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Geology Of Northeastern Nebraska And Environs: Cedar, Dakota, and Dixon Counties in Nebraska, and Plymouth and Woodbury County in Iowa

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FIELD TRIP GUIDE

(for the Nebraska Well Drillers Association)

GEOLOGY OF NORTHEASTERN NEBRASKA AND ENVIRONS: Cedar, Dakota, and Dixon Counties in Nebraska, and Plymouth and Woodbury County in Iowa

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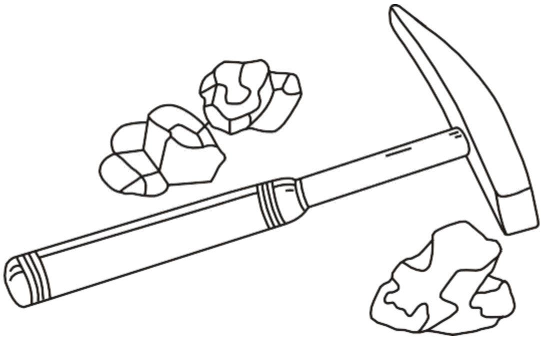

Conservation and Survey Division, School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska–Lincoln

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Geology of Northeastern Nebraska and Environs

Nebraska Well Drillers Association
and
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Itinerary
Geology of Northeastern Nebraska and Environs
October 19, 2017

Begin at South Sioux City, Nebraska (schedule is approximate: note that tour may run as much as one hour over scheduled time of completion).

7:45-8:00 (0.25 hr)	Registration and check-in @ selected motel. Brief introduction to trip
8:00-8:30 (0.5 hr)	Leave South Sioux City and proceed into Sioux City, Iowa, thence north-northwest to Stone State Park, Iowa.
8:30-10:00 (1.5 hr)	STOP 1: Stone State Park, Iowa: Overview of regional Cretaceous bedrock stratigraphy and examination of Dakota Formation/Group as basal unit of regional Cretaceous succession. Discuss Dakota Formatio/Group as secondary aquifer in eastern Nebraska (recent geologic investigation includes three new test holes through the Dakota Formation/Group near Winnebago, Jackson, and Hubbard, Nebraska), as well as in Iowa. Discuss revision of Papio-Missouri River NRD Groundwater Management Plan and Groundwater Rules and Regulations, which include modified triggers for groundwater quality and quantity. Return to South Sioux City by outbound route and continue to Ponca State Park in Nebraska (extend discussion of subjects enroute to next stop as necessary).
10:00-12:00 (2.0 hr)	STOP 2: Ponca State Park and lunch stop: Examine exposures of upper Dakota Formation/Group through Greenhorn Limestone and discuss stratigraphy, rock types, recognition in subsurface, depositional environments, and hydrogeologic significance. Briefly discuss geomorphology and hydrology of Missouri River. Continue discussion during lunch.
12:00-12:30 (0.5 hr)	Drive from Ponca State Park to Volcano Hill, northeast of Newcastle, Nebraska.
12:30-13:00 (0.5 hr)	STOP 3: Volcano Hill near Newcastle, Nebraska: Examine exposures of Carlile Shale and discuss stratigraphy, rock types, recognition in subsurface, depositional environments, and hydrogeologic significance. Discuss Codell Sandstone aquifer in detail. Discuss, and examine evidence for, near-surface oxidation of pyrite by percolating waters (acid rock drainage) and its potential impacts on mineral formation and water chemistry, as well as the history of the so-called "Ionia Volcano."
13:00-13:30 (0.5 hr)	Drive to vicinity of Bow Valley, Nebraska.
13:30-15:00 (1.5 hr)	STOP 4: Obert Trough near Obert Nebraska: View and discuss local landscape and its relationship to surficial sediments and Pleistocene glacial, eolian, and fluvial processes.

15:00-16:00 (1 hr)	Return to South Sioux City on Nebraska Highway 12, stopping briefly at exposures of upper Carlile Shale and lower Niobrara Formation (Ft. Hays Limestone) along highway near intersection with Nebraska Highway 15. Conclusion of tour. Participants will be required to complete a field-trip related exercise on return trip. Completion of tour and sign out. Note that tour may run as much as one hour overtime.

Objectives of tour: This tour will summarize the regional geology and hydrogeology of a large portion of northeastern Nebraska. In the course of the tour, participants will examine Cretaceous and younger (Miocene-Holocene) strata in the contexts of regional stratigraphy, hydrostratigraphy, and geological history. Participants will learn to recognize particular bedrock and sediment units and place them in a vertical stratigraphic sequence. Significant emphasis will be placed on understanding aquifers hosted in bedrock (Dakota, Codell, and Niobrara aquifers). The tour will also elucidate surficial sediments, Pleistocene-Holocene landscape history and regional geomorphology and surface and shallow groundwater hydrology. Geology and hydrogeology will be placed in the context of current management efforts and concerns.

Tour leaders:

R. M. Joeckel: Associate Director for Conservation and Survey in the School of Natural Resources, Professor in School of Natural Resources and Department of Earth and Atmospheric Sciences, and Curator of Geology, University of Nebraska State Museum (Ph.D., Geology, University of Iowa, 1993).

D. P. Divine: Survey Hydrogeologist, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln (M.S., Geology, Washington State University, 2002).

P. R. Hanson: Associate Director, School of Natural Resources, Professor in School of Natural Resources (Ph.D., Geology, University of Nebraska, 2005).

1. Introduction

The objectives of this field trip (Fig. 1) are: (1) to explore the geologic and hydrologic framework of northeastern Nebraska and environs, (2) understand the key events that took place over one-hundred million years of Earth history to shape those aspects, (3) discuss even more ancient aspects of regional geology dating to billions of years ago, and (4) seek an understanding of the present landscapes of the area and their relevance to human civilization. The landscapes, surficial materials, and bedrock of northeastern Nebraska are the results of inexorable processes and great changes in Earth's history: ancient sea-level rises and falls, erosion and deposition by ancient and modern streams, changes in ancient climates, glacial advances and retreats, and the removal and accumulation of materials by the wind. The soils, landscapes, surface water and groundwater, and even the pattern of human settlement that we see today in the region are directly related to its geology and geologic history. Through the area of the field trip, humans interact intensively with geology and groundwater in both urban and rural settings.

The field-trip area (Fig. 1) is underlain by some important trends in subsurface geology that can be related to major geologic differences in areas slightly farther to the north and northeast. We will also seek a broader understanding of geology and hydrogeology that extends beyond the area of the field trip in order to provide important context and to elucidate contrasts that promote deeper understanding. Therefore, this field guide offers some brief comparisons with parts of southeastern South Dakota, northwestern Iowa, and southwestern Minnesota beyond the area of the trip.

2. Geologic Setting and Basement Rocks

Below the soils and surficial sediments (Figs. 2, 3), collectively called *regolith* (all unconsolidated Earth materials atop bedrock) with which we commonly interact are the different strata and bodies of rock that make up Earth's crust. Our understanding of the geologic setting of northeastern Nebraska must begin with a discussion of regional crustal rocks in the context of the large-scale structure of the North American continent. To that end, we emphasize that all of Nebraska lies on the North American *platform*—the sedimentary-rock-covered, comparatively stable interior of the continent. Platforms and shields (such as the Canadian Shield) make up the *craton* of a continent. A *shield* is an area of exposed basement rock on a continent. On the platform, a comparatively thin succession of sedimentary rocks that are generally less than 1,500 ft or 460 m thick in the area of the field trip, overlies the much older *basement* (Fig. 4), which consists chiefly of igneous and metamorphic rocks (collectively called *crystalline rocks*), which are more than one billion years in age and similar to rocks exposed in the shield. Geologic structure on the platform is gentle, although faults, gentle regional upwarpings of rock strata (*domes* and *arches*) and downwarpings (*basins*), as well as other structures, developed on it over geologic time (Fig. 5). Large-scale mountain building, volcanism, and other activity related to plate tectonics, however, have not taken place in the area encompassed by the platform for more than a billion years. Nevertheless, this intense geological activity did occur in the field-trip area during the very distant geologic past, before 1.6 million years ago. Multiple rock strata within the sedimentary-rock cover of the platform serve as aquifers, as do the unconsolidated sediments in most of the continental interior in the United States. Some basement rocks, whether within the platform or on the Canadian Shield, also serve as aquifers, but they have widely varying importance in terms of yield, water quality, and other properties.

Considering our position on the North American continent more broadly, it is important to consider that the field-trip area is at the southern edge of a region in which the sedimentary-rock cover pinches out against the uplifted and exposed basement rocks of the Sioux Quartzite Ridge (not to be confused with the Siouxana Arch; Fig. 5) in eastern South Dakota and western Minnesota. Farther to the northeast from the Sioux Quartzite Ridge, into southern and central Minnesota, the Phanerozoic succession of sedimentary rocks on the platform disappears entirely. The southeastern-most edge of widespread, exposed or near-surface basement rock is only 150 mi (240 km) north-northeast of Sioux City in the Minnesota River Valley of southern Minnesota, where gneisses approximately 3.5 billion years old are exposed. That area transitions northward into the Canadian Shield proper.

Although they are not exposed anywhere in Nebraska, basement rocks are still present deep underneath sedimentary rock strata in the State. Furthermore, the few wells that have been drilled into buried basement rocks in Nebraska (none of them for water supply) have revealed a compelling story about the origins of the entire continent. Northeastern and northcentral Nebraska are underlain by no less than three distinct masses of basement rock: (1) the Trans-Hudson orogen, which underlies only a small part of northern Nebraska and extends far northward into the western Dakotas and Canada; (2) the Central Plains orogen, which underlies almost all of Nebraska and extends far south- and westward; and (3) the Superior Craton, which underlies the area of the field trip and extends far north- and eastward into the eastern Dakotas, western Minnesota, Manitoba, and beyond. The two *orogens* are extensive masses of crystalline rock that were produced by plate-tectonic mountain building in the distant geologic past, between 1.6 and 2.0 billion years ago. They are crustal rocks that were accreted onto the growing continent. The Trans-Hudson orogen includes rocks from much older *microcontinents* that were joined together by plate tectonics. The Superior Craton is a very old continental core more than 2.5 billion years of age. It includes some rocks that are slightly more than 4 billion years old—an age equivalent to nearly 90% of all of Earth's history! These observations indicate that Nebraska was very geologically active a very long time ago: bits of continental crust were amalgamated to make a greater whole, mountains were uplifted, ancient seas were closed up, volcanoes erupted, and there were high-magnitude earthquakes. All of this activity occurred so long ago that not even simple multicellular organisms had appeared yet. The juxtaposition of these three different masses of basement rock in Nebraska's subsurface is at least as important as that of features like the Rocky Mountains, the Basin and Range, and the Colorado Plateau in the western U.S., the difference being that the latter are visible at the land surface and the former are not.

The Sioux Quartzite (Fig. 5), which, at more than 1.6 billion years of age, fully qualifies as basement rock, can be found within an hour's drive or less of Sioux City. The Sioux Quartzite crops out in and around Sioux Falls, South Dakota, in northwestern-most Iowa (e.g., Gitchie Manitou State Preserve: Koch, 1969; Witzke et al., 2010) and in southwestern Minnesota (e.g., Blue Mounds State Park: Jisra et al., 2011). In contrast, one would have to drive at least six-and-a-half hours westward from Sioux City to see old crystalline rocks in the Black Hills or the Rocky Mountains. The Sioux Quartzite is a particularly hard and very erosion-resistant rock—the hardest rock that most of us will ever encounter. It was uplifted to form the roughly west-east-trending Sioux Quartzite Ridge (or Sioux Ridge). The ridge is not, in itself, a continuous, positive relief feature at the land surface today. Although it is an uplifted part of the basement, it is definitely not a part of the Canadian Shield. Rather, the ridge is part of an old and much larger, northeast-to-southwest-trending structural feature appropriately called the Transcontinental Arch. The Transcontinental Arch is a particularly large and broad arch—so large, in fact, that it can be difficult to define. The Sioux Quartzite itself extends in the subsurface as far south as northern Knox and northeastern-most Boyd counties in Nebraska. There is evidence that the Sioux Quartzite Ridge, as a part of the Transcontinental Arch, was uplifted more than once between ~540 and ~80 million years ago, and that it was a low positive feature that stood above ancient sea level during particular times (Bunker, 1981; Koch, 1986). The ridge was uplifted a final time—perhaps by less than 400 ft (120 m)—sometime after ~80 million years ago (Koch, 1986), as a far-field effect of the Laramide Orogeny (latest Cretaceous-early Paleogene), which was the major mountain-building phase of the Rocky Mountains.

Large-scale geologic structures in and around the area of the field trip also include faults, basins, and smaller arches in between basins (Fig. 5). These features came into being at different times in Earth's history. There are probably numerous faults in basement rocks that we are unable to see or map. Some authors (Sims and Petermar, 1986; Houser, 1987), in fact, have inferred the presence of an old, 220 mi- (375 km-) long strike-slip fault, trending from central South Dakota southeastward into northeastern Nebraska, to be the southwestern limit of the Sioux Quartzite in the subsurface. This inferred—and as far as is known, unnamed—fault has never, of course, been mapped at the land surface. If it exists, it is a major structural feature that would be about one-third the length of the famed San Andreas Fault System in California. Basins and arches in the surrounding region are younger, and appear to have been activated and reactivated at times during the past half-billion years. The Salina Basin lies immediately south of the field trip area and extends through the eastern half of Nebraska and into Kansas (Coleman and Cahan, 2012). It is considered to be a Paleozoic *sag basin*, that is, a basin produced by gentle downwarping of Earth's crusts due to *mantle downwelling* (large-scale, slow, downward flow in the solid mantle that tugs the overlying crust down with it) or *isostasy* (in effect, the buoyancy-like compensation of the crust to loading and unloading). The Kennedy Basin, also a sag basin, lies west of the field trip area in northcentral Nebraska and southcentral South Dakota (Coleman and Cahan, 2012). It is bounded by the Siouxana Arch on its southeast side and by the Chadron Arch to the southwest. These two sage basins influenced where and how sediments were deposited, and the thickness of their accumulation, in the geologic past. The Chadron Arch and its companion Cambridge Arch to the southeast, lie far west of the field-trip area and trends northwest-southeast across the western half of Nebraska. The Siouxana Arch which is closer to the field-trip area, but still to the west, trend northeast-southwest from southeastern South Dakota into central Nebraska.

Even though there are major geologic structures under northeastern Nebraska and environs, earthquakes have been rare and weak through the more than 160 years of the historical record. The 2017 U.S. Geological Survey forecast for ground shaking intensity, due to natural and induced earthquakes, in all of Nebraska, all of Iowa, and the southern half of South Dakota was only IV on the Modified Mercalli Scale, that being "shaking light, felt indoors by many, outdoors by few" (U.S. Geological Survey, 2017). In northern South Dakota and northern Minnesota, the forecast for ground-shaking intensity decreases to III, but the forecast for areas from the Kansas-Nebraska border southward into central Oklahoma increases from VI to VIII+ due to the risk of induced seismicity (U.S. Geological Survey, 2017).

3. Sedimentary Rocks atop Basement

The crystalline rocks of the basement are overlain by sedimentary rocks that were deposited during particular time intervals over the past 540 million years. Much of this sedimentary rock began as soft sediments that were laid down in ancient, shallow seas that extended across parts of the continent whenever global sea level was high (*epicontinental seas*); much less of it resulted from deposition on ancient land surfaces. The bedrock stratigraphy in the field trip is, in total, similar to that elsewhere in eastern Nebraska, but the pattern it presents within the field-trip area is surprisingly complicated due to tectonics and erosion in the distant geologic past. Parts of the Paleozoic succession of rock strata are absent due to ancient erosion in parts of northwestern Iowa, southeastern South Dakota, and northeastern Nebraska (Fig. 5). Lowermost Cretaceous strata in northeastern Nebraska, those of the Dakota Formation/Group (which are also the lowermost Mesozoic rocks in the region), overlie either

Pennsylvanian, Lower Mississippian, Ordovician, Cambrian, or even Proterozoic rocks, depending on the location (Bunker, 1981; Adler, 1987). Thus, part—or even all—of the Paleozoic rock succession is missing under most of the area of the field trip. The Pennsylvanian System, which is comparatively thick and underlies basal Cretaceous strata of the Dakota Formation/Group in most of eastern Nebraska, is thought to be absent under: (1) all of Dakota County but its southernmost part, (2) all of Dixon County but its southwestern corner, (3) in all of Cedar County but its southwestern corner, and under the northeastern to northern parts of Knox County, Nebraska (Bunker, 1981; Fig. 5). Basal Cretaceous strata in northwestern Cedar and northern Knox counties overlie Proterozoic (late Precambrian) rocks (e.g., Sioux Quartzite), as is the case parts of eastern South Dakota and southwestern Minnesota.

Along the margins of the Sioux Quartzite Ridge in eastern South Dakota and western Minnesota, Cretaceous strata—the same ones that we will see during the field trip—are bent upward and truncated against the Sioux Quartzite Ridge (Koch, 1986), due in part to its emergence above sea level during much of the Cretaceous and in part to the later Laramide uplift of the feature. Cretaceous strata dip gently away from the ridge and older sedimentary rock strata, ranging in age from Cambrian through Pennsylvanian, thicken markedly southwestward from the subsurface extent of the Sioux Quartzite across Nebraska (Houser, 1987).

The unconsolidated glacial, alluvial, and eolian sediments (Fig. 2) that are visible at the land surface in northeastern Nebraska are underlain by Cretaceous sedimentary bedrock (Figs. 6, 7), which crops out locally along the more deeply-incised streams and rivers in the area. The sequence of Cretaceous bedrock strata from near the Kansas-Nebraska border to southeastern South Dakota is, in ascending stratigraphic order: (1) Dakota Formation (Dakota Group in Nebraska), (2) Graneros Shale, (3) Greenhorn Limestone, (4) Carlile Shale, (5) Niobrara Formation, and (6) Pierre Shale. Of these bedrock units, only the Dakota Formation is of fluvial, estuarine, and nearshore marine origins, whereas the other five units are of marine origin. The stratigraphy of the interval from the upper Dakota Formation to the base of the Greenhorn Limestone is somewhat problematic in northeastern Nebraska and environs; the Graneros Shale, for example, is considered to be absent in the field-trip area by more recent authors (Brenner et al., 2000). The succession of Cretaceous sedimentary rocks in the Western Interior of North America was accumulated because of widespread crustal subsidence and eustatic (worldwide) sea-level rise, which led to flooding by an epicontinental seaway (the Western Interior Seaway) during much of the Albian through Maastrichtian stages of the Cretaceous Period. Cretaceous sedimentation in the field-trip area began with the deposition of the Dakota Formation in the late Albian Stage of the Early Cretaceous, approximately 100 million years ago (Fig. 7). It ended with the terminal deposition of the Pierre Shale during the Maastrichtian stage, approximately 70 million years ago (Fig. 7). A Conservation and Survey Division test hole drilled in northeastern Knox County in 2014 (04-LC-14) indicates that the regional Cretaceous succession there is at least 874 ft (266 m) in thickness, and this package of strata thickens markedly westwards into western Nebraska and beyond.

