UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
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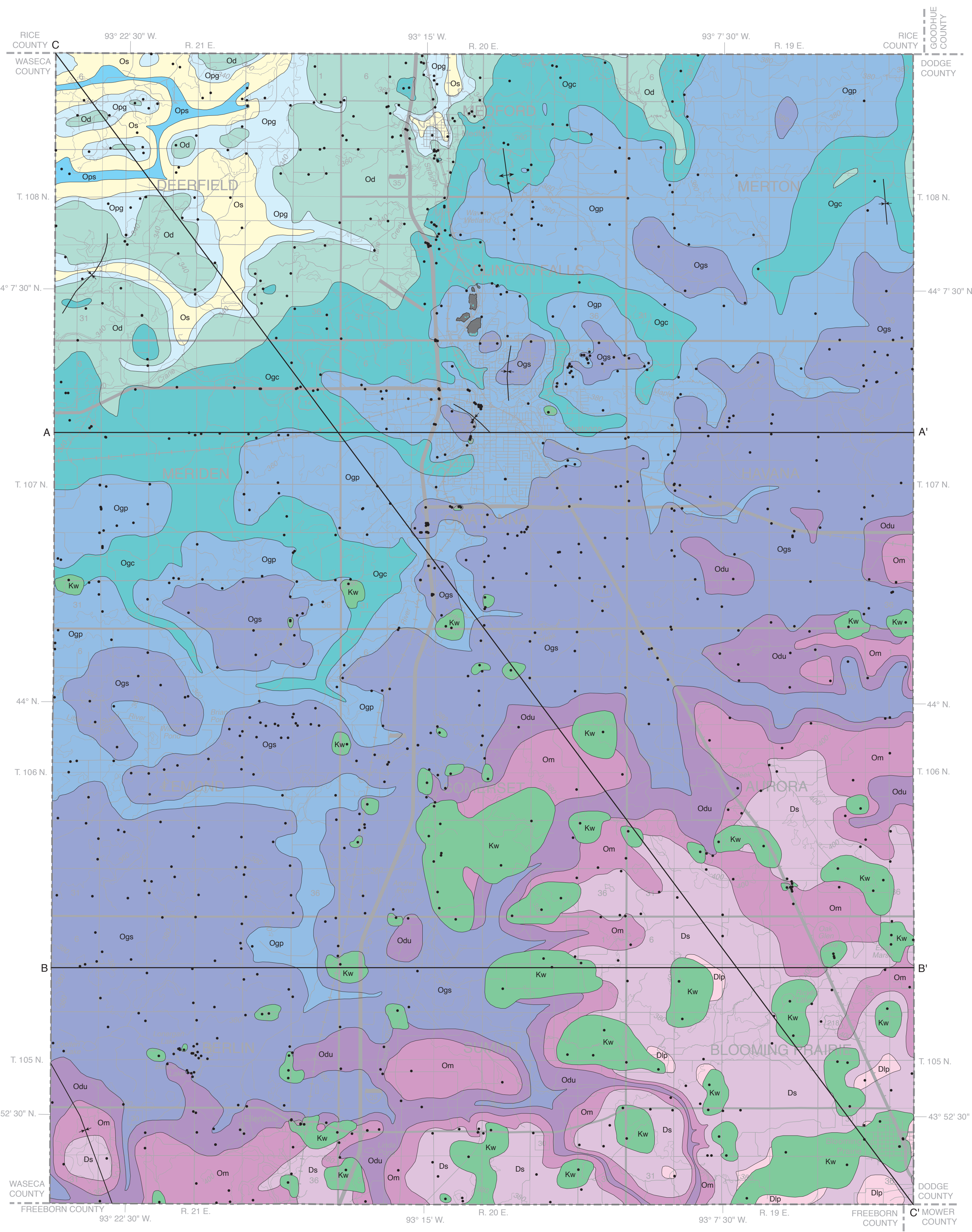
BEDROCK GEOLOGY

By

Andrew J. Retzler

2022



Digital base modified from the Minnesota Department of Transportation BaseMap data; digital base annotation by Jordan A. Mayer.

Elevation contours were derived from the U.S. Geological Survey 30-meter Digital Elevation Model (DEM) by the Minnesota Geological Survey.

