08 | 0.02 | 0.06 |
| **Al** (%) | 6.39 | 5.85 | 5.84 |
| **As** (ppm) | 2 | 1.8 | 1.2 |
| **Ba** (ppm) | 500.7 | 734.4 | 736.4 |
| **Be** (ppm) | 1.7 | 1.75 | 1.65 |
| **Bi** (ppm) | 0.08 | 0.08 | 0.08 |
| **Ca** (%) | 4.7 | 5.1 | 5.2 |
| **Cd** (ppm) | 0.26 | 0.24 | 0.28 |
| **Ce** (ppm) | 86.1 | 98.4 | 90.1 |
| **Co** (ppm) | 35.9 | 39.8 | 42.4 |
| **Cr** (ppm) | 37 | 37 | 25 |
| **Cs** (ppm) | 2.9 | 4.1 | 4 |
| **Cu** (ppm) | 56 | 29 | 37 |
| **Fe** (%) | 10.25 | 11.85 | 12.05 |
| **Ga** (ppm) | 24.7 | 25.75 | 25.6 |
| **Ge** (ppm) | 0.1 | 0.15 | 0.15 |
| **Hf** (ppm) | 3.3 | 0.7 | 0.3 |

| Element (continued) | R20-2002-01 919 ft | R20-2002-01 940 ft | R20-2002-01 947 ft |
|---|---|---|---|
| **In** (ppm) | 0.21 | 0.16 | 0.175 |
| **K** (%) | 1.01 | 1.29 | 1.31 |
| **La** (ppm) | 37 | 43.5 | 38.5 |
| **Li** (ppm) | 19.4 | 21.8 | 23.2 |
| **Mg** (%) | 1.96 | 2.19 | 2.39 |
| **Mn** (ppm) | 1745 | 2030 | 2100 |
| **Mo** (ppm) | 2.95 | 1.35 | 2.35 |
| **Na** (%) | 1.98 | 1.65 | 1.61 |
| **Nb** (ppm) | 7.8 | 3.2 | 1.6 |
| **Ni** (ppm) | 13.2 | 12 | 11.4 |
| **P** (ppm) | 4700 | 4980 | 5180 |
| **Pb** (ppm) | 10.5 | 9 | 8.5 |
| **Rb** (ppm) | 31.2 | 45.3 | 48 |
| **Re** (ppm) | 0.002 | 0.002 | <0.002 |
| **S** (%) | 0.59 | 0.25 | 0.3 |
| **Sb** (ppm) | 0.8 | 0.6 | 0.4 |
| **Se** (ppm) | 1 | 1 | 1 |
| **Sn** (ppm) | 1.8 | 1.8 | 1.6 |
| **Sr** (ppm) | 277 | 221 | 212 |
| **Ta** (ppm) | 0.4 | 0.2 | 0.1 |
| **Te** (ppm) | <0.05 | <0.05 | <0.05 |
| **Th** (ppm) | 4 | 4.2 | 3.4 |
| **Ti** (%) | 1.74 | 1.83 | 1.8 |
| **Tl** (ppm) | 0.3 | 0.34 | 0.36 |
| **U** (ppm) | 1.6 | 1.3 | 1.3 |
| **V** (ppm) | 136 | 144 | 158 |
| **W** (ppm) | 0.6 | 0.4 | 0.3 |
| **Y** (ppm) | 54.4 | 58.2 | 56.6 |
| **Zn** (ppm) | 158 | 200 | 222 |
| **Zr** (ppm) | 145 | 44.5 | 24 |
| **Au** (ppb[4]) | 4 | <2 | <2 |
| **Pt** (ppb) | 25 | 35 | 40 |
| **Pd** (ppb) | <2 | <2 | <2 |

[1] Analyses were carried out at ALS Chemex Labs, Vancouver, British Columbia, Canada, using ME-ICP06 analytical package for oxide analyses, ME-MS61 analytical package for trace element analyses, and PGM-MS23 for PtPdAu trace level analyses. Analyses are courtesy of WMC Exploration Inc., Denver, Colorado