Geologists began to develop the stratigraphic framework of regional Cretaceous strata in the middle to late 1850s. Astounding as it may seem today, observations made in northeastern Nebraska contributed to the understanding of geology across the western interior of the United States as far as the Rocky Mountains. Both the Dakota and Niobrara formations were described and named in present-day Nebraska in 1862 (Meek and Hayden, 1862). The Graneros Shale, Greenhorn Limestone, and Carlile Shale were named some four decades later in the vicinity of Pueblo, Colorado (Gilbert, 1896).

4. Geomorphology and Quaternary Stratigraphy

Although some of the sediments and all of the rock strata from which it has been eroded are older, the actual landscape of northeastern Nebraska today (Fig. 3) is essentially the product of glacial ice, flowing water, and wind active during the Pleistocene (2.6 Ma-11.7 ka) and Holocene (post-11.7 ka) epochs of the Quaternary Period. Nearby parts of southeastern South Dakota and northwestern Iowa were glaciated multiple times, at least twice more than northeastern Nebraska was. All in all, the last 2.6 million years were a geologically momentous time in the field-trip area and environs.

The development of the modern landscape begins with the onset of continental glaciation around 2.5 million years ago. The Laurentide Ice Sheet, which attained a maximum thickness of ~3,000 m (~10,000 ft) or more in the far north of Canada, advanced southward into the field-trip area multiple times during the Pleistocene Epoch. At least seven advances into the middle of the North American continent, including the eastern one-quarter of Nebraska (Fig. 3), took place during pre-Illinoian times, between ~2.5 Ma and ~640 ka (Roy et al., 2004; Balco et al., 2005; Rovey and Bettis, 2014). Thus, the old terms “Nebraskan” and “Kansan,” as applied to pre-Illinoian glacial advances and deposits, are now obsolete because their usage implies but two glacial episodes prior to the Illinoian Stage. The processes and deposits of pre-Illinoian glaciation are far from fully understood, in part because of their great age in comparison with much younger Pleistocene and Holocene deposits, such as loesses and alluvial sediments. Aber (1991, 1999) postulated that advances of the Laurentide ice sheet during pre-Illinoian times involved two lobes of that ice sheet: (1) an earlier Minnesota Lobe, which advanced from the northeast (i.e., present Minnesota); and (2) a later Dakota Lobe, which advanced from the northwest, i.e., present South Dakota). Distinctive, very hard, rounded cobbles and boulders (*glacial erratics*, that is, exotic rock types brought into another area from some distance away by ice-sheet advances) of pinkish, reddish, and even purplish Sioux Quartzite are excellent indicators of glaciation in eastern Nebraska. Sioux Quartzite erratics—some of which are as large as automobiles—are common in pre-Illinoian glacial tills in eastern Nebraska and northeastern Kansas, as far south as the Kansas River, such that some authors recognize a “Sioux Quartzite erratic fan,” that is, and elongate and somewhat fanshaped, large-scale distribution of cobbles and boulders of that distinctive rock type across glaciated terrain in the aforementioned region (e.g., Willard, 1980; Aber, 1999). These glacial erratics were eroded—presumably by glacial plucking—from exposures of the quartzite in the Sioux Falls area in eastern South Dakota and western Minnesota. According to Aber (1991, p. 297), the commonness of such glacial boulders was first noted by the French explorer Étienne de Veniard, Sieur de Bourgmont in the early 1700s, long before any geologic map of the region had been made.

During the Illinoian Stage of the Pleistocene Epoch (~300,000-125,000 years ago), there were three advances of the Laurentide Ice Sheet into the Midwestern U.S (Illinois State Geological Survey, undated). The ice sheet advanced from the northeast into eastern South Dakota and a part of northwestern Iowa, but not into Nebraska, during Illinoian times (Illinois State Geological Survey, undated). Farther east, the ice sheet advanced over almost all of Illinois (hence the same of the glacial stage), into parts of southeastern Iowa, and across the northeastern boundary of Missouri (Illinois State Geological Survey, undated). Doubtless, cold climates—and even periglacial conditions—existed in northeastern Nebraska during Illinoian advances of the ice sheet into adjacent parts of South Dakota and Iowa.

The Wisconsinan Stage, the last glacial episode during the Quaternary, began approximately 75,000 years ago and it had a lasting impact on the field-trip area and far beyond. Those impacts were still being made in very recent geologic times. One important feature was the James Lobe of the Laurentide Ice Sheet, which appears to have been associated with an *ice stream (*a narrow corridor of faster-moving ice within a much larger ice sheet), that originated some 750 miles (1200 km) to the northwest in present Saskatchewan (Margold et al., 2015, fig. 2). The James Lobe extended southward across eastern South Dakota to the Nebraska border or just over it and created the present James River Lowland. The bed underneath the James Lobe was soft, and basal sliding and bed deformation were likely important components of ice movement under the low-stress conditions that are thought to have prevailed (Clark et al., 2007). Meltwater draining from the glacier probably flowed out of a network of small (1 m or less in depth) conduits at the interface of the glacier's base and the underlying till that it had deposited (Carlson et al., 2007). Glacial ice remained in southeastern South Dakota well after the LGM, recently as 16,000 years ago (Dyke et al., 2002), and perhaps even as recently as 12,000 years ago (Lundstrom et al., 2009). Coeval with the advance of the James Lobe was that of the Des Moines Lobe, which extended into central Iowa and was associated with an ice stream that originated in present Manitoba (Margold et al., 2015, fig. 2). The field-trip area would have had *permafrost*—permanently frozen ground, as in much of Alaska today—at the time of the Last Glacial Maximum (LGM) around 21,000 years ago (French and Millar 2014, fig. 1), and probably well after that time.

Flowing water, in the form of rivers and smaller streams, has exerted the most obvious influence on the appearance of the modern landscape in the field-trip area. The story of how the present rivers of Nebraska developed is an amazing, although underappreciated, saga. Large, drainage lines with an eastward component of flow, such as the present North Platte, South Platte, and Platte rivers, did not exist until after the Laramide Orogeny and the disappearance of the Western Interior Seaway at the end of the Cretaceous and during the earliest Paleogene, around 65 million years ago. Thereafter, drainage from the Rocky Mountains was a permanent feature of the interior of North America. There is evidence that rivers drained eastward all of the way across Nebraska and Kansas into Iowa and Missouri until the onset of continental glaciation approximately 2.5 million years ago, near the beginning of the Pleistocene Epoch (Boellstorff 1978a, 1978b; Roy et al. 2004; Balco et al. 2005). The Missouri River, which forms the boundary between Nebraska and Iowa today, did not exist prior to the Pleistocene, and it may be astounding to consider that such a major feature as its present valley can be no older than slightly more than half a million years. Prior to the first advance of the Laurentide Ice Sheet, major rivers in South Dakota flowed eastward and then northward towards Hudson Bay (Todd, 1914; Flint, 1949). These rivers were diverted by the ice sheet as in covered the Hudson Bay Lowland and flowed southward. Similar glacial drainage diversions of the ancestral Missouri River system are apparent in North Dakota and Montana (Alden, 1958; Howard, 1958). Farther back in geologic time, during the Pliocene Epoch (5.3-2.6 million years ago), and probably even into the early Pleistocene, gravel-transporting streams from the Rocky Mountains crossed Nebraska from the Panhandle east-northeast into northeastern Nebraska, and probably eastward into Iowa to meet the ancestral Mississippi River in the southeastern part of that state (Swinehart et al., 1985; Witzke and Ludvigson, 1990; Swinehart and Diffendal 1998).

Wind played a prominent role in shaping the landscape of the field-trip area during the Pleistocene Epoch, through both erosion and deposition. Three prominent loess units are found on uplands throughout much of eastern and south-central Nebraska. These units are, in ascending stratigraphic order: Loveland Loess, Gilman Canyon Formation (Pisgah Formation in Iowa), and Peoria Loess. The Loveland Loess dates to the Illinois glacial period, specifically from ~160,000 to ~140,000 years ago). The Peoria Loess dates to the last glacial period (~25,000 to 14,000 years ago), the Gilman Canyon Formation to an interglacial period (~25,000-45,000 years ago). Throughout most of south-central and eastern Nebraska the Peoria Loess has a fairly consistent thickness on uplands, and in many locations is immediately underlain by Gilman Canyon Formation and Loveland Loess. In northeastern Nebraska, however, the Peoria Loess is highly variable in thickness, and the two older loess units are absent in many places. Various hypotheses have been suggested to explain both of these observations. CSD personnel propose a hypothesis in which the presence of eolian sand on the landscape prohibits the local accumulation of loess. Outside of the Nebraska Sand Hills, eolian sand deposits and dunes are predominantly found in stream valleys along the abandoned courses of rivers such as the Platte, Elkhorn, and Loup rivers. In northeastern Nebraska eolian sand is found both along river valleys and underlying other sediments in the uplands. The source of this eolian sand is probably pre-Illinoian glacial outwash, which underlies much of the landscape. Eolian erosion exerted a strong, but not yet fully documented, role in shaping northwest-southeast-oriented ridges and valleys in parts of northeastern to northcentral Nebraska during the Pleistocene (e.g., Wayne and Guthrie, 1991; Joeckel et al., 2010).

5. Hydrogeology

In understanding the hydrogeology of Nebraska, it is important to consider the multiple secondary aquifers that underlie the state, and not merely the primary aquifers (Fig. 8). Six aquifers are utilized in the field-trip area: the three deeper aquifers (Maha/Dakota, Codell, and Niobrara) are hosted by bedrock strata and the three shallower ones (the High Plains aquifer, Quaternary glacial sediments, and Quaternary alluvium) are hosted by unconsolidated materials such as sand and gravel. Of these aquifers, only the High Plains and alluvial aquifers are considered to be primary aquifers in Nebraska The bedrock aquifers are all considered to be secondary aquifers, and the glacial sediments are minor aquifers.

The deepest of the bedrock aquifers is the Maha aquifer of the Great Plains Aquifer System, which is frequently referred to as the “Dakota aquifer” for the Cretaceous stratigraphic unit (Dakota Group or Dakota Formation) that hosts it in eastern Nebraska and surrounding areas (Fig. 8). The Dakota aquifer underlies the entire field trip area and extends well beyond. It produces well yields in excess of 1,000 gpm (63 L/s) in northeastern Nebraska. The average depth of a Dakota aquifer well is about 240 ft (73 m) in Dakota County and 660 ft (201 m) in Cedar County, Nebraska.

Moving upward through the stratigraphic section, the next-deepest aquifer is the Codell aquifer (Fig. 8). It is hosted by the Codell Sandstone Member near the top of the Carlile Shale (the remainder of that formation can be considered an aquitard). We will not see the Codell Sandstone Member on this field trip although we will see the Carlile Shale. The Codell aquifer hosts relatively few wells and it is much less productive than the Dakota aquifer, having an average well yield of about 15 gpm (0.95 L/s).

The third deepest aquifer, also the shallowest of the bedrock aquifers, is the Niobrara aquifer, hosted by the Niobrara Formation, which contains chalky limestones and other marine sedimentary rocks (Fig. 8). The Niobrara aquifer is especially important in Cedar County, where there are about 200 wells that source all of their water from the Niobrara aquifer, and an equal number that source at least part of their water from the aquifer. Niobrara wells vary widely in yield, and most are 100 ft (30 m) deep or less.

The High Plains aquifer is present as outliers of the Miocene Ogallala Group (Fig. 6) under the dissected plains between Verdigre and Bazile creeks, and also east of Bazile Creek, in Cedar County. Wells in these sediments are likely to have high yields. Quaternary alluvium is present in the valleys of the Niobrara and Missouri rivers. Alluvial sediments are shallow and easily accessible by drilling, but they have limited areal extents. The water supply of Sioux City, Iowa, which has a population in excess of 80,000, relies on groundwater pumped from Missouri River alluvium and sandstones in the Dakota Formation/Group, which are hydrologically connected. Sioux City has 10 municipal wells, each of which is 90 to 300 ft in depth, which are located on the floodplain near the river itself. Seven of these wells are vertical and other three are radial collector wells. Individual wells produce between 900 and 7,500 gpm, the radial collector wells accounting for the high end of that range. South Sioux City, Nebraska, with a population of approximately 13,000, currently relies on six vertical wells of approximately 150 to 175 ft in depth, which yield water from Missouri River alluvium and underlying sandstones in the Dakota Formation/Group. A seventh well is being drilled in October of 2017. The South Sioux City municipal wells produced 1,200 to 1,400 gpm when they were new, but production declines considerably over time, even with reconditioning. In both communities, well water is treated for iron and manganese and it is chlorinated and fluoridated before being distributed.

It is useful to make a comparison between the hydrogeology of the field-trip area and that of areas a short distance to the north and northeast where basement rocks are near the surface, or even exposed. Basement rocks are generally hard and fractured and they frequently lack significant intergranular porosity, unlike primary aquifers in Nebraska. Thus, the overall hydrogeology in areas of basement rock is different from what we are accustomed to in Nebraska, as is the siting and performance of water wells.

The Sioux Quartzite, so prominent in the Sioux Falls, South Dakota-Minnesota area, actually serves as an aquifer in parts of both of those states. In southwestern Minnesota, joints and fractures, as well as some limited zones of loose sand within the Sioux Quartzite, transmit groundwater to wells that yield from 1 to 450 gpm (Anderson, 1986), although yields are chiefly in the lower part of that range. In Minnehaha County, South Dakota, where Sioux Quartzite wells generally yield less than 50 gpm (Niehus and Lindgren, 1994). Buried valleys, incised into the Sioux Quartzite and filled with glacial sediments and much older Cretaceous sediments, also serve as both confined and unconfined aquifers in the Sioux Falls area, in Minnehaha County South Dakota and Rock County, Minnesota (Lindgren, 1997). There is some geothermal potential around the southern margin of the subcrop of the Sioux Quartzite in northeastern Nebraska.

In Nebraska, we are accustomed to aquifers hosted by unconsolidated sediments and sedimentary rocks. Consider that igneous and metamorphic rocks, including basement rocks such as the Sioux Quartzite and the old basement rocks exposed in southern Minnesota, can serve as aquifers because: (1)

they are fractured, (2) some of them have overlying zones of porous regolith (weathered material), and (3) some of them have leached zones with secondary porosity (e.g., Anderson, 1986). Suffice it to say, however, that the hydrogeology of near-surface basement rocks in the not-so-far-away Minnesota River Valley, and the Canadian Shield farther beyond, is very different from that of much of the Central Lowland, where the field-trip area lies, as well as the Great Plains.

6. Groundwater Management

Groundwater level changes in the field-trip area since predevelopment times have included both localized rises and falls (Fig. 9). Long-term groundwater monitoring is an important aspect of resource management. During this field trip, we travel through the Papio-Missouri River and Lewis & Clark Natural Resources Districts (NRDs). The Lewis & Clark NRD has designated sub-areas of management that include what they call the Niobrara Chalk Bedrock Reservoir (Niobrara aquifer in this field guide) and the Dakota Sandstone Bedrock Reservoir (Dakota aquifer in this field guide; Maha aquifer in U.S. Geological Survey terminology). The NRD requires a permit for all wells designed or modified to pump more than 50 gallons per minute, except livestock or domestic wells. Permits applications are scored based on a Water Well and Irrigated Acre Expansion Permit Ranking System that assigns points based on a number of factors. Niobrara Class Permit applications require an accurate pumping water level and pumping rate after test pumping a well for 15, 30, 60, 90, and 120 minutes, when possible. Dakota Class Permit applications must include the results of an irrigation suitability water quality test. If spring static groundwater levels in the Lewis & Clark NRD drop below the 1991 levels for two consecutive years, their quantity trigger is activated and a variety of actions may be implemented.

The Papio-Missouri River NRD Groundwater Management Plan identifies wells in the following bedrock aquifers: 1) Carlile Shale and Greenhorn-Graneros Formations; 2) Dakota Sandstone; and 3) the

Pennsylvanian System. The Groundwater Management Plan does not, however, divide the NRD into formal sub-areas. The largest of these aquifers by far is the Dakota aquifer, which includes more than 800 wells in the NRD (Divine and Sibray, 2017). Quantity triggers are activated when the saturated thickness of an unconfined aquifer declines by 10% in 50 percent of the wells measured for three consecutive years using a running average baseline. Quantity triggers in confined aquifers such as the Dakota aquifer are not yet defined due to a lack of data. Quality triggers are activated when nitrate concentrations are greater than 5 ppm in 50 percent of samples.

7. Mineral Resources

There are multiple potential and realized mineral resources in the area of the field trip. Thin lignite coals can be found in the Dakota Formation/Group in northeastern Nebraska and northwestern Iowa (Burchett, 1977; Ravn, 1981). Despite a certain amount of excitement over the matter, attempts at mining lignite from the Dakota Formation/Group in northeastern Nebraska were ultimately futile (Burchett, 1977). The Dakota Formation/Group contains industrial clay resources that are suitable for the manufacture of brick and tile and have been used for that application for more than a century. Sioux City Brick and Tile at Sergeant Bluff, Iowa uses the unit’s claystones and shales to make widely marketed products. The company now operates a sales office in Omaha. The Niobrara Formation and the Greenhorn Limestone are potential sources of agricultural lime. There are localized, minor sources of sand and gravel in the field-trip area as well.

8. Field Trip Stops

8.1. STOP 1: Stone State Park, Woodbury and Plymouth Counties, Iowa.

At Stone State Park, we will examine the Dakota Formation/Group (Fig. 7). We will also discuss the aquifer hosted by this stratigraphic unit. Condra and Reed (1959) elevated the unit to group status in Nebraska, while it has retained formation status in South Dakota, Iowa, and Kansas; there is a need to revise the stratigraphic scheme of these authors, which is approaching 60 years of age. Working in eastern Nebraska and western Iowa, Brenner et al. (2000) favored the regional application of both the formational status of the unit and its subdivision into a lower and upper members (Nishnabotna and Woodbury members, respectively).