Universal Transverse Mercator Projection, grid zone 15
1983 North American Datum

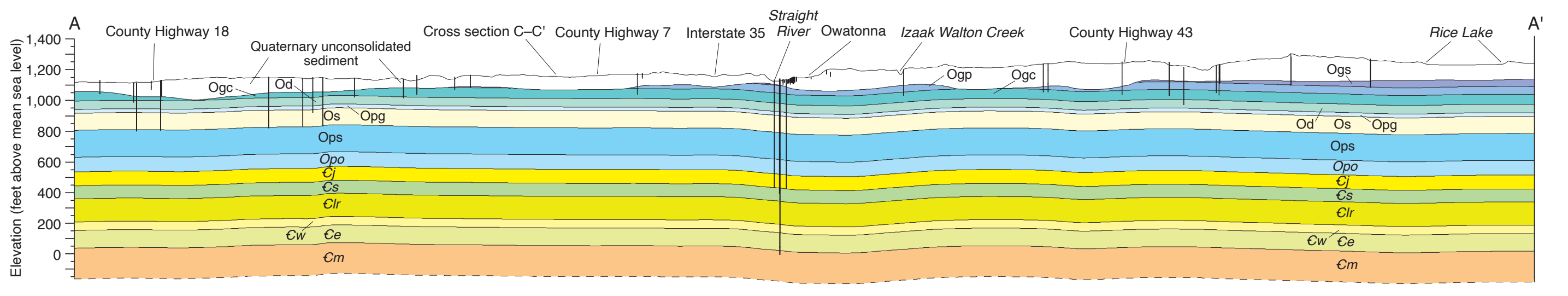
SCALE 1:100 000

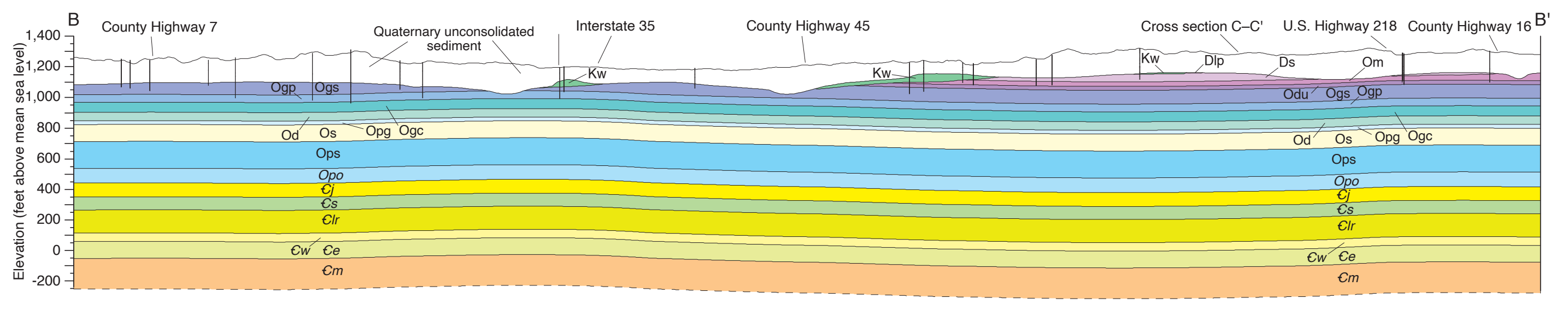
1 0 1 2 3 4 5 MILES

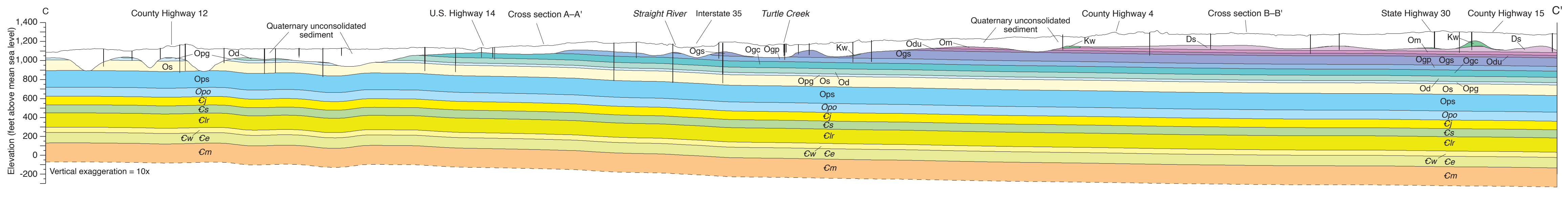
1 0 1 2 3 4 5 6 7 8 KILOMETERS

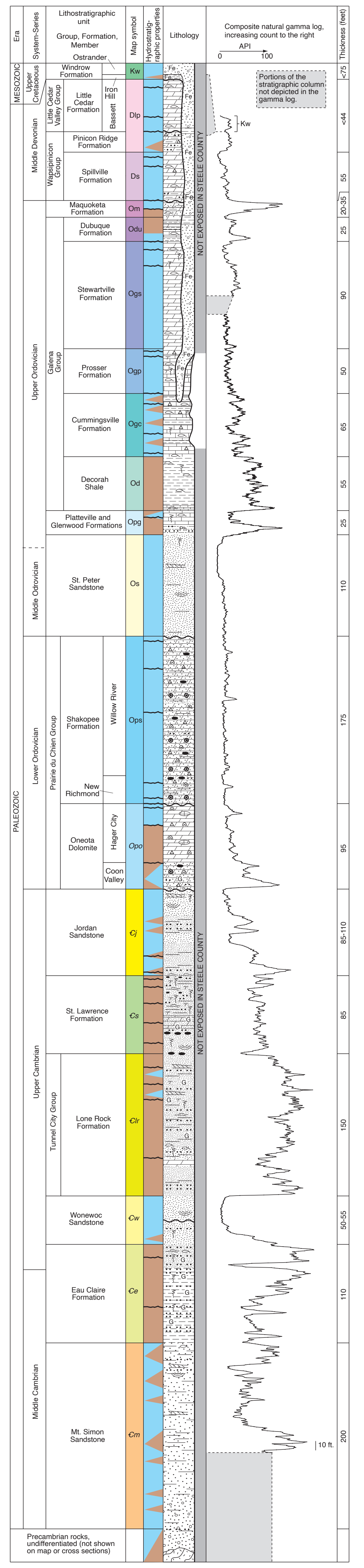
CONTOUR INTERVAL 20 METERS

GIS compilation by A.J. Retzler
Edited by Lori Robinson









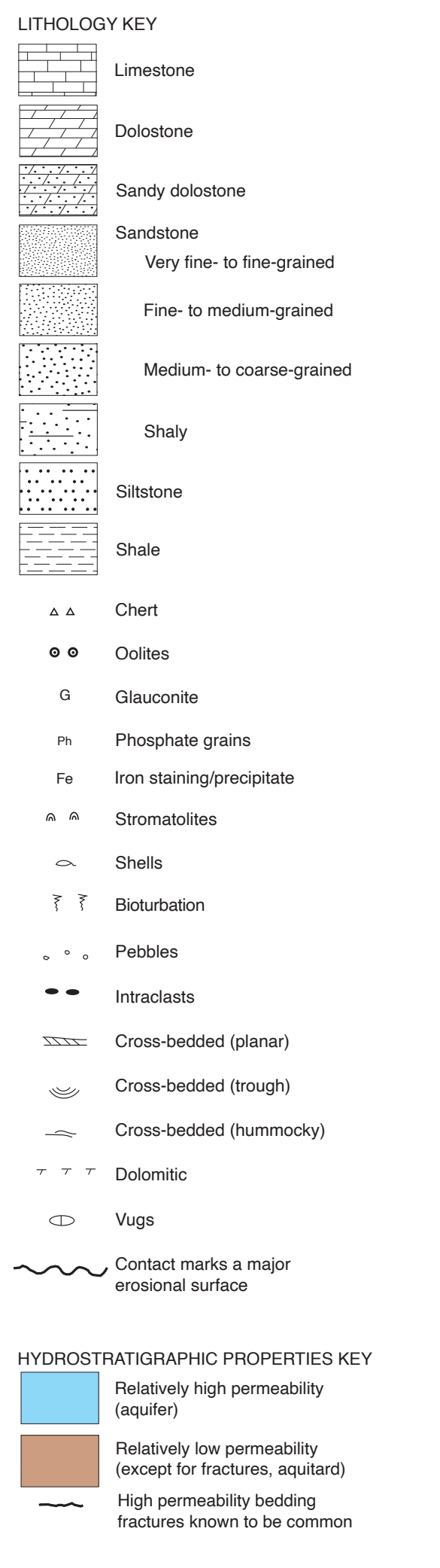
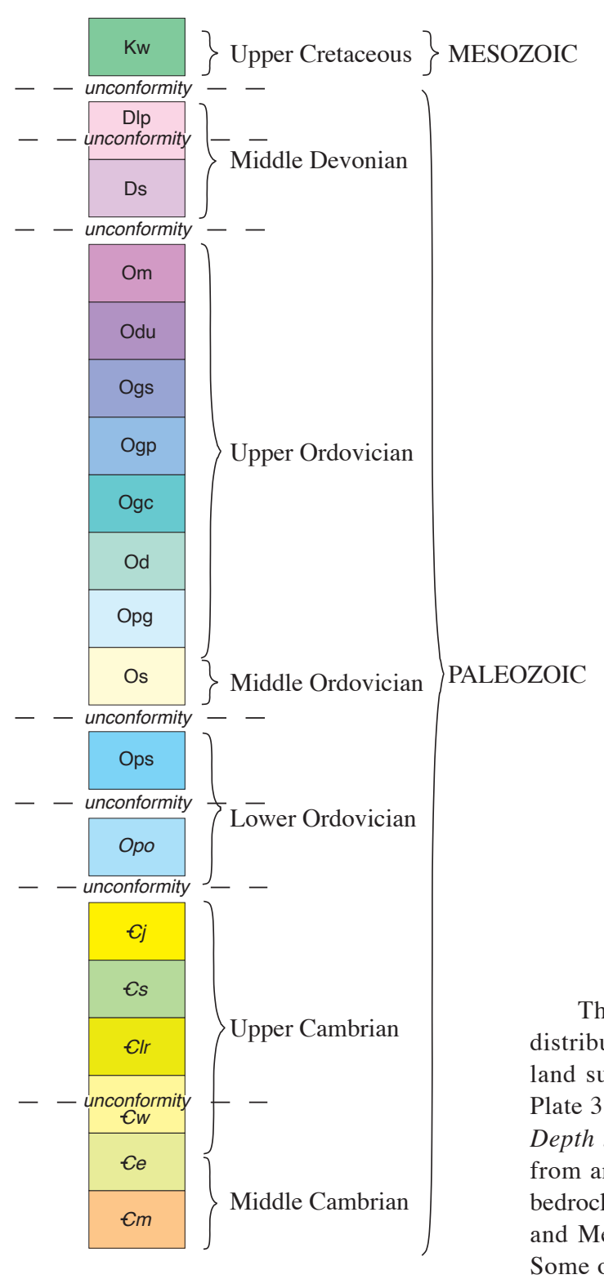
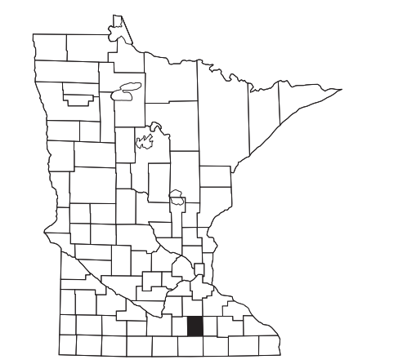


