2019

Geology of Southeastern Nebraska

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Geology of Southeastern Nebraska

Nebraska Well Drillers Association
and
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(Nebraska Geological Survey)
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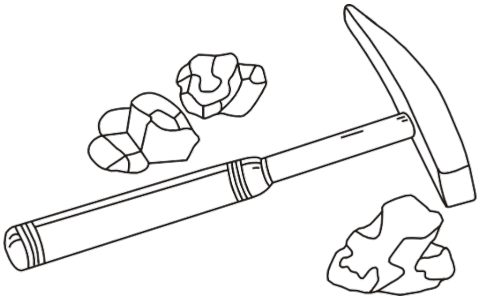

NEBRASKA GEOLOGICAL SURVEY

Guidebook No. 36
Conservation and Survey Division
School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska-Lincoln

October 18, 2019

CONSERVATION AND
SURVEY DIVISION
School of Natural Resources

Itinerary
Geology of Southeastern Nebraska
October 18, 2019
Begin trip at Otoe County Fairgrounds in Syracuse, Nebraska.
(Approximate schedule: note that tour may run as much as one hour over the scheduled time of completion.)

07:30-08:00 (0.5 hr.)	Registration, check in, and brief introduction to trip
08:00-08:30 (0.5 hr.)	Leave Syracuse and proceed to Cook, Nebraska area. Introduce first stop enroute.
08:30-09:15 (0.75 hr.)	STOP 1: Cook, Nebraska. Hydrology and hydrogeology of vicinity of South Fork of Nemaha River, including aspects of surface water connections to groundwater and paleovalley aquifer. Stop at bridge on 737 Rd approximately 1.25 mi east of intersection with 622 Rd.
09:15-09:30 (0.25 hr.)	Leave Cook, Nebraska area and proceed to Tecumseh. Discuss regional geology, including Elk Creek carbonatite enroute
9:30-10:00 (0.5 hr.)	STOP 2: Tecumseh, Nebraska city park. Discuss geology and hydrogeology of the vicinity with an emphasis on results from ENWRA surveys.
10:00-10:30 (0.5 hr.)	Drive to Humboldt, Nebraska. Brief restroom stop at Sapp Brothers gas station. Proceed 0.75 mi east to Stop 3.
10:30-11:15 (0.75 hr.)	STOP 3: Humboldt, Nebraska. View small exposure of Admire Group (Pennsylvanian) strata, presumed to be Janesville Shale, at electrical substation 0.8 mi east of town on north side of NE Hwy 4, on the upthrown western side of the Humboldt Fault.
11:15- 11:45 (0.5 hr.)	Drive to vicinity of Salem, Nebraska via NE Hwy 4, US Hwy 75, and NE Hwy 8. Discuss regional geology enroute.
11:45-13:00 (1.25 hr)	STOP 4 and lunch: View road cut exposing Roca Shale and Grenola Limestone (Permian) just off NE Hwy 8 on 706 Rd, via 645 Blvd, 1.2 mi south of Salem, Nebraska. Lunches will be distributed at the stop.
13:00-13:30 (0.5 hr.)	Drive, via NE Hwy 8 and US Hwy 159 and then by and 661 Avenue and 703 Trail, to a point confluence of Big Nemaha and Missouri Rivers southeast of Rulo, Nebraska. Discuss history of limestone and coal production and view flooding en route.
13:30-14:00 (0.5 hr)	STOP 5: Area of Missouri-Big Nemaha confluence SE of Rulo. View sandstone in White Cloud Member of Scranton Shale (Pennsylvanian). View effects of spring 2019 flooding and discuss surface-water hydrology.
14:00-14:30 (0.25 hr)	Drive southeast to White Cloud Casino via 703 Trail/KS Hwy 7 and 330 Rd, then turn around at Casino for return trip through Rulo. View flood effects and recently active landslides along west bank of Missouri River.
14:30-16:00 (1.5 hr)	Return to Syracuse, Nebraska.

1. Introduction

Southeastern Nebraska is both fascinating and frustrating in terms of geology and hydrogeology, providing multiple contrasts. Sedimentary bedrock lies barely below the land surface in many parts of the field-trip area but easily accessible exposures are rarer than ever. The oldest vertebrate fossils from the state, including some remarkably preserved lungfish, come from southeastern Nebraska. Nevertheless, our knowledge of ancient plant and animal communities is, at best, a highly incomplete collection of mere glimpses into the distant past. Major geologic structures are definitely present in southeastern Nebraska, but there is exceedingly little evidence for them at the land surface. Interesting igneous and metamorphic rocks (collectively known as *crystalline* rocks), some of which have economic potential, are tantalizingly close to the surface—shallower in some places than in any other part of the state—but they never crop out at the surface. Nebraska's only viable coal mine was in the southeastern part of the state, an area which still has active oil wells, but the state uses far more coal and petroleum (oil and natural gas) than it ever produced. Finally, while Nebraska is justifiably known to be a groundwater-rich state, the field-trip area in the southeastern part of the state does not overlie the High Plains aquifer and major aquifers are absent over much of it.

The objectives of this field trip (Fig. 1) are:

1. To develop an understanding of the surficial geology and hydrostratigraphy of southeastern Nebraska; to learn about new data collected in the Eastern Nebraska Water Resources Assessment (ENWRA), an ongoing hydrogeological research partnership involving multiple Natural Resources Districts (NRDs) that began in 2006.
2. To observe and appreciate groundwater-surface water connections in the field-trip area. Interesting aspects of the interaction of the two reservoirs in the hydrologic cycle are visible, or will be discussed, during the course of the trip.

3. To develop an overview of bedrock and basement geology, as well as structural geology, in the field-trip area and environs.

4. To become familiarized with mineral and energy resources in the field-trip area and environs. These resources have a surprisingly long history of speculation, exploration, development, and use, and it is nearly certain that there will be additional developments in the future.

2. Geologic Setting and Basement Rocks

Nebraska lies on the North American *platform*—the sedimentary-rock-covered, generally stable (in terms of tectonics over the past several hundred million years) interior of the continent. In places in the field-trip area, approximately 152 m (500 ft) of sedimentary rock strata overlie the much older *basement*, which consists chiefly of igneous and metamorphic rocks, which are generally more than one billion years in age. Thus, parts of the field-trip area are underlain by the shallowest basement rock in all of Nebraska. Regional basement rocks, which are not exposed anywhere in Nebraska, are more similar to those in a *shield*, an area of exposed basement rock on a continent, such as North America's Canadian Shield. Platforms and shields make up Earth's continents as geologists define them. Note that the buried Midcontinent Rift, which extends from Lake Superior into northeastern Kansas, and which underlies the northern part of the field-trip area, is direct evidence for the failed rifting or "splitting" of the ancient Laurentia—the center around which present North America was gradually built by plate tectonics—into two or more parts. After the Midcontinent Rift became quiescent and the jigsaw-puzzle parts of Nebraska's basement rocks were finally assembled, *tectonism* (movements of Earth's crust) in present Nebraska and surrounding areas in the continental interior was relatively mild and the geologic history of the area was dominated by the deposition and erosion of sediments in response to changes in global sea level. During the Pennsylvanian and Permian, worldwide sea-level changes related to the growth and shrinkage of glaciers in the Southern Hemisphere was a particularly important control on sediment accumulation. There were still a few notable episodes of tectonism in the field-trip area, however, during the past half-billion years.

Basement rocks under southeastern Nebraska are varied (Fig. 2). Granitic basement rocks are the most widespread basement rocks in the field-trip area, but there is a smaller area of basement consisting of gneiss (and other, associated metamorphic rocks) atop the Nemaha Uplift, and both basalt and clastic sedimentary rocks fill the Midcontinent Rift in the subsurface of the northern part of the field-trip area (Carlson and Treves, 2005). The basement rocks under southeastern Nebraska range in age from approximately 1.84 Ga (Ga = giga-annum or billion years ago) for certain gneisses and other associated metamorphic rocks to approximately 1.1 Ga for some of the basalts and clastic sedimentary rocks in the Midcontinent Rift; all of the basement rocks except for those within the Midcontinent Rift, are part of the Central Plains orogen, a vast subsurface expanse of igneous and metamorphic rocks that resulted from mountain-building and igneous activity along the southern margin of the ancient Laurentia well more than a billion and a half years ago (Sims and Petermar, 1986; Carlson and Treves, 2005). Basement rocks in the field-trip area are not considered to be aquifers by virtue of their overall low storage volume (porosity) and minimal connection between pore spaces (permeability). Additionally, any water that is contained in them will likely be of poor quality due to long-term water-rock interactions at comparatively great depths relative to the overlying sedimentary rocks. It is unlikely, therefore, that the crystalline basement rocks under the field-trip area (or anywhere in Nebraska) will ever have any utility in water supply.

Geologic structure—the deformation of rock by crustal stresses—on the North American platform is considered to be gentle relative to the Appalachian region or to the mountainous western United States and Canada. The aforementioned “gentleness” of geologic structure, however, is only relative: by Nebraskan standards, the southeastern part of the state is distinguished by some prominent faults, a major uplifted block of Earth's crust, and some folds. In fact, southeastern Nebraska is the part of the state in which geologic structure is most obvious, but only if the observer has a keen eye and goes to the (very few) right places. Structural geology is discussed in a forthcoming section.

3. Sedimentary Cover Rocks and the Problematic Pennsylvanian–Permian Boundary

The term *sedimentary cover rocks* refers to all sedimentary bedrock strata above basement rocks in a given area—the piles of marine and nonmarine sediment that accumulated over hundreds of millions of years and eventually became lithified. The sedimentary cover rocks in the field-trip area are exclusively Paleozoic, ranging in age from Cambrian to Permian, spanning a very approximate age range of 540 to 290 Ma (Ma = mega-annum or million years ago). The only sedimentary cover rocks that are exposed at the surface in the field trip are Upper Pennsylvanian and Lower Permian strata, which have a highly approximated age range of 295 to 304 Ma (Walker et al., 2018). These strata consist of multiple kinds of limestones, shales, mudstones, siltstones, and some ancient-channel- and ancient-valley-filling bodies of sandstone with minor, localized conglomerates (Figs. 3,4). The deposition of the marine and nonmarine sediments from which these rocks were produced was controlled by eustatic (worldwide) changes in sea level, as well as other factors.

The Pennsylvanian (or Upper Carboniferous, as it is known in Europe)–Permian boundary, which is currently dated at 298.9 Ma (Walker et al., 2018), is worthy of discussion in the context of this field trip. Consider that the identification and *dating* of a boundary between two periods on the geologic time scale is challenging enough, but *placing* that boundary within successions of rock at many disparate locations around the world can be highly problematic. A *boundary stratotype*, or a "specified sequence of strata that contains the specific point that defines a boundary between two stratigraphic units"

(Murphy and Salvador, 1999), must be established according to rigorous criteria, including that: (1) there must be an essentially continuous succession of sedimentary rocks representing the interval of geologic time that includes the boundary; (2) the strata should be undeformed by tectonics, be marine in origin, have many marker horizons (distinctive, traceable layers) and contain abundant fossils with widespread geographic distributions (for use in the correlation of strata at distant locations); and (3) the place where the boundary stratotype is established should be easily accessible, well-studied and published upon. Needless to say, fulfilling all of these given criteria in a single place is very difficult and establishing a boundary stratotype is not an easily and quickly accomplished task. Also, note that boundary stratotype is quite different from a *type section* or stratotype, which is merely a point or interval in a succession of strata that is the standard for defining, describing and naming a particular layer (e.g., Roca Shale). There are almost innumerable type sections (there are several in southeastern Nebraska), but very few boundary stratotypes, and perhaps now it is easy to understand why that is the case.

The placement of the Pennsylvanian–Permian boundary in the Midcontinent of North America was highly problematic for decades (effectively, for more than a century), and different authors placed it between different named rock layers (see Sawin et al., 2006), creating confusion. Moreover, the boundary stratotype for the base of the Permian was only established at the end of the 20th century (Davydov et al., 1998), and then in the Ural Mountains of Kazakhstan, fully 9,650 km (6,000 mi) away from the field-trip area. Using fossils and other data, Sawin et al. (2006) finally placed the Pennsylvanian–Permian boundary in Nebraska and Kansas at the contact between the Glenrock Limestone Member and the Bennett Shale Member in the lower part of the formation-rank Red Eagle Limestone within the Council Grove Group, effectively moving upward in the regional stratigraphic column a once-widely-agreed-upon placement of the Pennsylvanian–Permian boundary at the top of the

Wabaunsee Group. Thus, both the intervening Admire Group and the lower part of the Council Grove Group—both of which were long classified as Permian—are now considered to be Pennsylvanian. Care should be taken in the citation of any papers or geologic maps published prior to Sawin et al. (2006) that deal with the Pennsylvanian and Permian strata of eastern Nebraska. Stratigraphic charts of the Pennsylvanian and Lower Permian succession produced by the Nebraska Geological Survey (Conservation and Survey Division) at least as late as the 1970s (e.g., Burchett, 1977) showed a prominent unconformity at the Pennsylvanian–Permian boundary, which was placed at the top of the Wabaunsee Group (now considered to be Pennsylvanian). We speculate that this placement, in addition to being incorrect relative to the later work of Sawin et al. (2006) evinces an obsolete notion that there should or must be an *unconformity* (a contact representing a significant of period of nondeposition or erosion for which the geologic record is missing) between two geologic systems (even though such is commonly the case in continental settings) and, perhaps, that it may be preferable to place a boundary at an unconformity. Both of these notions would be considered incorrect in the modern practice of stratigraphy.

The maximum thickness of Pennsylvanian strata in the field-trip area exceeds 1,500 ft (460 m). An even larger thickness of strata exists below the Pennsylvanian System in the southeastern Nebraska and adjacent parts of Iowa and Missouri, but these older sedimentary rocks do not crop out. Cambrian (roughly 500-485 Ma), Middle and Upper Ordovician (roughly 467 to 444 Ma), Lower Silurian (roughly 425 to 419 Ma), Upper Devonian (roughly 383-359 Ma), and Middle and Lower Mississippian (roughly 347 to 323 Ma; Walker et al., 2018) sedimentary rocks underlie the lowermost Pennsylvanian strata (Cherokee Group) in that region (note that the Cherokee Group as well is not exposed in Nebraska, but that it is exposed farther to the east and south in Iowa and Missouri). This buried succession of pre-Pennsylvanian Paleozoic rocks is dominated by marine carbonate rocks, that is, limestones and *dolostones* (former limestones altered—mineralogically and in other ways—after deposition by the introduction of dissolved magnesium from circulating groundwaters). The dominant mineral in limestones is *calcite* ($CaCO_3$) and that in dolostones is *dolomite* ($CaMg[CO_3]_2$). Pre-Pennsylvanian rocks are present in the Forest City Basin in the eastern part of the field-trip area, where some of them are oil reservoirs, but they were stripped by ancient erosion over the top of the buried Nemaha Uplift in the western part of field-trip area and, therefore, are now absent in that area.

In the counties immediately to the west (Gage County) and north (Cass County) of the field-trip area, Cretaceous strata are present locally on top of Pennsylvanian and Permian strata, as is also the case in parts of Omaha and Lincoln metropolitan areas. There are, however, no Cretaceous strata in the field-trip area. They are likely to have been present at one time (latest Cretaceous or even earliest Paleogene), but they were very gently folded by the Laramide reactivation of structure in the Nemaha Tectonic zone, and subsequently eroded (Joeckel et al., 2018).

4. Structural Geology

The most prominent geologic structure in the field-trip area is the Nemaha Uplift (referred to by some authors as the Nemaha Ridge) a buried block of uplifted basement rock that has no expression in terms of surface relief today. Together with various associated faults, this uplift is a part of the much more extensive, Nemaha Tectonic Zone, a tectonic belt that extends approximately 650 km (400 mi) south-southwest to north-northeast from the vicinity of Oklahoma City to the Omaha area (Berendsen and Blair, 1995). The Nemaha Uplift is asymmetrical, being bounded sharply on its eastern side by high-angle reverse faults (Figs. 5,6), but having a much gentler slope on its western side (Steeples, 1982, 1989; Berendsen and Blair, 1995).

