

BEDROCK GEOLOGY Andrew J. Retzler

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INTRODUCTION

The geologic map, cross sections, and stratigraphic column on this plate depict the type, distribution, and structure of the bedrock units in Hennepin County that are either exposed at the land surface or lie beneath unconsolidated Quaternary glacial sediments of variable thickness (see cross sections and Plate 3, Surficial Geology; Plate 4, Quaternary Stratigraphy; and Plate 6, *Bedrock Topography and Depth to Bedrock*). The map shows how the bedrock surface would appear if it was viewed from an aerial perspective and the overlying Quaternary sediments were stripped away. The bedrock units near the land surface in Hennepin County consist of sedimentary rocks of Paleozoic age that form distinguishable and mappable layers designated as formations. Some of these units are commonly exposed along the Mississippi River bluffs within the county. Several of the Paleozoic bedrock formations are major reservoirs for water supply in the county, and provide a stable platform that supports major metropolitan buildings and bridges.

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. Surfaces representing the elevation of the tops of the mapped formations are also available as digital elevation models 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. Most of the Paleozoic units shown on this plate, with the exception of the Platteville Formation, Glenwood Formation, and St. Peter Sandstone, are buried by Quaternary sediments and cannot be seen at the land surface in Hennepin County. The sedimentary rocks differ in their resistance to weathering and erosion, as depicted graphically by the weathering profile on the lithology column of Figure 1. The units that cover the largest areas of the map are the most resistant to weathering and commonly form plateaus composed of carbonate rock (limestone and dolostone). The soft sandstone and shale units erode more easily and typically occur as thin veneers atop the carbonate rock plateaus or lie along valley walls.

Most layers designated as aquitards in the county have a much lower permeability in the vertical direction than do aquifers. Examples in Hennepin County include the lower Jordan Sandstone, and St. Lawrence and Eau Claire Formations, whose rocks are composed mostly of very fine-grained sandstone and shale with small, poorly connected pore spaces. Carbonate rock with relatively sparse fractures, such as 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, including the St. Lawrence Formation.

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 meters) of depth below the bedrock surface is a best approximation (Runkel and others, 2006a, 2014a).

In addition to this hydrostratigraphic classification, the Minnesota Department of Natural Resources, as Part B of the Hennepin County 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

PALEOZOIC

Decorah Shale (Late Ordovician)—Dominantly grayish-green shale interbedded with thin beds of fossiliferous limestone. Fossiliferous, yellowish-brown limestone beds are most common at the base of the Decorah Shale, and are recognized as the basal Carimona Member (Mossler, 2008). The Decorah Shale is present as erosional remnants capping buried mesas of Platteville Limestone in the eastern part of the county. Although not fully preserved in the county, water-well logs in adjacent counties indicate the Decorah Shale has a maximum preserved thickness of 90 feet (27 meters). Opg Platteville Formation and Glenwood Formation (Late Ordovician)—The carbonate Platteville Formation and underlying shale of the Glenwood Formation are combined into a single map unit with a full thickness of 30 to 35 feet (9 to 11 meters). *Platteville Formation*—The Platteville Formation is 25 to 30 feet (8 to 9 meters) thick. It is composed of 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). In the Twin Cities metropolitan area, the Platteville Formation is subdivided into four members: (from top to bottom) the Magnolia, Hidden Falls, Mifflin, and Pecatonica (Runkel and others, 2015b). These correspond to major depositional facies and are distinguished primarily by lithology and bedding style (Runkel and others, 2015b). The Platteville Formation is the dominant uppermost bedrock unit across the eastern part of the county, in particular the Minneapolis metropolitan area. Glenwood Formation—The principal lithology of the Glenwood Formation is a grayishgreen to brownish-gray, calcareous, sandy, and phosphatic shale. The Glenwood Formation is 3 to 7 feet (1 to 2 meters) thick.

COUNTY ATLAS SERIES ATLAS C-45, PART A **Hennepin County** Plate 2—Bedrock Geology

THE MINNESOTA ENVIRONMENT AND NATURAL RESOURCES TRUST FUND AS RECOMMENDED BY THE LEGISLATIVE-CITIZEN COMMISSION ON MINNESOTA RESOURCES, AND THE MINNESOTA LEGACY AMENDMENT'S CLEAN WATER FUND



the lithology, most common range in thickness, vertical succession, age, and hydrostratigraphic properties for all units shown on the map. The gamma log is a compilation of the following borehole geophysical logs on file at the Minnesota Geological Survey: County Well Index unique numbers 200393, 223723, and 782102.