Figure 1. Generalized stratigraphic column depicting the lithology, estimated range in thickness, vertical succession, geologic age, and hydrostratigraphic properties for all units shown on the map and corresponding cross sections. A representative composite gamma log of these units in Steele County is shown to the right of the lithologic column, where borehole geophysical data are available. The gamma logs illustrated are from the following borehole geophysical logs: CWI unique numbers 219022, 818296, and 508143 (on file at the Minnesota Geological Survey and available online at <https://z.umn.edu/borehole_geo>).

CORRELATION OF MAP UNITS





LOCATION DIAGRAM

INTRODUCTION

The geologic map, cross sections, and stratigraphic column on this plate depict the type, distribution, and structure of the bedrock units in Steele County that are either exposed at the land surface or lie beneath unconsolidated Quaternary sediments of variable thickness (see Plate 3, *Surficial Geology*; Plate 4, *Quaternary Stratigraphy*; Plate 6, *Bedrock Topography and Depth to Bedrock*). The map shows how the bedrock surface would appear if it were viewed from an aerial perspective and the overlying Quaternary sediments were stripped away. The bedrock units nearest the land surface in Steele County consist of sedimentary rocks of Paleozoic and Mesozoic age that form distinguishable and mappable layers designated as formations. Some of these units are exposed north of Owatonna along the Straight River, mainly in active and inactive bedrock quarries. All of the inactive bedrock quarries in this area are presently flooded. Several of the Paleozoic bedrock formations are major reservoirs for water supply in the county, while others closer to the surface provide aggregate and crushed stone materials.

Characteristics of each formation are given in the stratigraphic column (Fig. 1) and in the description of map units. The accompanying bedrock geologic cross sections add the dimension of depth and illustrate the stratigraphic, structural, and topographic relationships of the bedrock units, as well as the variable thickness of the overlying Quaternary sediments. Projected onto these cross sections are the locations and approximate depths drilled (shown as vertical lines) from available water-well data in the County Well Index (CWI) database within a 1,640-foot (0.5 kilometer) buffered area adjacent to each line of cross section. Surfaces representing the elevation of the tops of the mapped formations are also available as Digital Elevation Models (DEMs) for use in GIS programs. The geologic formations are thin in relation to their aerial extent, and would only be one-tenth as thick as shown on the cross sections if no vertical exaggeration were used. The exaggeration necessary to show the thin rock formations gives the appearance of steeper slopes on bedrock unit contacts, the land surface, and bedrock topography. Only two of the units shown as first bedrock on this plate are exposed at the land surface, the Prosser Formation and underlying Cummingsville Formation; elsewhere the bedrock is covered by as much as 295 feet (89.9 meters) of Quaternary unconsolidated sediment (see Plate 6).

Production of the map and associated products relied on several data sources, including outcrops, water-well and other drilling records from the County Well Index database, soil and engineering test borings from the Quaternary Data Index (QDI) database, rock core, drill cuttings samples, borehole geophysical logs, and previously published geologic maps of adjacent counties (Mossler, 1995, 1998; Runkel, 1998; Tipping and others, 2007; Retzler, 2019; Steenberg, 2020). Figure 2 highlights some of the bedrock outcrops and rock-core samples examined during this project. This map supersedes a combined 1:100,000-scale bedrock geology map of Steele, Dodge, Olmsted, and Winona Counties (Tipping and others, 2007). Significant improvements and modifications were made to the interpretations of the previous map based on additional water-well records, drill cuttings, rotary-sonic drill core, and borehole geophysical logs. These improvements include generating model-ready top and bottom bedrock-surface DEMs for all of the bedrock units in Steele County down to the Mt. Simon Sandstone, better definition of the thicknesses and extents of the Galena Group formations (particularly the Stewartville and Prosser Formations), better understanding of the lithologic and facies trends of the Dubuque and Maquoketa Formations, and improved delineation and characterization of the patchy Mesozoic (Upper Cretaceous) Windrow Formation. Bedrock structure was also mapped in greater detail, revealing a number of local folds superimposed on the regional dip of these strata. Collectively this provides significantly improved depiction of the subsurface geologic characteristics, including hydrogeologic units, which has implications for modeling groundwater flow and contaminant transport.

The various data sources and their irregular distribution and density can be seen on the map and Plate 1, *Database Map*. The spatial distribution and coverage of these data should be considered when assessing the reliability of the map at any particular location. Areas with a high density of bedrock control points (outcrops and boreholes) are more likely to have an accurate interpretation of the bedrock geology, whereas areas with widely spaced control points may be less reliable. The bedrock surface DEMs supplementing this map were interpolated using the Esri ArcMap Topo to Raster tool and similarly inherit these biases in the data. Furthermore, the accuracy of the DEMs is dependent upon the contour interval used when mapping the topographic surface of each unit and the errors inherited in the Topo to Raster interpolation method. For this map, the bedrock-surface DEMs on average are accurate to within ± 12.5 feet (± 3.81 meters). Significant efforts were made to ensure the accuracy of the bedrock surfaces; however, users should always refer to and consider the two-dimensional geologic map because it represents the most accurate and reliable representation of uppermost bedrock across the county.

During production of this map, 1,359 located water-well records and 358 located engineering test and giddings soil probe borings existed within Steele County in the County Well Index and the Quaternary Data Index databases, respectively. Of those, 1,027 reached Mesozoic and/or Paleozoic bedrock. Geologic interpretations of subsurface material were made by the author based on material descriptions by drillers or the analysis of other geologic data sources (such as drill cuttings, core samples, and geophysical data).