It is fascinating to consider that the Nemaha Uplift, which we cannot actually see at the present land surface, evolved over a few hundreds of millions of years in response to major tectonic events happening hundreds of kilometers away and closer to the margins of the evolving North American continent. Indeed, research indicates that there were multiple phases of tectonism around the Nemaha Uplift (Burberry et al., 2015): (1) an significant episode involving normal (extensional) faulting prior to the end of the Mississippian Period (approximately 323 Ma), during which Cambrian through Mississippian strata were folded; (2) the main phase of uplift involving reverse (compressional) faulting during some interval of time centered around the Mississippian–Pennsylvanian boundary and in association with mountain-building events far to the south and west (Ouachita-Marathon orogeny and the uplift of the Ancestral Rockies); (3) continued crustal compression during the Pennsylvanian and Permian; and (4) subtle deformation (long-wavelength, low-amplitude folds) caused by far-foreland reactivation during the early part of the Laramide orogeny, which extend, in total, through the time interval of 80 to 55 Ma. The Laramide orogeny was a major mountain-building event in western North America, the effects of which are still very obvious in the Rocky Mountain region.

The presence of the Nemaha Uplift in the subsurface of Nebraska, Kansas, and Oklahoma is a determining factor in many aspects of regional geology. It impacts the distribution and exploitation of petroleum resources, and in the field-trip area it abruptly truncates the oil-producing Forest City Basin, which extends east-and southward into adjacent states. The uplift also influences the location, characteristics, and movement of deep groundwater, whether directly or indirectly (e.g., Burrows and Appold, 2014). The Elk Creek carbonatite, a potentially important mineral deposit, lies within the uplifted basement block and straddles the line between Johnson and Pawnee Counties in Nebraska. More than 460 m (1,500 ft) of sedimentary cover rocks and some amount of basement rock were eroded from the crest of the Nemaha Uplift in its main phase of uplift during the Late Mississippian–Early

Pennsylvanian; seismic profiles verify that this amount of throw (vertical movement) occurred along the eastern flank of the uplift during its main phase of uplift (Steeples, 1982, 1989). At some point in earliest Pennsylvanian time, the crest of the Nemaha Uplift in southern Nebraska stood something like 500 m (1,600 ft) above the adjacent Forest City Basin), and possibly even higher (Anderson and Wells, 1968). If that amount of relief were present in the area today, we would rightly consider the Nemaha Uplift to be a low, fault-bounded mountain range. Before the end of the Pennsylvanian Period, the gradient from the uplift to the basin was still high enough that conglomerates containing cobbles and small boulders of granite gneiss, eroded from the crest of the uplift, were deposited along its flanks as a "granite wash" (Joeckel et al., 2007).

The Forest City Basin, immediately east of the Nemaha Uplift, extends from southeastern Nebraska (most of Richardson County, plus eastern Nemaha and southeastern-most Otoe counties) into southwestern Iowa, central Missouri, and eastern Kansas as far as the Bourbon Arch in the southern part Kansas. The basin is *an intracratonic sag basin* (a relatively gentle downwarping in Earth's crust in the continental interior) that extends over an area of approximately 83,000 km^2 or 3,200 mi^2. The Forest City Basin is something of an exception as a sag basin because it is partially fault-bounded alongside the Nemaha Uplift. Moreover, the presence of the fault-bounded Nemaha Uplift on its western margin confers an asymmetrical cross section on the basin, which had a depocenter adjacent to the fault-bounded eastern side of the uplift.

5. Hydrogeology

Surficial geology in the field-trip area is dominated by loess and the silty soils that formed thereon (Figs. 7, 8). Most of the wells in the field-trip area are screened in unconsolidated Quaternary sediment that serves as local aquifers. These local aquifers were deposited in a variety of hydraulic settings and include: (1) alluvial aquifers, which exist in the sediments filling the valleys of modern streams; (2) paleovalley aquifers, which are hosted by the buried, valley-filling deposits of Pleistocene streams; and (3) localized, groundwater-bearing sands and gravels within tills. Additionally, a few wells (including approximately 20 in Richardson County) draw water from Pennsylvanian or Permian bedrock, but these rock units are not recognized as aquifers in the field-trip area. Paleovalley aquifers and wells in limestone bedrock will be the focus of the hydrogeology discussion on this field trip.

The bedrock surface in the field-trip area was exposed to chemical and physical weathering for an unknown period of time, but particularly during the Pleistocene Epoch (2.59 Ma-11.7 ka). The bedrock surface was dissected by shifting drainage systems during the Pleistocene, and perhaps during even the Pliocene, producing a topographically complex bedrock surface that is now mostly buried. These old valleys are called paleovalleys. The relatively large paleovalleys are important from a water resources perspective because they often contain coarser-grained Quaternary sediment and greater thicknesses thereof relative to surrounding areas, thus yielding larger volumes of water to wells. Several paleovalleys are located in the field-trip area, with the most significant stretching more than 100 km (62 mi) across northern Saline County, southern Lancaster County, and northern Johnson County (Fig. 9). This paleovalley is referred to as either the Crete-Princeton-Adams aquifer or the Dorchester-Sterling aquifer. Glaciation significantly changed the topography in eastern Nebraska, completely obscuring the location of the paleovalley. The geometry of the paleovalley is complex, as is the sedimentary deposition within the valley (Divine and Korus, 2012). Generally speaking, the base of the valley is currently about 110 m (360 ft) below ground surface in the vicinity of Friend and Dorchester, and about 60 m (200 ft) deep in the vicinity of Cook. The cities of Syracuse (Otoe County) and Tecumseh (Johnson County) are located approximately 10 km (6 mi) north and south of the paleovalley, respectively, and both cities use the paleovalley aquifer for municipal supply. In Johnson County, the villages of Cook and Sterling both source water from the paleovalley. Johnson County Rural Water District No. 1 and Otoe County Rural Water District No. 3 also both have wells in the paleovalley.

Three smaller paleovalleys have been mapped in Richardson County (Divine, 2017). Unlike the Dorchester-Sterling paleovalley, these paleovalleys closely coincide with the locations of modern valleys. One paleovalley corresponds generally with Muddy Creek. The two other paleovalleys underlie the North and South Forks of the Big Nemaha River. These two paleovalleys merge near the village of Salem, which is also where the modern streams merge to form the Big Nemaha River. If not for detailed analysis of test holes that show older alluvium underlying Recent alluvium (Emery, 1964), and the presence of abandoned terraces along the South Fork of the Big Nemaha River in Pawnee County (Korus and Howard, 2015), it would be very difficult establish that paleovalleys preceded these two current valleys.

Although the modern Muddy Creek and the Muddy Creek paleovalley are closely aligned, there are some areas in which the two valleys are slightly offset. The paleovalley axis is typically located slightly to the northeast of the current valley, except in the northern third of Richardson County, where the paleovalley axis is southwest of the current valley. There also appears to be a slight bedrock ridge, less than 20 feet high, toward the northern end of the paleovalley. This paleovalley extends westward into parts of Nemaha, Pawnee, and Johnson counties (Summerside et al., 2005; Dreeszen and Burchett, 1971). The City of Humboldt is located about 6 km (3.5 mi) south of this paleovalley, but their municipal wells are located in the paleovalley. Richardson County Rural Water District No. 1 and Pawnee County Rural Water District No. 1 also have supply wells in this paleovalley aquifer.

None of Pennsylvanian and Pennsylvanian bedrock units present in the field-trip area are considered aquifers, but some of them do supply water to domestic and livestock wells. A recent inventory of bedrock wells in Richardson County identified 20 registered wells screened entirely within bedrock, 18 of which probably draw water from the Council Grove Group. The lowest screen relative to the top of bedrock is about 83 feet into bedrock. South of the South Fork of the Big Nemaha River, detailed stratigraphic information is limited, but between the North Fork of the Big Nemaha River and Muddy Creek, bedrock wells appear to be screened across the Grenola, Roca, Red Eagle, Johnson and Foraker Formations of the Council Grove Group. One bedrock livestock well in T. 3 N., R. 13 E. appears to draw water from the White Cloud Member of the Scranton Shale (Wabaunsee Group), and also possibly the Cedar Vale Member of the same formation and the Burlingame Member of the Bern Formation (Wabaunsee Group). A bedrock domestic well on the other side of the county in T. 2 N., R. 17 E. may be screened in the Wood Siding Formation, and is the only other Wabaunsee bedrock well identified at this time in Richardson County.

In most cases, the static water level reported by the driller in bedrock wells is below the top of bedrock (analogous to unconfined conditions), but there are about five wells in which the static water level may be above the top of bedrock (analogous to a confined aquifer). Although many people think of bedrock wells as intercepting vertical fractures, it is much more likely that a well will intercept and get water from horizontal bedding planes (Walker, 1956). When the horizontal crevice(s) that supply water to the well are connected laterally to water in a confined aquifer or to unconfined groundwater where the water table is at a higher elevation than the crevice(s), the water level in the well may be above the top of bedrock (Walker, 1956). This hydraulic condition may also occur in faulted areas where the water has moved downward along the fault and the upper hanging wall acts as a confining layer (Johnson, 1962). The domestic well in T. 2 N., R. 17 E. has a static water level more than 24 m (80 ft) above the top of bedrock, based on the measurement reported by the well driller at the time of well installation. This well is probably receiving recharge laterally through horizontal fractures or bedding planes that are connected to Quaternary sediments having a higher hydraulic head elevation than the bedrock surface.

6. Hydrology

Surface water in the field-trip area generally flows into the Little Nemaha or Big Nemaha rivers and their tributaries. Only creeks whose headwaters are within about 10 km (6 mi) of the Missouri River flow directly to it because the highly dissected topography has numerous drainage divides relative to other areas of Nebraska. The Big Nemaha River and Muddy Creek probably cut their current valleys sometime in the interval between the end of the pre-Illinoian glaciations about 640,000 years ago (Reed et al., 1966; Roy et al., 2004) and the deposition of the Loveland Loess began about 165,000 years ago (e.g. Emery, 1964; Forman and Pierson, 2002). Historic bedrock surface maps indicate that these current valleys coincide with older valleys of a previous drainage system that existed before glaciation (Dreeszen and Burchett, 1971). Prior to glaciation, the upper Missouri River flowed north across central Canada and into Hudson Bay. This course was blocked by ice sheets during the Pleistocene, and the present middle Missouri River valley formed only after the final retreat of ice sheets from Nebraska.

Evidence of an ancient earlier drainage system is present in northeastern Richardson County at Indian Cave State Park. The Indian Cave Sandstone is sediment that filled a large river valley that drained eastern part of present North America approximately 300 million years ago (Fischbein et al., 2009). At Indian Cave State Park, the ancient valley filled by the Indian Cave Sandstone cuts through the Onaga Shale Formation at the base of the Admire Group. The Indian Cave Sandstone contains very fine to medium sandstone and minor conglomerates, as well as intervals of shale and sandstone-shale heteroliths (interbedded deposits typically formed in tidal flats).

7. Water Quality

Surface Water

The United States Congress passed the current version of the Clean Water Act in 1972 with the goal to “restore and maintain the chemical, physical, and biological integrity of the Nation’s waters.” The first major component of the act provided funding to municipalities and states to build sewage treatment plants, which were not previously required. The second component of the act established two permit systems to regulate discharges of pollutants. The first system is called the National Pollutant Discharge Elimination System (NPDES) which is largely administered by states; the second is the “dredge and fill” permit program administered predominantly by the U.S. Army Corps of Engineers. On this field trip we only discuss the NPDES permit program. The definition of “the Nation’s waters,” also known as Waters of the United States (or WOTUS) has been the subject of much litigation, including recently. Originally, the term was defined as navigable waters, and although the term has become broader, the focus is still firmly on discharges to surface water. Federal circuit courts disagree on whether indirect discharge of pollutants to groundwater requires an NPDES permit.

NPDES permits apply to point sources, meaning a discernible and discrete conveyance, which includes ditches and concentrated animal feeding operations, but excludes agricultural stormwater runoff. Anyone who wants to discharge a pollutant from a point source to surface water can do so, but only with a permit that limits amounts of pollutants that can be discharged. That permit is issued by the Department of Environment and Energy in Nebraska. Each state agency that administers the NPDES program must also designate beneficial uses for all individual water bodies in the state and determine if the water quality in each body supports the beneficial uses. This assessment must occur every two years and be reported to the United States Environmental Protection Agency (EPA). If the water quality is too poor to support the beneficial uses, the state may be required to establish a total maximum daily load (TMDL) for each pollutant that is non-compliant.

Nebraska has defined four categories of beneficial uses: primary contact recreation; aquatic life; water supply (divided into public drinking water, agriculture, and industrial); and aesthetics. These uses are assigned to stream segments and lakes. In the Nemaha river basin, 326 stream segments were assessed, the most in any of the 13 river basins in the state (Nebraska Department of Environmental Quality, 2018). All of the stream segments were assigned aesthetic, agricultural, and warm water aquatic life beneficial uses. Twenty stream segments were assigned as having value for primary contact recreation (e.g. swimming); two segments for public drinking water supply, and one for industrial supply. Overall, the water quality in the Nemaha river basin is rated as fair (on a scale of poor, fair, good, and excellent), with only the Big Blue and Little Blue basins scoring lower (Nebraska Department of Environmental Quality, 2018).

On the Missouri River, recreational use is impaired by *Escherichia coli* (*E. coli*) bacteria and the aquatic life use is impaired by mercury. As a result, Nebraska will designate its reaches as category 5, meaning TMDLs will need to be established (which is not an easy process). Other category five streams in the river basin include: Winnebago Creek (aquatic life impaired by an unknown pollutant); Big Nemaha River (recreation use impaired by *E. coli* bacteria); and South Fork Little Nemaha River (aquatic life impaired by atrazine). Both the North Fork and South Fork of the Big Nemaha River have been categorized as 4a, meaning they are impaired, but TMDLs have been established. In both cases, the recreational use was impaired by *E. coli* bacteria (Nebraska Department of Environmental Quality, 2018).

Groundwater

In 1974 the U.S. Congress passed the Safe Drinking Water Act (SDWA), which sets national limits on contaminant levels in drinking water to ensure that it is safe for human consumption. This law applies to drinking water sourced by public water systems (not private domestic wells) from both surface water and groundwater, but because about 88% of drinking water in Nebraska is sourced from groundwater, we will discuss this law in the context of groundwater. In Nebraska, the SDWA is administered by the Department of Health and Human Services; some other states assign the same state agency responsibility for both the Clean Water Act and the Safe Drinking Water Act. Federal oversight is provided by EPA. The law requires public water systems to monitor their water for contaminants and report the monitoring results to the state agency (or EPA). Larger water systems must typically sample and report more frequently than smaller systems. Each quarter the results are published in a federal database called the Safe Drinking Water Information System (SDWIS/FED).

The maximum contaminant level for nitrate in drinking water is 10 mg/L, but a public water system testing over 5 mg/L may be required to perform quarterly sampling. In Nebraska 86 of the 552 groundwater-based community water systems must are required to perform quarterly monitoring for nitrate. If a water system exceeds 10 mg/L two times in a rolling 12-month period, an administrative order will be issued, mandating the system to reduce the concentration by taking steps such blending water from different wells, buying water from another water system, drilling a new well, or building a treatment plant. Elevated anthropogenic nitrate concentrations in groundwater have been a recognized problem in the field-trip area and statewide for several decades. In 2001 the Nebraska legislature passed LB329 which directed the Nebraska Department of Environmental Quality to report annual on groundwater quality monitoring in Nebraska and required the NRDs to submit their monitoring data as the basis for the report. The Nebraska Quality-Assessed Agricultural Contaminant database is the central repository for this data, which includes sample results for nitrate and more than 400 pesticides (Nebraska Department of Environmental Quality, undated). The NRDs submitted much of their historical data predating 2001, and the database contains at least 3,000 nitrate results for every year since 1994. The most recent data shows a median nitrate result near 7 mg/L (Nebraska Department of Environmental Quality, 2018). Visually the data appears to have an upward trend, although the potential trend is probably not statistically significant at this time (Nebraska Department of Environmental Quality, 2018). There are limitations to the dataset, which include: samples come from a variety of different aquifers, well types, and screen intervals; the same set of wells are not sampled every year; and areas with high nitrate are preferentially sampled.