Geological Society of America Abstracts with Programs, v.

Croixan) Jordan Sandstone, and the nature of the Cambrian-

Ordovician boundary in the upper Mississippi valley:

Geological Society of America Bulletin, v. 106, p. 492-506.

—1996, Bedrock geology of Houston County, Minnesota:

Minnesota Geological Survey Open-File Report 96-4, 11 p.,

J.F., 2007, High resolution sequence stratigraphy of lower

Paleozoic sheet sandstones in central North America: The role

of special conditions of cratonic interiors in development of

a classic cratonic sheet sandstone: Stratigraphy across the

Sauk II-Sauk III boundary in the upper Mississippi valley

D.J., 1999, Cambrian-Ordovician boundary strata in the

central mid-continent of North America: Acta Universitatis

2006a, A hydrogeologic and mapping investigation of the

St. Lawrence Formation in the Twin Cities metropolitan

area: Minnesota Geological Survey Open-File Report

2015a, Fracture stratigraphy in lower Paleozoic bedrock of

the central midcontinent, North America: Geological Society

of America Abstracts with Programs, v. 47, no. 5, p. 12.

and Retzler, A.J., 2015b, Hydraulic conductivity and

Runkel, A.C., Steenberg, J.R., Tipping, R.G., Jansen, S.,

Runkel, A.C., Mossler, J.H., Tipping, R.G., and Bauer, E.G.

Geological Society of America Bulletin, v. 110, p. 188-210.

stratal architecture: Geological Society of America Bulletin,

cutting samples, borehole geophysical logs, seismic soundings, geophysical images, and previously published geologic maps of Hennepin and adjacent counties (Olsen and Bloomgren, 1989; Mossler and Tipping, 2000; Runkel and others, 2006a; Mossler, 2013; Steenberg and Chandler, 2013; Steenberg and Retzler, 2016). This map supersedes the previous bedrock geology map of Hennepin County (Olsen and Bloomgren, 1989), a larger-scale seven-county Twin Cities metropolitan area bedrock geology map (Mossler and Tipping, 2000), and several quadrangle bedrock geology maps covering portions of Hennepin County (Mossler, 2007, 2009). Significant improvements and modifications were made to the interpretations of the previous maps based on additional water-well records, drill cuttings, and borehole geophysics, enabling better definition of hydrogeologically significant units. These improvements include: the Prairie du Chien Group is separated into the Shakopee Formation and Oneota Dolomite, the St. Lawrence Formation is mapped separately from the Tunnel City Group (previously Franconia Formation), and the Tunnel City Group is separated into the uppermost Mazomanie Formation and lowermost Lone Rock Formation. Further refinement was also made to the unconformable contact between the St. Peter Sandstone and Jordan Sandstone (areas where the Prairie du Chien Group is absent) in western Hennepin County. Faults and folds in the county were mapped to reflect significant, apparent offset in the Paleozoic formations. This provides greatly increased detail in the depiction of the subsurface geologic characteristics, which has implications for modeling groundwater flow and contaminant transport. The different data sources and their irregular distribution and density can be seen on Plate 1, Data-Base 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 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 digital elevation models 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 digital elevation models is dependent upon the contour interval used when mapping the topographic surface of each unit and the errors inherit in the Topo to Raster interpolation method. For this map, the bedrock surface digital elevation models on average are accurate within \pm 12.5 feet (\pm 3.8 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, as it represents the most accurate and reliable representation of uppermost bedrock across the county.

To create this map, over 20,000 located water-well records and 6,000 located engineering test and giddings soil probe borings were accessed in the County Well Index, nearly 9,400 of which reached Paleozoic bedrock. Geologic interpretations of subsurface material were made by the author based on material descriptions by drillers or gathered from other data sources and are recorded in

In Hennepin County, Paleozoic bedrock lies on top of a thick sequence of Mesoproterozoic rocks of the Keweenawan Supergroup, associated with the Midcontinent Rift (see cross sections and Fig. 2; Jirsa and others, 2012). These rocks include sandstone, siltstone, and shale of the Hinckley Sandstone and Solor Church and Fond du Lac Formations (unit *Mss*), as well as volcanic rocks composed mostly of basalt, including the Chengwatana volcanic rocks (unit Mcv) and the North Branch mafic volcanic sequence (unit *Mbv*; Jirsa and others, 2012). Due to their deep burial and limited subsurface data, the distribution of these individual units is less certain than those of the Paleozoic formations. Therefore, the top of these units and the overlying base of the Mt. Simon Sandstone is dashed on the cross sections. No new mapping of these Precambrian units or their associated faults was done for this project. Instead, a recent compilation map of the Precambrian bedrock geology of Minnesota is depicted (see Fig. 2; Jirsa and others, 2012).