In Steele County, Paleozoic and Mesozoic bedrock lies on top of Mesoproterozoic rocks of the Keweenawan Supergroup associated with the Midcontinent rift (Jirsa and others, 2012). These rocks include sandstone, siltstone, and shale of the Hinckley Sandstone, and Solor Church and Fond du Lac Formations (Jirsa and others, 2012). The distribution, depth, and thickness of these Mesoproterozoic rocks is poorly constrained in this region due to their deep burial and limited subsurface data. Bounding the Midcontinent rift on either side in Steele County are two deeply buried thrust faults inferred by aerial geophysical imagery that offset these rocks: the Belle Plain fault in the southwest and an unnamed fault in the northeast (Jirsa and others, 2012). Both faults strike north–northwest and were presumably inactive during deposition of the overlying Paleozoic and Mesozoic rocks in this area because no data indicate discernible areas of significant, discrete offset within these rocks across Steele County. No new mapping of the Mesoproterozoic units or their associated faults was done for this project.

The Paleozoic rocks of Steele County are characterized by relatively thin, widespread layers of sandstone, shale, and carbonate deposited in shallow seas during the Cambrian, Ordovician, and Devonian Periods of the Paleozoic Era, from about 500 to 375 million years ago. The older Cambrian formations are dominated by siliciclastic sedimentary rock, including sandstone and siltstone with minor shale (such as the Jordan Sandstone and Tunnel City Group). Carbonate rock occurs only as relatively thin layers within these units. Ordovician and Devonian formations, in contrast, are dominated by thicker units of carbonate rock (such as the Prairie du Chien and Galena Groups), with the exception of the St. Peter Sandstone and Decorah Shale. Carbonate rock units of the upper Galena Group formations are used as aggregate or crushed stone in one active quarry in Owatonna, where bedrock is within 50 feet (15 meters) or less of the land surface (see Plate 6). Rock quarries are less abundant in Steele County than counties further east (such as Olmsted and Mower Counties) due to the overall widespread coverage of thick Quaternary glacial sediments. The deepest bedrock unit penetrated by water wells in Steele County is the Cambrian Mt. Simon Sandstone in Owatonna. However, the majority of water wells in Steele County are much shallower.

The Paleozoic strata of Steele County lie just west of the axial trace of a broad, cratonic depression known as the Hollandale embayment. These stratigraphic layers are slightly tilted (less than 1°) southeast as part of the regional structural trend of the embayment. As a result, progressively younger bedrock formations subcrop from northwestern to southeastern Steele County. This general trend is locally interrupted by deep valleys that incise older bedrock formations, and by broad, open fold structures. The stratigraphic top of the St. Peter Sandstone was contoured at 25-foot (7.6-meter) intervals to help constrain the location of structural folds in Steele County and to derive the bedrock-surface DEMs for all other units (above and below the St. Peter Sandstone) mapped in this atlas (Fig. 3). This unit was selected to portray these structures because its upper contact is distinct and easily recognized by water-well drillers. It also provides a fair amount of spatial coverage across Steele County from the water wells that penetrate it, with the exception of the southeastern corner (see Fig. 3). In general, folds were inferred where changes in the elevation of the top of the St. Peter Sandstone indicate a gradual change in slope greater than that of the regional 1° southeast structural trend. The axial trace of most folds in Steele County trend north–northwest, or roughly perpendicular to the regional structural dip of the Paleozoic strata. Faults crosscutting the Paleozoic strata were not identified in Steele County.

The Mesozoic rocks of Steele County are part of the Cretaceous Windrow Formation, which is dominated by variably thick, patchy, and poorly cemented siliciclastic sediments. The Windrow Formation lies unconformably atop the Ordovician and Devonian carbonate rock units of the Paleozoic Era. It was deposited on the exposed Paleozoic carbonate bedrock across a low, featureless plain within a terrestrial environment during the Cretaceous Period (Mossler, 2000). Some mapped Windrow Formation materials are likely in-place weathering products or residuum of underlying Paleozoic bedrock, but other parts of the formation are derived from sediments deposited in streams and on floodplains. The distribution and thickness of this unit are difficult to constrain without high-quality subsurface information, such as drill cuttings or core. It is commonly overlooked and misinterpreted to be unconsolidated Quaternary glacial sediment in water-well drilling records due to its abundance of poorly consolidated, sub-rounded to sub-angular sand and pebbly sand. For these reasons, the Windrow Formation may have a significantly greater extent than is depicted on the map and in the corresponding cross sections.

HYDROSTRATIGRAPHY

Some of the Paleozoic bedrock formations include aquifers that are a significant source of groundwater for Steele County. About 65 percent of wells in the county draw water from Paleozoic bedrock. This map and associated products, such as the bedrock-surface DEMs, provide a three-dimensional depiction of the rock properties that control flow in these water-bearing layers. Such rock properties are called hydrostratigraphic properties. The hydrostratigraphic classification, shown by brown and blue colors on the hydrostratigraphic properties column of Figure 1, distinguishes layers that are dominated by relatively high-permeability material (easily transmitting water), versus layers dominated by lower-permeability material (relatively harder to transmit water). This generalized characterization for Steele County is based on hydrogeologic reports by Runkel (1996), Paillet and others (2000), Runkel and others (2003, 2006a, b, 2018), Tipping and others (2006), Luhmann and others (2011), Green and others (2012), and unpublished borehole and core data collected by the Minnesota Geological Survey. The high-permeability layers are potential aquifers, able to yield economic quantities of water in most places. The low-permeability layers are potential aquitards that retard vertical flow, hydraulically separating the aquifer layers from one another in many places, and protecting water resources in the underlying layers from surface contamination. Fractures parallel to bedding that have high permeability are likely to be present, as least locally, in all formations in Steele County, but are placed on the column where the hydrogeologic reports cited above indicate they are most common in the region. Deeper in the subsurface, the hydrogeologic properties of much of the Upper to Middle Cambrian and Mesoproterozoic bedrock units are poorly understood, and these units do not supply water to Steele County, at least in part, because sufficient water resources are available at shallower depths within the unconsolidated Quaternary glacial sediment, St. Peter Sandstone, and fractured Ordovician and Devonian carbonate formations.

In Steele County, most aquifers are layers dominated by relatively coarse-grained sandstone or composed mostly of carbonate rock. The sandstone aquifers, primarily the St. Peter Sandstone, transmit water more easily in both horizontal and vertical directions through the pore spaces between sand grains, as well as through fractures. The carbonate rock aquifers, such as the Galena Group and Prairie du Chien Group, transmit water mostly through a relatively dense network of interconnected fractures and solution cavities. It should also be noted that layers designated as aquifers can locally contain low-permeability strata that serve as small, internal aquitards.

Most layers designated as aquitards in the county have a much lower permeability in the vertical direction than do aquifers. Examples in Steele County include the Decorah Shale and Glenwood Formation, whose rocks are composed mostly of shale with small, poorly connected pore spaces. Carbonate rock containing a relatively sparse network of fractures and/or interbedded with shale, such as the upper Dubuque Formation or the lower part of the Prairie du Chien Group (Oneota Dolomite), are also aquitards. However, layers designated as aquitards with very low permeability in the vertical direction may locally contain horizontal fractures that are conductive enough to yield large quantities of water.