In the Nemaha NRD the paleovalley aquifer in the northwestern corner of the county generally has the highest nitrate concentrations (Chen, 1998; Inman, 2002) and 73 mi^2 of that area were designated as a Quality Phase II Management area in 2003. Atrazine was also detected in water samples collected in shallow aquifers, especially in the alluvium of the North Fork of the Big Nemaha River (Tanner and Steele, 1991).

Much of the focus on groundwater quality is on relative shallow groundwater that has generally low dissolved mineral content and is easily (and cheaply) accessible. However, deep groundwater also circulates (just on a much longer time frame), and deep aquifers can have relatively high intergranular and/or fracture porosity and permeability (e.g. the St. Peter Sandstone). The water quality in these deep aquifers can impact their use. Perhaps the most important component of deep water quality is the amount of total dissolved solids (TDS). Concentration ranges of TDS are assigned the terms fresh, brackish, saline, and brine from order of lowest to highest. Seawater has a TDS concentration of 35,000 mg/L; water with concentrations above that limit are considered brine. Limited data available for Pennsylvanian-Permian units in the field-trip area indicate that the TDS varies from 1,340 mg/L (brackish) to 50,700 mg/L (brine) (Carlson et al., 1992). The U.S. Geological Survey views brackish groundwater as an unconventional water source that may be used in place of fresh water in future water-short areas and has mapped brackish groundwater at a national scale (Stanton et al., 2017). Additionally, saline to brackish aquifers are potentially useful injection targets for wastewater and carbon dioxide (e.g. Burrows and Appold, 2015). The Safe Drinking Water Act requires that any aquifer targeted for injection have a TDS concentration of at least 10,000 mg/L to insure that no aquifers that have potential future beneficial use are ruined by contaminant storage.

8. Mineral and Fossil Fuel Resources

Southeastern Nebraska has the greatest variety of mineral and fuel resources in the state. The strictly technical definition of *mineral resources*, which contrasts with the colloquial use of the term, is worthy of explanation. Mineral resources, in the strictly technical sense, are materials in or on Earth's crust from which the economic extraction of a commodity is either currently or potentially feasible (e.g., U. S. Bureau of Mines and U. S. Geological Survey, 1976). In contrast to mineral resources, the extraction of *mineral reserves*, in comparison, is known to be feasible. Thus, reserves can be considered a "surer bet," whereas the viability of the broader and more nebulous category of resources depends, at any given time, on the state of technology and geological knowledge, as well as social, political, legal, economic, and environmental issues. The difference between resources and reserves is worthy of consideration with respect to the Elk Creek carbonatite, which was unknown prior to 1970, and which has been subjected multiple phases of exploration and assessment.

Industrial Minerals

Limestone, sand and gravel, and industrial clays have all been mined in the field-trip area (Fig. 10). There were numerous limestone quarries in the field-trip area during the 19th and 20th centuries, but only two have operated in recent years, one near Pawnee City operated by Hamm Quarries, and another near Dubois operated by Martin Marietta (both in Pawnee County). In Gage County, immediately to the west of the field-trip area, chert and cherty limestone were mined as railroad ballast in the early 20th century (Barbour, 1909), and some of the same strata extend into the field-trip area. Brick and tile manufacturing from local materials (loess, glacial sediments, and Pennsylvanian shales) was still a prominent industry in the field-trip area during the early 20th century. Barbour (1917) reported one active brick and/or tile plant each in the cities of Auburn (Nemaha County), Humboldt (Richardson County), and Table Rock (Pawnee County), as well as two active brick operations in Nebraska City (Otoe County). In contrast, there are but two, large brick and tile manufacturers in all of Nebraska in 2019, both outside of the field-trip area, and both using materials mined from the Cretaceous Dakota Formation. The production of building, sidewalk, and paving bricks at Table Rock began in the 1880s and continued to 1931 (Table Rock Historical Society, undated). The raw material for these products was shales in the Wabaunsee Group (Pennsylvanian), and probably the Scranton Formation in particular. Shales in the Langdon Formation of the Wabaunsee Group (Pennsylvanian) were probably the source of raw materials for brickmaking at Humboldt. Western Brick and Supply in Nebraska City was still mining shales in the Willard and Langdon Formations of the Wabaunsee Group and producing brick and tile (and eventually lightweight aggregate as well) in 1967 (Burchett and Reed, 1967), but their operations ceased long ago. Nevertheless, Pennsylvanian shales probably remain a viable potential source of industrial clays in the field-trip area.

Metals and Rare Earth Elements

The Elk Creek carbonatite, which underlies an area straddling the line between Johnson and Pawnee Counties (Fig. 10), contains a world-renowned deposit of the critical metal niobium and the rare-earth elements (REEs). Discovered through geomagnetic surveys around 1970, the Elk Creek carbonatite attracted considerable interest and exploration in the first half of the 1980s and again in the since 2000.

Niobium and REEs are important mineral commodities that must be understood in terms of their value to modern civilization and their global economics. Niobium is an important alloying element in steels (ferroniobium), conferring strength and heat-resistance (e.g., in parts of jet and rocket engines). Rare-earth elements (REEs), on the other hand, are a group of 17 elements on the periodic table that have similar chemical properties. In total, the REEs have important applications in certain alloys, television phosphors, superconductors, advanced ceramics, special glasses, chemical catalysts, magnets, enamels, lasers, capacitors, batteries, luminous paints, nuclear reactors, and yet other manufactured items. Niobium has been the focus of interest with respect to the Elk Creek carbonatite for more than a decade. Brazil was responsible for no less than 88% of global niobium production in 2017 and Canada was a distant second-largest producer at 10% (U. S. Geological Survey, undated). Currently, the USA does not produce niobium and, therefore, if the Elk Creek deposit is to be developed, Nebraska will have the only niobium mine in the nation. China has been the world's largest producer of REEs for some time, and when the USA began producing REEs again in 2018, American output was estimated to be slightly more than one-tenth of Chinese production and a small part of national demand; accordingly, the USA was estimated to have imported $160 million in rare-earth compounds and metals in 2018 (U. S. Geological Survey, 2019).

Carbonatites—the type of rock that hosts the Elk Creek deposit—are a special and comparatively rare type of igneous rocks that are made up chiefly of carbonate minerals rather than the silicate minerals that make up the vastly overwhelming volume of igneous rocks in earth's crust. The Elk Creek carbonatite is a magnetite (Fe_3O_4) dolomite ($CaMg[CO_3]_2$) carbonatite, so named because those minerals are the dominant components of the rock overall.

Fossil Fuels

Interest in finding and exploiting coal in southeastern Nebraska began at least as early as 1856 and there were attempts at mining thin seams of coal through the remainder of the 19th century at sites near Nebraska City (Otoe County), Aspinwall (Nemaha County), Tecumseh (Johnson County), and perhaps elsewhere (Burchett, 1977). Burchett (1977) identified eight separate coals in the Wabaunsee Group (Pennsylvanian) in southeastern Nebraska). The only economically viable coal mine ever to have existed in Nebraska was the Honey Creek Coal Mine (Fig. 10), located southeast of Peru (Nemaha County), which opened in 1906 and operated for a few years thereafter (Barbour, 1907). Barbour (1907) reported that the maximum thickness of the mined seam was 0.89 m (2.9 ft)

Petroleum exploration and development in the Forest City Basin overall is ongoing and it has a history extending over more than a century and a half. According to Charpentier (1995), the first oil exploration in the basin was in 1860 in Miami County, Kansas. Interest in oil in Nebraska developed later, and it gradually became apparent that geologic conditions would always limit the geographic extent and volume of oil production in the southeastern corner of the state. Oil was reported near Salem (Richardson County) as early as 1883 (Schottenhamel, 1979), although there is no way to know the exact nature of its occurrence there. If that account is true, perhaps oil had migrated upward along faults to the surface, knowing that the area is distinguished by the presence of geologic structure overall and in view of documented cases of such phenomena elsewhere in the world, but this suggestion is utter speculation. It is certain that the first true “oil boom” in southeastern Nebraska did not occur until 1938–1942 (actual oil production began late in 1939), although interest in potential oil and gas leases in Richardson County developed at least as early as 1914 (Schottenhamel, 1979).

Even though a number of wells were drilled over the years in Otoe (19), Johnson (22), Pawnee (32), and Nemaha (55) Counties, without success in terms of oil production, many more (748, although the majority of these wells also never produced oil) have been drilled in Richardson County. Not surprisingly, all of the oil production from the Forest City Basin in the state—and, indeed, from all of southeastern Nebraska—is from Richardson County alone, and then from a rather small number of producing wells. The Nebraska Oil and Gas Conservation Commission recognizes eight oil fields in the county: Barada, Barada SW, Dawson, Falls City, Honey Creek, Shubert, Shubert West, and Snethen (Fig. 11). Four well permits were issued in Richardson County between January and mid-September of 2019 alone and a new well was spudded in at least as recently as October 2017. Petroleum production from Richardson County declined from 278,680 bbl in 1952 to 14,013 bbl in 1998, then it increased again from 2010 to a recent peak in production of 92,976 bbl in 2015 (Fig. 12).

By far, most of the oil that has even been produced in the Forest City Basin in Nebraska has come from the buried succession of ancient marine sedimentary rocks typically identified as the “Hunton Group,” “Hunton Formation,” or simply “Hunton” in older oil-well logs and reports (Fig. 13). Smaller amounts of oil have come from the underlying, older (Ordovician) strata that are sometimes identified in logs as the “Viola Limestone”, or merely “Viola,” and as the “Simpson Group” in older well logs (Condra and Reed, 1959, p. 70). The application of these and other unit names in the subsurface of the Forest City Basin is highly problematic and stems from the uncritical misapplication of rock unit names from one state (chiefly Oklahoma) to another.

The name Hunton Limestone was first given to certain Silurian and Devonian strata in the southeastern part of the former Indian Territory, now the state of Oklahoma, in the very early 20th century (Taff, 1902). The name "Hunton," which was first used in oil-rich Oklahoma, came to be applied over a very large, multistate area in the interior of the USA (U.S. Geological Survey, undated) as petroleum production spread. Eventually, the name "Hunton" was chiefly applied to an interval of dolostone-rich Middle and Upper Devonian strata that are equivalent to the Wapsipinicon and Cedar Valley Groups and the Lime Creek Formation, which crop out in eastern Iowa (Condra and Reed, 1959, p. 63; Bunker et al., 1988, fig. 1; Lindberg, 1987). This dolostone interval, together with any underlying Silurian carbonate sedimentary rocks in the Forest City Basin, comprise a stratigraphic interval that is easily recognizable in wells because it lies between two thick shale-rich stratigraphic intervals (Fig. 13).

The very widespread shale frequently named as the "Chattanooga Shale" in older well logs overlies the so-called "Hunton Group" in the Forest City Basin (Fig. 13). It is the upper shale-rich stratigraphic interval mentioned in the preceding paragraph. Nevertheless, the Chattanooga Shale (Upper Devonian), in the truest sense, is recognized over parts of the interior USA that lie well east of the Forest City Basin. The name is inapplicable in the Forest City basin, therefore, and the interval referred to by it appears to be equivalent to other Upper Devonian strata ("Maple Mill") in Iowa (Lindberg, 1987; Bunker et al., 1988, fig. 1; Fig. 13). Below the so-called "Hunton" and undifferentiated Silurian strata in the Forest City Basin is the lower of the two aforementioned shale-rich stratigraphic intervals, the Maquoketa Formation (Upper Ordovician), which was first recognized in outcrops in northeastern Iowa. Fortunately, the usage of that name in the Forest City Basin is defensible (Lindberg, 1987; Bunker et al., 1988, fig. 1; Fig. 13). Below the Maquoketa Formation, the interval called "Viola" in some petroleum well logs is actually the Galena Group (Middle and Upper Ordovician) and the even deeper interval referred to as "Simpson" in some logs is the Saint Peter

Sandstone and overlying Platteville Formation (Middle Ordovician), which crop out in the upper Mississippi Valley, but which can still be correlated into Nebraska (Fig. 13).

The preceding discussion demonstrates that the widespread and casual application of particular names to units of sedimentary rock in the subsurface has created persistent problems in an area like the Forest City Basin. Strata that are buried in a given area cannot be studied in detail at Earth's surface in that area. Rather, exposures of such units, or their equivalents, may be hundreds of kilometers away in areas with somewhat different geologic histories. Furthermore, it is frequently the case that old, deeply-buried sedimentary successions in a given area have yet to be studied in detail using modern stratigraphic methods and applying up-to-date philosophies. Unfortunately, it is now a matter of conjecture whether they will ever be studied in such a manner. With respect to the subsurface sedimentary rock strata of eastern Nebraska, we credit Condra and Reed (1959, p. 63) for realizing that it was better to make comparisons with, and extend terminology from outcrops in eastern Iowa, rather than employing other approaches such as importing terminology from the quite different geologic setting of Oklahoma.

A comparison of Richardson County with western Nebraska, another part of the state that still produces oil, may be useful: interest in oil production there too began in the late 1880s, but it did not lead to a successful well until 1949, a decade later than the first well in Richardson County. The amount of oil produced in western Nebraska, however, has far exceeded production in the northern Forest City Basin in Richardson County.

It is also curious that the greatest yearly amount of *produced water* (water and brine that is pumped out of the ground in the process of extracting oil and gas) from oil wells in Richardson County since 1952 was attained very recently, in 2018 (12,908,110 bbl). The volume of produced water pumped from any give oil field in the world can be a few to a few tens of times the volume of oil that is pumped. Produced water typically has a complex chemical composition, typically contains some oil and other organic compounds, higher salinity values than surface water, and high concentrations of dissolved solids. Because of these characteristics it has little or no economic value relative to petroleum and it must be treated—potentially, by numerous different methods—and reused or disposed of by acceptable means, such as deep underground injection. Produced water can be recycled or reused after treatment under particular circumstances with respect to water quality and regulations. Some applications include the washing of equipment and vehicles and dust suppression on- or near-site, and even irrigation and stock water if treatment is proper and if the total dissolved solids content of the treated water is low enough. Perhaps most importantly, produced water can be used to get additional oil out of mature oil fields (enhanced oil recovery or EOR). *Waterflooding* is the injection of produced water into an oil reservoir in a mature oil field for the purposes of EOR. The practices of *horizontal drilling* and *hydraulic fracturing* ("fracking") tend to generate more produced water than vertical drilling. A significant part of the economics of petroleum production lies in assessing, minimizing, and planning for the costs of dealing with produced water.

9. Field Trip Stops

9.1. STOP 1: Hydrology and hydrogeology of vicinity of South Fork of Nemaha River, including aspects of surface water connections to groundwater and paleovalley aquifer. Stop at bridge on 737 Rd approximately 1.25 mi east of intersection with 622 Rd (40°30'31.07"N, 96°08'16.02"W).

This stop is a location where the South Fork of the Little Nemaha River crosses the eastern end of the Dorchester-Sterling paleovalley. In 1980 a study measured pressure heads (the elevation of the potentiometric surface) in the paleovalley aquifer in this vicinity at about 12 m (40 ft) above the river bed during the non-irrigation season and 1.5 m (5 ft) above the riverbed during the irrigation season

(Folkman, 1980). The paleovalley aquifer was pressurized because the sand and gravel is overlain by a confining unit of clay and silt and water conserves its potential (elevation) energy when it recharges to a confined aquifer. Where wells are installed in a confined aquifer, the pressure pushes the water up the well to an altitude similar to that of the recharge area (assuming pumping has not significantly reduced the pressure in the aquifer) (Fig. 14). The highest pressure head measured by Folkman (1980) where the riverbed crosses the paleovalley aquifer was about 338 m (1,110 ft), who also documented five flowing wells in the vicinity of Cook.