The Paleozoic rocks of Hennepin County are characterized by relatively thin, widespread layers of sandstone, shale, and carbonate deposited in shallow seas during the Cambrian and Ordovician Periods of the Paleozoic Era, from about 500 to 450 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 formations, in contrast, are dominated by thicker units of carbonate rock (for example the Prairie du Chien Group and the Platteville Formation), with the exception of the St. Peter Sandstone. Use of these Paleozoic bedrock resources as aggregate or dimension stone is no longer practical within Hennepin County, because the areas in which bedrock exists within 50 feet (15 meters) or less of the land surface coincide with dense urban areas. Across most of Hennepin County, bedrock units are slightly tilted (less than 1°) southeast towards

the central Twin Cities metropolitan area. As a result, progressively older bedrock formations subcrop from eastern to western Hennepin County. This general trend is locally interrupted by deep valleys that incise older formations, and by faults and folds. A fault is recognized where changes in the elevation of a bedrock contact occur within a very short distance, generally elevation changes of 50 feet (15 meters) or more within a distance of 1,000 feet (305 meters). A fold is inferred where these elevation changes indicate more gradual slopes. The stratigraphic top of the Jordan Sandstone and Wonewoc Sandstone were contoured at 25-foot (15-meter) intervals to show the inferred location of faults and folds in Hennepin County. Figure 3 shows an example of the contoured elevations for the top of the Wonewoc Sandstone and the inferred faults and folds. These two units were selected to portray these structures because both are well-recognized and distinct contacts to well drillers, and they provide the best spatial coverage from the numerous wells that penetrate them. Displacement of Paleozoic bedrock along faults in Hennepin County can be as much as 250 feet (76 meters) depending on location; sufficient in places to juxtapose several different formations along the fault contact (see cross sections and Fig. 3). Bedrock that has dropped alongside a fault (labeled with a

- Os St. Peter Sandstone (Middle to Late Ordovician)—The upper 110 to 140 feet (34 to 43 meters) of the St. Peter Sandstone, referred to as the Tonti Member, are mostly a white to tan, fine- to medium-grained, friable quartzose sandstone. Bedding and structures are generally absent. It is exposed in outcrops along the Mississippi River bluffs. The lowermost 20 to 40 feet (3 to 12 meters), referred to as the Pigs Eye Member, include white, gray, red, and green feldspathic shale and siltstone interbedded with coarser-grained sandstone similar to that of the overlying Tonti Member. The Pigs Eye Member is not exposed in Hennepin County. The thickness of the St. Peter Sandstone varies from about 150 to 175 feet (45 to 53 meters). The basal contact of the formation with the underlying Shakopee Formation (unit Ops) is a major erosional unconformity (Smith and others, 1993). In much of western Hennepin County, the St. Peter Sandstone lies unconformably atop the Jordan Sandstone, with the Prairie du Chien Group absent (Retzler and others, 2016; this map). In these places, the lowermost 15 to 20 feet (4 to 6 meters) commonly include a dark red-brown, ironcemented sandstone with intraclasts of light to dark gray chert and ooidal chert that are inferred to be weathered remnants of the Prairie du Chien Group.
 - Prairie du Chien Group (Early 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 using geophysical logs and drill cuttings penetrating the Prairie du Chien Group in Hennepin County. The boundary of these two formations as depicted on this map is therefore more speculative than for other unit contacts. The thickness of the Prairie du Chien Group beneath the St. Peter Sandstone varies greatly across Hennepin County, from absent to 130 feet (40 meters).
- Shakopee Formation (Early Ordovician)-A heterolithic unit composed mostly of light brown to red-brown, thin- to medium-bedded dolostone, sandy dolostone, sandstone. and shale. It contains oolites, intraclasts, microbial mounds, chert nodules, quartz sandstone, and green-gray shale partings. Based on a limited amount of high quality drill cuttings and geophysical data, the Shakopee Formation is on average 40 feet (12 meters) thick.
- Oneota Dolomite (Early Ordovician)—Predominantly a yellowish-gray to light brown, medium- to thick-bedded dolostone that, except in its lowermost part, generally lacks sedimentary features such as onlites and quartz sand characteristic of the Shakopee Formation. The formation contains two members, the Hager City and the Coon Valley, but they are not mapped separately. 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. The thickness of the Coon Valley Member is variable—it is locally absent to 55 to 60 feet (16 to 18 meters) thick. The Hager City Member is primarily very finely crystalline dolostone, with microbial textures. Its thickness ranges between 30 and 35 feet (9 and 10 meters).