Horizontal and vertical fractures are more common where bedrock layers are at or near the bedrock surface. As a result, aquitards in such conditions are likely to have higher permeability compared with more deeply buried portions of the same formation, and may have a diminished ability to retard water flow to underlying aquifers. There is no precise boundary between shallow and deep conditions of burial, but in most areas of southeastern Minnesota, about 50 feet (15.2 meters) of depth below the bedrock surface is a best approximation (Runkel and others, 2006a, 2018).

In addition to this hydrostratigraphic classification, the Minnesota Department of Natural Resources, as Part B of the Steele County Geologic Atlas, will conduct a thorough hydrogeologic study of the groundwater flow system, aquifer capacity, and aquifer sensitivity that may or may not result in modifications or additions to this classification. Furthermore, designations of aquifers versus aquitards made here may not correspond precisely with those made for regulatory purposes by the Minnesota Department of Health.

DESCRIPTION OF MAP UNITS

MESOZOIC

Kw **Windrow Formation (Upper Cretaceous)**—The Windrow Formation unconformably overlies the Devonian and Ordovician carbonate units, from the Bassett Member of the Little Cedar Formation down to the Cummingsville Formation of the Galena Group. It is divided into two members: the Ostrander Member and the underlying Iron Hill Member. The mapped extent of the Windrow Formation as shown on the map and cross sections is approximate and conservative because it is difficult to verify its occurrence without high-quality water-well records, drill cuttings, core samples, and/or borehole geophysical logs. Nineteen feet (5.8 meters) of the Windrow Formation were recovered in rotary-sonic core STL-1 (CWI unique number 341104). Total thickness of the Windrow Formation is variable, ranging from absent to as much as 75 feet (22.9 meters) in Steele County.

Ostrander Member—Yellowish-brown, orange-red, and grayish-white, very friable, fine- to coarse-grained, rounded to sub-angular quartzose sandstone and pebbly chert conglomerate with minor gray to black and orange, thinly-laminated to massive, waxy clay and silty clay (Figs. 2C, D). The sandstone is commonly micaceous and commonly contains thin beds or nodules of pyrite- or iron-cemented sand. Chert pebbles are commonly very well-rounded, and polished. Many contain silicified invertebrate fossil fragments of probable Devonian and Ordovician age. The Ostrander Member may also include paleosols, as indicated by rotary-sonic core STL-1 (CWI unique number 341104). This core contains light gray to white, kaolinitic clay with probable oxidized root traces and siderite nodules, known as sphaerosiderite (Fig. 2C). Sphaerosiderite has also been noted within paleosols of the Cretaceous Dakota Formation in Iowa (Ludvigson and others, 1998). The Ostrander Member commonly overlies the Iron Hill Member, but has also been described as lying directly atop Paleozoic strata (Mossler, 1998). The thickness of the Ostrander Member is variable, ranging from absent to as much as about 75 feet (22.9 meters) in Steele County.

Iron Hill Member—Green, white, tan, red, orange, and black, pebbly clay and silty clay intermixed with chert fragments, silt, and/or sand that formed as part of a weathering residuum atop weathered Devonian or Ordovician carbonate bedrock. Deposits are commonly heavily mineralized and cemented with iron oxides. The Iron Hill Member commonly forms irregular masses devoid of sedimentary structures and has been documented to occur on karst topography as fillings in enlarged joints and sinkholes (Sloan, 1964). The thickness of the Iron Hill Member is variable, ranging from absent to as much as about 10 feet (3.0 meters) in Steele County.

PALEOZOIC

Dlp **Bassett Member of the Little Cedar Formation and the Pinicon Ridge Formation, undivided (Middle Devonian)**—The Bassett Member of the Little Cedar Formation and the Pinicon Ridge Formation are combined into a single map unit with a full thickness of about 44 feet (13.4 meters) in Steele County. Description of this combined unit is based on a limited number of wells with drill cuttings and borehole geophysical logs.

Bassett Member of the Little Cedar Formation—Light to medium gray, thick-bedded dolostone. Total thickness of the Bassett Member varies between about 40 and 70 feet (12.2 to 21.3 meters; Mossler, 2008). Only about 14 feet (4.3 meters) or less of the Bassett Member are preserved in Steele County.

Pinicon Ridge Formation—Composed mainly of light gray to yellowish-gray, silty or sandy dolostone with thin beds of dark gray and olive-gray shale and minor yellowish-gray limestone (Mossler, 1998, 2008). It can also contain abundant chert nodules and sparry calcite- and quartz-filled vugs. The upper and lower parts can contain more shaly dolostone and shale (Mossler, 1998). Total thickness of the Pinicon Ridge Formation is about 30 feet (9.1 meters).

Ds **Spillville Formation (Middle Devonian)**—Finely crystalline, light brown to grayish-orange dolostone with abundant fossil-moldic porosity and dog-tooth, sparry calcite-filled vugs (Fig. 2E). The basal few feet are sandy to silty and may contain minor amounts of shale or shaly dolostone (Mossler, 1998). Twenty feet (6.1 meters) of the Spillville Formation were recovered in rotary-sonic core STL-1 (CWI unique number 341104). Total thickness of the Spillville Formation is about 55 feet (16.8 meters).

Om **Maquoketa Formation (Upper Ordovician)**—Dark gray-brown, silty and sandy dolostone with light olive-gray shale and light gray-white, dolomite-cemented, fine- to coarse-grained, quartzose sandstone with cross-stratification. Sand-sized phosphate grains and some chert grains are abundant throughout. One possible hardground surface with rip-up clasts within a dark gray-brown dolostone bed is present in core near southeastern Steele County drilled for the Dodge County Geologic Atlas (CWI unique number 340102; core DOR-2; Retzler, 2019). The lithology of the Maquoketa Formation in Steele County and neighboring Dodge County is known only from poorly sampled drill cuttings and rotary-sonic core; however, it appears to differ from nearby Mower and Olmsted Counties (Mossler, 1998; Retzler, 2019; Steenberg, 2020), particularly in the presence of quartzose sandstone. The upper contact of the Maquoketa Formation with the overlying Spillville Formation is unconformable. The total thickness of the Maquoketa Formation can vary between about 20 and 35 feet (6.1 to 10.7 meters). A representative total thickness of 30 feet (9.1 meters) was used in deriving the corresponding DEMs and in representing the Maquoketa Formation in cross section. Additional high-quality drill cuttings, core samples, and natural gamma-ray logs are needed to better constrain and describe the Maquoketa Formation in this area.

Galena Group (Upper Ordovician)

Odu ***Dubuque Formation***—Brown to gray-brown and light gray to yellowish-gray, thin- to medium-bedded limestone and dolostone interbedded with light olive-gray to light gray, calcareous shale (Figs. 2F, G). Parts of the Dubuque Formation are fossiliferous with abundant crinoids and brachiopods and less common bryozoans, trilobites, and bivalves. The Dubuque Formation appears to be more dolomitic and less shaly throughout Steele and Dodge Counties than has been described in nearby Olmsted, Mower, and Fillmore Counties (Sloan, 1987; Mossler, 1998; Retzler, 2019; Steenberg, 2020). Eleven feet (3.4 meters) of the Dubuque Formation were recovered in rotary-sonic core STL-2 (CWI unique number 341105). Total thickness of the Dubuque Formation is about 25 feet (7.6 meters).