The South Fork of the Little Nemaha River is interesting because there are gaps in the confining unit through which groundwater water from the paleovalley aquifer discharges via seeps and springs. Folkman (1980) discovered seven springs either directly in the riverbed or along its banks at low stage. The discharge from one spring located in the immediate vicinity of this stop (section 1 of T. 6 N., R. 11 E., CDCC) varied from 25 gpm in July to 80 gpm in early September 1980. It is possible to wade into a spring when it occurs in the sandy river bed, but the submerged springs can be difficult to locate due to changes in discharge and the migrating river bed.

Identifying recharge areas of confined aquifers is difficult because groundwater flow paths are complex and water of different ages from different recharge areas mix within an aquifer. Given this observation, it is worth speculating about potential recharge areas in an effort to better understand the scale of the groundwater system (how distant the recharge areas may be), how variable the recharge volume may be, and how vulnerable the supply is to contamination (e.g. land use in possible recharge areas). Because Folkman measured a maximum pressure head of about 338 m (1,110 ft) in the vicinity of Cook, the water table elevation of the recharge area must also be at least that high and there should be hydraulic connection between surface water/precipitation and the sand and gravel unit serving as the aquifer within the paleovalley. The most difficult element of this analysis is the hydraulic connection between the source of the recharge water (stream or precipitation) and the aquifer. Normally the drilling of test holes is required to assess subsurface geology, but in this case there is a resistivity profile (Fig. 15) (Aqua Geo Frameworks, 2019). This profile was collected as part of the Eastern Nebraska Water Resources Assessment (ENWRA), which will be discussed in more detail at the next stop. The first important feature of this figure is near Easting 2680000 where the water table plots at about 1,100 ft and shallow sand and gravel (bright pink in color) is continuous with deeper sand and gravel that extends to approximately Easting 2710000. The sand and gravel increases in clay content with depth and laterally toward the riverbed, and it is possible to see how water may have recharged the aquifer at a higher elevation, become confined as it moved through the aquifer, and then discharged at the river.

A prior ENWRA survey in Lancaster County found another likely connection between surface water and the paleovalley aquifer (Divine and Korus, 2012), suggesting the paleovalley is recharged at multiple locations. Folkman (1980) suggested that even though the South Fork of the Little Nemaha River near Cook gained groundwater overall from the aquifer, certain reaches of the river may lose water to the aquifer. This variability in gaining and losing between reaches and with changing hydrologic conditions is not uncommon for other rivers and streams in Nebraska.

9.2. STOP 2: Summary of recent work performed by the Eastern Nebraska Water Resources Assessment (ENWRA). Tecumseh, Nebraska city park (40°22'0.56"N, 96°11'19.94"W).

At the last stop we starting discussing the Eastern Nebraska Water Resources Assessment (ENWRA). This project is a cooperative effort between 10 local, state, and federal agencies with a common goal to better understand and manage groundwater and hydrologically connected surface water in the glaciated part of the state. ENWRA is sponsored through various state grants, cooperative federal funds, and annual funding from six eastern Nebraska Natural Resources Districts (NRDs). The partner and advisory agencies of ENWRA include: Nebraska Geological Survey (Conservation and Survey Division), Nebraska Department of Natural Resources (NeDNR), Nebraska Department of Environment and Energy (NeDEE), the U.S. Geological Survey (USGS), and the Water Science Center (WSC) in Lincoln, Nebraska.

At the project inception, the ENWRA team decided on a pilot study approach in which various technologies (including airborne geophysics) were applied to three distinct glacial terrain study sites to determine the most efficient way to characterize the heterogeneous nature of aquifers and connected surface waters (e.g. Divine et al., 2009). Through the initial pilot work and subsequent assessment activities, airborne electromagnetic (AEM) survey has become a useful method to characterize the subsurface in eastern Nebraska over the past 13 years. AEM survey projects now cover 90% of eastern Nebraska and total over 24,000-line km (15,000 mi). During a survey, geophysical data of the subsurface is collected every 3 m (10 ft) along the flight lines. The data are processed and summarized into points of subsurface information spaced every 15 to 45 m (50 to 150 ft) and used to generate subsurface profiles of electrical resistivity along each flight path. These profiles can be combined to form three-dimensional images of the subsurface.

In addition to the geophysical surveys, ENWRA has prioritized test hole drilling to collect detailed lithologic and stratigraphic information, as well as down-hole geophysical data. Information obtained from test holes is used to optimize the location and screen intervals of monitoring wells and to compliment airborne geophysical data. Although many boreholes have been drilled in eastern Nebraska, the average linear spacing of the borehole information is often inadequate to characterize hydrostratigraphy due to the rapidly changing ground elevation lithology from one hole to the next. The AEM surveys provide a “picture” of conditions between boreholes to better understand aquifer boundaries and surface water/aquifer interconnections. AEM surveys may identify where:

- aquifer material is plentiful versus more limited;
- groundwater recharge areas are likely;
- buried aquifers are in contact with alluvial aquifers and/or surface water; and
- deeper, previously unknown aquifer resources potentially exist.

Although imaging confidence generally decreases with depth, depths of investigation can reach up to 490 m (1,600 ft) below ground depending on the AEM system's configuration. However, clay-rich (conductive) materials like thick glacial tills or shales will mask the resolution of deeper materials, as will saline groundwater. The average depth of investigation was over 137 m (450 ft) for the Nemaha flights discussed below.

The two AEM surveys recently conducted in the Nemaha NRD were conducted as follows: 1) a general north-south and east-west oriented grid in the central portion of the district covering about 830 km^2 (320 mi^2) with approximate flight line spacing of 1.6 km (1 mi); and 2) a block flight covering 36 km^2 (14 mi^2) with line spacing of approximately 300 m (990 ft).The grid flights targeted areas east of Sterling, Nebraska generally associated with the Dorchester-Sterling paleovalley and its erosional/depositional margins, as well as areas generally south and east of Tecumseh where hydraulic connection between aquifer units is uncertain. The more tightly-spaced block flight targeted the Shubert, Nebraska area (Fig. 16). Fourteen test holes were subsequently advanced along the grid flight lines and provided localized subsurface detail and additional control on both individual aquifer units and the bedrock surface. The recent test holes were completed as monitoring wells for the Nemaha NRD, one of which now monitors the same unit that supplies a Johnson County Rural Water District well.

9.3. STOP 3: Small exposure of Admire Group (Pennsylvanian) strata, presumed to be Janesville Shale, at electrical substation 0.8 mi east of town on north side of NE Hwy 4, on the upthrown western side of the Humboldt Fault (40°10'28.10"N, 95°55'34.74"W).

This stop presents a very small outcrop with a very large story. The outcropping limestone and underlying shale at the site are probably part of the Janesville Shale (Fig. 4), a formation within the Admire Group, which was formerly considered to be Permian, but which fell within the Pennsylvanian once the Pennsylvanian–Permian boundary was shifted upward in the composite regional stratigraphic section by Sawin et al. (2006). Strata of irrefutable Permian age (e.g., the prominent Cottonwood Limestone Member of the Beattie Limestone in the Council Grove Group), which are much higher in the composite regional stratigraphic section, crop out at roughly the same elevation less than 0.8 km (0.5 mi) to the east-northeast of this small exposure. Thus, there is evidence that geologic structure exists in the immediate area, namely the extensive Humboldt Fault or Humboldt Fault Zone, which marks the western boundary of the Forest City Basin (Fig. 2) (Fig. 6). Note that the term *fault zone* refers to a group of closely-spaced major and subordinate faults that form a clear spatial trend, whereas the term *fault* implies but a single fault and, thus, the difference between the two terms is substantive. Note further that there is no *fault scarp* (offset of the ground surface directly associated with movement along a fault that extends to the surface) visible in the vicinity of the stop. Consider why this may be the case: the time expired since last movement, the net effect of erosion (by running water and even by the multiple glacial advances during the Pleistocene), and burial by surficial sediments should be

The past movement of Upper Pennsylvanian and Lower Permian strata in the area of this stop is direct evidence for the reactivation of geologic structure after the main phase of uplift of the Nemaha Uplift. Steeples (1982, 1989), in characterizing seismic profiles across the Forest City Basin and Nemaha Uplift in Nemaha County Kansas, observed that Pennsylvanian strata were “draped over the edge of the Nemaha Ridge [Nemaha Uplift]" (Fig. 6). This point is worthy of further consideration because Nebraska geologists such as R. R. Burchett (1935-2015), the Conservation and Survey Division geologist who mapped much of eastern Nebraska, commonly referred to the Humboldt Fault and some other faults in Nebraska as zones of "faulting or steep dip" because: (1) the data available to him—outcrops and well logs, but no seismic profiles—did not allow him to differentiate between the two potential conditions; and (2) there is almost no evidence at all for fault movement in bedrock outcrops in southeastern Nebraska (e.g., Burchett and Arrigo, 1978). Even with seismic profiles, Steeples (1982, 1989) essentially concurred that Pennsylvanian strata extending across the uplift appeared more to dip than to have major offsets from through-going faults. Of course, pre-Pennsylvanian strata alongside the eastern edge of the Nemaha Uplift are abruptly truncated against the uplift because of the sizeable offset created during the main phase of uplift.

An unpublished work map of the Humboldt area by R. R. Burchett (Fig. 17) indicates essentially flat-lying rock strata at Humboldt, but eastward dips of 2–3º on strata immediately east of Stop 4, and eastward dips of as much as 14º at a point northeast of this stop. Burchett's work map also shows the inferred position of the Humboldt fault lying within 0.4 km (0.25 mi) east of Stop 3. Thus, Stop 3 lies on the upthrown (higher) western side of the Humboldt Fault very close to the fault. Deciphering Burchett's abbreviated notations on his map, it appears that he estimated at least 63 m (200 ft) of displacement in Upper Pennsylvanian and Lower Permian strata in this area, that is, the equivalent of approximately half the height of the Nebraska State Capitol in Lincoln, and possibly even more. Consider how much careful work is required to correlate and actually apply a name to the thin, and admittedly nondescript, interval of limestone and shale at this stop, especially in an area with significant geology structure but few outcrops. Also, consider how much more work will be needed to improve our understanding of geologic structure in southeastern Nebraska.

The strata at this stop also have some minor significance in terms of understanding groundwater. Seasonally, at least, there is a seep line at the contact between the shale (below) and the limestone (above) units visible at the stop. The limestone has secondary porosity in the form of *joints* (fractures without offsets), but the shale functions as an aquitard. Thus, water percolating through the overlying soil and weathered bedrock is transmitted through the joints in the limestone and then laterally across the top of the shale to discharge along the artificial slope of the roadcut.

9.4. STOP 4: Road cut on both sides of 706 Road exposing Roca Shale and Grenola Limestone (Council Grove Group; Permian), 1.2 mi south of Salem, Nebraska (40°03'30.75"N, 95°42'53.38"W).

This road cut is one of exceedingly few places in all of Nebraska where one can see actual geologic structures without having them explained in the lengthy and somewhat abstract matter required to make sense of Stop 3. *Open folds*—folds exhibiting a separation of between 90° and 170° between their two limbs or sides—are visible here. The shallow-marine sedimentary rock strata that we see at this site could only have been deformed after the main phase of uplift of the Nemaha Uplift because the rocks are younger than that phase and because they once continued westward over the crest of the uplift, from which they have since been eroded. We cannot ascertain whether the deformation of strata visible at the stop occurred yet during the Permian Period or much later during reactivation associated with the distant Laramide Orogeny. Burchett and Arrigo (1978) identified gentle anticlines in the Tarkio Limestone Member of the Zeandale Limestone (Wabaunsee Group; Pennsylvanian) in southeastern Nebraska, which constitute additional evidence for the post-Pennsylvanian deformation of bedrock in the field-trip area.

The Roca Shale and Grenola Limestone (Council Grove Group; Permian) (Fig. 4) are important from a hydrogeological perspective because the bedrock wells in the vicinity of Dawson (central

Richardson County) are likely screened across these formations, in addition to the Red Eagle, Johnson, and Foraker Formations, which are also in Council Grove Group.

9.5. STOP 5: Point for overview of: (a) Missouri and Big Nemaha Rivers and floodplains, and (b) exposure of White Cloud Sandstone (ancient river/estuary deposit) on east bank of Big Nemaha River. Stop will be on the west side of the bridge over the Big Nemaha River on 703 Lane (40°01'30"N, 95°23'4.84"W).

Two modern rivers and the probable deposits of one ancient river or *estuary* (river mouth along a coastline) are visible at this site. The approximately 300 million-year-old deposits—which have yet to be studied in detail—are sandstones and shales in the White Cloud Shale Member in the lower part of the Scranton Formation or Scranton Shale (Wabaunsee Group; Pennsylvanian). Condra (1927) first named this unit, which, technically, retains formation status in Nebraska (Condra and Reed, 1959) in the absence of a modern revision of stratigraphy there. The White Cloud Shale is considered a member of the Scranton Shale in Kansas (Kansas Geological Survey, undated), and we employ that classification herein. The outcrops of sandstone in the White Cloud Shale Member along the south bank of the Big Nemaha River are large and of good quality by regional standards, and they have attracted the attention of geologists for many decades. Hopefully, they will be studied in detail in the near future.

A livestock well more than 50 km (30 mi) away on the west side of the Humboldt Fault Zone appears to draw water from the White Cloud Shale, and also possibly the Cedar Vale Member of the Scranton Shale and the Burlingame Member of the Bern Formation (all of which are parts of the Wabaunsee Group). The registered well log for this well (Well ID 89143) is detailed and shows thin alternating layers of limestone (brown, then gray) and shale (olive, red, yellowish brown, and gray). One six-foot-thick gypsum unit was noted, but no sandstone, further suggesting that the sandstone viewed at this location is restricted to certain locales, and perhaps to the sedimentary fills of incised valleys or channels.

The explorers Lewis and Clark passed the mouth of the Big Nemaha on July 11, 1804 and Clark's journal makes note of a "Sand Island" opposite the mouth of the Big Nemaha River, which he estimated to be 80 yards (73 m) wide at its mouth; he also noted that prairies began to be prominent in the area (University of Nebraska-Lincoln, undated). The river, which has been extensively engineered, is approximately 60 m in width at its mouth. Historical flood crests occurred on the river at the Falls City, Nebraska gaging station in the following years, in decreasing order of magnitude: October 1973, July 1993, June 1965, June 1949, and July1958 (National Weather Service, undated). Historical flood crests on the Missouri River at Rulo occurred in March 2019 (28.13 ft or 8.57 m), June 2011, June 2010, April 1952, and July 1993 (National Weather Service, undated). Monthly discharge, however, clearly peaked in 2011 (Fig. 18). The floods of 1993 and 2011 remain prominent in the memories of many Nebraskans (as well as other Midwesterners), but the all-time high crest of the Missouri River at Rulo on March 20, 2019 is noteworthy because of its recent occurrence and by virtue continued high water thereafter. The March 2019 flooding on the river was set up by record snowfall in Nebraska, rapid warming and melting in the first half of the month, followed by rain and rapid runoff over still-frozen ground. Three phases of flooding on the Missouri River occurred between March and September of 2019. Flood stage was exceeded from late September into the third week of October 2019. Also, at the time of the completion of this field guide in October 2019, the effects of springtime flooding during 2019 were still widely visible on the river bottom in the vicinity of Stop 5, and they probably will be for some time thereafter.