The Dakota Formation/Group is dominated by fluvial to estuarine sandstones and mudrocks (shales, mudstones, and claystones), and it represents the deposition response of ancient rivers to the onset of rising and high global sea levels during the middle part of the Cretaceous Period. It contains the only continental deposits, as opposed to marine deposits, in the regional succession of Cretaceous deposits. Paleosols (ancient soils), multitudinous plant fossils, and even a few dinosaur bones that have found in the formation provide evidence of paleoenvironments on land, albeit along a low-lying ancient coastline. During early Dakota Formation/Group times, large river systems flowed northeast-to-southwest across northwestern Iowa into northeastern Nebraska, as well as westward in the Lincoln-Omaha area of southeastern Nebraska (Brenner et al., 2000; Joeckel et al., 2004). These observations indicate drainage reversal relative to the conditions that have prevailed in the Western Interior since the onset of the Laramide Orogeny and the retreat of the last epicontinental seaway about 64 million years ago.

The informally named Dakota aquifer (Maha aquifer of the U.S. Geological Survey) is an important secondary aquifer in Nebraska (as well as Iowa), where there were approximately 3,400 registered active wells screened entirely in the Dakota aquifer as of 2015 (Figs, 8, 10). Most of these wells are within a northeast-southwest band over the subcrop of the Dakota Formation/Group, although about 10% of Dakota wells are located west of this belt, where younger Cretaceous confining units overlie the Dakota Group, particularly in Dixon, Cedar, Knox and Boyd counties (Fig. 10) (Divine and

Sibray, 2017). Large pressure heads exist in the latter three counties and some wells flow. The greatest average depth (approximately 1,020 ft or 311 m) of wells in the Dakota aquifer is in Boyd County, and the shallowest average depth is in Cass County (approximately 130 ft or 40 m). The average depth to water is much less variable, ranging from about 200 ft (61 m) in Knox County to about 65 ft (20 m) in Cass and Thayer counties. Large pressure heads in the deep wells reduce the depth to water in these wells and the overall difference in depth to water in the aquifer across the state.

Groundwater in the Dakota aquifer moves predominantly to the east in eastern Nebraska (Fig. 11). The potentiometric surface elevation varies from about 1,300 ft (396 m) in wells on the western side of the aquifer to about 1,100 ft (335 m) in wells on the eastern edge. Knox County appears to be an exception to this rule: there, the potentiometric surface elevation may be as high as 1,500 ft (457 m) and groundwater flows to the north (Korus et al., 2013).

Most Dakota aquifer wells in Nebraska (74%) are private domestic wells. Irrigation wells account for 11% of the total number, livestock wells for 4%, monitoring wells for 4%, public supply (with and without spacing protection) for 3%, commercial wells for 1%, and unspecified other uses for 3% (Figure 12). The average yield for irrigation and commercial wells is about 550 gpm (35 L/s).

Water quality in the Dakota aquifer varies considerably in Nebraska and the surrounding region (Fig. 13). Fresh water (total dissolved solids less than 1,000 mg/L) occurs mostly along the eastern and southern margins of the aquifer (Gosselin et al., 2001). High sulfate concentrations in northeastern Nebraska push the total dissolved solids (TDS) concentration to 1,000 mg/L or greater in many wells (Gosselin et al., 2001). Nevertheless, the Dakota aquifer is still used in that area, but primarily for livestock and irrigation wells. Dakota aquifer wells with localized high sodium chloride are fairly common in Lancaster County and may have TDS concentrations that are brackish to brine (>1,000 to >35,000 mg/L TDS). These wells are used mostly for domestic purposes in association with reverse osmosis treatment systems. The source of the high sodium chloride is probably dissolution of evaporate layers in underlying Paleozoic rocks; the saline water in the Paleozoic rocks moves into the Dakota aquifer where the pressure head pushes groundwater upward through gaps in confining units (e.g. Kelly et al., 2011; Harvey et al., 2007). The Dakota aquifer is also used for irrigation in Lancaster County, but these wells are susceptible to increasing sodium chloride concentrations in response to pumping (Gosselin et al., 2001).

8.2. STOP 2: Ponca State Park, Dixon County, Nebraska.

At Ponca State Park, we will examine the stratigraphic interval that includes the upper Dakota Formation/Group and much of the overlying Greenhorn Limestone. Although Pabian and Lawton (1984) indicated the existence of the Graneros Shale between the Dakota Formation and the Greenhorn Limestone at the park (Fig. 14), Brenner et al. (2000) did not recognize the unit in northeastern Nebraska, northwestern Iowa, and southeastern South Dakota, considering that which was previously called “Graneros Shale” in the area to be equivalent to the Hartland Shale Member of the Greenhorn Limestone, a younger stratigraphic unit. Although the details of this revised correlation are important and highly relevant to the understanding of regional stratigraphy, they are well beyond the scope of this field guide.

The Graneros Shale and Greenhorn Limestone are mapped together in Nebraska because they are both comparatively thin and, we surmise, because of prior difficulties in differentiating them. These formations were deposited as sea level continued to rise during the Cenomanian and Turonian stages. The Graneros Shale consists of clay, silt, and minor sand washed into near-shore marine environments, including deltaic ones. The Greenhorn Limestone consists of marine shelf and open-seaway sediments deposited farther from shorelines, namely: calcareous shales, shaly chalks, chalky limestones, and calcarenites consisting of fossil fragments. By the time the sediments of the Greenhorn Formation were deposited, the shoreline of the Western Interior Seaway had retreated some distance eastward of the field-trip area.

The member-level stratigraphy of the Greenhorn Limestone changes from the type area in Colorado (Lincoln-Hartland-Bridge Creek members), to western Kansas, and into central Kansas (Lincoln-Hartland-Jetmore-Pfeifer members) (Hattin, 1975; Scott et al., 1998), but it has not yet been clarified in print in Nebraska. The Cenomanian-Turonian boundary lies near the top of the Hartland Shale Member in Kansas (Scott et al., 1998).

8.3. STOP 3: Volcano Hill, Dixon County, Nebraska.

At Volcano Hill, we will examine the Carlile Shale, which overlies the Greenhorn Limestone in the regional succession of Cretaceous strata. We will see evidence for *acid rock weathering*, a result of the breakdown of the sedimentary mineral pyrite (FeS_2) into sulfuric acid once it is exposed to atmospheric air and water, and for the related formation of unusual secondary minerals. We will also discuss the Codell aquifer, which is hosted by the Codell Sandstone, a member of the Carilie Shale, even though we will not see that sandstone at the field trip stop.

The Carlile Shale (Turonian), which is recognized from northeastern New Mexico to the Canadian border, is considered to consist of three members in Kansas and Nebraska. These members are, in ascending stratigraphic order: (1) the Fairport Chalk, which is mostly chalky shale; (2) the Blue Hill shale, which is dominantly silty clay shale, and (3) the Codell Sandstone. Thus, the Carlile Shale is a succession of marine basin shelf sediments consisting of both: (1) carbonate sediments produced by marine organisms in open-seaway settings, and (2) terrigenous sediments (silt and clay) that were washed into nearer-shore shelf environments from areas above sea level to the east (Hattin, 1962). The carbonate-rich sediments dominate in the lower part of the formation, but it is considered to be a regressive deposit overall.

Acid rock weathering in the Carlile Shale was described in detail by Joeckel et al. (2011). *Acid rock weathering* refers to the natural chemical reaction through which sulfide minerals, once exposed to air and water and, break down to produce sulfuric acid. This reaction is described by the following chemical equations:

1. $2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$

(pyrite reacts with oxygen and water to produce ferrous iron and sulfate ions, plus acidity)

2. $4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$

(ferrous iron oxidizes into ferric iron)

3. $Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$

(iron hydroxide is produced)

4. $4FeS_2\,(s) + 15O_2 + 14H_2O \leftrightarrow 16H^+ + 8SO_4- + 4Fe(OH)_3\,(s)$

(the net effect of equations #1-3)

Acid rock drainage sites on pyrite-bearing Cretaceous shales in Nebraska can produce pH values as low as 3-5. At Volcano Hill (or the Ionia Volcano), there was an historical misconception of igneous activity because the oxidation of pyrite gave off heat and water vapor. This kind of activity seems to be dormant or extinct at the site, but there is ample evidence for the oxidation of pyrite in the recent past. Multiple secondary sulfate minerals have been identified at the site, and these could only have formed after the oxidation of pyrite. Jarosite ($KFe^{3+}{}_3[SO_4]_2[OH]_6$), which contains ferric iron, is particularly common. In some places in the exposure, approximately 20% of the rock volume is yellow (10YR 7/6 and 7/8) jarosite infillings and linings. Dark yellowish brown (10YR 4/4) ferric hydroxide stains, which indicate the oxidation of ferrous iron and is combination with oxygen and hydroxyl ions, are common on fracture surfaces. The secondary mineral melanterite ($Fe_2SO_4 \cdot 7H_2O$), which contains ferrous iron, is a transient mineral phase relative to the ever-present jarosite at the site; it appears as fine, bluish, hairlike crystals. Halotrichite ($FeAl_2[SO_4]_4 \cdot 22H_2O$), which also contains ferrous iron, appears from time to time as a very thin, white crust on the surface, also mostly in the barely weathered lower part of the outcrop at the base of the hill. Secondary selenite gypsum, which is also a byproduct of pyrite oxidation, ($CaSO_4$ $2H_2O$) is common at the site, and individual crystals may show "ghosts" of twinning in ultraviolet light. A thin bentonite in the lower part of the exposure been altered from the original smectite clay by acid weathering to kaolinite.

The Codell Sandstone, which crops out in some places in the field-trip area, is both an aquifer and a petroleum reservoir in the interior of North America. Recognizing the Codell Sandstone in boreholes in eastern Nebraska may be difficult because the unit is relatively thin—between 8 and 80 ft (2.4 to 24 m) in thickness—and because it may consist of as many as three separate sandstones separated by thin shales (Divine et al., 2016). The location of the Codell Sandstone member within the Carlile Shale can be anywhere within the top 50 ft (15 m) of that latter formation (Divine et al., 2016).

The Codell aquifer supplies groundwater to about 70 active domestic and stock wells in a 460 mi^2 (1,190 km^2) area in eastern Boyd and northern Knox counties in Nebraska (Fig. 15, 16). The average yields of wells in the Codell aquifer in Nebraska is approximately 15 gpm (0.95 L/s) and the average depth of wells is approximately 285 ft (87 m). The transmissivity of the Codell aquifer in northeastern to northcentral Nebraska varies from approximately 700 to 18,000 gpd/ft (1 to 26 cm^2/s). The aquifer is confined in most places and the pressure head causes the water in wells to rise above the top of the aquifer, but it is likely to be unconfined at some locations in the Missouri River valley where it is in direct contact with alluvium (Kume, 1977). For the most part, the Codell aquifer supplies domestic and stock wells; across Nebraska, Kansas, and South Dakota, groundwater in the aquifer tends to have high sodium and salinity hazards that make it unsuitable for irrigation (Jorgensen, 1971; Kume, 1977; Souders, 1976; Weigand, 1991).

The structural contour map of the Carlile Shale-Niobrara Formation contact in eastern Boyd and western Knox counties (Fig. 17) ranges from a high elevation of about 1,150 ft (354 m) above mean sea level to a low of about 1,080 ft (329 m) at the southern edge of the study area. The structural contour map of the top of the Codell Sandstone Member (Fig. 18) is similar to that of the Carlile-Niobrara contact in that they both dip generally south in Knox County, but minor differences between the two surfaces exist. The depth of the top of the Codell below the Carlile-Niobrara contact varies from 0 ft in parts of Boyd County to a maximum of about 50 ft (15.2 m) in a small area in the Missouri River valley (Divine et al., 2016).

The static water level elevation in the Codell aquifer (Fig. 19) indicates that the groundwater flows north-northeasterly towards the Missouri River trench. Outside the trench the static water level contours represent a potentiometric surface, which ranges from a low of about 1,200 ft (366 m) above mean sea level in the northeast part of the study area to a high of about 1,320 ft (402 m) in the southern part of the study area. In South Dakota, the gradient in the Codell aquifer is also towards the Missouri River Trench, which is probably a natural discharge area (Jorgensen, 1971; Kume, 1977). Registered well logs from Nebraska indicate that the Missouri River alluvium is in direct contact with the Codell at some locations, so it is probable that the river is also a discharge point for groundwater flowing north through the Codell aquifer from Nebraska (Divine et al., 2016).

Groundwater in the Codell aquifer tends to be elevated in total dissolved solids, sodium, chloride, and sometimes sulfate (Fig. 20). It typically yields “soft water” with low calcium and magnesium concentrations (Divine et al., 2016; Kume, 1977; Jorgensen, 1971). The sodium chloride concentration is sufficiently high to preclude use of the Codell aquifer for irrigation, and chloride concentrations appear to be higher in deeper wells (Divine et al., 2016). The elevated sulfate concentrations in the aquifer may result from pyrite or marcasite weathering in the overlying Pierre or

Carlile shales, which may be most pronounced in wells that are located along drainages where the Niobrara Formation subcrops and the Niobrara-Carlile contact is probably subjected to the greatest amount of weathering (Joeckel et al., 2011).

8.4. STOP 4: Obert Trough and Surrounding Area, Cedar County, Nebraska.

At this stop we will examine effects of eolian processes that were at work in northeastern Nebraska during the Pleistocene. We will also discuss the local bedrock, the Cretaceous Niobrara Formation, and its role as a secondary aquifer.

Northeastern Nebraska contains some very complicated surficial geology, among the most complex in the state. The geomorphically distinctive rolling uplands south of the Missouri River in Cedar County are underlain or cored by Cretaceous bedrock (Niobrara Formation and Carlile Shale), pre-Illinoian glacial sediments (till, outwash, glaciolacustrine deposits), and eolian sand. Locally these deposits are covered with Peoria Loess which exceeds 14 m in thickness in places. This loess blanket, however is highly variable on uplands in the region. Dramatic differences in loess thickness that can be estimated from upland dissection (Fig. 26): thick loess is heavily dissected. In addition, older loess units that underlie the Peoria throughout most of central and eastern Nebraska are typically absent in the region. Both of these phenomenon have been somewhat difficult for geologists to explain. Further, eolian sand is also present on some uplands in the region, and these deposits are commonly capped with a thin (< 1.5 m) silt deposit. Geologists and soil scientists have also had difficulty in determining the origin of the eolian sand.

A comparatively unique feature of landscapes in northeastern Nebraska is the orientation of loess-covered hills. Wayne (1985, 1991) identified that many hills in the region were preferentially oriented with their long axes lying parallel to N45°W, and attributed their formation to wind erosion of surficial sediments during the advance of the James River Lobe in South Dakota. Such oriented hills are not uncommon in some loess terrains near the edge of the Laurentide Ice Sheet in the upper Midwest. In Iowa and Illinois oriented hills similar to those in Cedar County have been termed “paha” (Mason et al., 1999; Flemal et al., 1972; Ruhe, 1969), in Europe such hills are called “greda”. Wayne’s interpretation of these landforms was based solely on their morphology and not subsurface investigations.

Given the unique nature and complicated geology of the region, the Conservation and Survey Division decided to generate surficial geologic maps in the region. We produced six surficial geological maps in the region in order to: (1) study the oriented hills, and (2) understand the highly variable Peoria loess thicknesses and the presence of eolian sand. In addition, our mapping efforts led us to re-examine the whether the James Lobe moved into Nebraska during the Wisconsin glaciation. The interpretation of these data is ongoing, but we expect to publish findings in the near future.

Variable thicknesses of Peoria Loess were documented through coring in numerous locations on the six quadrangles mapped. Often these differences were quite dramatic with Peoria thicknesses exceeding 10 m (~30 ft) in areas directly adjacent to locations that had little or no loess cover. One such area was the “Obert trough” (Figs. 26, 27). The Obert trough has a similar orientation to hills in the area that were noted by Wayne (1991). Two possible explanations were generated to explain formation of the trough. One is that eolian deflation occurred in the Holocene after the Peoria Loess was deposited. The other hypothesis, which e we favor, is that eolian sand was likely moving on the ground surface in the trough during deposition of the Peoria Loess. Previous studies have argued that actively moving eolian sand would have acted to prohibit loess accumulation (Mason et al., 1999). The eolian sand present in the troughs is frequently capped with a thin cover of Peoria Loess, suggesting that deflation happened in the Pleistocene, rather than the Holocene.

The Peoria Loess was also found to be thicker on the northern edges of stream valleys relative to the more southerly edges. It is likely that stream valleys were also sources of eolian sand that was blown out of the valleys by predominant northerly and northwesterly winds during the Pleistocene. These stream valleys were a likely source of sand given their Pleistocene fills were sandy, but pre-Illinoisan outwash was likely also a significant source of sand in the area. In short, dramatic differences in Peoria loess thickness most likely stem from the abundance of sand that was present on portions of the landscape—those either near outwash or downwind of stream valleys. The oriented hills are also likely a function of preferential deposition of loess by winds that were predominantly blowing from the north and northwest.

The Niobrara Formation (latest Turonian-Campanian) is the bedrock under much of northern Cedar County and it crops out in many places. It is an entirely marine deposit consisting of a lower member, the Fort Hays Limestone, and an upper one, the Smoky Hill Chalk. There are rhythmic alternations of different *lithofacies* (sedimentary rock types) within the formation that appear to be the result of climatic changes driven by Earth’s orbital parameters, a notion that was first expressed by G. K. Gilbert in the 1890s (Locklair and Sageman, 2008).

The Niobrara Formation is a source of petroleum in parts of the Western Interior, but it also serves as an aquifer in parts of Nebraska where it lies close to the land surface. Niobrara aquifer wells are located in Cedar County, northeastern-most Madison County, and in or near Nuckolls County (Fig. 21). Cedar County hosts the greatest number of wells and it is the only area in which high-capacity irrigation wells screened entirely in the Niobrara aquifer are common. Cedar County has about 200 registered active Niobrara wells, 88 of which are irrigation wells that yield about 440 gpm (1,665 lpm) on average (Divine and Sibray, 2017).

The contour map of the top of the Niobrara Formation along the bedrock belt (Fig. 22) was constructed from the geologic logs of more than 7,300 wells and test holes. The elevation of the top of the formation ranges from a high of about 2,350 ft (716 m) in Red Willow County on the eastern flank of the Cambridge Arch, to a low of about 1,200 ft (366 m) in Knox County, within the Missouri River trench (Divine et al., in press).