Ogs ***Stewartville Formation***—Yellowish-gray and white-gray, vuggy dolostone and dolomitic limestone. Bedding is typically medium to thick near the base and thin and crinkly near the top. The Stewartville Formation typically displays a sugary, coarse-grained crystalline texture compared to the fine-grained, micritic texture more characteristic of the underlying Prosser Limestone, and its beds are commonly highly burrow mottled. The Stewartville Formation is commonly fossiliferous in the lower and upper parts near its contact with the underlying Prosser Formation and overlying Dubuque Formation. Fossils include brachiopods, gastropods, horn corals, crinoids, cephalopods, and receptaculitids, and are commonly preserved as internal or external molds. Thirty-one feet (9.4 meters) of the Stewartville Formation were recovered in rotary-sonic core STL-2 (CWI unique number 341105; Fig. 2H). Total thickness of the Stewartville Formation is about 90 feet (27.4 meters).

Ogp ***Prosser Formation***—Fine-grained, fossiliferous, yellowish-gray to grayish-brown, intermittently silty and sandy limestone and dolomitic limestone. Bedding is typically thin to medium and flaggy, and fossils tend to be concentrated in thin coquina layers. Fossils include brachiopods, gastropods, bivalves, echinoderms, bryozoans, trilobites, horn corals, and cephalopods. The Prosser Formation contains chert nodules and is more micritic than the underlying Cummingsville Formation. The Prosser Formation is exposed in one outcrop along the bank of the Straight River (Fig. 2A) and in one active quarry north of Owatonna (Fig. 2B). In the recent past, it was presumably exposed in several other inactive quarries in this area that have since been flooded. Total thickness of the Prosser Formation is about 50 feet (15.2 meters).

Ogc ***Cummingsville Formation***—Fossiliferous, yellowish-gray to white-gray, silty and sandy limestone interbedded with green-gray, calcareous shale. The limestone is thin- to medium-bedded and commonly contains more silt and sand than the overlying Prosser Formation. Fossils in abundance include bryozoans, crinoids, and brachiopods. Less common are trilobites, horn corals, cephalopods, and gastropods. Chert nodules are locally abundant, particularly in the upper half. The Cummingsville Formation is exposed in one active quarry north of Owatonna (Fig. 2B). In the recent past, it was presumably exposed in several other inactive quarries in this area that have since been flooded. Total thickness of the Cummingsville Formation is about 65 feet (19.8 meters).

Od ***Decorah Shale***—Grayish-green shale containing thin beds of fossiliferous, blue-gray limestone. Fossils in abundance include bryozoans, crinoids, horn corals, and brachiopods. Less common are trilobites, cephalopods, gastropods, and bivalves. Ferruginous ooids of a brassy color are common in the upper half of the Decorah Shale, where they are cemented within thin limestone beds or disseminated throughout the shale. Total thickness of the Decorah Shale is about 55 feet (16.8 meters).

Opg **Platteville Formation and Glenwood Formation (Upper Ordovician)**—The carbonate rock of the Platteville Formation and underlying shale of the Glenwood Formation are combined as a single map unit with a full thickness of about 25 feet (7.6 meters).

Platteville Formation—Thin- to medium-bedded, tan to gray limestone and dolostone. It is commonly burrow mottled and fossiliferous. It contains fine- to coarse-grained quartz sand and phosphate grains in the lowermost 2 feet (0.6 meter). Two feet (0.6 meter) of the Platteville Formation were recovered in rotary-sonic core STL-3 (CWI unique number 341106). Total thickness of the Platteville Formation is about 15 to 20 feet (4.6 to 6.1 meters).

Glenwood Formation—Grayish-green to brownish-gray, calcareous, sandy, and phosphatic shale. The Glenwood Formation is about 5 to 10 feet (1.5 to 3.0 meters) thick.

Os **St. Peter Sandstone (Middle to Upper Ordovician)**—White to tan, fine- to medium-grained, friable quartzose sandstone. Bedding and structures are generally absent; however, subtle cross-stratification is rarely present. Iron staining and burrows are commonly present in the uppermost few feet. Total thickness of the St. Peter Sandstone is about 110 feet (33.5 meters).

Prairie du Chien Group (Lower Ordovician)—Dominated by dolostone interlayered with lesser amounts of quartzose sandstone. The Prairie du Chien Group is formally divided into two formations: the Shakopee Formation and underlying Oneota Dolomite. It is commonly difficult to discern the contact between the Shakopee Formation and Oneota Dolomite without high-quality drill cuttings and borehole geophysical logs. Total thickness of the Prairie du Chien Group is about 275 feet (83.8 meters).

Ops ***Shakopee Formation***—The Shakopee Formation is a heterolithic unit composed mostly of tan to gray, thin to medium-bedded dolostone, sandy dolostone, sandstone, and shale. It contains oolites, intraclasts, microbial mounds, chert nodules, quartzose sandstone, and green-gray shale partings. The Shakopee Formation is separated into two members: the Willow River and the underlying New Richmond. The Willow River Member is dominated by dolostone and sandy dolostone with thin quartzose sandstone and minor shale beds. The dolostone and sandy dolostone beds commonly contain oolites, oomoldic texture, and stromatolites. The New Richmond Member is composed of fine- to medium-grained quartzose sandstone, as well as oolitic sandy dolostone. The contact between these members was not confidently discernible using data from currently available water-well records and drill cuttings in Steele County. To the east in Olmsted County, recent mapping indicated that the Willow River Member is generally 120 to 150 feet (36 to 46 meters) thick, and the New Richmond Member reaches thicknesses of 25 feet (7 meters) or less (Steenberg, 2020). Total thickness of the Shakopee Formation is about 175 feet (53.3 meters). The Shakopee Formation is the oldest unit to subcrop in Steele County and is encountered as first bedrock within a buried bedrock valley in the northwest.

Opo ***Oneota Dolomite (shown only on cross sections)***—The Oneota Dolomite is separated into two members: the Hager City and the Coon Valley. The Hager City Member is predominantly a yellowish-gray to light brown, medium- to thick-bedded dolostone that generally lacks sedimentary features, such as oolites and quartz sand, characteristic of the overlying Shakopee Formation. Thickness of the Hager City Member varies from about 65 to 70 feet (19.8 to 21.3 meters). The basal Coon Valley Member is a heterolithic unit composed of thinly bedded dolostone, sandy dolostone, and beds of fine- to coarse-grained, poorly sorted quartzose sandstone. Glauconite and pyrite are also common. The thickness of the Coon Valley Member varies from about 25 to 30 feet (7.6 to 9.1 meters). Total thickness of the Oneota Dolomite is about 95 feet (29.0 meters).