After Stop 5 and while continuing southeastward to White Cloud Casino via 703 Trail or Kansas Highway 7 and 330 Road, several small, recent landslides on the White Cloud Shale are visible. These features appear to be *translational landslides* (landslides with a planar, rather than curved, plane of failure) that involved the failure and downslope movement of a thin layer of soil or slightly weathered shale resulting saturation brought on by heavy snow and rain during 2019. They were not apparent in immediately preceding years. These landslides, although they are small, illustrate how less than one year's change in weather conditions can have significant local impacts. It is important to ponder the potential costs of remediation (clearing the debris from slides from the road and roadside), and perhaps road repairs as well, that might be ensue even for a small stretch of local roadways. Consider thereafter the costs of more several weather, more frequent events, and the further potential of escalating infrastructure-maintenance costs.

One might think that given the volume of surface water so apparent in this area, public supply would not present any problems. Unfortunately, that is not necessarily the case. In Atchison and Holt Counties (the two Missouri counties that are across the river from Nemaha and Richardson counties, respectively) there are 12 public water systems total, none of which use surface water, and only one of which uses groundwater under the influence of surface water that it purchases. Five systems (each serving an average population of 530) pump their own groundwater, and six purchase groundwater. In Nebraska, Auburn uses groundwater under the influence of surface water in addition to the groundwater that they pump, and Brownville purchases groundwater. Falls City, Rulo, and Salem also purchase groundwater, although Falls City also pumps some groundwater. The remaining 12 public water systems in Nemaha and Richardson Counties in Nebraska all supply their own groundwater. (U.S. Environmental Protection Agency, undated).

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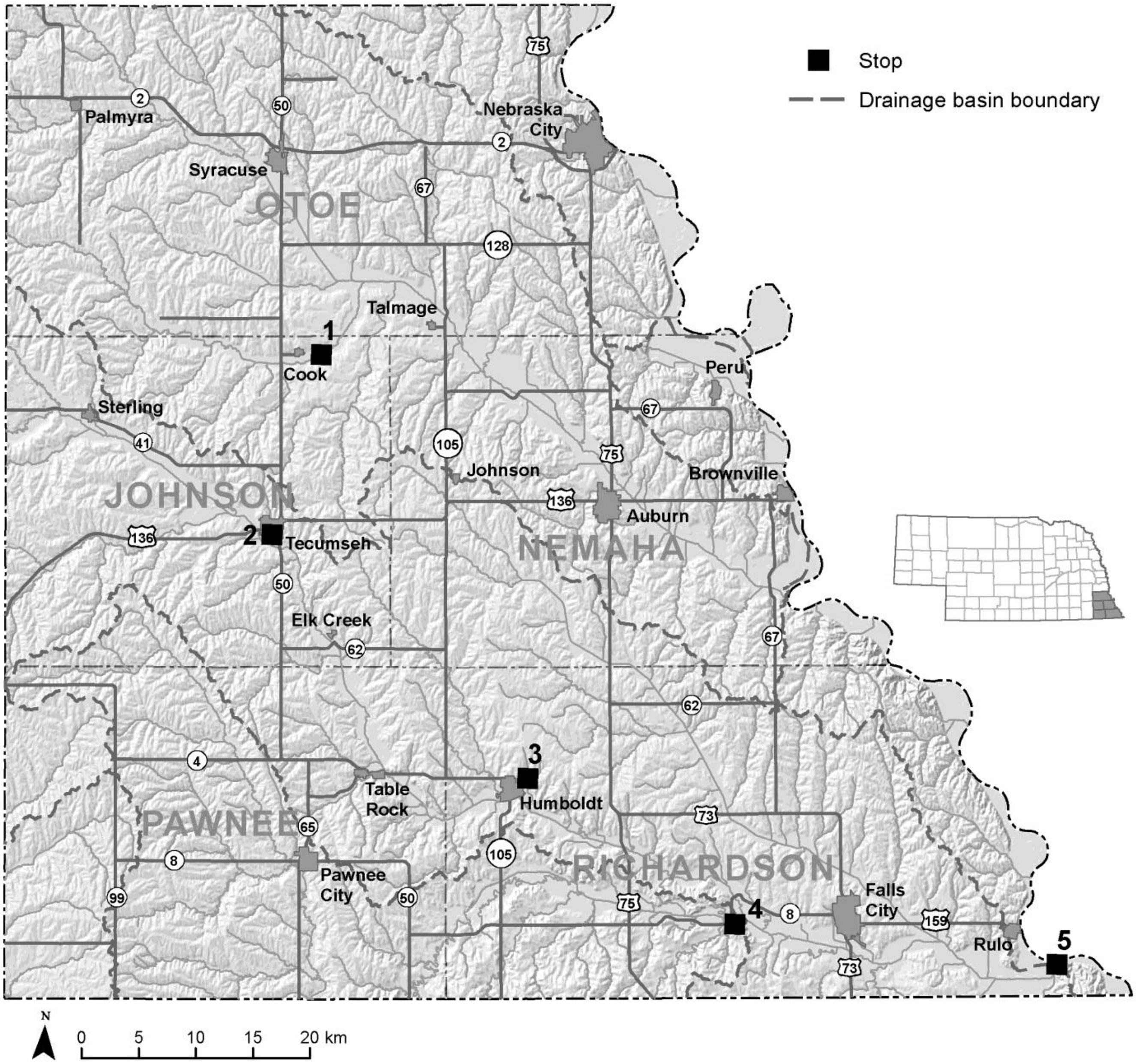


Fig. 1. Shaded-relief map of the field-trip area with numbered stops. Outlines of drainage basins are dashed. Structural features shown in Figure 2 are buried and have no clear influence on land-surface topography.

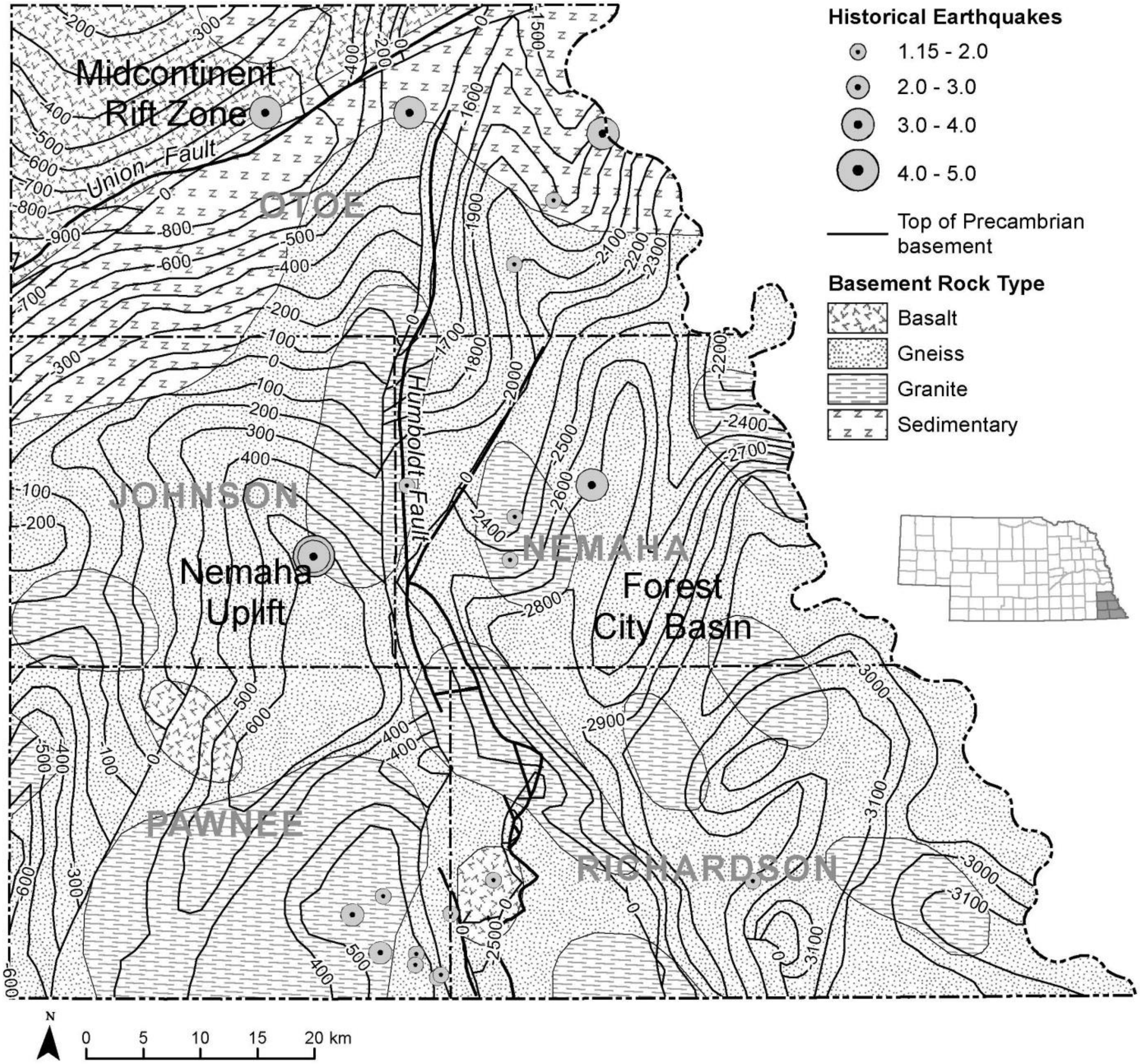


Fig. 2. Bedrock geologic map of Precambrian basement rock in the field-trip area. Values are in feet above or below mean sea level (contour interval: 100 ft). Earthquake magnitudes are relative to the Richter scale. Features shown as faults may be faults *per se*, zones of steep dip, or both.

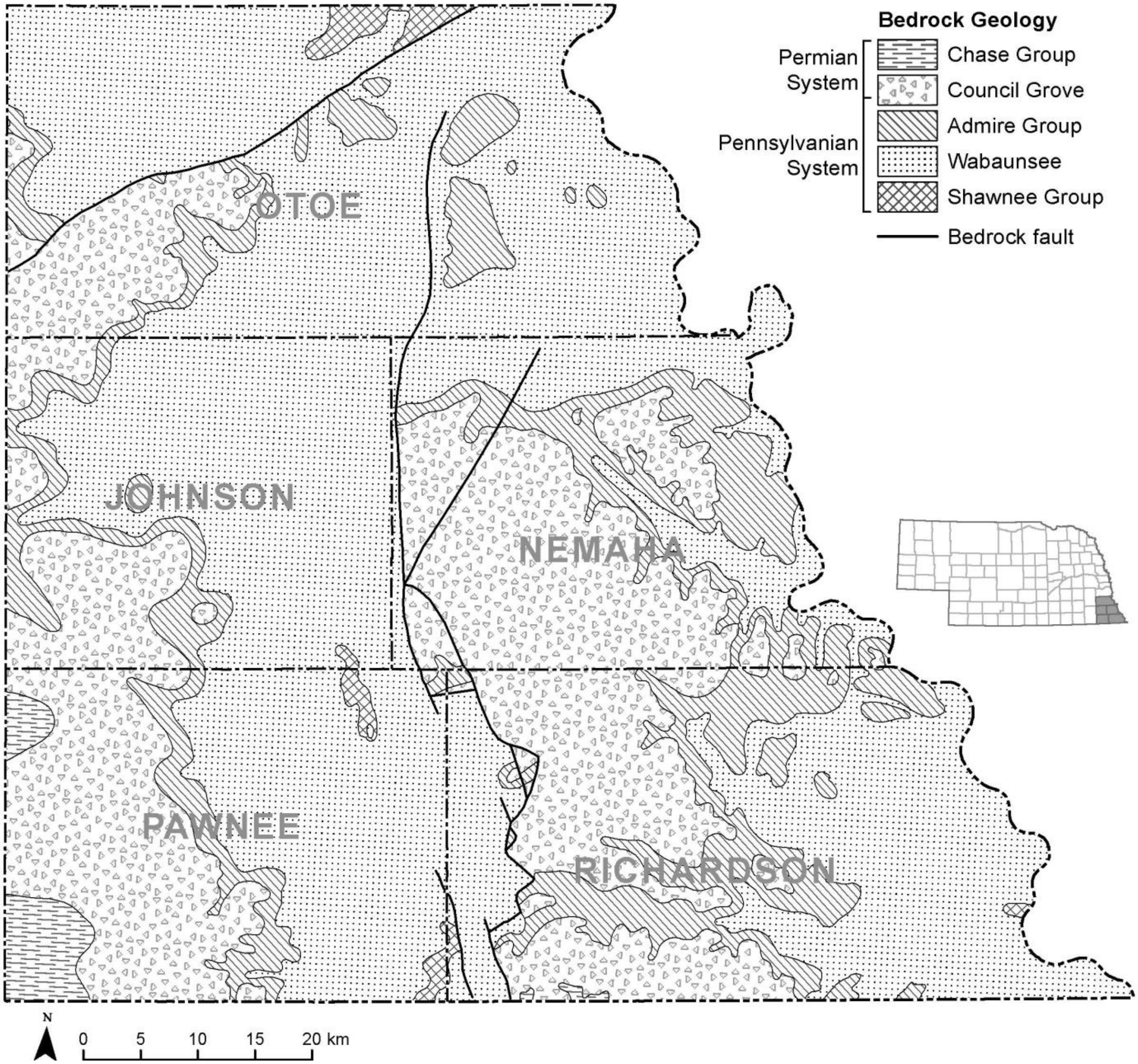


Fig. 3. Bedrock geologic map of the field-trip area. The Pennsylvanian-Permian boundary is in the Council Grove Group. Bedrock faults shown are the Humboldt Fault. Features shown as faults may be faults *per se*, zones of steep dip, or both (see Fig. 2). Note that faults strongly influence the distribution of bedrock strata in western Richardson and Nemaha Counties.