[2] All iron as $Fe_2O_3$

[3] Parts per million

[4] Parts per billion

**Table 4. CIPW normative mineral calculations using a $Fe_2O_3$/FeO ratio of 0.2**

| Normative Minerals[1,2] | CIPW[3] norm for sample R20-2002-01, 919-foot depth (wt. %) | CIPW norm for sample R20-2002-01, 940-foot depth (wt. %) | CIPW norm for sample R20-2002-01, 947-foot depth (wt. %) |
|---|---|---|---|
| **Quartz** | **3.01** | **1.67** | **0.57** |
| **Feldspar:** | **50.87** | **46.06** | **45.71** |
| Orthoclase | 8.27 | 10.26 | 10.15 |
| Albite | 23.11 | 18.49 | 17.08 |
| Anorthite | 19.49 | 17.31 | 18.48 |
| **Diopside:** | **11.23** | **13.64** | **11.48** |
| Wollastonite | 5.55 | 6.73 | 5.68 |
| Enstatite | 1.99 | 2.36 | 2.09 |
| Ferrosilite | 3.69 | 4.55 | 3.71 |
| **Hypersthene:** | **22.05** | **24.05** | **26.01** |
| Enstatite | 7.73 | 8.21 | 9.36 |
| Ferrosilite | 14.32 | 15.84 | 16.65 |
| **Olivine** | **0.00** | **0.00** | **0.00** |
| **Magnetite** | **3.95** | **4.47** | **4.53** |
| **Hematite** | **0.00** | **0.00** | **0.00** |
| **Ilmenite** | **6.03** | **6.79** | **7.22** |
| **Apatite** | **2.85** | **3.33** | **4.48** |
| Total | 100.00 | 100.00 | 100.00 |

[1] Middlemost (1989)

[2] Calculations made using Minpet software; calculations are courtesy of S. Treves, Department of Geosciences, University of Nebraska–Lincoln

[3] Cross-Iddings-Pirsson-Washington method of normative mineral calculation

**Table 5. Water quality of two Union County aquifers and two water samples from test hole R20-2002-01**

| Parameter | Missouri aquifer[1] | Dakota Formation aquifer[1] | R20-2002-01 dolostone (446 ft) | R20-2002-01 sandstone (760 ft) | South Dakota drinking water standard[2] |
|---|---|---|---|---|---|
| **Common Inorganics[3]** | | | | | |
| Alkalinity | 375 | 240 | 151 | 161 | |
| Ammonia | 0.58 | ---[4] | 0.46 | 0.22 | |
| Calcium | 126 | 105 | 207 | 244 | |
| Chloride | 7 | 21 | 46 | 60 | |
| Fluoride | 0.31 | 1.58 | 2.26 | 2.71 | 4.0 |
| Iron | 4.3 | 3.43 | 0.27 | 0.79 | |
| Magnesium | 34.8 | 35 | 38.3 | 42.4 | |
| Manganese | 2.87 | 0.1 | 0.14 | 0.10 | |
| Nitrate + Nitrite | < 0.1 | < 0.05 | < 0.1 | < 0.1 | 10 |
| Conductivity (µmho/cm)[5] | 933 | 1220 | 1690 | 1740 | |
| pH (pH units) | 7.21 | --- | 7.62 | 7.41 | |
| Potassium | 5.9 | 19 | 22.5 | 23.2 | |
| Sodium | 16.3 | 109 | 87.9 | 94.5 | |
| Dissolved Solids | 616 | 838 | 1260 | 1353 | |
| Sulfate | 141 | 373 | 685 | 709 | |
| Bicarbonate | 458 | 292 | 184 | 196 | |
| Carbonate | 0 | --- | 0 | 0 | |
| Hardness | 458 | 405 | 674.5 | 783 | |
| Hardness (grains/gal) | 26.6 | 23.5 | 39.1 | 45.4 | |
| **Trace Metals[6]** | | | | | |
| Antimony | < 0.2 | --- | --- | < 0.4 | 6 |
| Arsenic (mg/L) | 12.8 | --- | --- | < 0.001 | 50 |
| Barium | 166 | --- | --- | 12.0 | 2000 |
| Beryllium | < 0.2 | --- | --- | < 0.4 | 4 |
| Cadmium | < 0.2 | --- | --- | < 0.2 | 5 |
| Chromium | 15.7 | --- | --- | < 0.2 | 100 |
| Copper | < 0.3 | --- | --- | 0.7 | 160 |
| Lead | < 0.1 | --- | --- | < 0.1 | 1 |
| Mercury | < 0.2 | --- | --- | < 0.1 | 2 |
| Nickel | 4.5 | --- | --- | 4.9 | |
| Selenium | < 0.5 | --- | --- | 1.8 | 50 |
| Thallium | < 0.1 | --- | --- | < 0.1 | 2 |
| Cyanide (mg/L) | < 0.010 | --- | --- | < 0.010 | 0.2 |
| **Radionuclides[7]** | | | | | |
| Gross-alpha (pCi/L) | < 0.3 | --- | --- | 16 ± 4.8 | 15 |
| Radium 226 (pCi/L) | --- | --- | --- | 4.1 ± 0.7 | |
| Radium 228 (pCi/L) | --- | --- | --- | 4.8 ± 0.5 | |
| Uranium (ug/L) | --- | --- | --- | 0.6 | |