E Jordan Sandstone (Late Cambrian)—Dominantly white to yellow, medium- to coarsegrained, friable quartzose sandstone characterized by coarsening-upward sequences consisting of two interlayered facies (Runkel, 1994). They are medium- to coarsegrained, cross-stratified, generally friable, quartzose sandstone; and very fine-grained, commonly bioturbated, feldspathic sandstone and lenses of siltstone and shale. The major part of the very fine-grained facies forms a regionally continuous interval that gradationally overlies the St. Lawrence Formation (unit €s), 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, 1999, 2007), separates the Jordan Sandstone from the overlying Oneota Dolomite of the Prairie du Chien Group. In western Hennepin County, the Prairie du Chien Group is absent and the Jordan Sandstone unconformably underlies the St. Peter Sandstone. In these areas, the Jordan Sandstone is typically thinner than where it is overlain by the Prairie du Chien Group. It ranges in total thickness from 80 to 90 feet (24 to 27 meters). **St. Lawrence Formation (Late Cambrian)**—The St. Lawrence Formation is principally 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). The formation is 35 to 45 feet (8 to 12 meters) thick. The upper contact with the Jordan Sandstone is conformable and gradational. The gradational nature of the contact in well cuttings and on natural gamma logs can make selecting a precise contact between these formations challenging. Tunnel City Group (Late Cambrian)—The Tunnel City Group, formerly named the Franconia Formation (Berg, 1954), varies from about 135 to 145 feet (41 to 44 meters) in thickness across Hennepin County. It is formally divided into two formations: the Mazomanie Formation and the Lone Rock Formation (Mossler, 2008). The upper contact of the Tunnel City Group with the St. Lawrence Formation is conformable. The contact is fairly sharp, and the contrast between the siltstone and shale of the St. Lawrence Formation and the underlying fine- to medium-grained, quartzose sandstone in the Mazomanie Formation and the very fine- to fine-grained glauconitic, feldspathic sandstone and siltstone in the Lone Rock Formation of the Tunnel City Group is distinct and usually marked by an intraclastic conglomerate. Mazomanie Formation (Late Cambrian)—The Mazomanie Formation is dominantly white to yellowish-gray, fine- to medium-grained, cross-stratified, generally friable, quartzose sandstone with interbedded, brown, dolomitic sandstone. Glauconitic grains typically are absent and never exceed 5 percent (Berg, 1954). Skolithos burrows and sandstone intraclasts are common along discrete horizons. In northern Hennepin County, the Mazomanie Formation can reach as much as 50 feet (15 meters) thick. The Mazomanie Formation thins to absent towards the south-southwest, where it is progressively replaced laterally by the Lone Rock Formation. Lone Rock Formation (Late Cambrian)-The Lone Rock Formation underlies the Mazomanie Formation and intertongues with it. It consists of pale yellowish-green, very fine- to fine-grained glauconitic, feldspathic sandstone and siltstone, with thin, greenish-gray shale partings. Thin beds with dolomitic intraclasts are common. The Lone Rock Formation ranges in thickness from 85 feet to as much as 145 feet (26 to 44 meters) in southern Hennepin County where the Mazomanie Formation is absent.