A static water level elevation map in the Niobrara Formation in Cedar County (Fig. 23) was produced from water-level information collected in any month between 1997 and 2015 from about 165 wells screened entirely in the Niobrara aquifer, and therefore, the contours should be interpreted as average conditions during that time span (Divine et al., in press). The highest water-level elevation is approximately 1,480 ft (427 m) and about the lowest is approximately 1,220 ft (378 m). The potentiometric surface generally slopes north-northeast toward the Missouri River. Two groundwater divides, which correspond with highs on the bedrock surface, appear to exist: one between Antelope Creek and Second Bow Creek, and another between West Bow Creek and Bow Creek.

Half of all wells screened entirely in the Niobrara Formation are irrigation wells, almost all of which are located in Cedar County. Of the remaining wells, 23% are used for livestock, and 22% are private domestic wells. Public wells (2%), monitoring wells (2%), and commercial wells (1%) round out the well use types across the three locales where the Niobrara aquifer is used (Divine and Sibray, 2017, Fig. 24).

Water quality in the Niobrara aquifer is generally good, although sulfate, hardness, and total dissolved solids become elevated in the northern part of the study area (Fig. 25). Iron and/or manganese are also at or above the recommended limits at various places across the bedrock belt (Divine et al., in press). The high sulfur content may produce an undesirable rotten egg odor and black color when initially pumped from the well. The black color disappears fairly quickly, but may leave a black precipitate, and the water is corrosive to pump rods and pipes (Kume, 1977). Weathering of pyrite, an iron sulfide mineral, produces an acid solution enriched in iron and sulfate (Gosselin et al., 2001), which is the likely source of iron and sulfate to the Niobrara aquifer. Elevated sulfate concentrations have also been documented in the Codell aquifer in Boyd and Knox counties (Divine et al., 2016).

The Pierre Shale is the uppermost formation in the Cretaceous succession of northeastern Nebraska. It overlies the Niobrara Formation and it is present under a small part of northwestern Cedar County. Hydrostratigraphically, it serves as a prominent aquitard.

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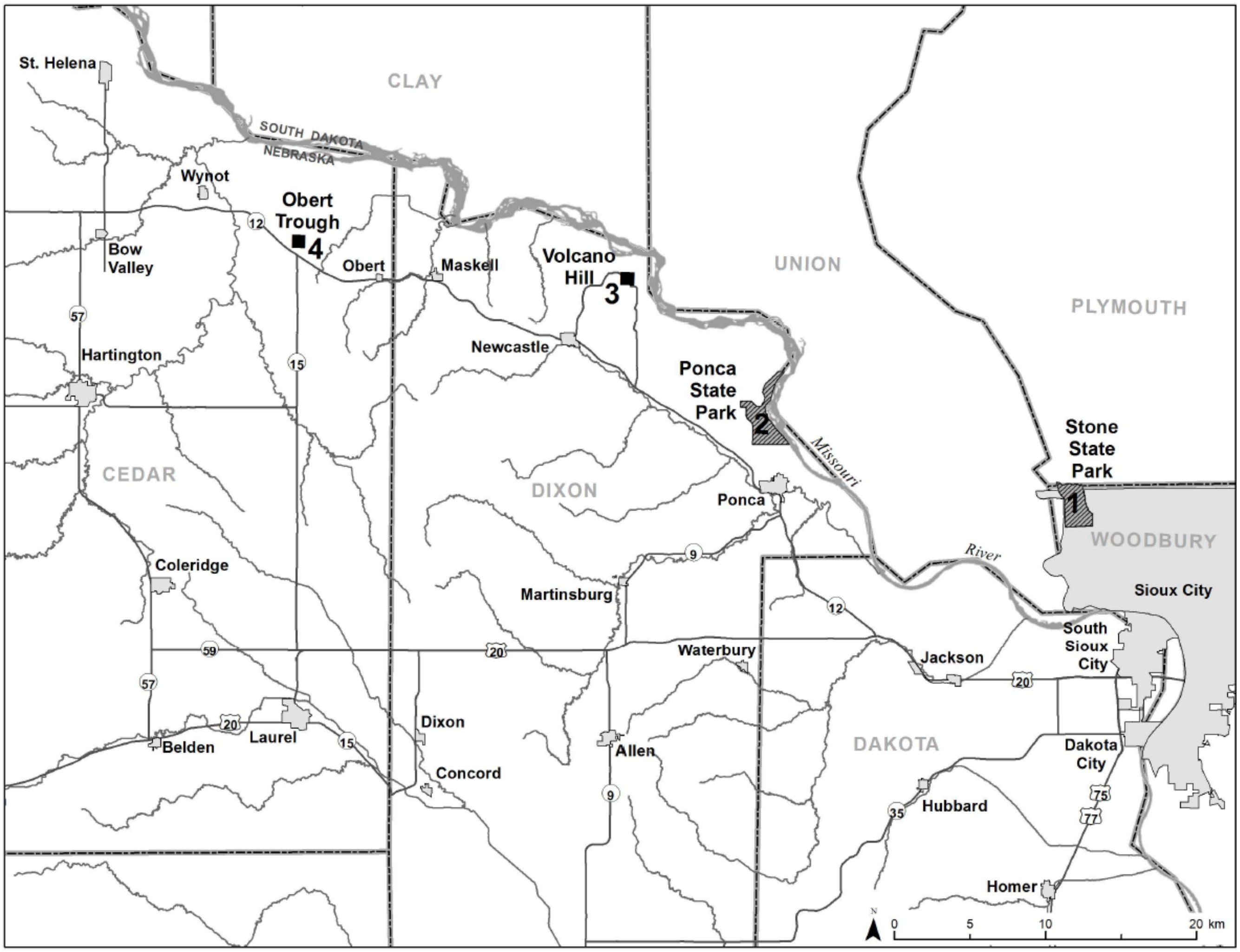


Fig. 1. Area of field trip.

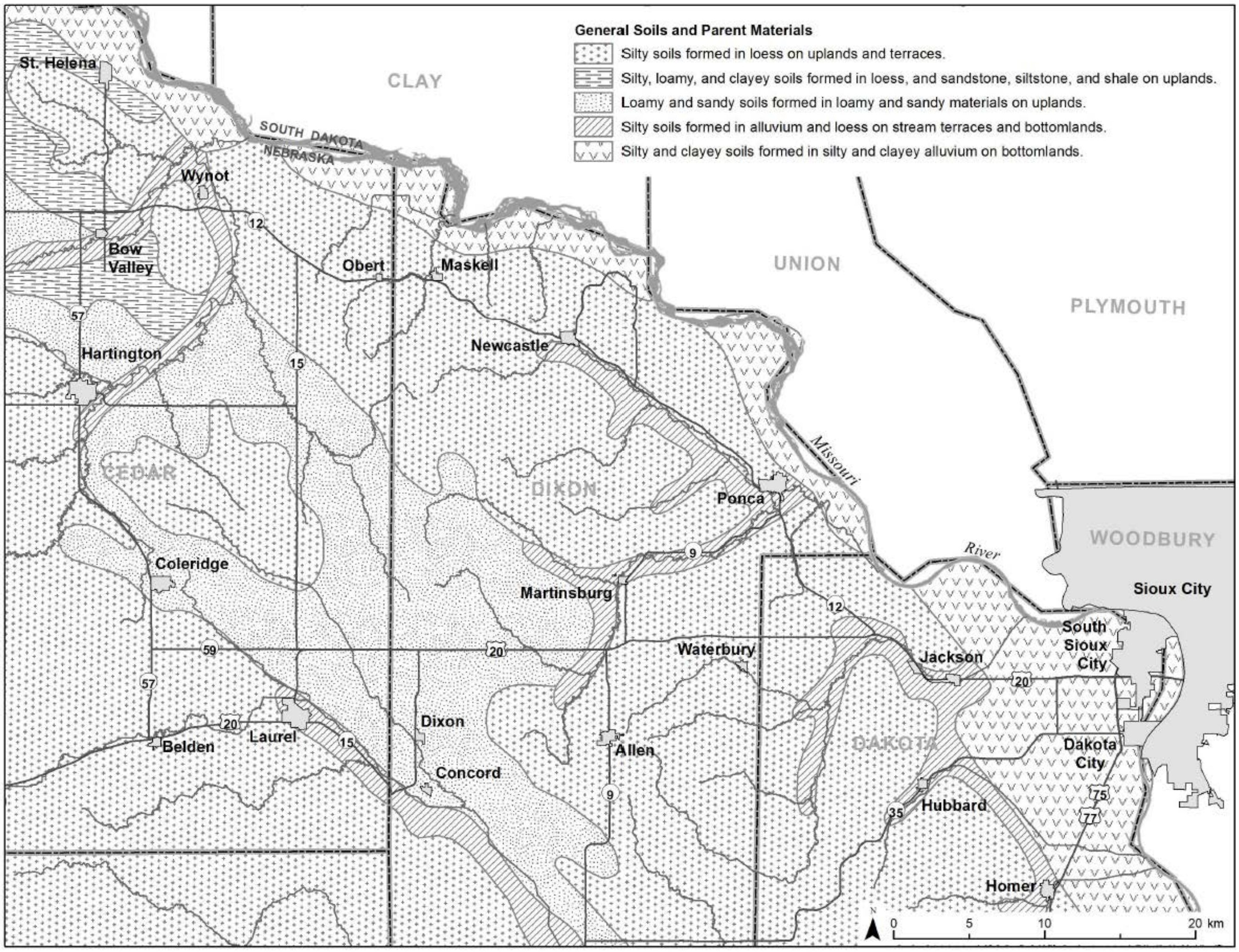


Fig. 2. General soils and parent materials in the field-trip area.

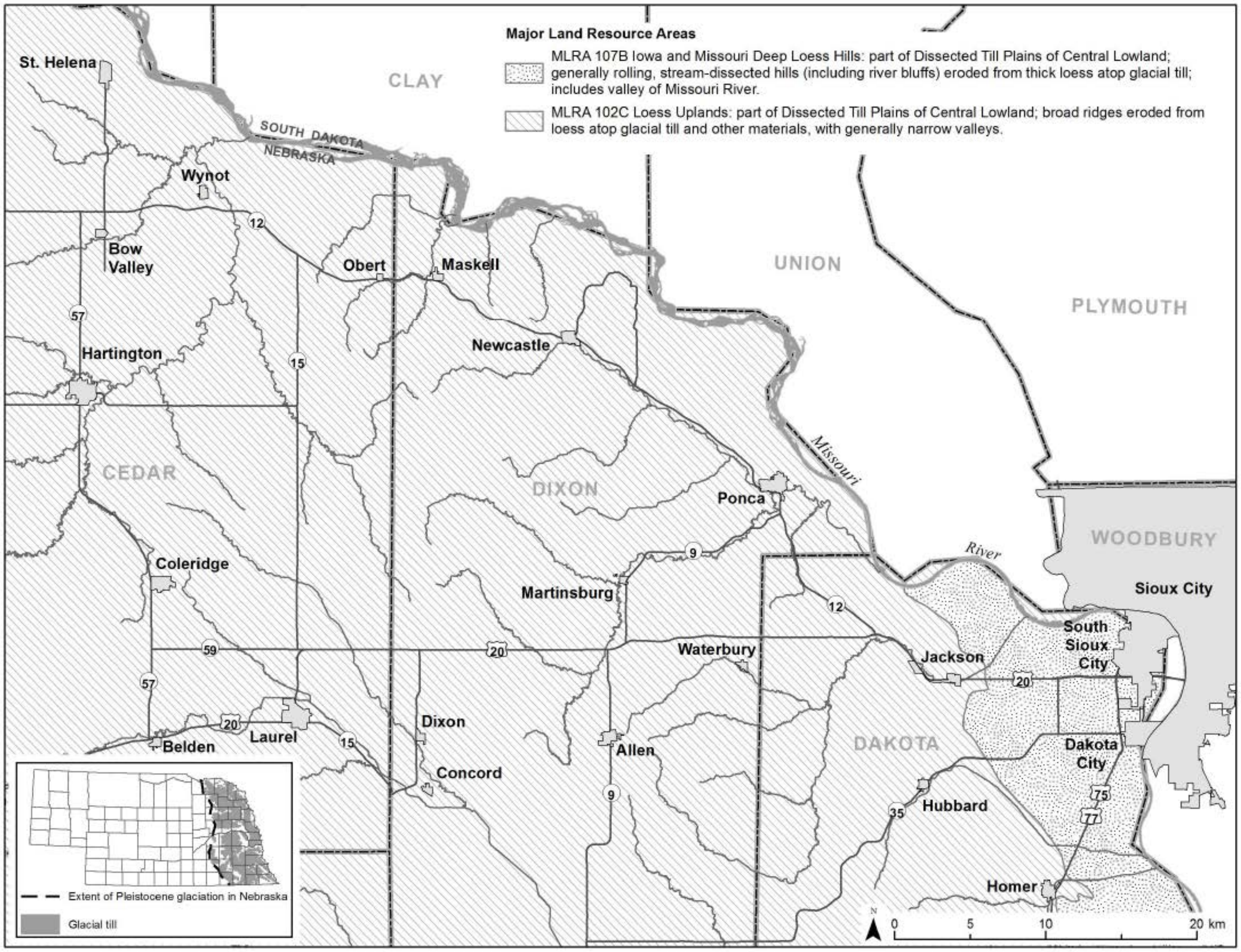


Fig. 3. Major Land Resource Areas recognized by Natural Resources Conservation Service in field-trip area.

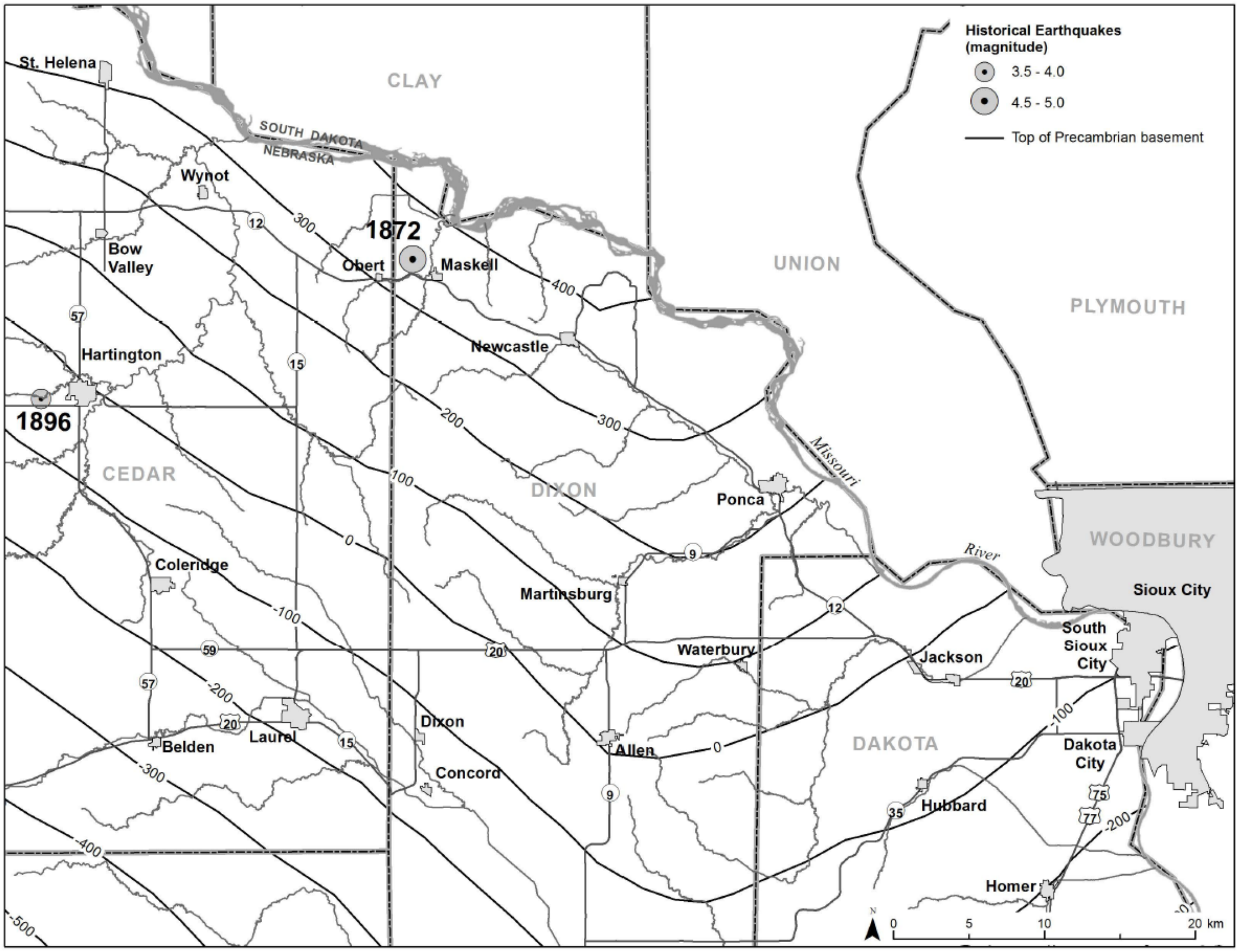


Fig. 4. Contour map (feet above mean sea level) of top of basement in field-trip area, with locations of historical earthquakes.