[1] Selected representative analyses
[2] Found at http://legis.state.sd.us/rules/rules/7404.htm#74:04:05
[3] All common inorganics reported in mg/L (milligrams per liter) unless otherwise indicated
[4] Not analyzed
[5] µmho/cm = micromhos per centimeter
[6] All trace metals reported in ug/L (micrograms per liter) unless otherwise noted
[7] Values are reported as indicated in either pCi/L (picocuries per liter) or ug/L

# APPENDIX A

## Specifications of the aeromagnetic survey and method of modeling the aeromagnetic data

### SPECIFICATIONS OF THE AEROMAGNETIC SURVEY

Selected specifications of the aeromagnetic survey are listed below. A more detailed list of specifications are available through Brian Molyneaux at the University of South Dakota. The survey started on November 27, 2001, and was completed on December 12, 2001.

#### Equipment Specifications

The survey was carried out using a twin engine aircraft Piper Navajo PA-31-325 modified to support a composite tail stinger. A cesium vapor magnetometer, Scintrex model CS-2, was mounted in the tail stinger. The resolution and sensitivity of the magnetometer is 0.001 nT counting at 0.1 per second ± 0.005 nT.

A global positioning system was used to document geographic position along each flight line. The NAD27 ellipsoid for Mean Continental USA was used with x-y-z delta shifts of 8, -160, and -176, respectively. The UTM zone is 14.

#### Survey Specifications

A total of 4,530 km was flown with 4,303 km of survey lines and 227 km of tie lines. The survey line interval was 100 m and the tie line interval was 2 km. The survey line direction was 113 degrees, the tie line direction was 42 degrees, average terrain clearance was 80 m, average ground speed was 80 m/s, and the data point interval was 8 m.

### METHOD OF MODELING THE AEROMAGNETIC DATA

The following explanation of the modeling procedure was kindly provided by Ron Bell.