Anticline

→ Syncline

Paleozoic fault

U/D Fault movement

Vertical exaggeration = 10x



TRUST FUND

Figure 2. Faults that displace Paleozoic bedrock in Hennepin County superimposed on the underlying Mesoproterozoic rock units and interpreted thrust faults modified from Jirsa and others (2012), and the first vertical derivative magnetic data reduced to pole from Chandler (1991). The two Mesoproterozoic faults, the Douglas fault and Pine fault, are the western-bounding, high-angle faults constraining the central horst structure of the Midcontinent Rift System, known as the St. Croix horst (Morey, 2001; Jirsa and others, 2012). The locations of the Douglas and Pine faults were reinterpreted from Jirsa and others (2012) from new insights on the bedrock geology during this mapping effort. Due to their similar trends and close proximity to the Mesoproterozoic thrust faults, many of the Paleozoic faults are interpreted to have originated from reactivation of the deep-seated Mesoproterozoic structures particularly those mapped just above and parallel to the deep-seated faults. Additionally, the mapped extent of the Twin Cities basin corresponds with the Paleozoic fault directly overlying the Pine fault see Fig. 4), and the thickness trends and abrupt absence of the Prairie du Chien Group shows a similar correspondence (see Fig. 5). The area in which the mapped Paleozoic fault diverges significantly from the mapped trace of the Mesoproterozoic Douglas fault is herein termed the Douglas fault zone. Lines of cross section are shown for reference. Please refer to the map unit descriptions for the labeled Mesoproterozoic rock units. Note that the Mesoproterozoic unit Mbv has a thin, approximately 30foot-thick (9-meter-thick) cover of unit *Mss* above it (as supported by water-well records), as well as foliation trends in the lava flows (as inferred from aeromagnetic data), both of which are not shown for the purposes of this figure. These are depicted in the corresponding cross sections, with the inferred foliation trends represented by long, dashed lines.

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551-600 501-550 451-500 401-450 351-400 301-350 201-250 Less than 200 **Figure 3.** Map depicting the elevation of the stratigraphic top of the Wonewoc Sandstone and corresponding mapped fold axes and faults in Hennepin County. Shaded intervals represent 25foot (7.6-meter) elevation intervals, with blue colors indicative of lower elevations and red colors of higher. In areas where the Wonewoc Sandstone is not penetrated by water-well data or is absent because of erosion, its top elevations are inferred from vertical projections of formation contacts stratigraphically higher or lower in the section, respectively. Furthermore, fold axes and faults were interpreted using a culmination of stratigraphic top contour data for bedrock geologic units other than the Wonewoc Sandstone, most notably the Jordan Sandstone. Note the radial pattern of the stratigraphic top elevation map in eastern Hennepin County, an effect of the Twin Cities basin (see Fig. 4).

Eroded edge of the

Elevation of the top of the

751-800

701-750

651-70

601-650

Wonewoc Sandstone (in feet)

Figure 5. Color-shaded map indicating the thickness of the Prairie du Chien Group in Hennepin County. Red colors correspond to areas where the Twin Cities basin extent Prairie du Chien Group is thicker and blue colors (in Hennepin County) to areas where it is thinner. The black outlined Prairie du Chien Group polygons represent the mapped extent of the St. Peter Sandstone. Color-shaded areas within those

Group (in feet) bedrock, and are thinner due to erosion during Less than 25 deposition of the overlying glacial sediment. Note the abrupt thinning and absence of the Prairie du Chien Group along an erosional line (dashed line) in close proximity to the Paleozoic fault system and outermost extent of the Twin Cities basin (thick black line) to the west-northwest. Areas in which the mapped extent of the St. Peter Sandstone lies beyond the erosional line (unshaded polygons) 1972; Mossler, 1972). indicate St. Peter Sandstone deposited directly atop Jordan Sandstone. This phenomenon is thought to be due to movement along the Paleozoic fault system during the reactivation of underlying Mesoproterozoic faults and the development of the Twin Cities basin, and is unique to Hennepin 0 2 4 County (Austin, 1972; Mossler, 1972, 2013; Olsen and Bloomgren, 1989; Mossler and Tipping, 2000; Retzler and others, 2016; this map).