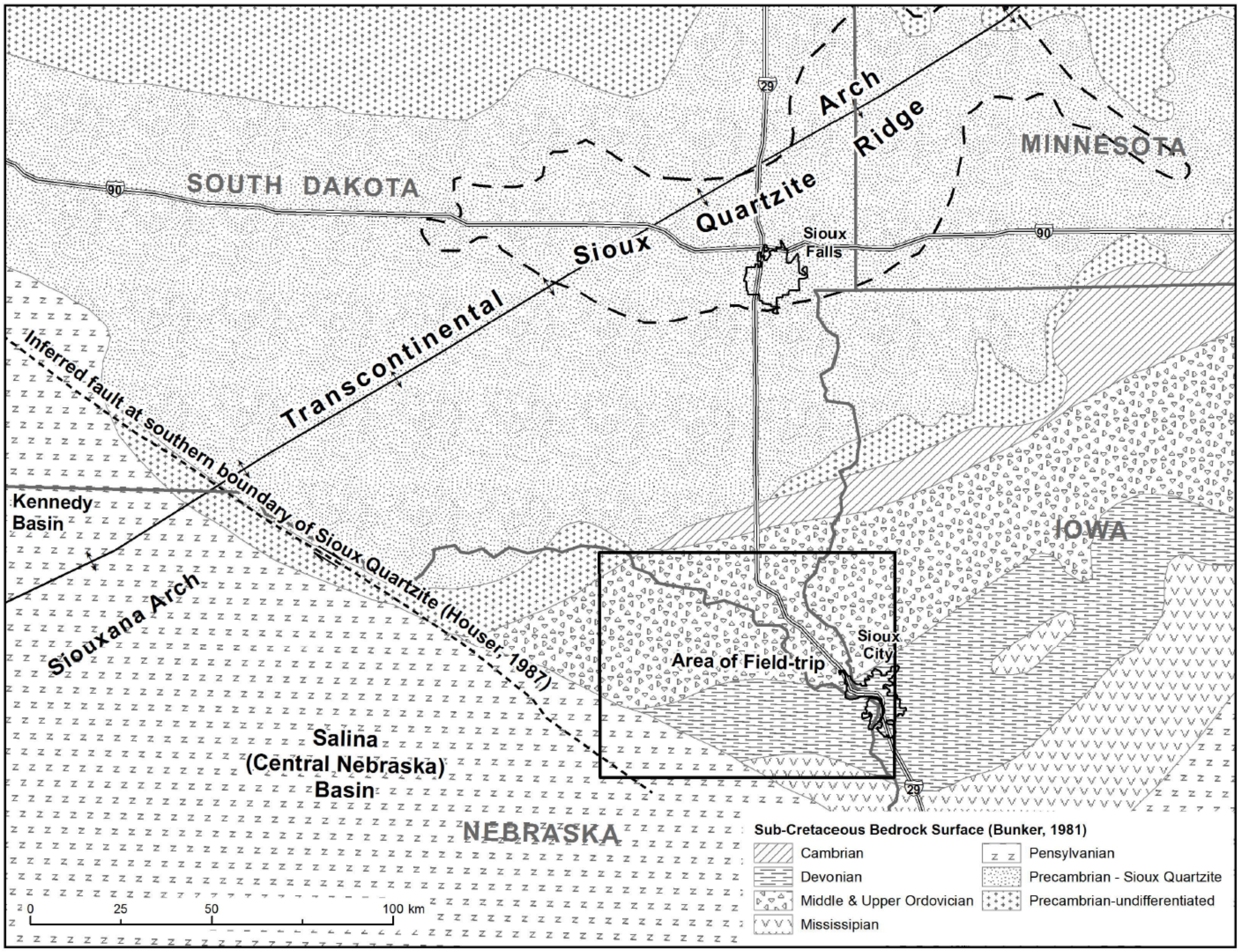


Fig. 5. Sub-Cretaceous bedrock surface, distribution of Sioux Quartzite, and selected geologic structures in region surrounding field-trip area.

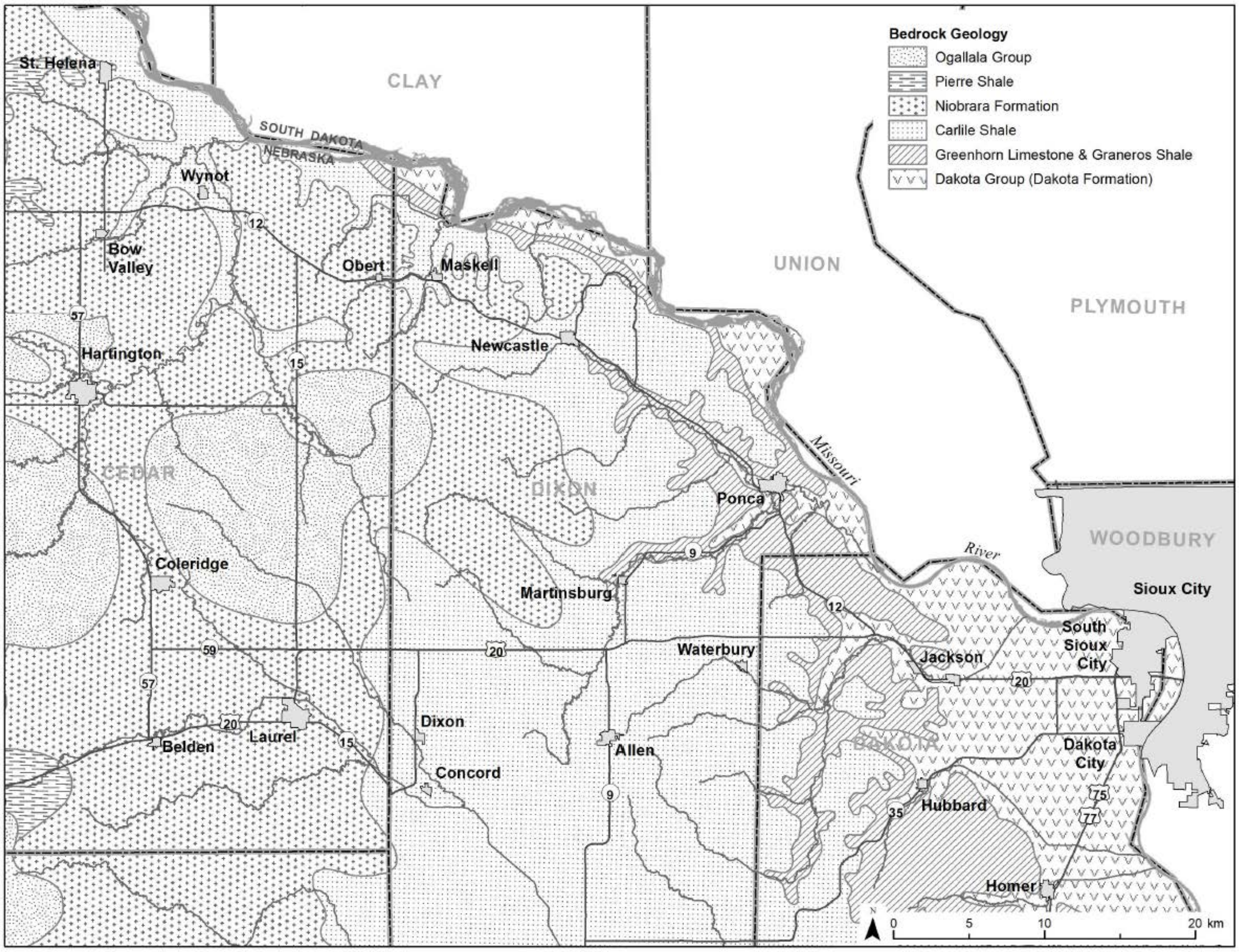
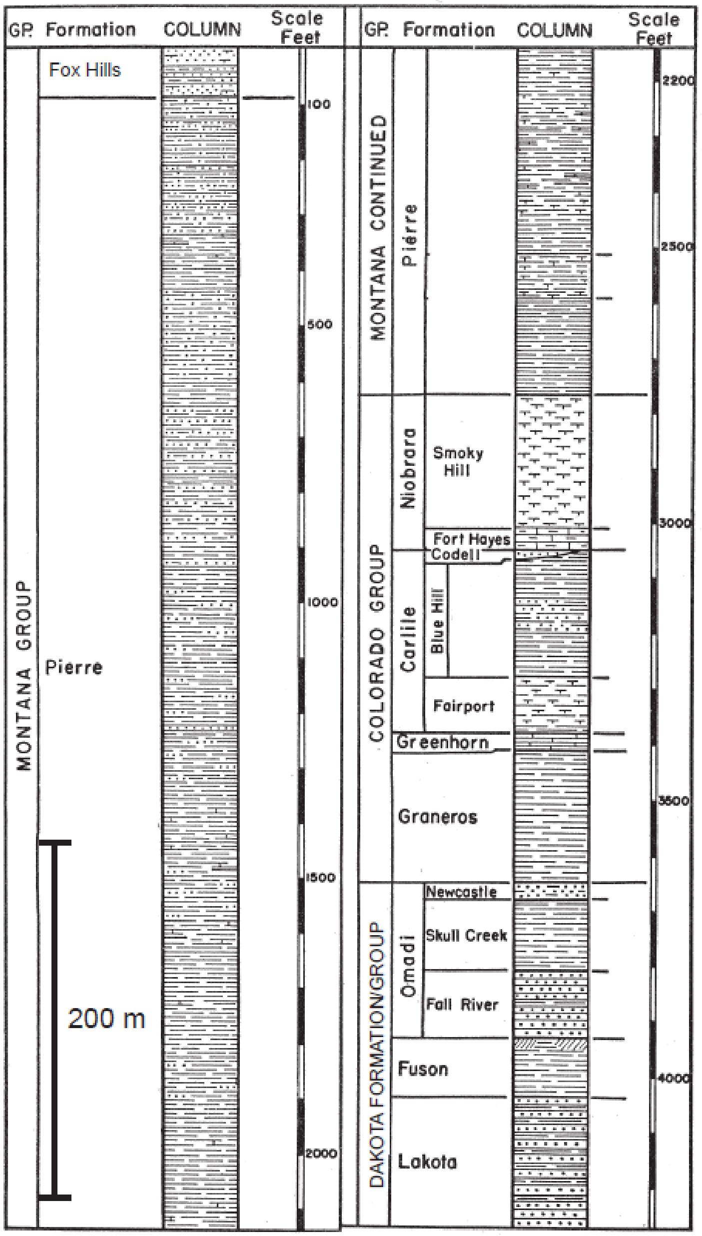


Fig. 6. Bedrock geologic map of field-trip area. Most of area is directly underlain by Cretaceous strata, except for small outliers of Ogallala Group (Miocene).

Composite Cretaceous System in Nebraska: Nearly 60 Years Old and in Need of Revision



The Fox Hills Sandstone (left-hand column) has been recognized by the CSD in the Panhandle, but there is no detailed published account of it in the State.

Condra and Reed (1959) recognized only two members in the Pierre Shale in Nebraska, and others are certainly present. A comprehensive attempt at correlating members of the formation into Nebraska from South Dakota, and across Nebraska itself, needs to be made.

The stratigraphy of the Greenhorn Limestone in Nebraska should be revisited.

The traditional concept of the "Graneros Shale" in Nebraska is problematic and should be revisited in the context of modern litho-, bio-, and chrono-stratigraphy. It is depisted here as being far too thick. In the field trip area, the interval called "Graneros Shale" is likely to be equivalent to the Hartland Shale, a member of the Greenhorn Limestone in Kansas.

Subdivision of "Dakota Group" into separate formations (Lakota, Fuson, Omadi) in Nebraska, especially in northeastern Nebraska, by Condra and Reed (1959) needs to be critically reviewed. It is unlikely to be correct relative to regional stratigraphy. In Iowa, the Dakota Formation is subdivided into the Nishnabotna and Woodbury members and, likewise, it is subdivided into the Terra Cotta and Janssen members in Kansas. Correlations east-to-west across Nebraska should also be reviewed because the equivalent stratigraphic interval thickens ans changes in lithofacies composition westward.

Fig. 7. Composite section of the Cretaceous System in Nebraska, modified from Condra and Reed (1959).

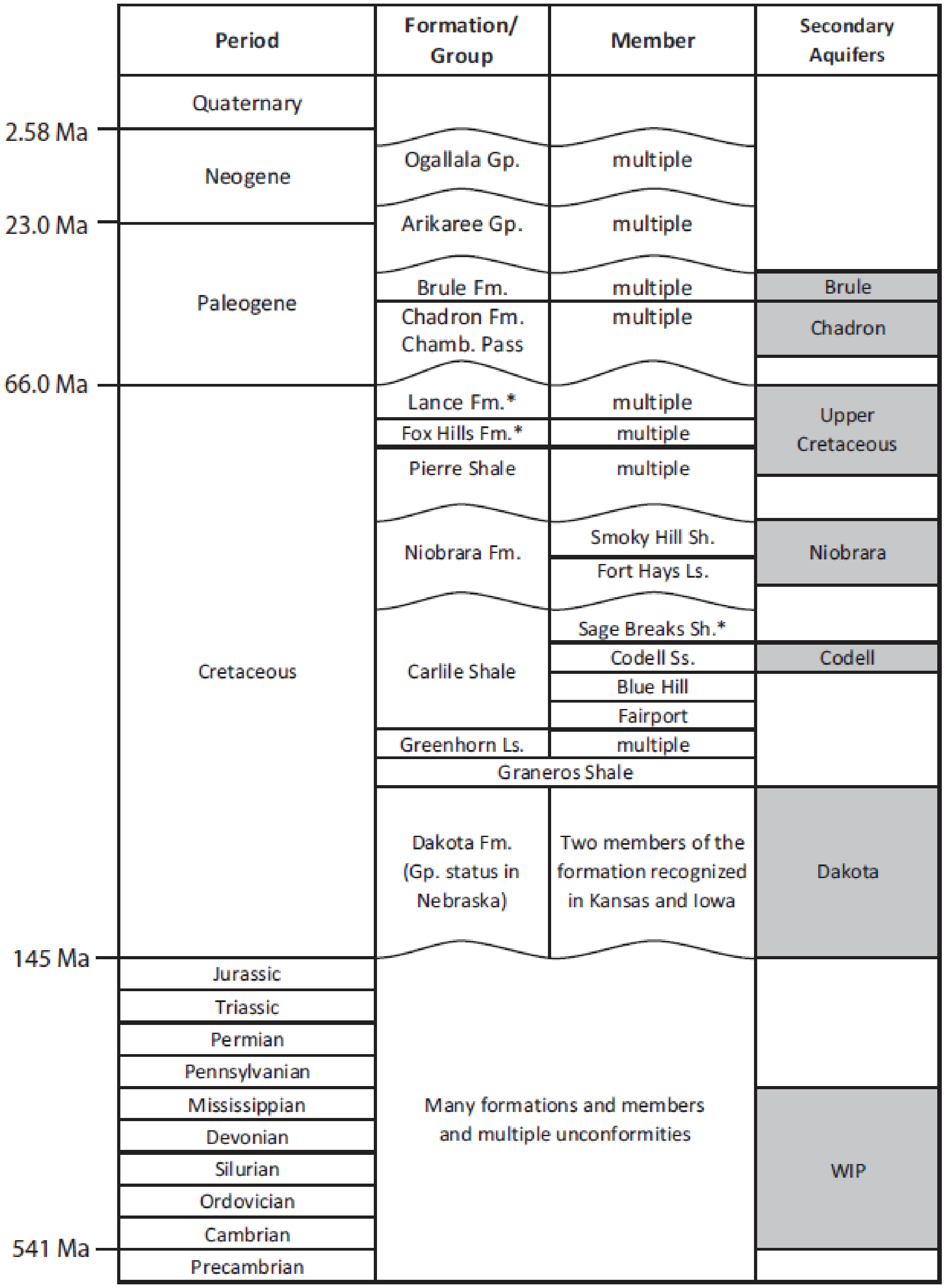


Fig. 8. Stratigraphic chart showing formations that host secondary aquifers in Nebraska, from Divine and Sibray (2017).

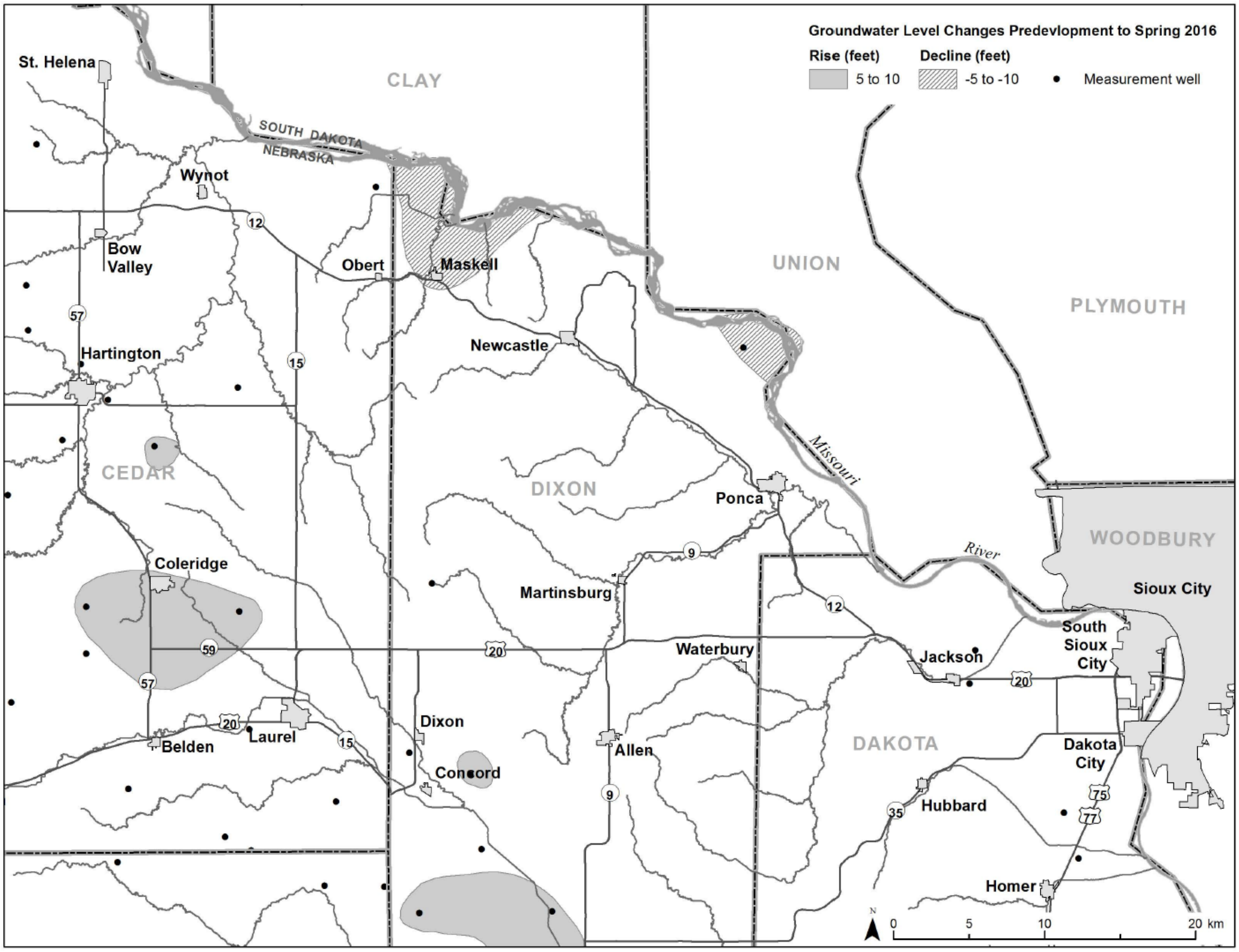


Fig. 9. Groundwater level changes in the field-trip area, predevelopment to 2016.