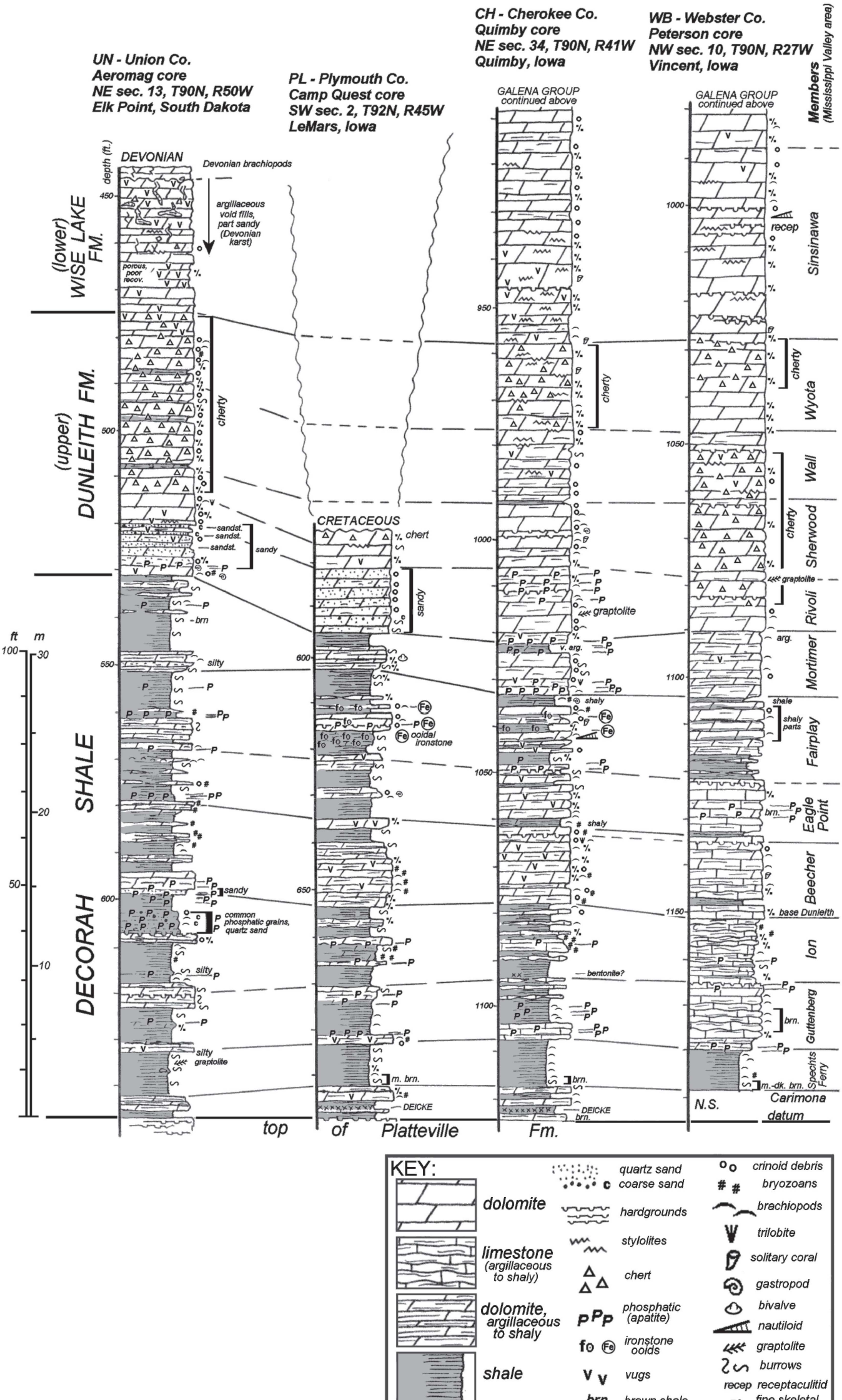
The modeling procedure began with the calculation of the response for a simple block body. The width of the body extends 500 meters to each side of the traverse line (line 5). The top surface of the body was set at 300 meters below the sensor (the sensor is set at 80 meters above the ground surface; see above specifications of the aeromagnetic survey), and the bottom surface was set at about 20,000 meters depth. The north and south extents of the body were set at the inflection points of the profile. The magnetic susceptibility was initially set at 3,500 micro-cgs, with the background at 0. The regional field of 55,600 nT was applied to provide the background response. The inducing field was set at 56,000 nT with an inclination of 70 degrees and a declination of 0 degrees.