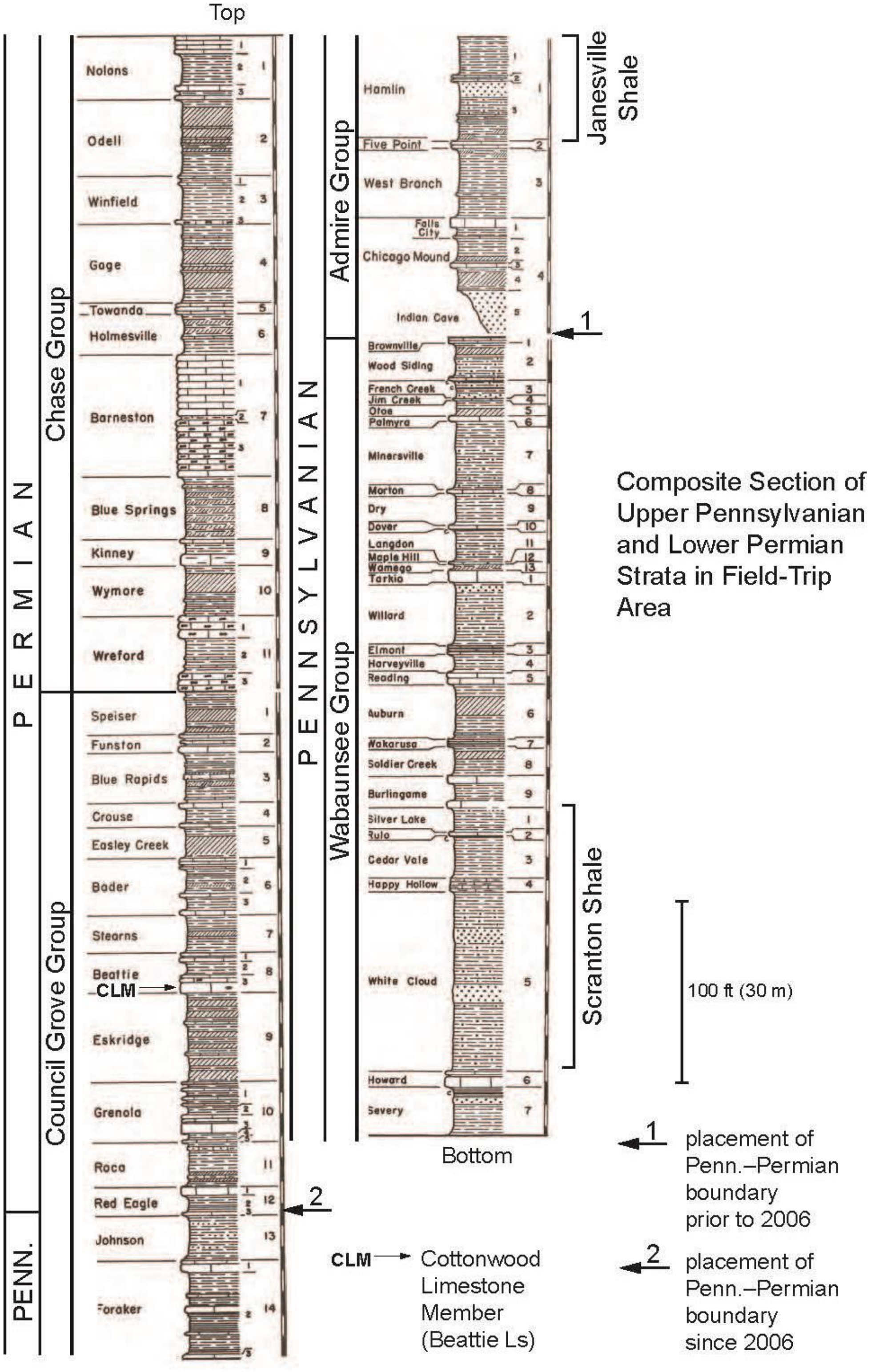
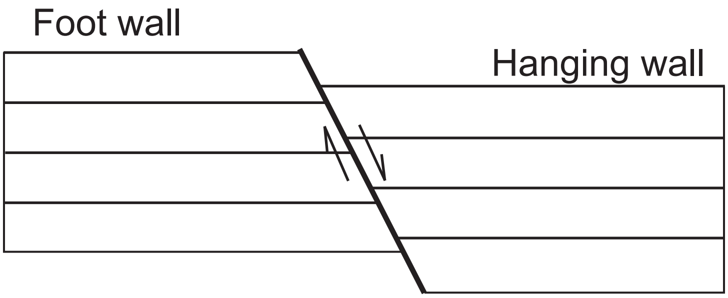


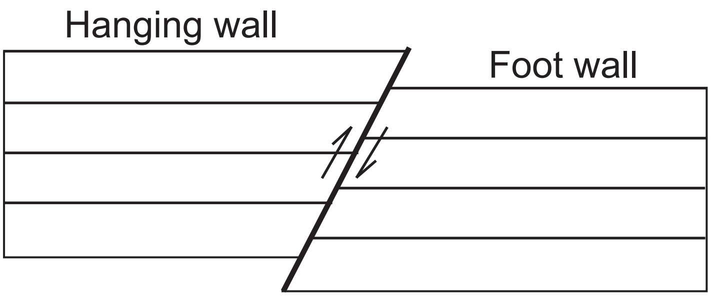
Fig 4. Composite section of the Pennsylvanian and Permian Systems in the field-trip area, modified from figures in Condra and Reed (1959). Note upward movement of Pennsylvanian─Permian boundary.

NORMAL fault



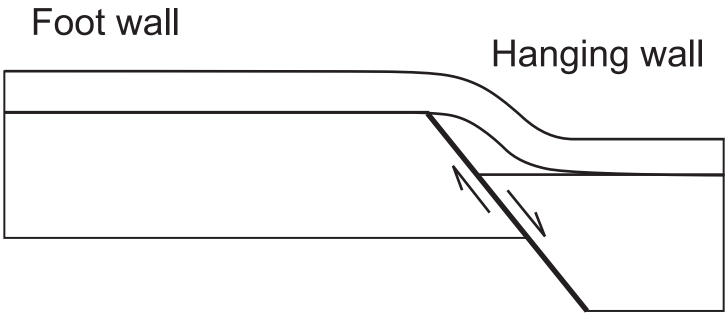
Results from EXTENSIONAL stress
Hanging wall moves DOWN

REVERSE fault



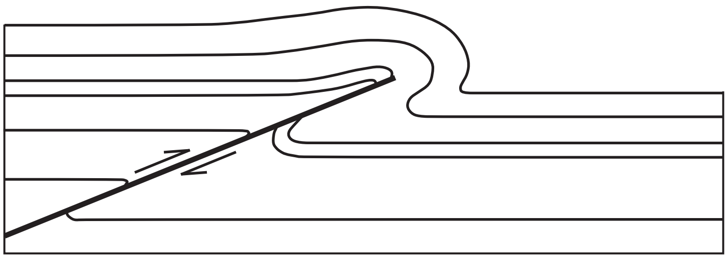
Results from COMPRESSIONAL stress
Hanging wall moves UP

DRAPE FOLD over a normal fault



A stratum overlying a normal fault (which!lies at depth) are deformed so as to appear draped over that fault

BLIND thrust fault
(thrust fault = low-angle reverse fault)



A fault does not extend to land surface, but!strata overlying it are deformed by it

Fig. 5. Diagrams illustrating selected types of faults and folds. The main phase of movement of the Nemaha Uplift involved very high-angle reverse faulting, but Pennsylvanian strata, deposited after that main phase, appear to be draped over the uplift at coarse scales of observation (e.g., seismic surveys).

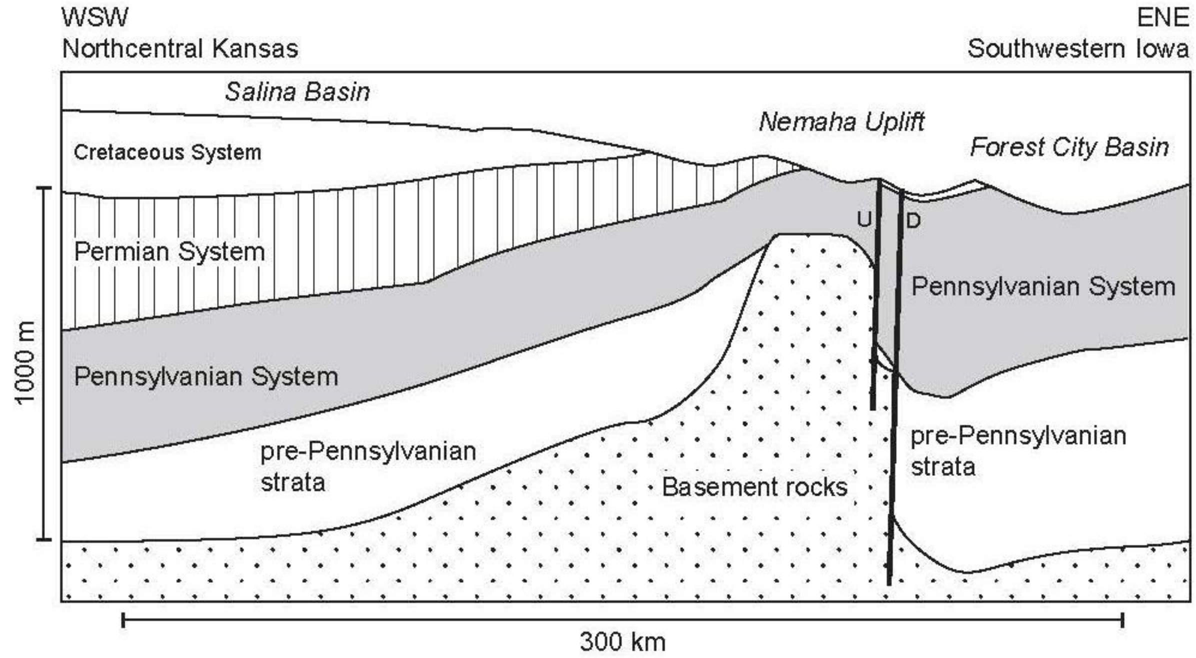


Fig. 6. Simplified cross section of Nemaha Uplift immediately south of field-trip area after Steeples (1982, 1989). Note that cratonic sag basins (Salina and Forest City) exist on either side of the basement uplift. Unlike the Salina Basin, the Forest City Basin is clearly fault-bounded on its western side. Permian strata have been eroded off the crest of the uplift. See Figure 3 to understand how fault movement along the eastern flank of the Nemaha Uplift affects the distribution of Upper Pennsylvanian and Lower Permian bedrock in the field-trip area. Structural features are buried and have no clear influence on land-surface topography.

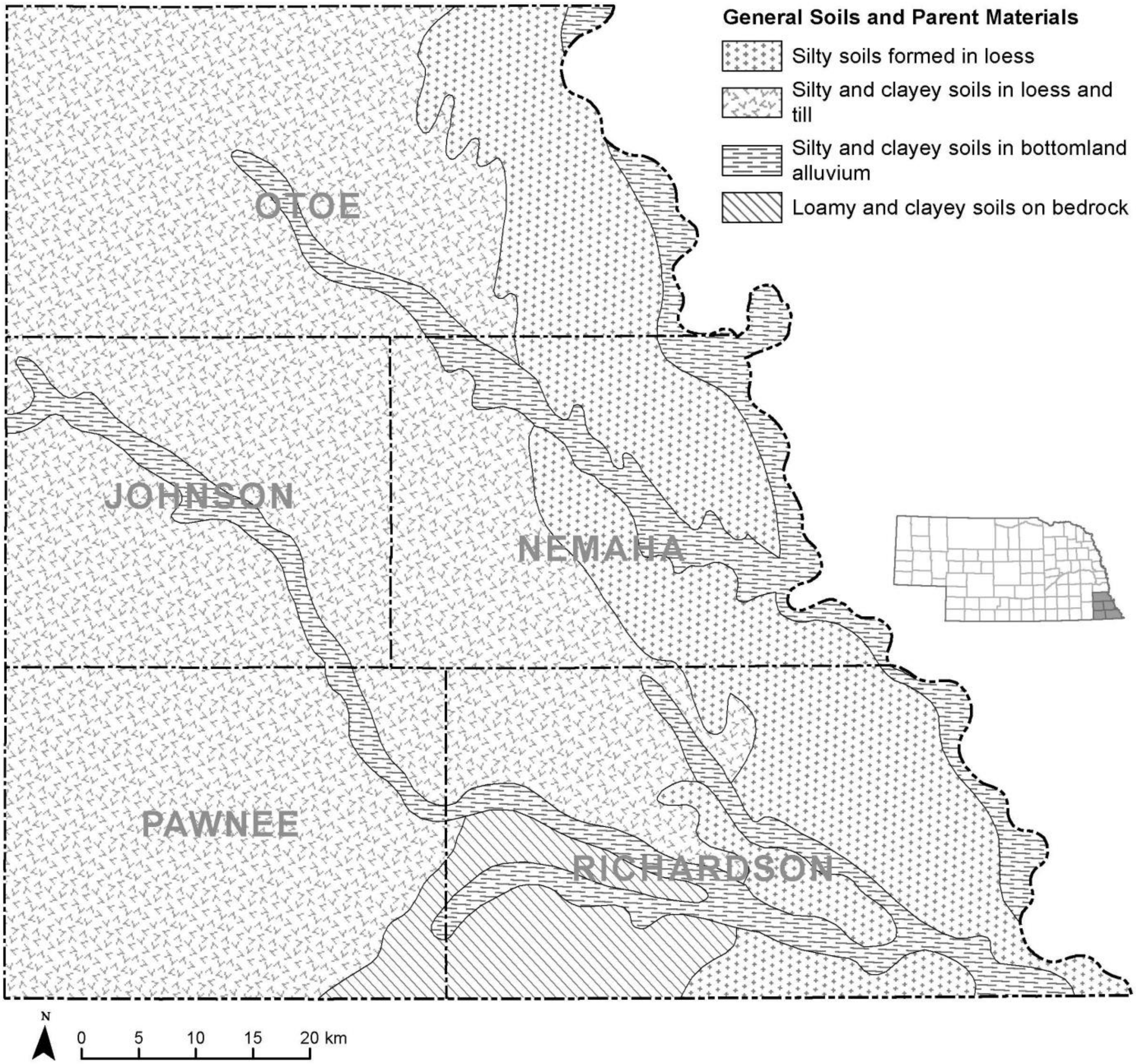


Fig. 7. General soils and parent materials in the field-trip area. Soils developed on Illinoian and Wisconsinan loess and pre-Illinoian glacial till dominate. Small areas of Pawnee and Richardson Counties have soils developed on shallow bedrock.

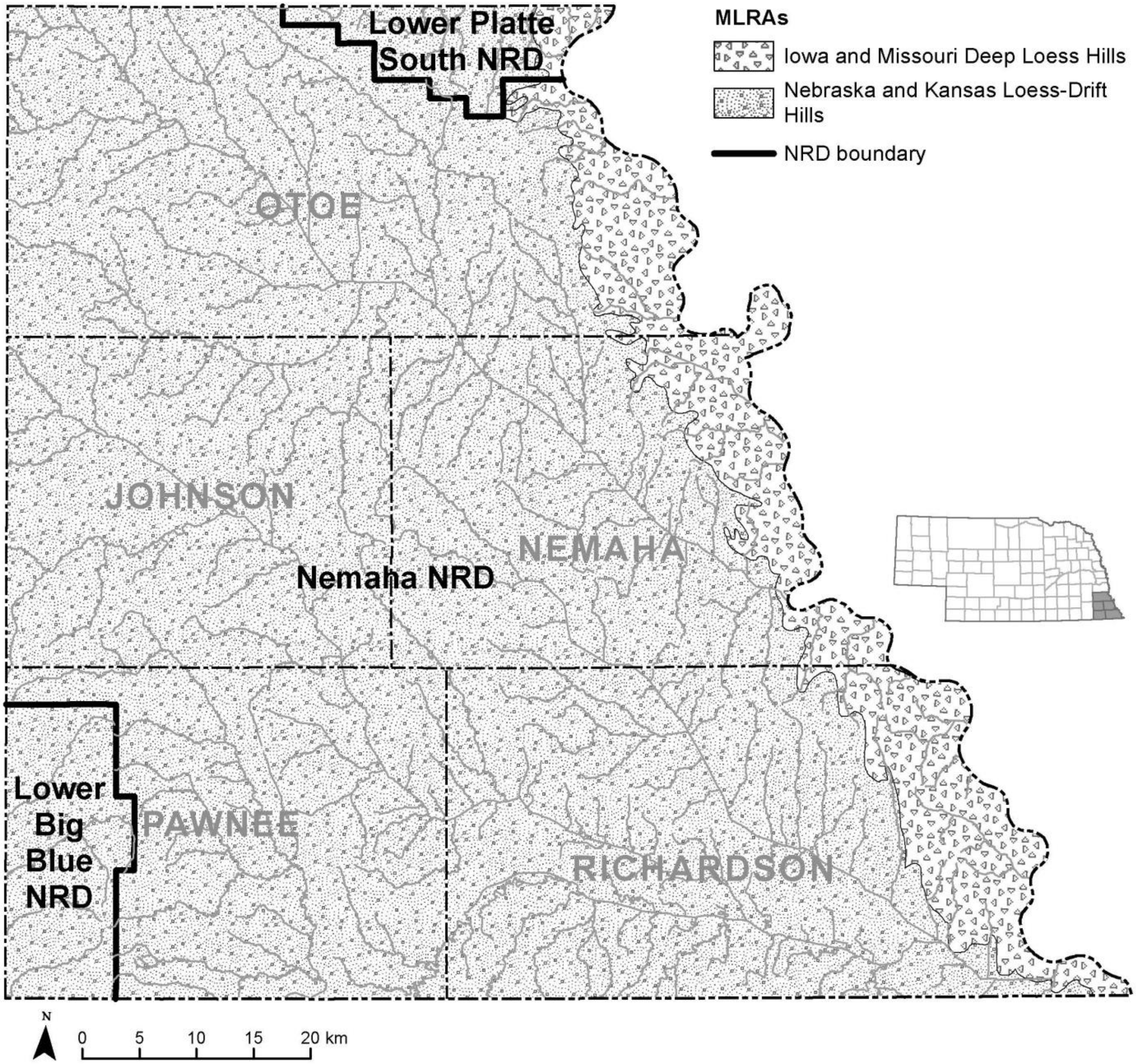


Fig. 8. Major Land Resource Areas recognized by the Natural Resources Conservation Service in the field-trip area. The Nebraska-Iowa Deep Loess Hills are characterized by thick Illinoian and Wisconsinan loesses over pre-Illinoian glacial tills. Jurisdictions of three regional Natural Resources Districts (NRDs) are also shown.