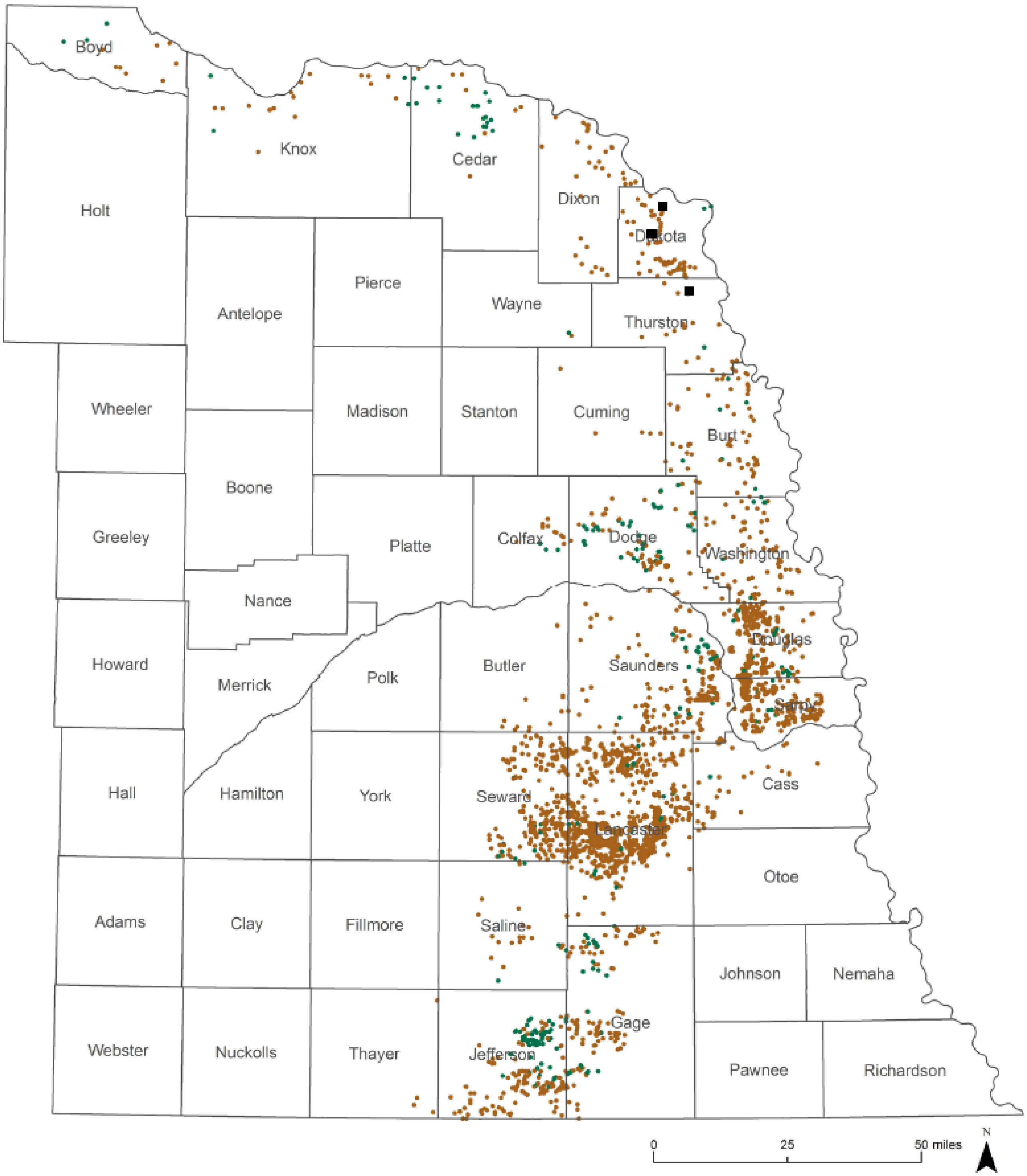


Fig. 10. Location of wells screened entirely in the Dakota Formation (dots) and three test holes drilled through the Dakota Formation in 2014-2016 (squares), modified from Divine and Sibray (2017).

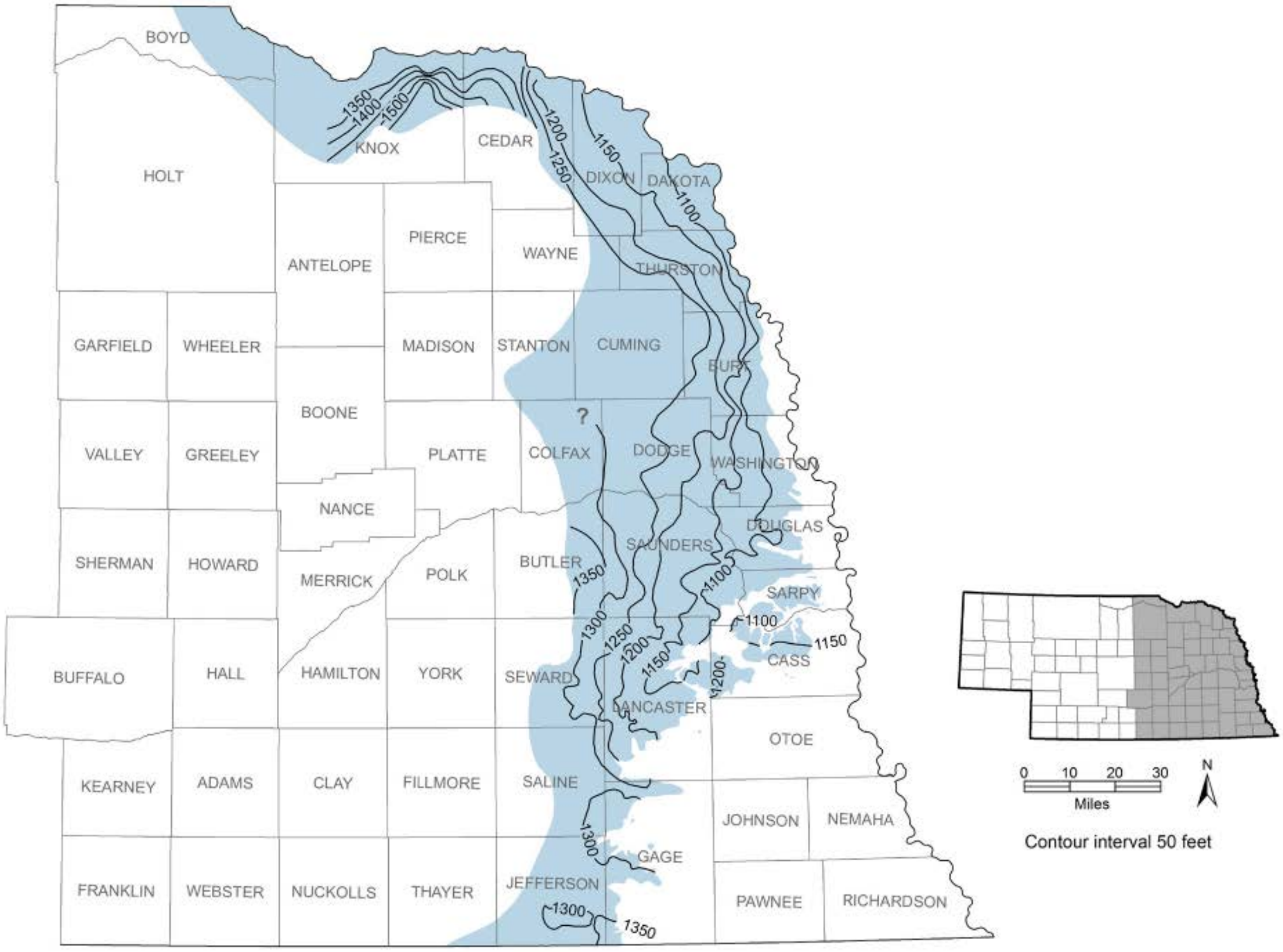


Fig. 11. Static water level contours in the Dakota aquifer. Contour interval is 50 feet, from Korus et al. (2013).

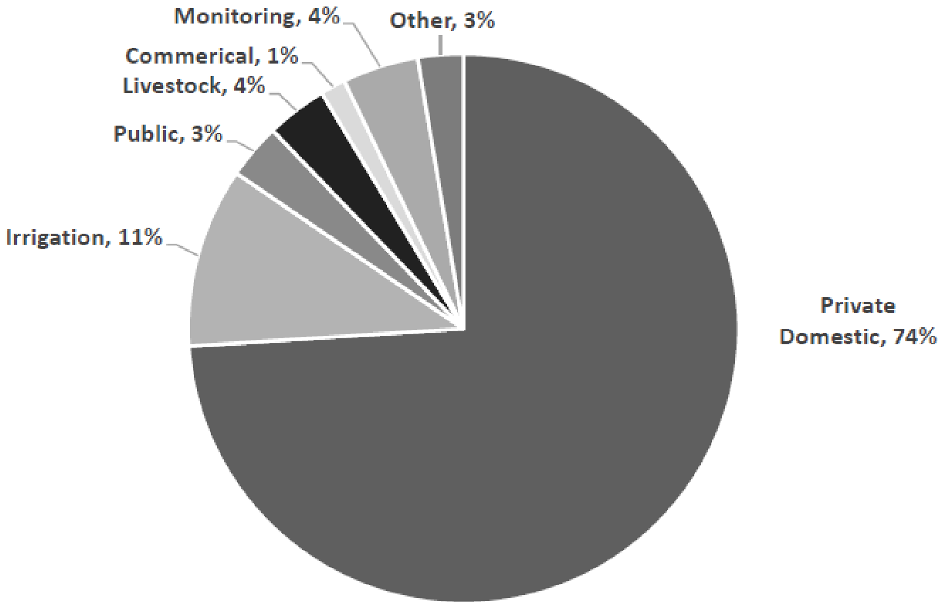


Fig. 12. Distribution of well types in the Dakota aquifer, from Divine and Sibray (2017).

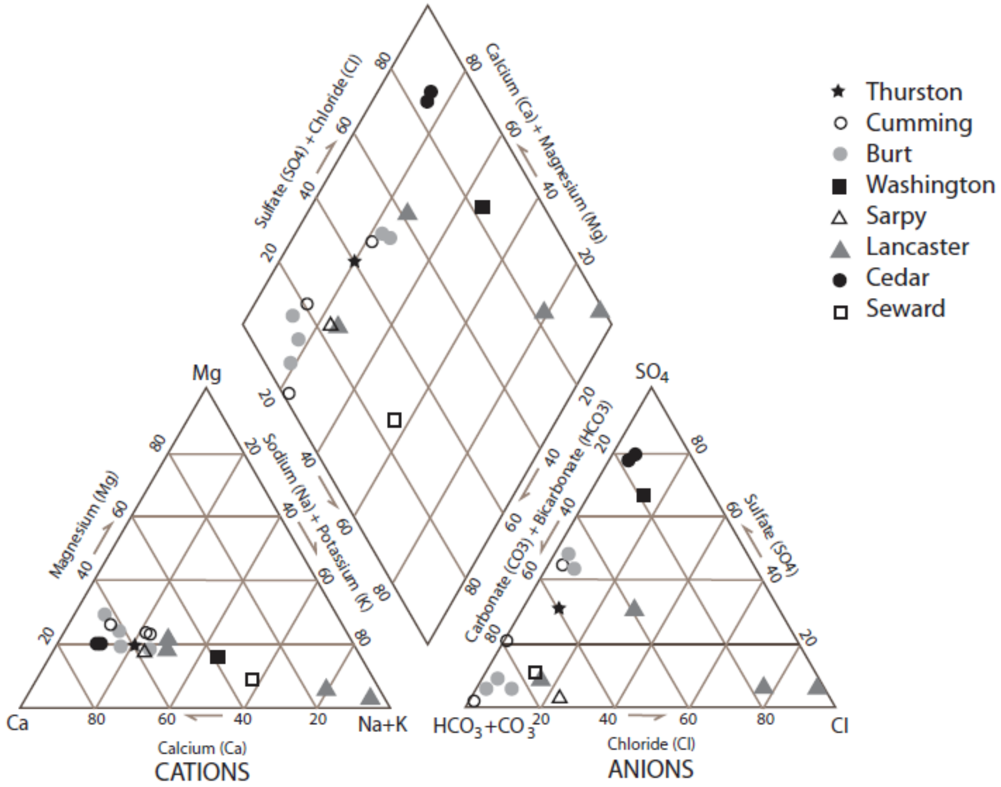
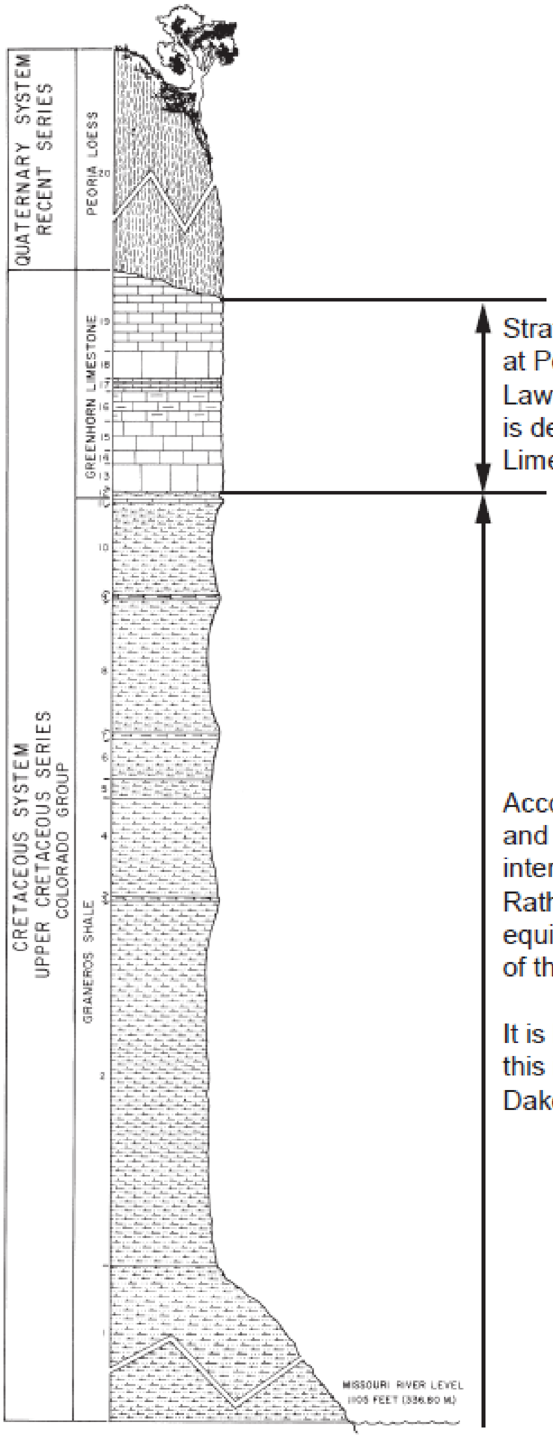


Fig. 13. Piper diagram showing major ion chemistry for Dakota wells in various counties, modified from Divine and Sibray (2017).

Ponca State Park: Greenhorn Limestone-Graneros Shale Problem



Stratigraphic section near boat landing at Ponca State Park, from Pabian and Lawton (1984). This part of the section is definitely a part of the Greenhorn Limestone.

According to Brenner et al. (2000) and some other authors, this interval is not the Graneros Shale. Rather, the upper part of it, at least, is equivalent to the Hartland Shale Member of the Greenhorn Limestone in Kansas.

It is likely that some of the lower part of this interval should be included in the Dakota Formation/Group.

Fig. 14. Stratigraphic section at boat ramp in Ponca State Park, modified from Pabian and Lawton (1984).

Fig. 15. Location of wells screened entirely in the Codell aquifer, from Divine and Sibray (2017).

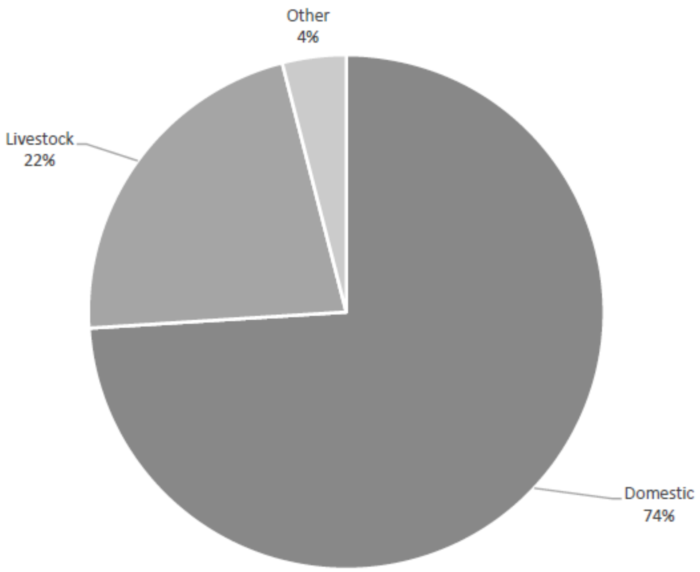


Fig. 16. Distribution of well types in the Codell aquifer.