The magnetic susceptibility was allowed to vary through the inversion process of the software package to achieve a reasonable fit between the calculated profile and the observed profile. This resulted in a susceptibility of 4,426 micro-cgs units. The susceptibility was then fixed and numerous nodes were inserted into the top surface of the body. These nodes were allowed to vary spatially vertically. The nodes at the north and south edges of the body were also allowed to vary in the lateral direction during the inversion procedure. The forward model was then fit to the observed data using multiple iterations of the inversion process until a “best fit” was achieved.

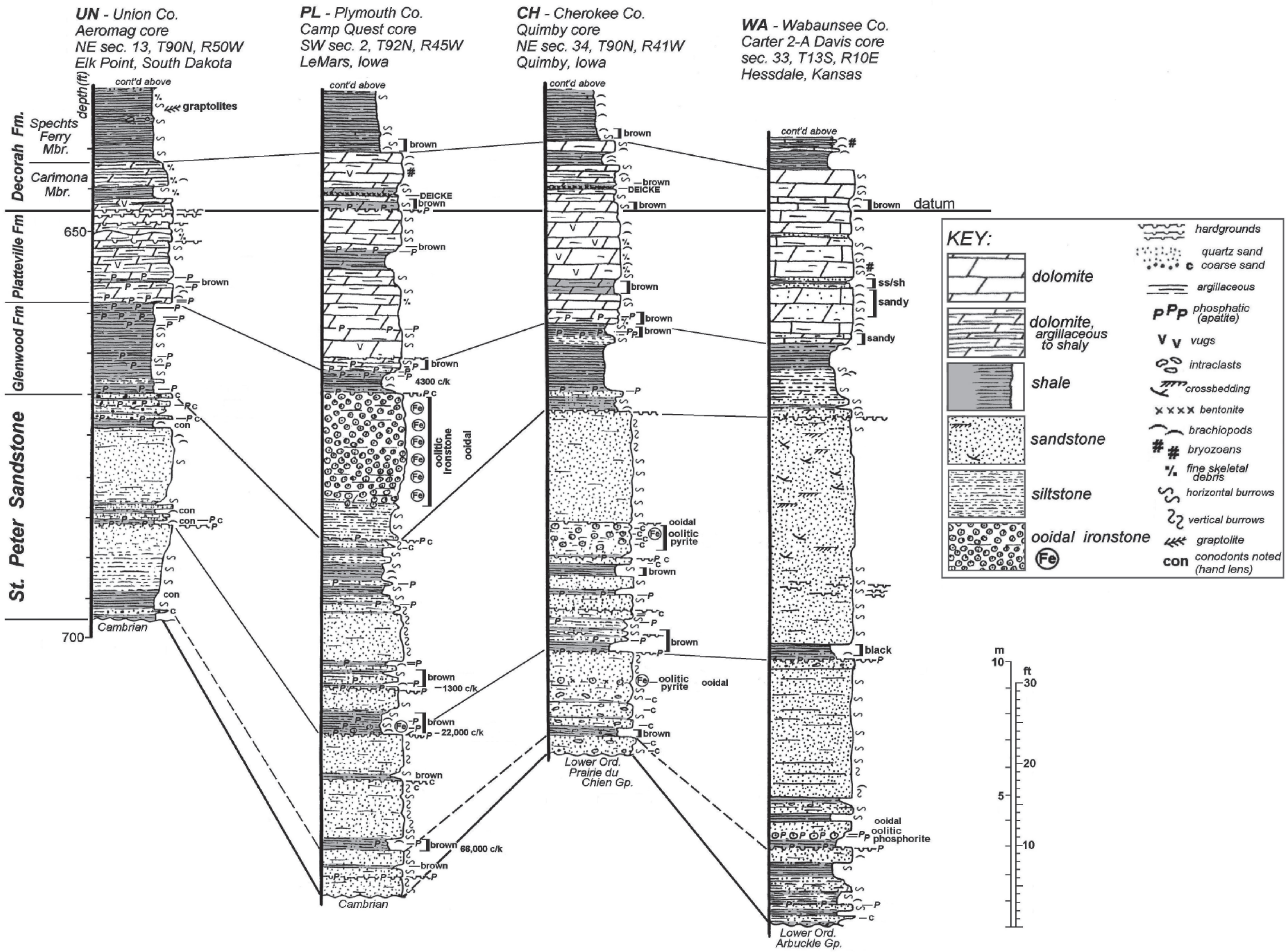
# APPENDIX B

## **Stratigraphic column of the R20-2002-1 core and correlation with cores from Iowa and Kansas**

The following figures were kindly provided by Brian Witzke of the Iowa Geological Survey.



UN - Union Co.
Aeromag core
NE sec. 13, T90N, R50W
Elk Point, South Dakota
PL - Plymouth Co.
Camp Quest core
SW sec. 2, T92N, R45W
LeMars, Iowa
CH - Cherokee Co.
Quimby core
NE sec. 34, T90N, R41W
Quimby, Iowa
WB - Webster Co.
Peterson core
NW sec. 10, T90N, R27W
Vincent, Iowa
Members
(Mississippi Valley area)
GALENA GROUP continued above
DEVONIAN
depth (ft.)
Devonian brachiopods
argillaceous void fills, part sandy (Devonian karst)
porous, poor recov.
(lower) WISE LAKE FM.
(upper) DUNLEITH FM.
SHALE
DECORAH
cherty
sandst.
sandy
silty
brn
common phosphatic grains, quartz sand
graptolite
CRETACEOUS
chert
ooidal ironstone
m. brn.