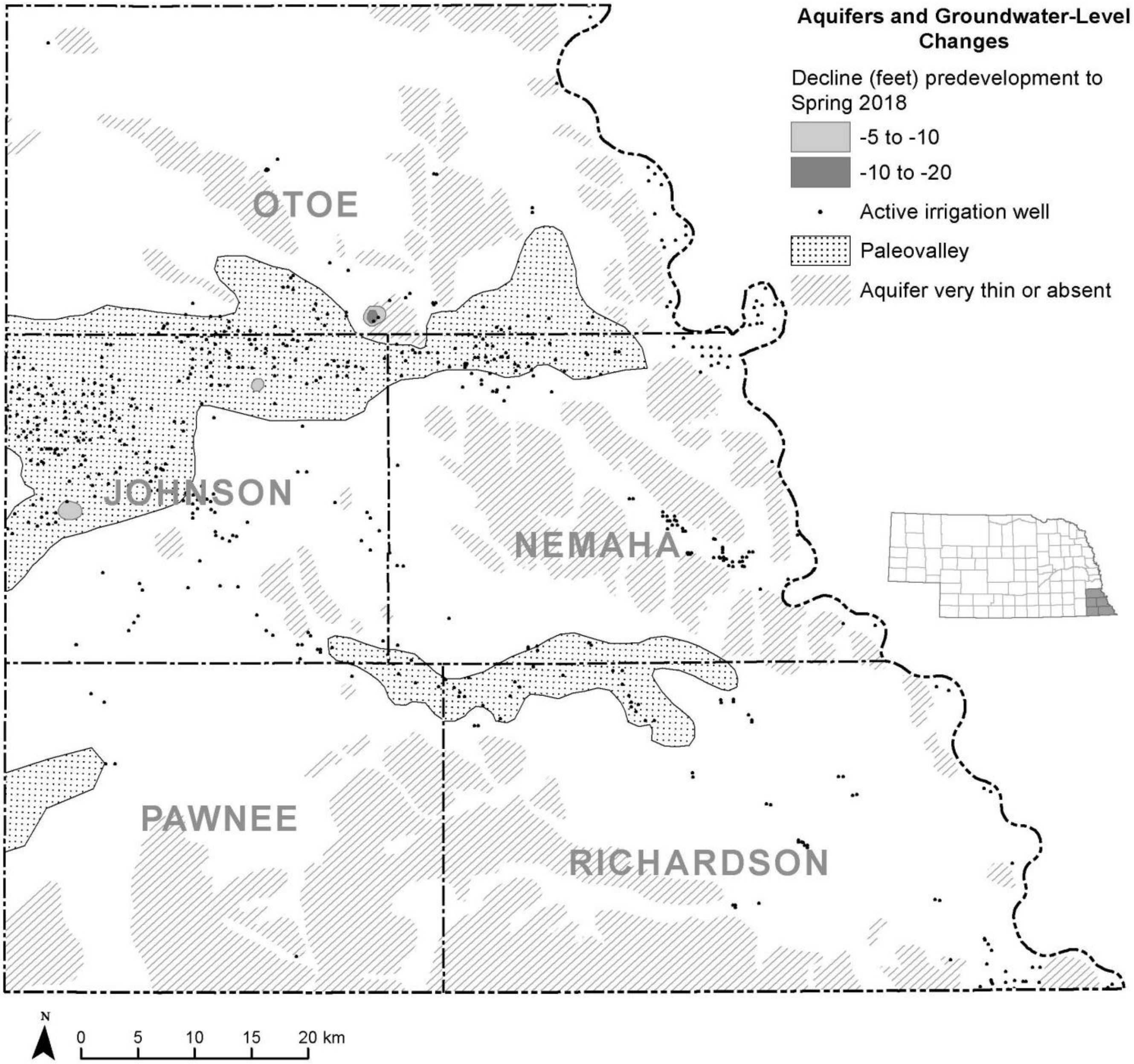


Fig. 9. Location of paleovalley aquifers and active registered irrigation wells, as well as areas where aquifers are thin or absent, in the field-trip area.

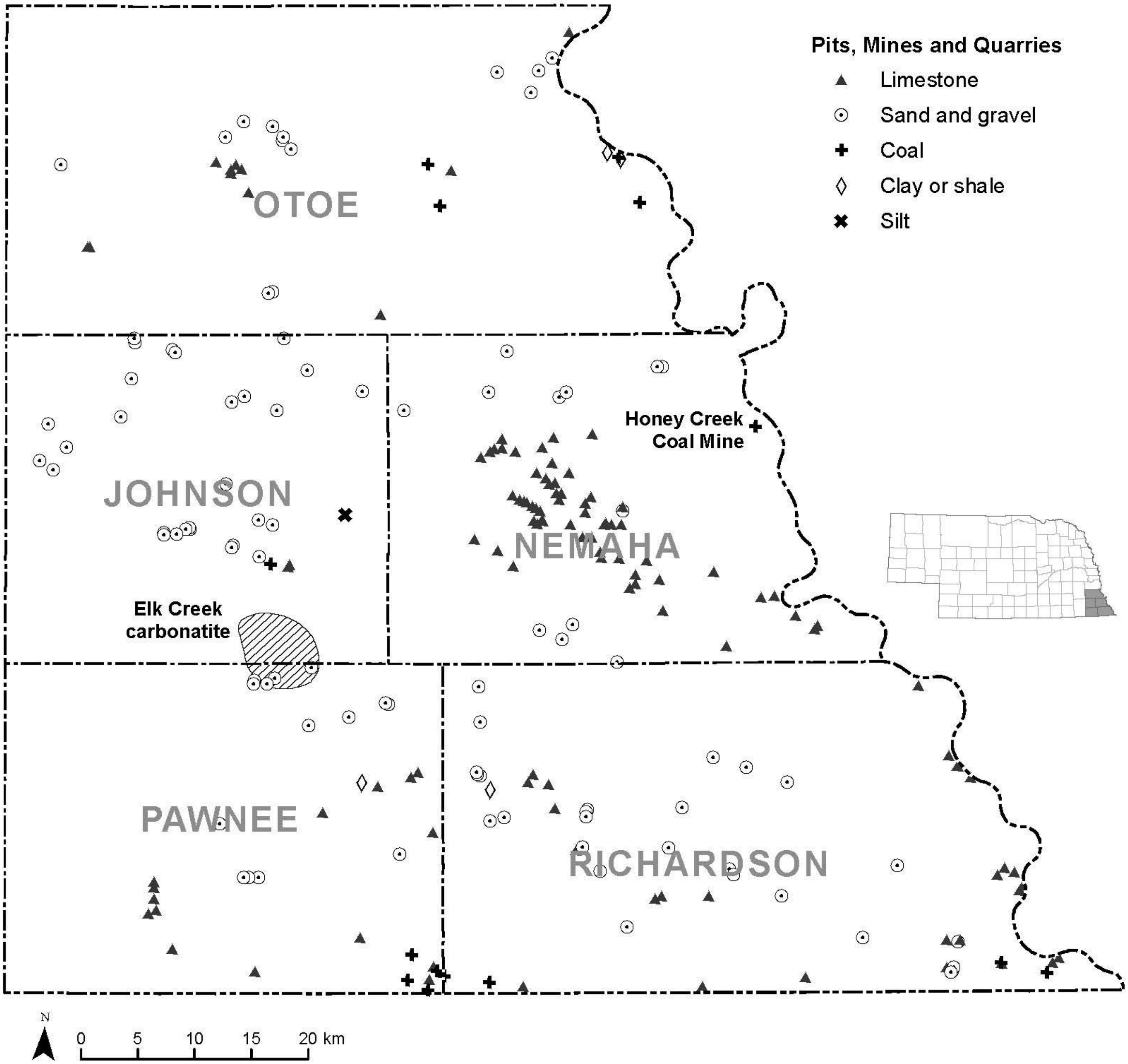


Fig. 10. Location of historic pits, mines, and quarries in the field-trip area. The Elk Creek carbonatite contains the metal niobium and also rare-earth elements; it is atop the Nemaha Uplift, but it is still buried by sedimentary rock strata. The Honey Creek Coal Mine (early 20th century) was the only commercially successful coal mine in Nebraska's history. Shale and clay mining for brick and tile production ended in the 20th century. Two limestone mines operate in the field-trip area as of 2019.

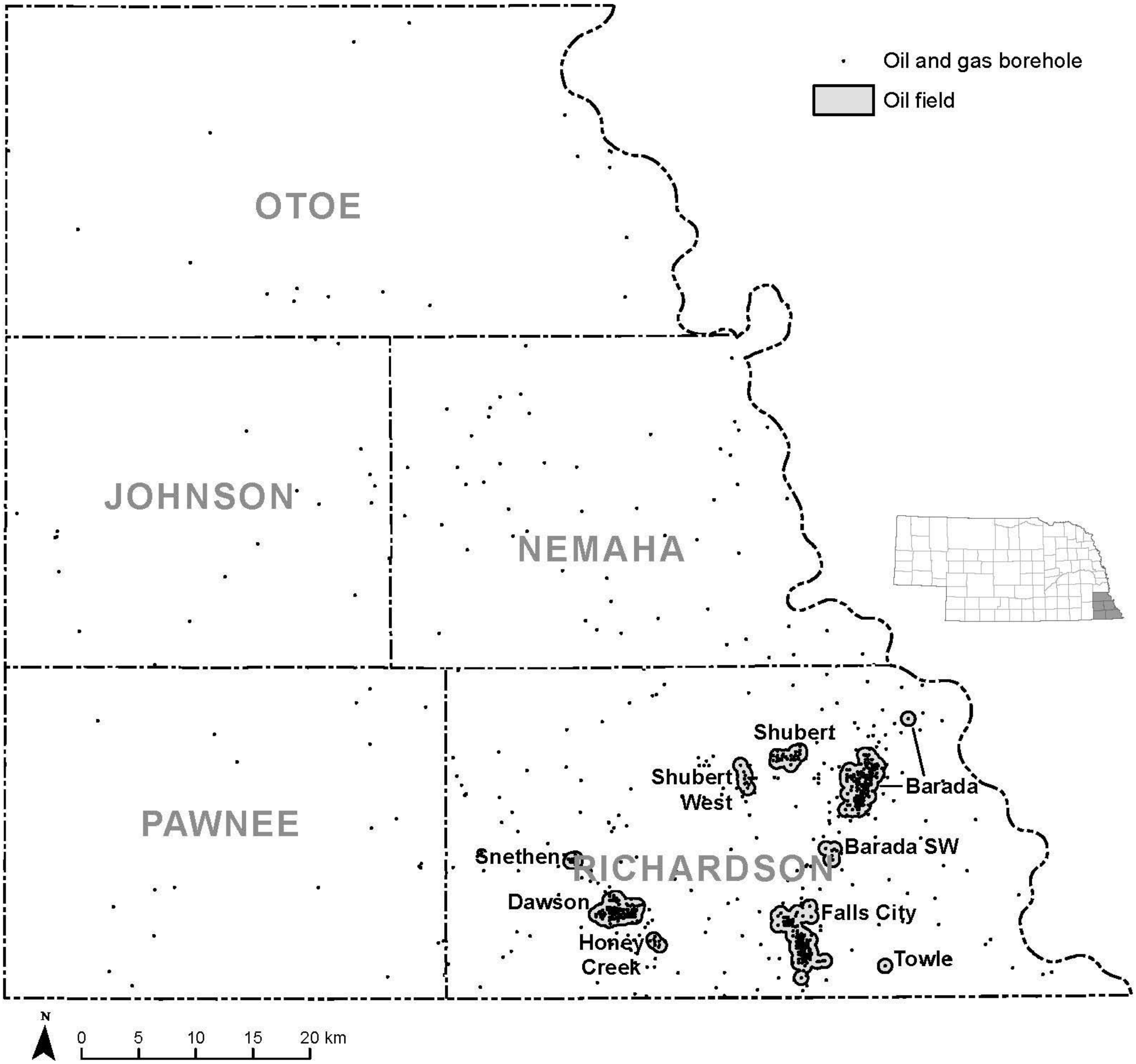


Fig. 11. Oil fields (named) and wells, chiefly wildcat wells, in the field-trip area. Oil production in southeastern Nebraska has been limited to Richardson County since the first well became operational in 1939.

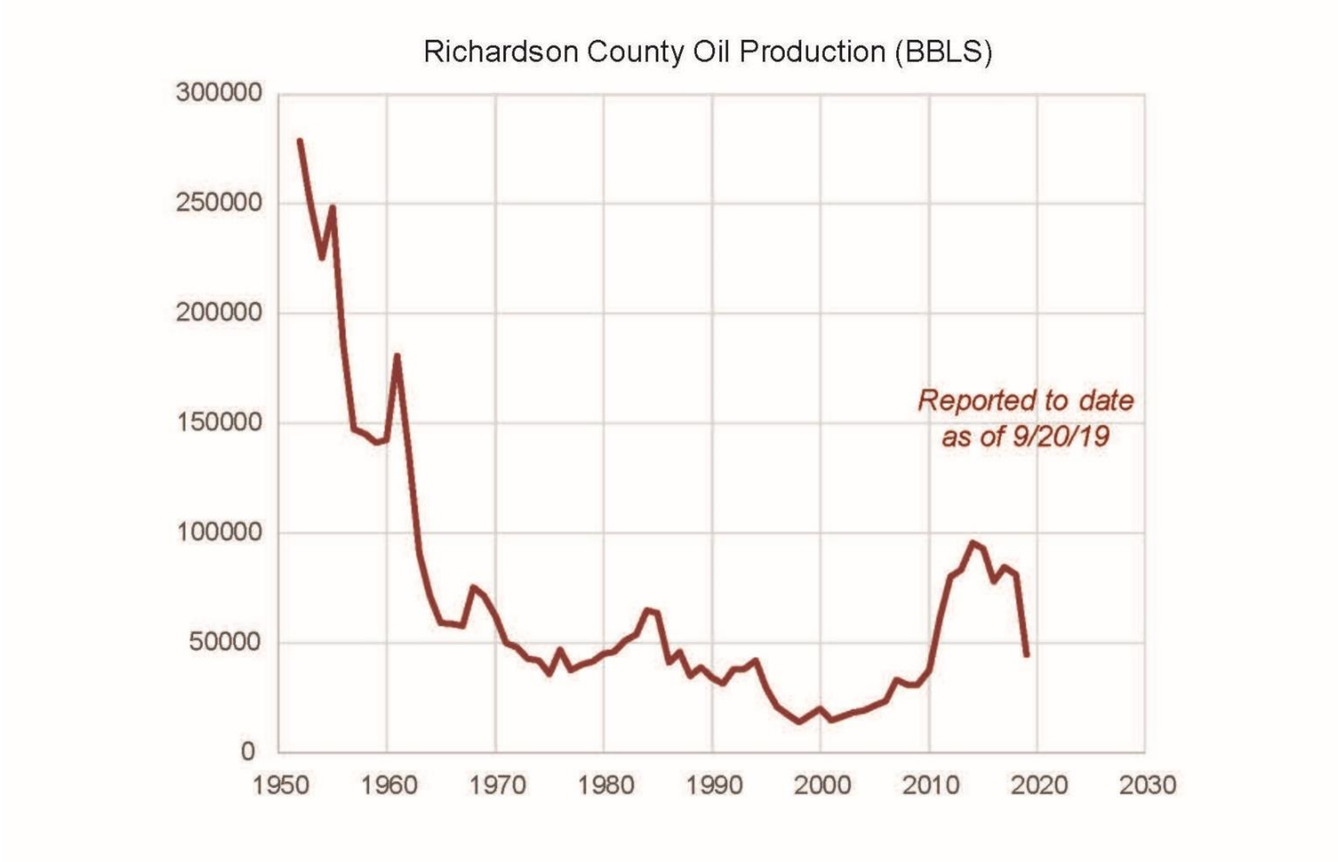


Fig. 12. Annual oil production in Richardson County (billions of barrels). Production had long been in decline prior to 2010.