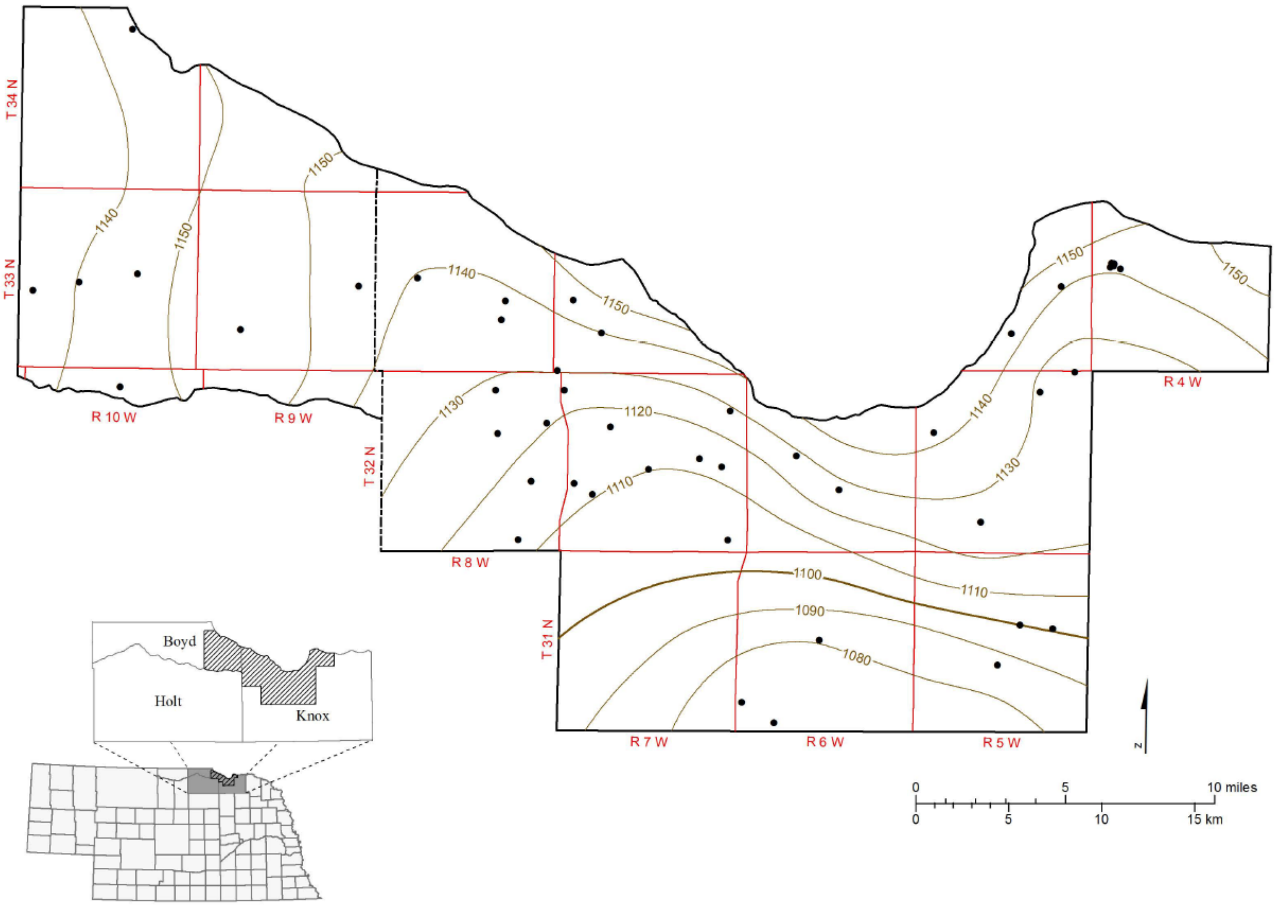


Fig. 17. Structure contour map of the Carlile Shale-Niobrara Formation contact. Dots indicate registered wells in which the contact was identified. Contour interval is 10 feet. From Divine et al. (2016).

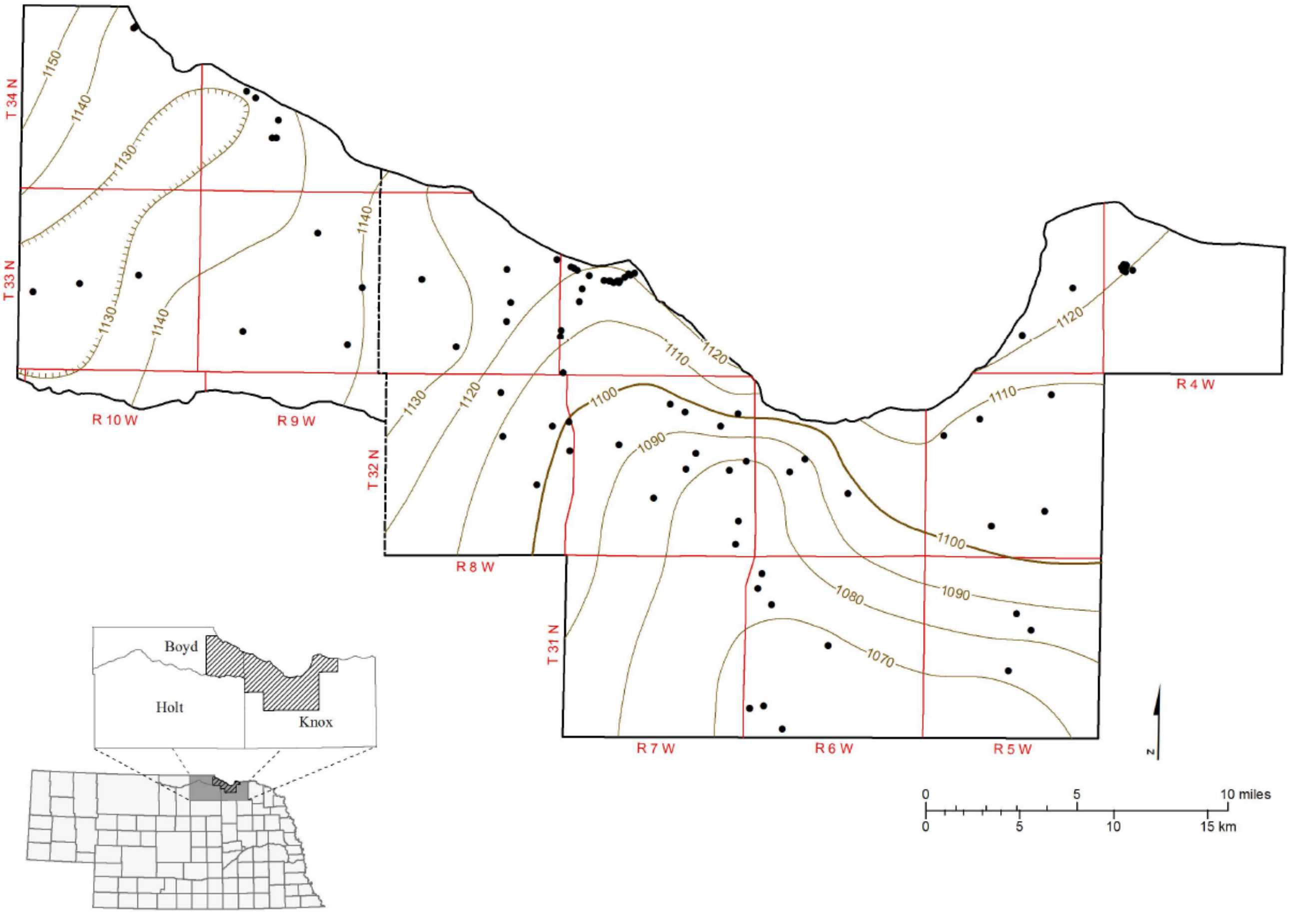


Fig. 18. Structure contour map of the top of the Codell Sandstone. Dots represent registered wells in which the top of the Codell was identified. Contour interval is 10 feet. From Divine et al. (2016).

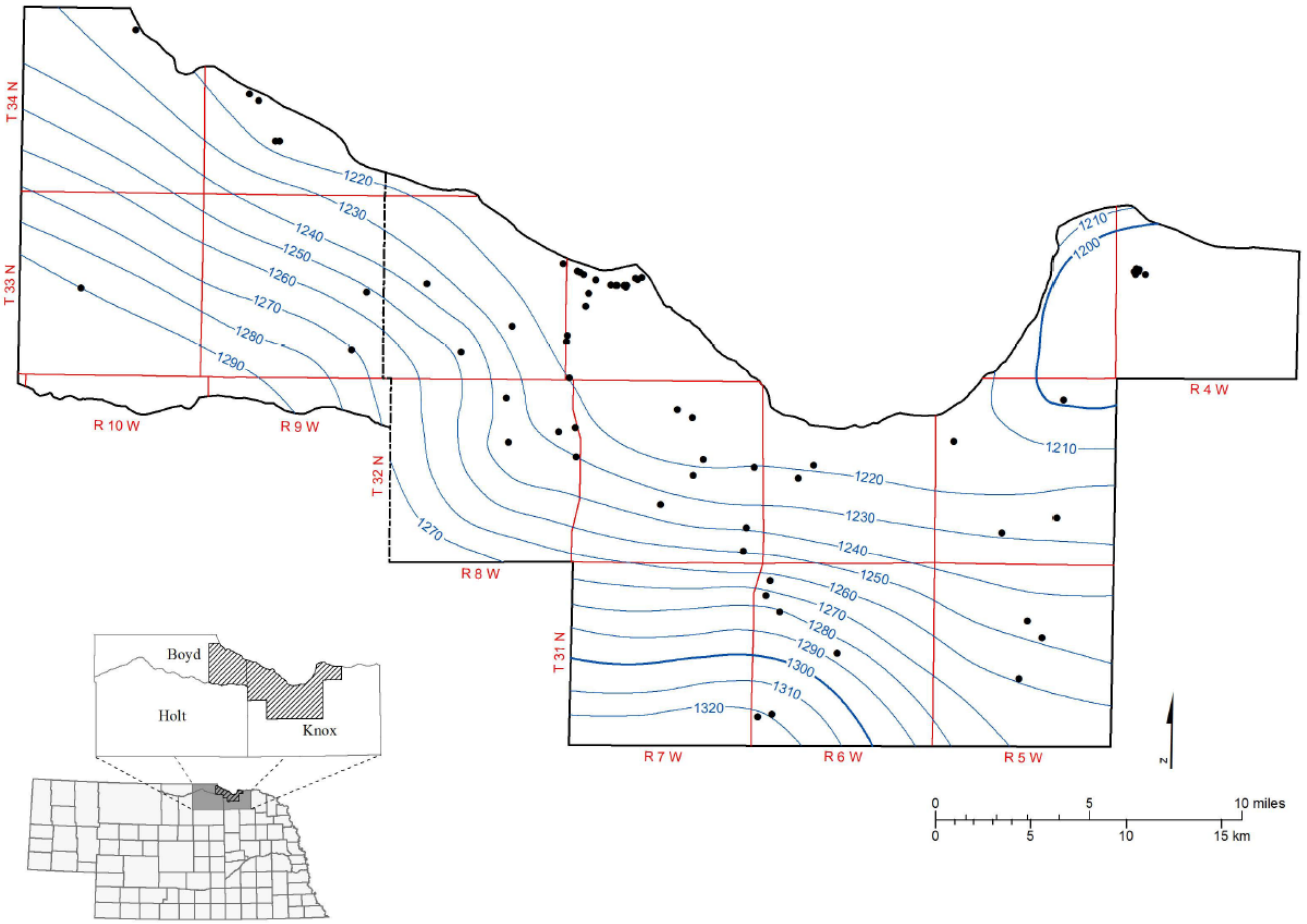


Fig. 19. Static water level contours in the Codell aquifer. Dots represent registered wells from which the initial static water level measurement was used. Contour interval is 10 feet. From Divine et al. (2016).

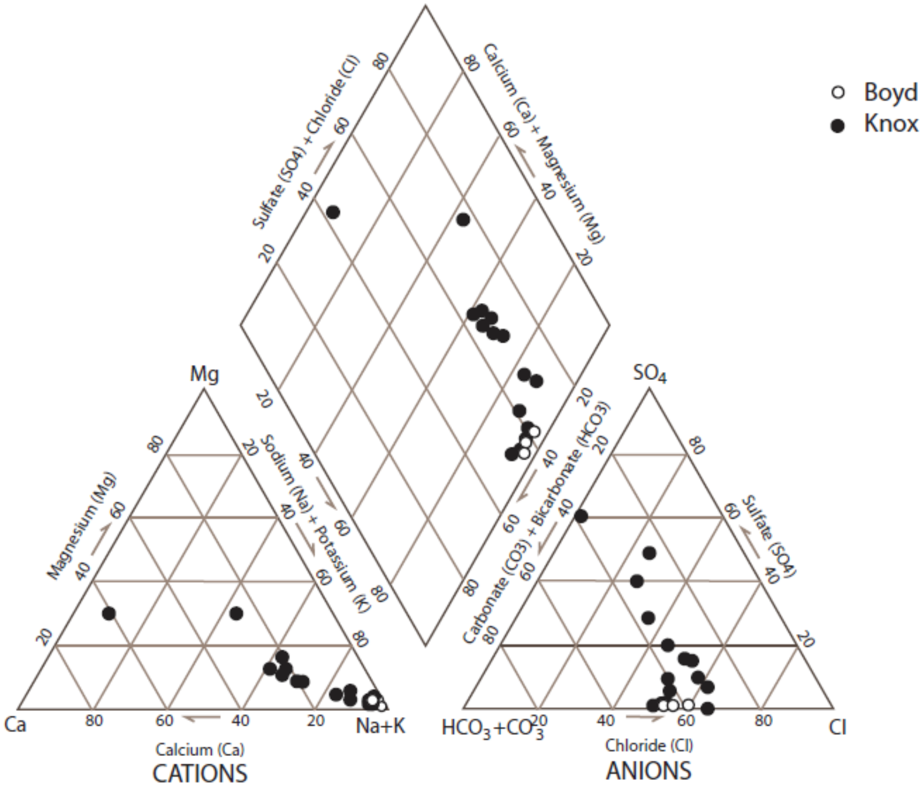


Fig. 20. Piper diagram showing major ion chemistry for Codell wells in Boyd and Knox counties, modified from Divine and Sibray (2017).

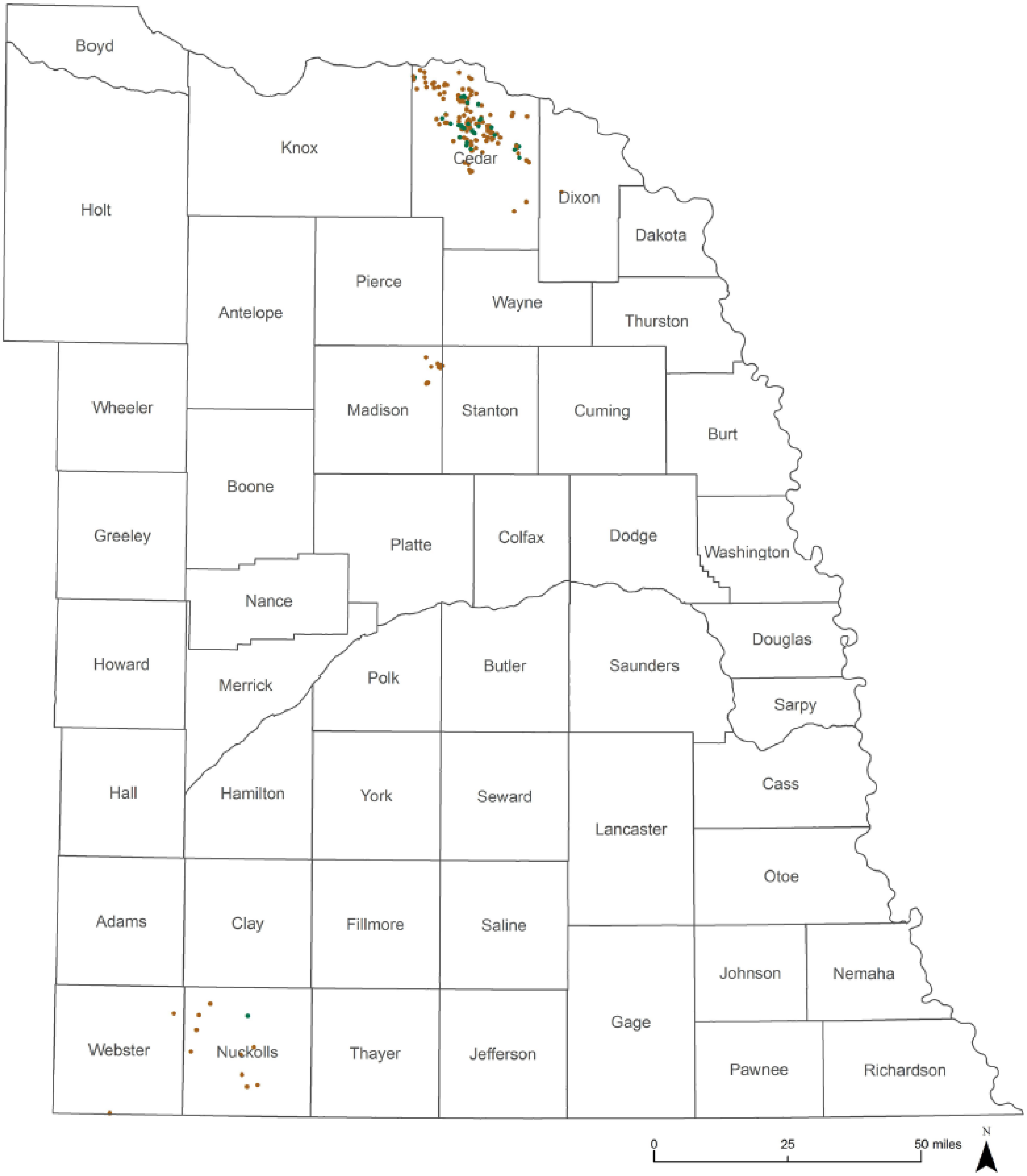


Fig. 21. Location of wells screened entirely in the Niobrara aquifer, from Divine and Sibray (2017).

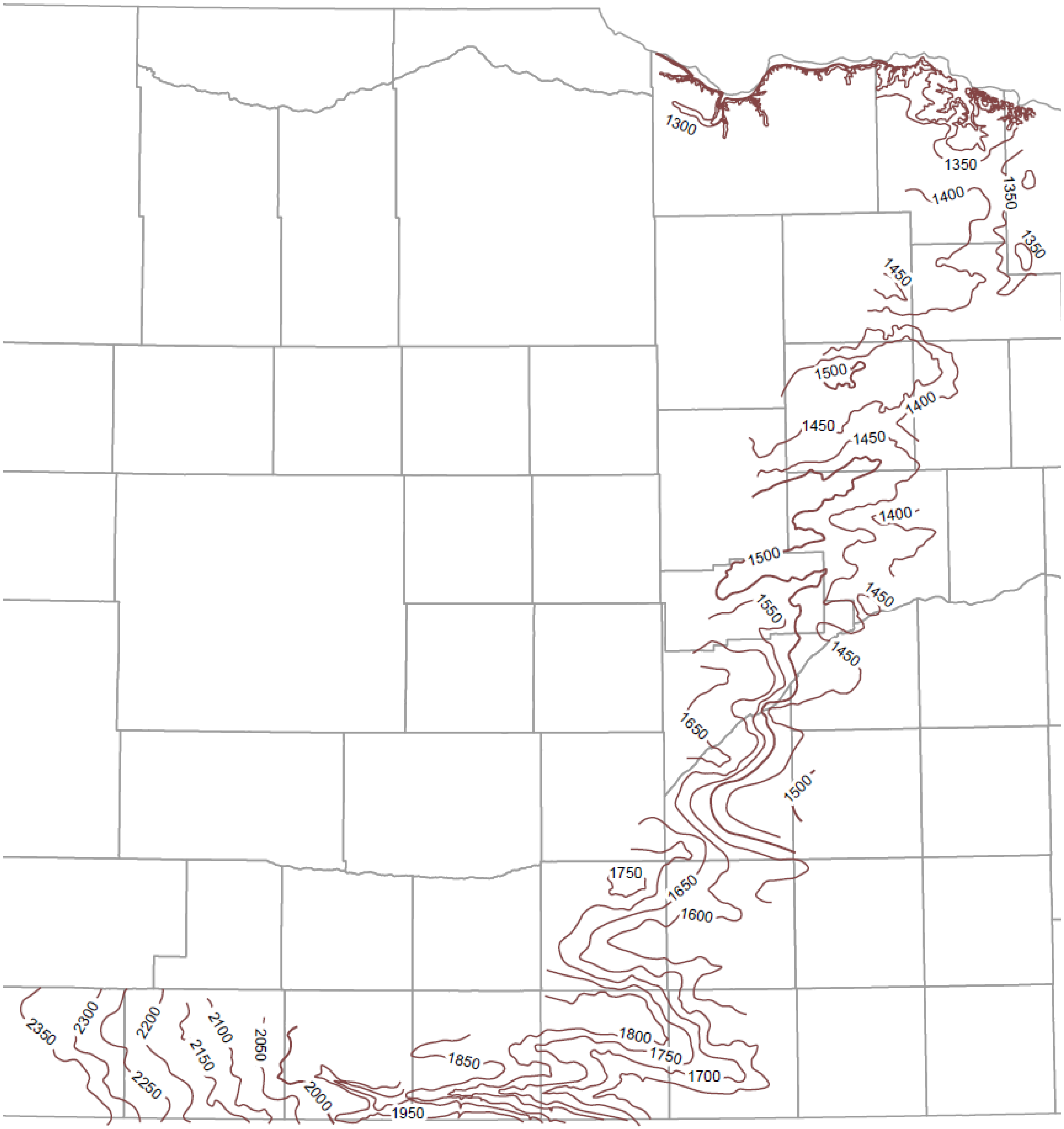


Fig. 22. Structure contour map of the top of the Niobrara Formation. Contour interval is 50 feet. From Divine et al. (2017).