Figure 4. Regional extent of the Twin Cities basin (blue outline), as illustrated by the elevation of the Mapped extent of polygons correspond to where a variable thickness stratigraphic top of the Jordan Sandstone, and its relation to the geographic location of Hennepin County the St. Peter Sandstone of the Prairie du Chien Group is present between . dhen (magenta outline) and mapped Paleozoic faults. The depicted extent of the basin was first interpreted Paleozoic fault the St. Peter Sandstone and Jordan Sandstone. by Mossler (2008) and reinterpreted herein using a digital elevation model of the stratigraphic top of the Miscellaneous Map M-194, scale 1:125,000. Color-shaded areas outside of these polygons Thickness of the Jordan Sandstone as proxy. The digital elevation model was interpolated using the ESRI ArcMap Topo represent the Prairie du Chien Group as first to Raster tool from a culmination of 50-foot (15-meter) elevation contours interpreted by Mossler (2013), Steenberg and Retzler (2016), and this mapping effort. The interpreted edge of the Twin Cities basin roughly corresponds to the 750-foot (228-meter) elevation contour of the stratigraphic top of the Jordan Map M-104, scale 1:250,000. Sandstone across much, but not all, of the interpolated extent shown. The Paleozoic faults represented Olsen, B.M., and Bloomgren, B.A., 1989, B are from Jirsa and others (2011), Steenberg and Retzler (2016), and this map. Note the close relationship between the Twin Cities basin and the Paleozoic faults—in particular, faults in Washington and Hennepin Counties that bound the eastern and western edges of the basin. The formation of the Twin Cities basin scale 1:100,000. is commonly attributed to isostatic and/or thermal adjustments accommodated by Midcontinent Rift structures and reactivated Paleozoic structures during Middle to at least Late Ordovician time (Austin, Resources Investigation Report 00-4142, 33 p. GEOLOGIC ATLAS OF HENNEPIN COUNTY, MINNESOTA "D" on the map) preserves relatively younger formations at the surface and bedrock that has been uplifted (labeled with a "U" on the map) brings older formations closer to the surface. Most faults trend northeastward, with a few trending approximately orthogonally to the northwest.

Current and previous structural mapping throughout Hennepin County and adjacent counties has identified a regional Paleozoic structural low named the Twin Cities basin (Fig. 4; Austin, 1972; Mossler, 1972, 2013; Olsen and Bloomgren, 1989; Retzler and others, 2016; this map). The formation of the Twin Cities basin is not well understood, but has long been attributed to isostatic and/or thermal adjustments accommodated by Midcontinent Rift System structures during Middle to at least Late Ordovician time (Austin, 1972; Mossler, 1972). Several of the faults in the Paleozoic strata of Hennepin County are directly above or subparallel to faults in the underlying Mesoproterozoic Midcontinent Rift rocks, as inferred from geophysical imagery, and are therefore interpreted to represent reactivation of these older structures during development of the Twin Cities basin (see Fig. 2 and cross sections). Furthermore, the Prairie du Chien Group thins abruptly and is absent toward these faults, unconformably placing the St. Peter Sandstone directly atop the Jordan Sandstone (Fig. 5). The erosional limit of the Prairie du Chien Group is depicted by a thick dashed line on the map. This phenomenon has not been documented in other parts of the state, and is interpreted to be the result of subaerial exposure and erosion of the Prairie du Chien Group during post-depositional structural movement related to the formation of the Twin Cities basin.

Drill cutting samples and bedrock core in areas where the Prairie du Chien Group is missing show a deposit of variably thick iron-cemented sandstone and ooidal chert intraclasts incorporated within the basal Pigs Eye Member of the St. Peter Sandstone (Fig. 1) at or near the unconformable contact with the Jordan Sandstone (Retzler and others, 2016; this map). The ooidal chert intraclasts are likely derived from the Prairie du Chien Group because it is the only Paleozoic unit in the Twin Cities metropolitan area known to contain ooids. Additionally, the presence of an unusual ironoxide coating and cement, as well as intraclasts, lends itself to an interpretation of a lag deposit of weathered Prairie du Chien Group material that was later reworked and deposited as the lowermost part of the St. Peter Sandstone (Retzler and others, 2016; this map).

Syndepositional structural movements and thickness changes in the Prairie du Chien Group have also been noted on the eastern rim of the Twin Cities basin atop a preexisting Midcontinent Rift horst in Washington County to the east and into western Wisconsin (Steenberg and others, 2015; Steenberg and Retzler, 2016). Folding within the Prairie du Chien Group, believed to be tectonic in origin, has also been documented in Wisconsin and Iowa by Ludvigson and McAdams (1980). Several other midcontinent structural features (such as the Michigan Basin, Wisconsin Arch, and Hollandale Embayment) were active roughly contemporaneously and possibly in response to farfield stresses generated during orogenic activity along present-day eastern North America (Howell and van der Pluijm, 1990; Smith and others, 1993). The development of the Twin Cities basin and its effect on Prairie du Chien Group deposition may also be an early manifestation of these orogenic far-field stresses (Steenberg and others, 2015; Retzler and others, 2016; Steenberg and

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Retzler, 2016; this map).