Ꞓj **Jordan Sandstone (Upper Cambrian; shown only on cross sections)**—Dominantly white to yellow, medium- to coarse-grained, friable quartzose sandstone characterized by coarsening-upward sequences consisting of two interlayered facies: medium- to coarse-grained, cross-stratified, generally friable, quartzose sandstone; and very fine-grained, commonly bioturbated, feldspathic sandstone and lenses of siltstone and shale (Runkel, 1994). The major part of the very fine-grained facies forms a regionally continuous interval that gradationally overlies the St. Lawrence Formation (unit *Ꞓs*), although there are lithologically similar intervals intercalated with the medium- to coarse-grained facies at higher stratigraphic intervals. An unconformity, locally marked by thin beds of quartz pebble conglomerate and silcrete-cemented sandstone clasts (Runkel and others, 2007), separates the Jordan Sandstone from the overlying Oneota Dolomite of the Prairie du Chien Group. Thickness of the Jordan Sandstone ranges from about 85 to 110 feet (25.9 to 33.5 meters). A representative total thickness of 90 feet (27.4 meters) was used in developing the corresponding DEMs and in representing the Jordan Sandstone in cross section.

Ꞓs **St. Lawrence Formation (Upper Cambrian; shown only on cross sections)**—Light gray to yellowish-gray and pale yellowish-green, dolomitic, feldspathic siltstone with interbedded, very fine-grained sandstone and shale. Lenses and layers of light gray, finely crystalline, sandy dolostone occur locally, especially in the lowermost few feet of the formation (Runkel and others, 2006a). Intraclastic beds are present near the top and base of the unit and glauconite is present throughout, but typically more concentrated in the lowermost 30 feet (9.1 meters). The upper contact with the Jordan Sandstone is conformable and gradational, making it difficult to select a precise contact between these formations even with well cuttings and/or borehole geophysical logs. Total thickness of the St. Lawrence Formation is about 85 feet (25.9 meters).

Tunnel City Group (Upper Cambrian; shown only on cross sections)

Ꞓlr ***Lone Rock Formation***—Pale yellowish-green, very fine- to fine-grained glauconitic, feldspathic sandstone and siltstone, with thin, greenish-gray shale partings. Pink and red dolostone beds are present near the base of the formation. The upper contact with the St. Lawrence Formation is conformable and fairly sharp because beds in the Lone Rock Formation are generally coarser-grained and less well-cemented. Total thickness of the Lone Rock Formation is about 150 feet (45.7 meters).

Ꞓw **Wonewoc Sandstone (Upper Cambrian; shown only on cross sections)**—Fine- to coarse-grained, moderately- to well-sorted, light gray, cross-stratified, quartzose sandstone. White, brown, and black linguliform brachiopod shells are locally abundant. The upper part is coarser-grained; the lower part is finer-grained, better sorted, and progressively finer-grained toward its base. The very fine-grained sandstone in the lower part is feldspathic. The Wonewoc Sandstone is conformable with overlying and underlying formations; however, there is a subtle unconformity marked by a pebbly sandstone layer within the formation (Runkel and others, 1998). The Wonewoc Sandstone was formerly referred to as the Ironton-Galesville Sandstone. Thickness of the Wonewoc Sandstone ranges from about 50 to 55 feet (15.2 to 16.8 meters). A representative total thickness of 55 feet (16.8 meters) was used in developing the corresponding DEMs and in representing the Wonewoc Sandstone in cross section.

Ꞓe **Eau Claire Formation (Middle to Upper Cambrian; shown only on cross sections)**—Yellowish-gray to pale olive-gray, fine- to very fine-grained, feldspathic sandstone, siltstone, and shale. White and brown linguliform brachiopod shells are common. The contact with the underlying Mt. Simon Sandstone is conformable and transitional, which is commonly apparent on natural gamma-ray logs. Total thickness of the Eau Claire Formation is about 110 feet (33.5 meters).

Ꞓm **Mt. Simon Sandstone (Middle Cambrian; shown only on cross sections)**—Pale yellowish-brown to grayish-orange-pink to light gray, medium- to coarse-grained, quartzose sandstone. Interbeds of shale, siltstone, and very fine-grained, feldspathic sandstone are common, particularly in its upper half (Mossler, 1992). Linguliform brachiopod shells are locally common in the upper one-third of the formation. Thin beds of quartz-pebble conglomerate occur at several stratigraphic positions, and are especially abundant near the base of the formation. The Mt. Simon Sandstone unconformably overlies Mesoproterozoic rocks. One water well partially penetrates the Mt. Simon Sandstone in Steele County, indicating a minimum thickness of 136 feet (41.5 meters). However, limited subsurface data in surrounding counties indicate a total thickness of about 200 feet (61.0 meters; Bloomgren, 1993; Mossler, 1995, 1998; Runkel, 1998; Steenberg, 2020), which was used in developing the corresponding DEMs and in representing the Mt. Simon Sandstone in cross section.

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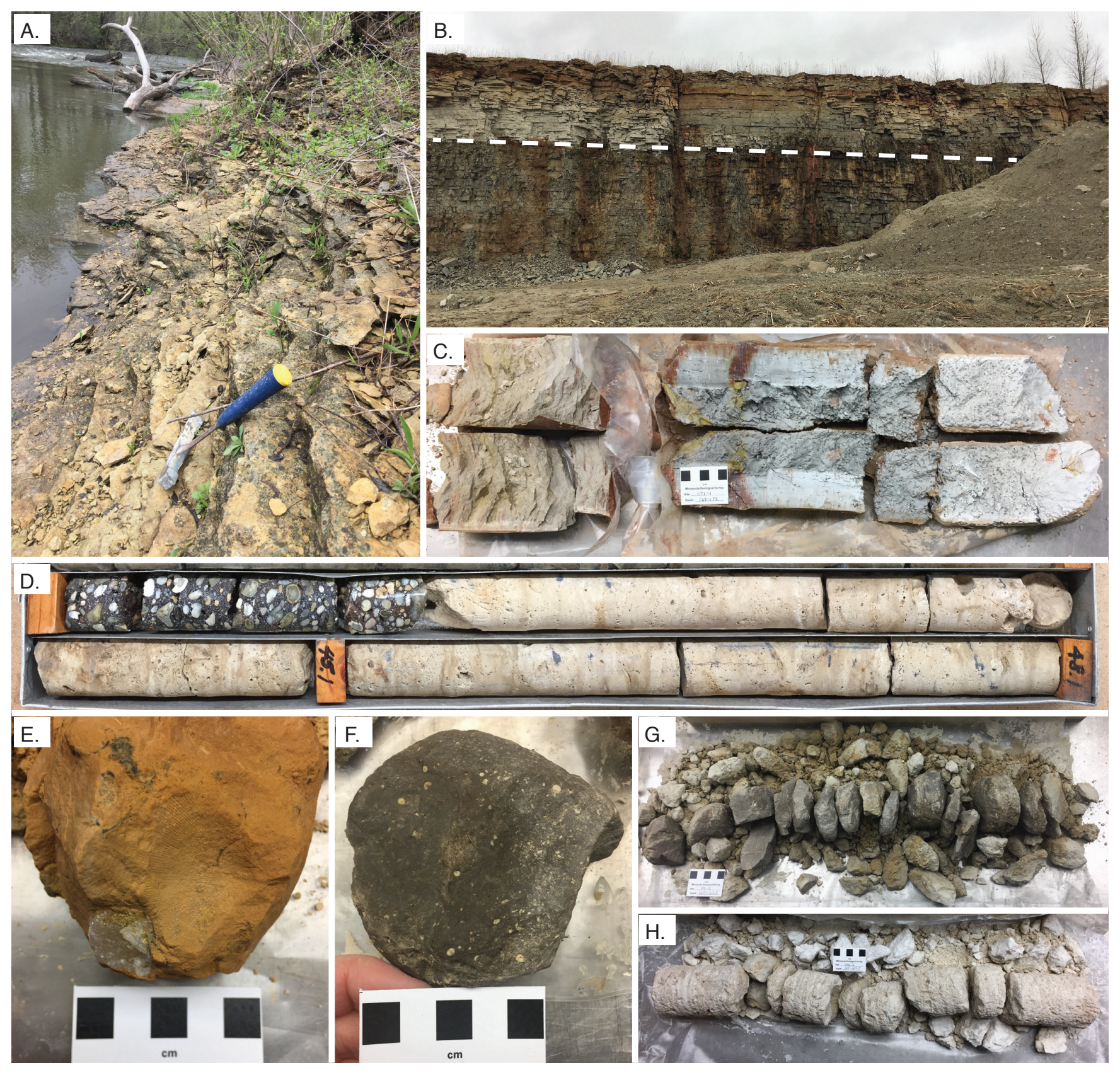