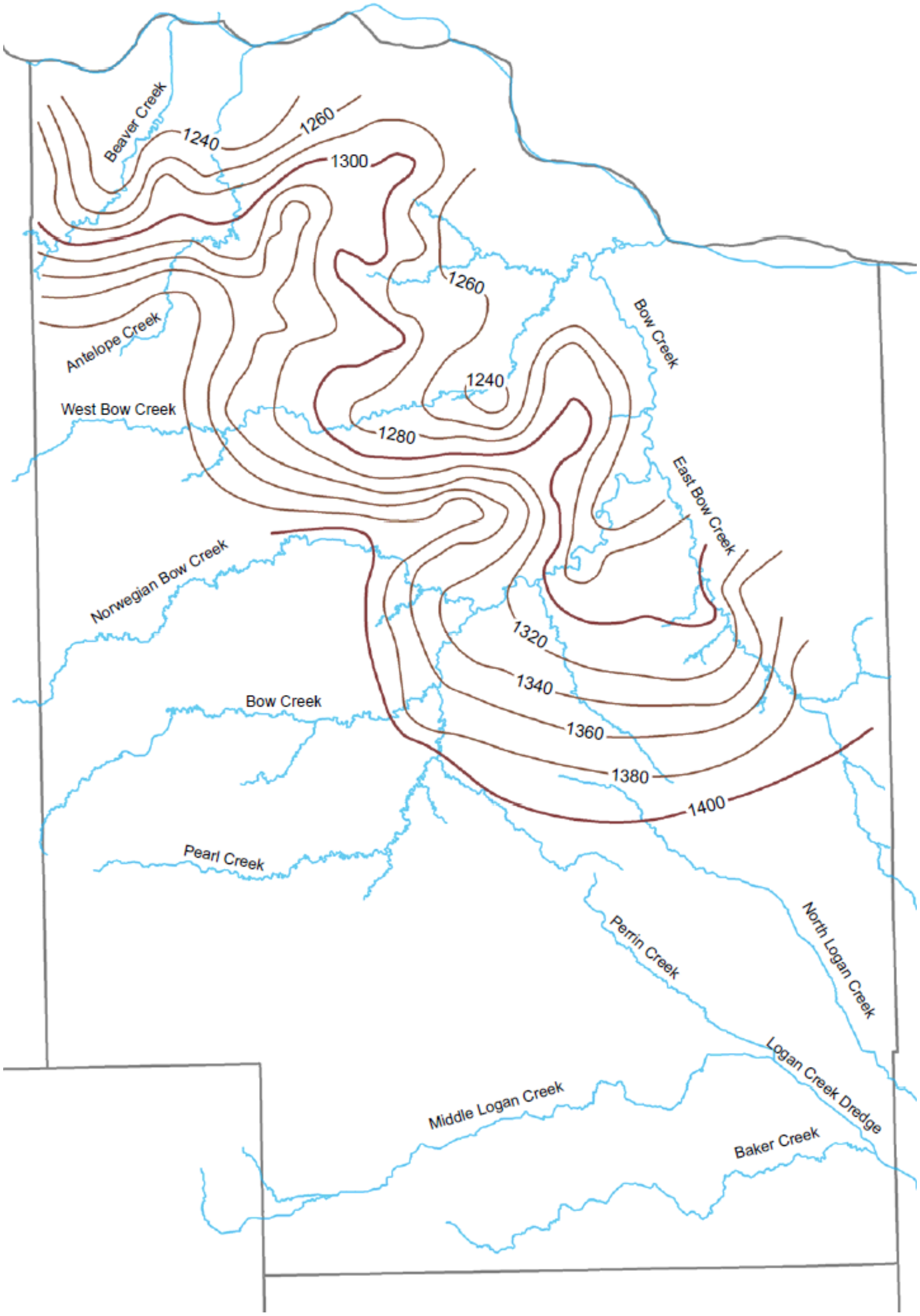


Fig. 23. Static water level contours in the Niobrara aquifer in Cedar County. Contour interval is 20 feet. From Divine et al., in press.

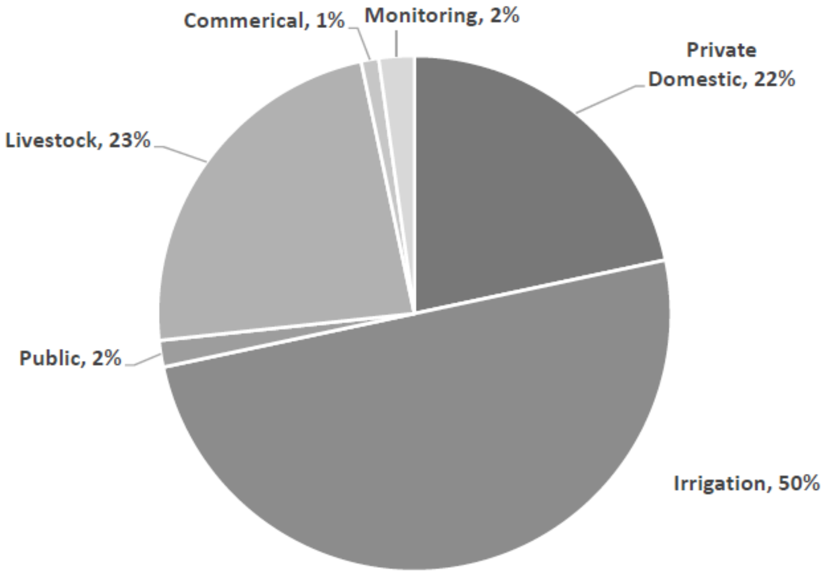


Fig. 24. Distribution of well types in the Niobrara aquifer, from Divine and Sibray (2017).

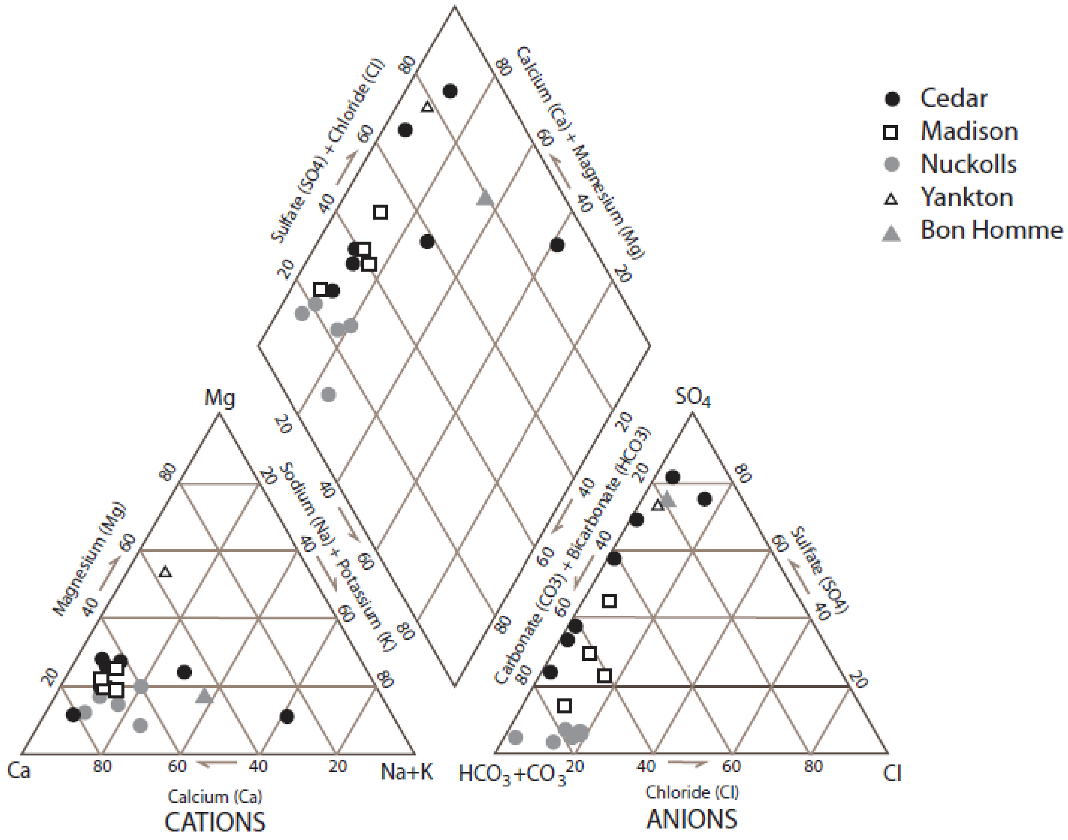


Fig. 25. Piper diagram showing major ion chemistry for Niobrara wells. Symbols for Cedar, Madison, and Nuckolls counties represent individual wells; sympbols for Yankton and Bon Homme counties represent county averages. Modified from Divine and Sibray (2017).

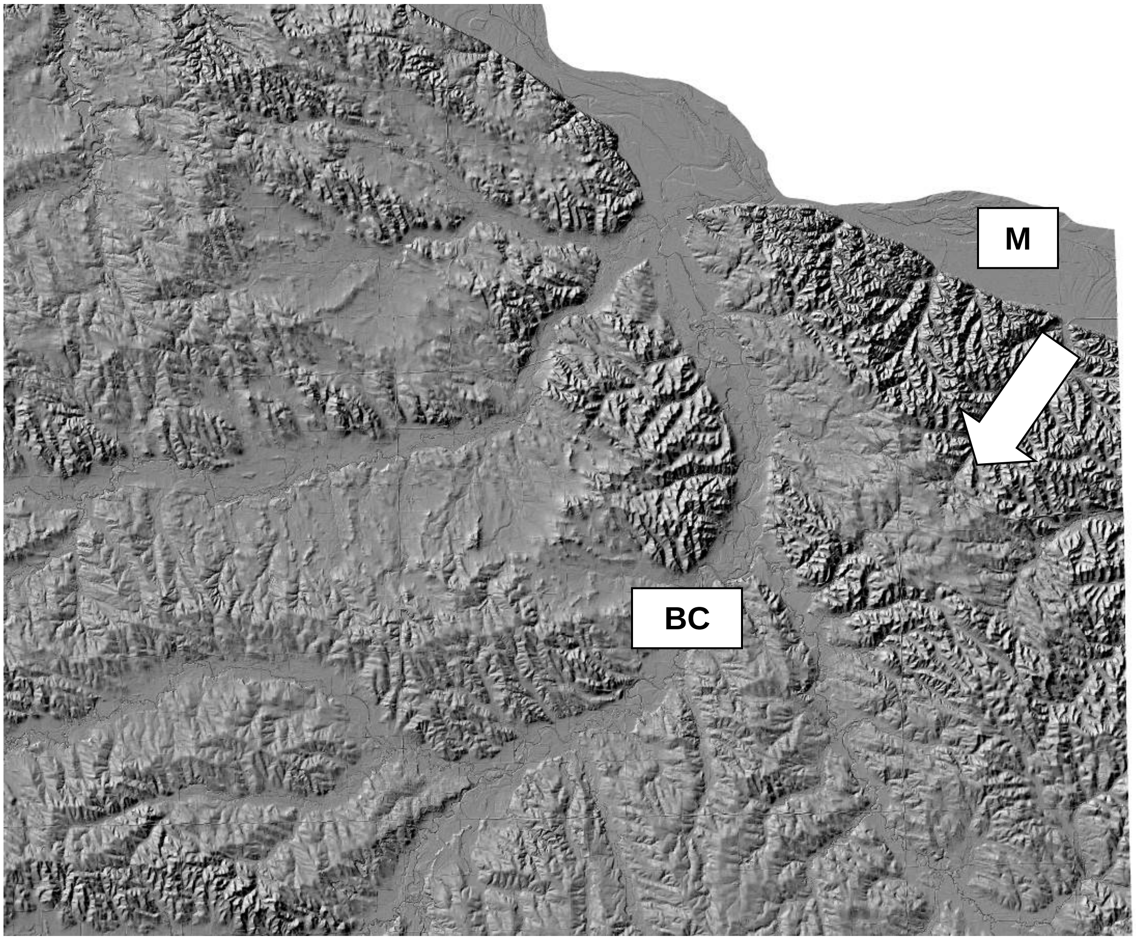


Fig. 26. Hillshade generated from LiDAR data for a portion of Cedar County, Nebraska around field trip stop #4. Northeastern edge of image shows Missouri River valley (MR) and valley of Bow Creek (BC), which trends approximately north-south. Total thickness of Peoria Loess in the area ranges from 8 to 12 m on stable uplands, and thickest loess is directly adjacent to Missouri River. Highly dissected uplands are indicative of thicker loess. Several stream valleys show thick loess on northern sides and thin loess on the southern sides. “Obert trough” (arrow) is in east-central portion of the image, which is approximately 26 km (6 mi) from top to bottom.

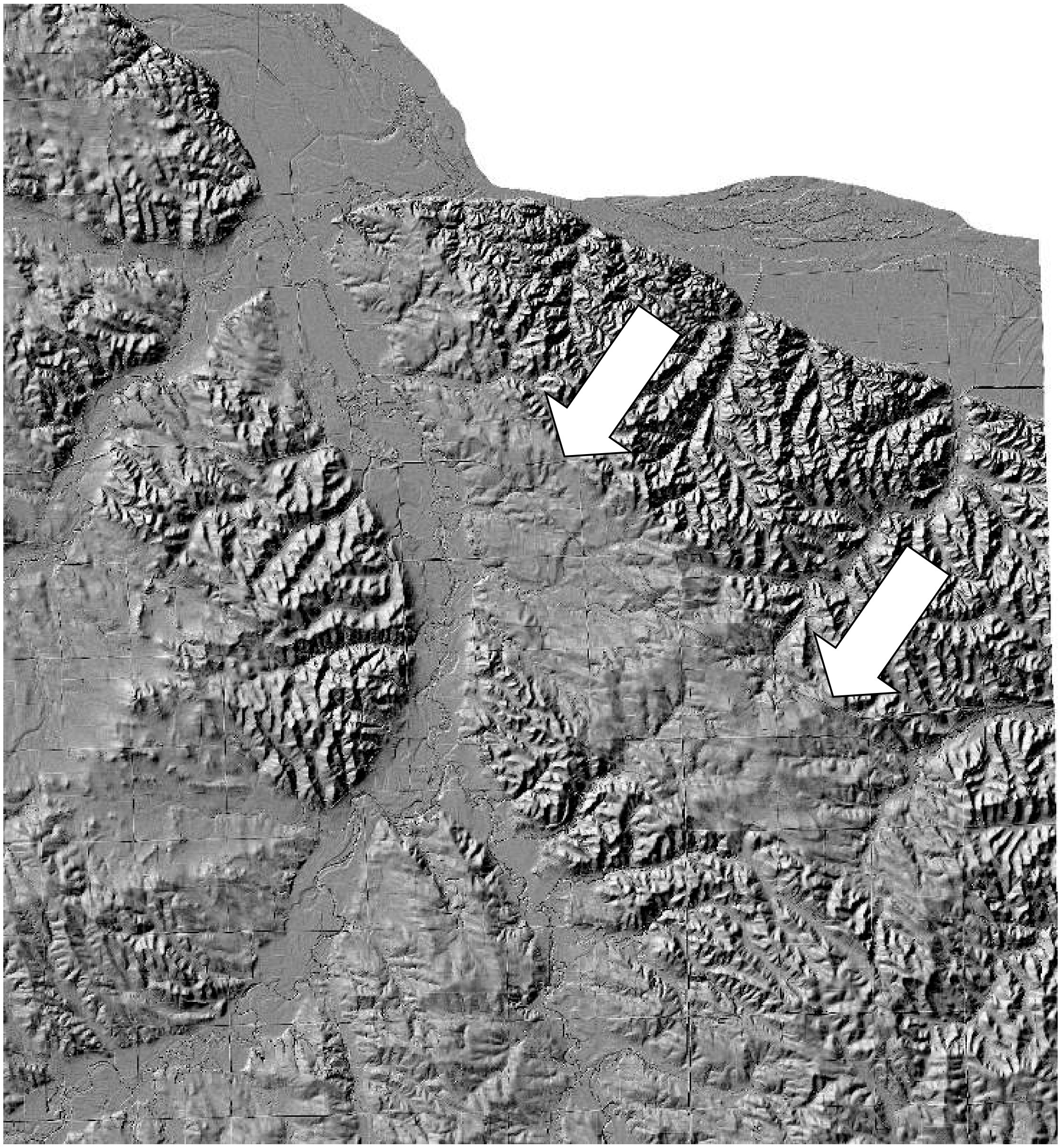


Fig. 27. Hillshade generated from LiDAR data showing “Obert trough” (arrow), which is approximately 10 km (6 mi) long and 3 km (2 mi) in width.