The Paleozoic bedrock formations contain significant sources of groundwater that provides the water supply for much of Hennepin County. This map and associated products, such as the bedrock unit digital elevation models, 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 (easily transmitting water) material, versus layers dominated by lower permeability (relatively harder to transmit water) material. This generalized characterization for Hennepin County is based on hydrogeologic reports by Runkel (1996), Paillet and others (2000), Runkel and others (2003, 2006a, b, 2014a, b), Tipping and others (2006), Anderson and others (2011), 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 been demonstrated to have high permeability are likely to be present, as least locally, in all formations in Hennepin County, but are placed on the column where the hydrogeologic reports cited above indicate they are most common. Most bedrock springs in Hennepin County emanate from the Platteville Formation in the metropolitan area and along the Mississippi River, where high permeability vertical and bed-parallel fractures are known to be common. The vast majority of Platteville Formation springs in the Twin Cities Metropolitan Area emanate from the contact between the uppermost Magnolia Member and underlying Hidden Falls Member due to a contrast in mechanical properties leading to the preferential termination of vertical fractures at or near this contact (Anderson and others, 2011; Runkel and others, 2015a, b). Deeper into the subsurface, the hydrogeologic properties of the Mesoproterozoic bedrock are poorly understood, and it does not supply water to Hennepin County, at least in part, because sufficient water resources are available

In Hennepin County, most aquifers are layers dominated by relatively coarse-grained sandstone, such as the upper part of the Jordan Sandstone, in which water can be more easily transmitted in both horizontal and vertical directions through the pore spaces between sand grains, as well as through fractures. Other aquifers, such as the upper part of the Prairie du Chien Group, are composed mostly of carbonate rock in which water is transmitted through a relatively dense network of fractures and solution cavities. However, layers designated as aquifers can locally contain low permeability

at shallower depths within the Paleozoic rocks.

Wonewoc Sandstone (Late Cambrian)—This sandstone unit, formerly referred to as the Ironton-Galesville Sandstone, is composed mostly of fine- to coarse-grained, moderately to well sorted, light gray, cross-stratified, quartzose sandstone (Mossler, 2008). White, brown, and black linguliform brachiopod shells are locally abundant. The upper part is the coarsest-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 thickness of the formation is 45 to 75 feet (14 to 23 meters). 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).

Ce Eau Claire Formation (Middle to Late Cambrian)—The formation is composed of 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 formation ranges from 80 to 90 feet (24 to 27 meters) in thickness. The contact with the Mt. Simon Sandstone is conformable and transitional, which is commonly apparent on natural gamma-ray logs.

Mt. Simon Sandstone (Middle Cambrian)—The Mt. Simon Sandstone is pale yellowishbrown 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. Based on a limited number of drill holes, the formation has a maximum thickness of about 280 feet (85 meters) in the southeastern portion of the county and thins to about 140 feet (42 meters) towards the west-northwest.

MESOPROTEROZOIC

Keweenawan Supergroup and Midcontinent Rift Intrusive Supersuite

Sandstone, siltstone, and local conglomerate (shown only on Fig. 2 and the cross sections)—Includes the quartzose Hinckley Sandstone and the more feldspar- and lithic-rich sandstones and shale of the Fond du Lac and Solor Church Formations deposited in eolian, fluvial, and lacustrine environments (Jirsa and others, 2012). *Mbv* North Branch mafic volcanic sequence (shown only on Fig. 2 and the cross sections)-

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> Every reasonable effort has been made to ensure the accuracy of the factual data on which this map interpretation is based; however, the Minnesota Geological Survey does not warrant or guarantee that there are no errors. Users may wish to verify critical information; sources include both the references listed here and information on file at the offices of the Minnesota Geological Survey in St. Paul. In addition, effort has been made to ensure that the interpretation conforms to sound geologic and cartographic principles. No claim is made that the interpretation shown is rigorously correct, however, and it should not be used to guide engineering-scale decisions without site-specific verification.

strata that serve as small, internal aquitards including parts of the upper Mt. Simon Sandstone and Part of the St. Croix horst volcanic sequence (Jirsa and others, 2012). Mcv Chengwatana volcanic rock; primarily mafic flows (shown only on Fig. 2 and cross section A-A')—Part of the St. Croix horst volcanic sequence (Jirsa and others,