DEICKE
shaly
v. arg.
bentonite?
brn.
recep
shale
shaly parts
arg.
base Dunleith
m.-dk. brn.
N.S.
Sinsinawa
Wyota
Wall
Sherwood
Rivoli
Mortimer
Fairplay
Eagle Point
Beecher
Ion
Guttenberg
Spechts Ferry
Carimona
datum
top of Platteville Fm.
ft
m
KEY:
dolomite
limestone (argillaceous to shaly)
dolomite, argillaceous to shaly
shale
quartz sand
coarse sand
hardgrounds
stylolites
chert
phosphatic (apatite)
ironstone ooids
vugs
brown shale
crinoid debris
bryozoans
brachiopods
trilobite
solitary coral
gastropod
bivalve
nautiloid
graptolite
burrows
receptaculitid
fine skeletal debris



UN - Union Co.
Aeromag core
NE sec. 13, T90N, R50W
Elk Point, South Dakota
PL - Plymouth Co.
Camp Quest core
SW sec. 2, T92N, R45W
LeMars, Iowa
CH - Cherokee Co.
Quimby core
NE sec. 34, T90N, R41W
Quimby, Iowa
WA - Wabaunsee Co.
Carter 2-A Davis core
sec. 33, T13S, R10E
Hessdale, Kansas
cont'd above
depth(ft)
Decorah Fm.
Spechts Ferry Mbr.
Carimona Mbr.
Platteville Fm
Glenwood Fm
St. Peter Sandstone
650
700
Cambrian
graptolites
brown
DEICKE
datum
con
4300 c/k
oolitic ironstone
ooidal
1300 c/k
22,000 c/k
66,000 c/k
oolitic pyrite
ss/sh
sandy
black
Lower Ord. Prairie du Chien Gp.
Lower Ord. Arbuckle Gp.
ooidal oolitic phosphorite
KEY:
dolomite
dolomite, argillaceous to shaly
shale
sandstone
siltstone
ooidal ironstone
hardgrounds
quartz sand
coarse sand
argillaceous
phosphatic (apatite)
vugs
intraclasts
crossbedding
bentonite
brachiopods
bryozoans
fine skeletal debris
horizontal burrows
vertical burrows
graptolite
con conodonts noted (hand lens)
m
ft
10
5
30
20
10