Figure 2. Photographs providing a general overview of select bedrock outcrops and rock-core samples in Steele County examined during this project.

A. Small outcrop of the Prosser Formation along the bank of the Straight River near Northwest 36th Street in Owatonna (hammer for scale).

B. A quarry wall in Owatonna exposing the upper Cummingsville Formation and lower Prosser Formation (white, dashed line along approximate contact). The vertical, red-brown staining is due to several groundwater spring/seep exit points along the quarry face that roughly approximate the Cummingsville/Prosser Formation contact. The quarry wall is about 50 feet (15.2 meters) in height. Permission from the quarry operators is required to access this site.

C. An example of a probable paleosol of the Ostrander Member, Windrow Formation. Up is to the left. This interval shows tan to light gray, oxidized, silty clay overlying a light gray and white, kaolinitic clay and silty clay with abundant red-brown, millimeter-scale siderite nodules (sphaerosiderite; CWI unique number 341104; rotary-sonic core STL-1; depth interval approximately 169.0 to 172.0 feet [51.5 to 52.4 meters]).

D. Iron-oxide-cemented quartz sand and pebbly chert conglomerate of the Ostrander Member, Windrow Formation, unconformably atop tan to buff, burrow mottled, fossil-moldic dolomitic limestone and shaly, dolomitic limestone of the Prosser Formation (up is to the left; MNDOT engineering boring T-1; DNR inventory number 18047; QDI unique number 6170; depth interval approximately 40.1 to 48.1 feet [12.2 to 14.7 meters]; core box length is 3.5 feet [1.1 meters]).

E. Tan-orange dolostone of the Spillville Formation containing a large brachiopod external mold and sparry calcite vug fill (CWI unique number 341104; rotary-sonic core STL-1; depth approximately 193.5 feet [59.0 meters]).

F. Dark brown-gray, fossiliferous dolostone of the Dubuque Formation containing numerous recrystallized, white, millimeter-sized crinoid ossicles (CWI unique number 341105; rotary-sonic core STL-2; depth approximately 169.0 feet [51.5 meters]).

G. Dark brown-gray, fossiliferous dolostone of the Dubuque Formation (up is to the left; CWI unique number 341105; rotary-sonic core STL-2; depth interval approximately 165.0 to 167.5 feet [50.3 to 51.1 meters]).

H. Light gray to white, crinoid-moldic dolostone and dolomitic limestone with a sugary texture of the Stewartville Formation (up is to the left; CWI unique number 341105; rotary-sonic core STL-2; depth interval approximately 185.0 to 187.5 feet [56.4 to 57.2 meters]).

MAP SYMBOLS

Geologic contact, approximately located

Fold—Axial trace of anticline, syncline. Fold limbs typically have shallow dips and are inferred from subsurface data.

Location of drill hole that penetrated bedrock

A —— A' **Location of geologic cross section**

Bedrock outcrop

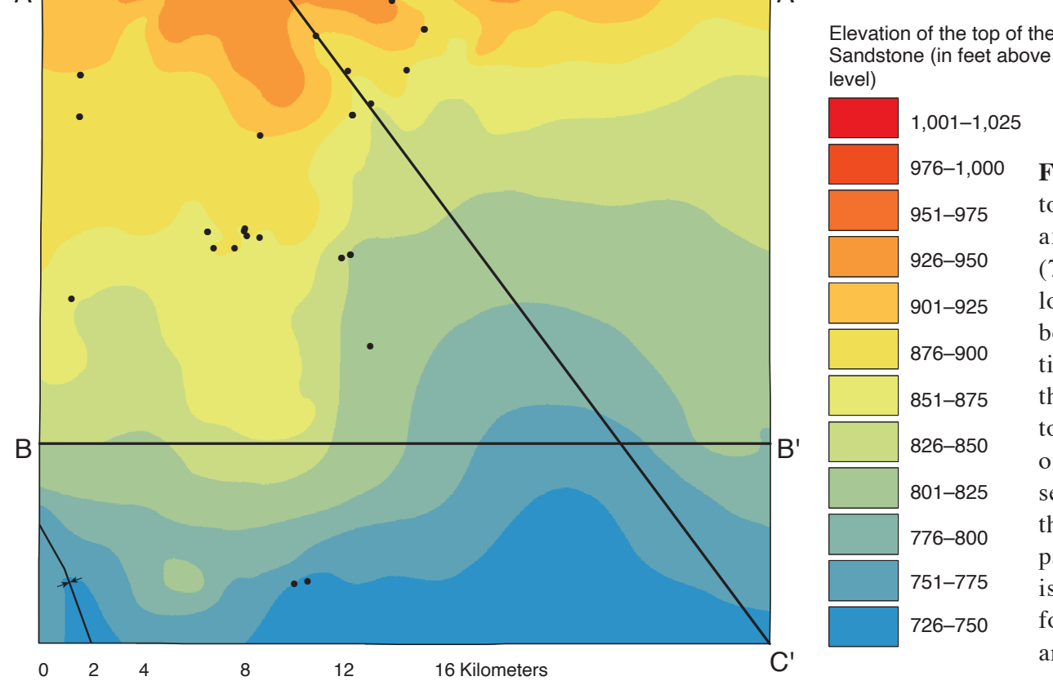

Figure 3. Map depicting the elevation of the stratigraphic top of the St. Peter Sandstone and corresponding mapped fold axes in Steele County. Shaded intervals represent 25-foot (7.6-meter) elevation intervals, with blue colors indicative of lower elevations and red colors of higher. All of the available boreholes penetrating the top of the St. Peter Sandstone at the time of this publication are shown as points. In areas where the St. Peter Sandstone is not penetrated by borehole data, its top elevation is inferred from vertical projections downwards of interpreted formation contacts stratigraphically higher in section (these wells are not shown on this figure). In contrast, the top elevation of the St. Peter Sandstone in areas where it is partially or fully eroded (indicated by the diagonal line pattern) is inferred from vertical projections upwards of interpreted formation contacts stratigraphically lower in section (these wells are not shown on this figure).

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