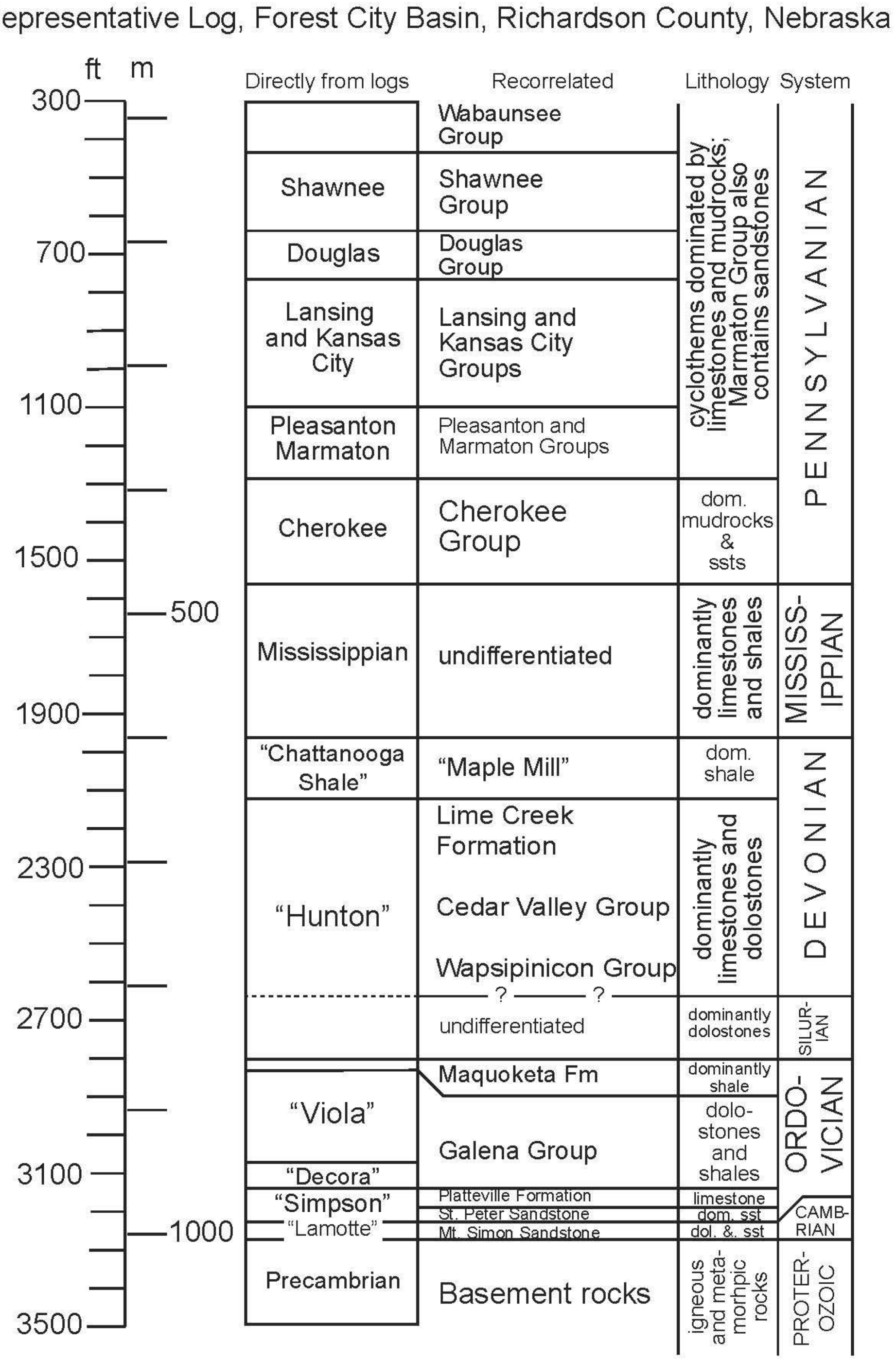


Fig. 13. Representative log of Paleozoic strata in Forest City Basin, Richardson County, Nebraska. Note incorrect stratigraphic terminology (e.g., "Hunton," "Viola," etc.) that appears in many older well logs, versus correct stratigraphic terminology applied with recorrelation with outcrops in eastern Iowa and other areas.

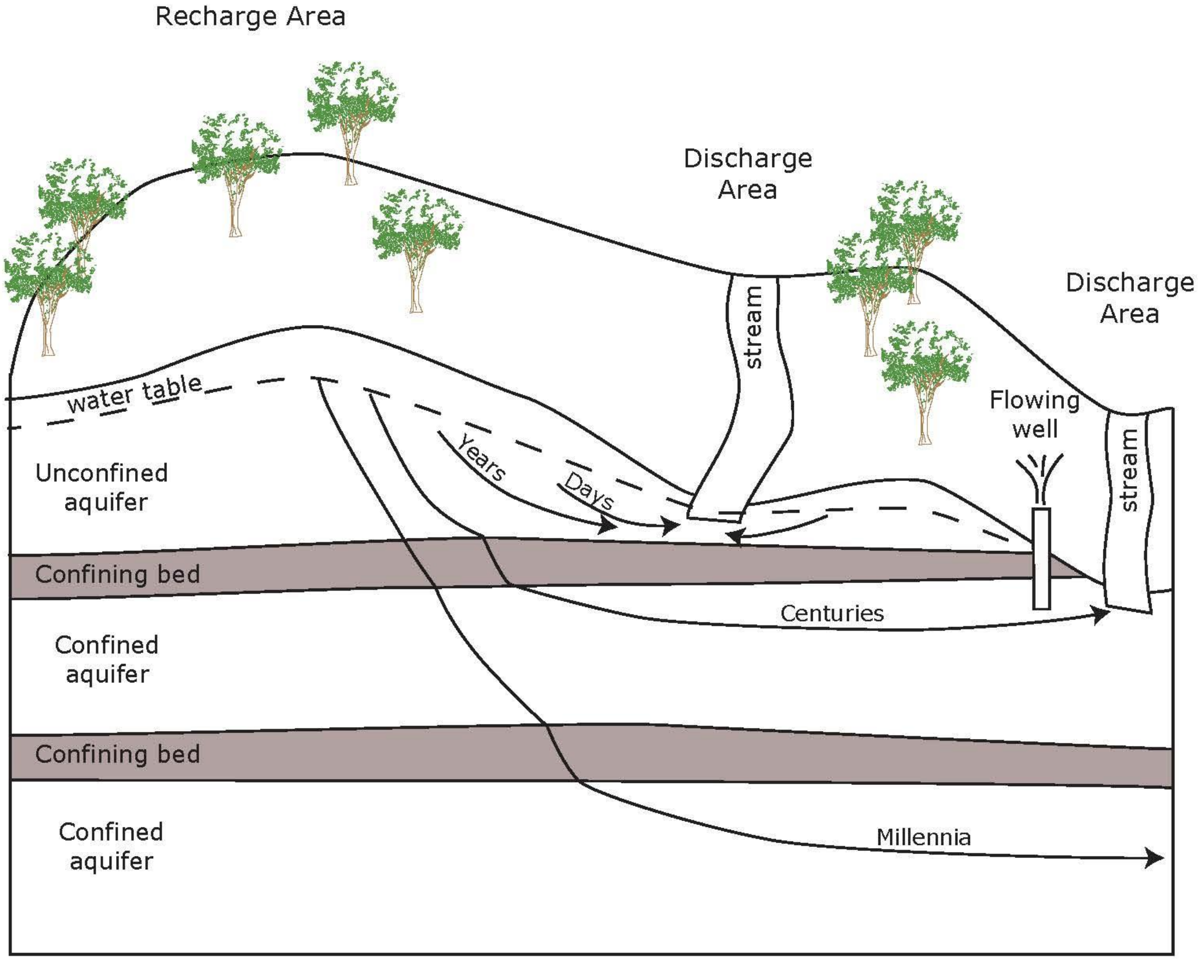


Fig. 14. Modified from Winter et al., 1999. Diagram showing different scales of groundwater flow through unconfined and confined aquifers. Water enters aquifers at recharge areas and moves both vertically and horizontally through aquifers until it discharges naturally to surface water or is pumped at a well. Groundwater moves at different spatial and temporal scales depending on regional geology and topography. Very deep groundwaters can reside in confined aquifers for tens of thousands of years or more.

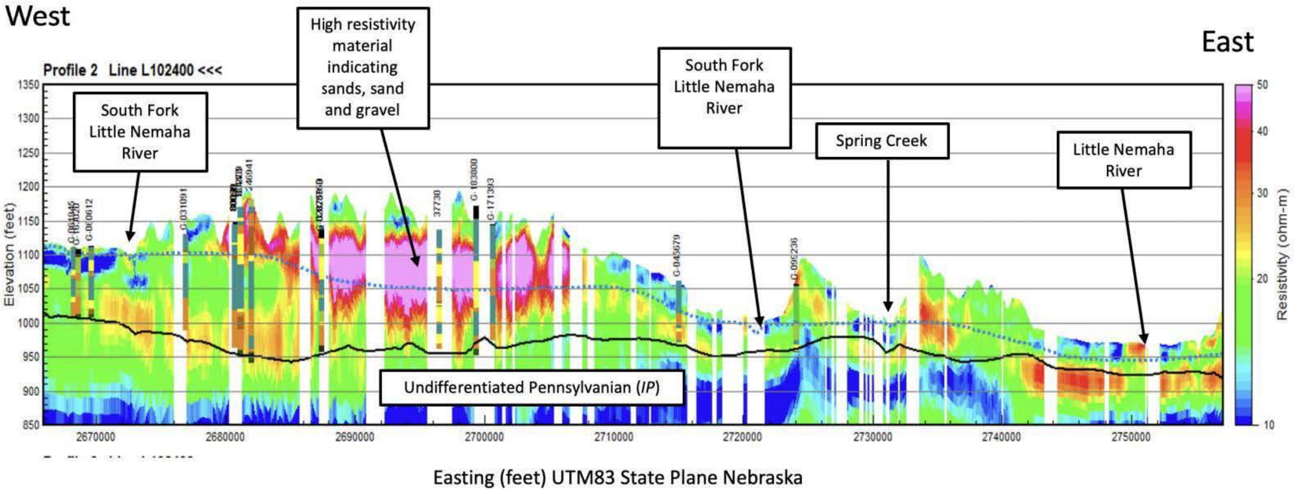


Fig. 15. Airborne electromagnetic profile north of Cook, Nebraska showing a potential recharge area for groundwater supplying base flow to the South Fork Little Nemaha River. Figure excerpted from Aqua Geo Frameworks (2019).

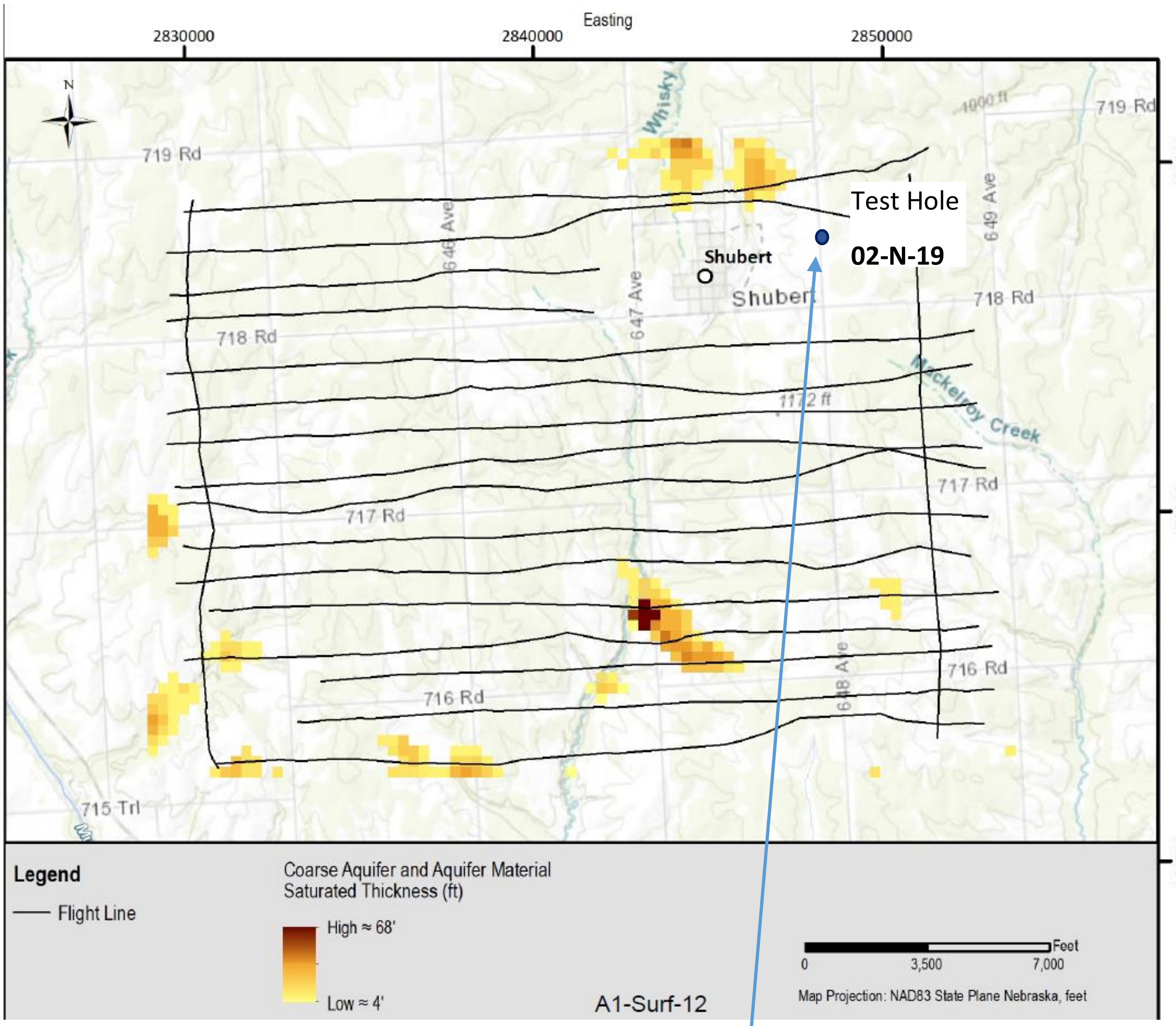
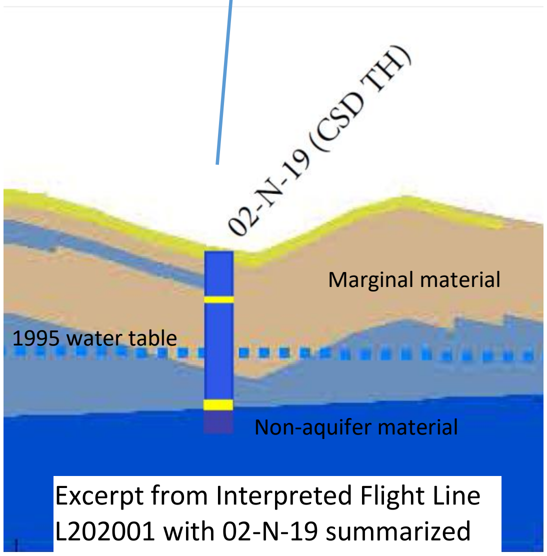
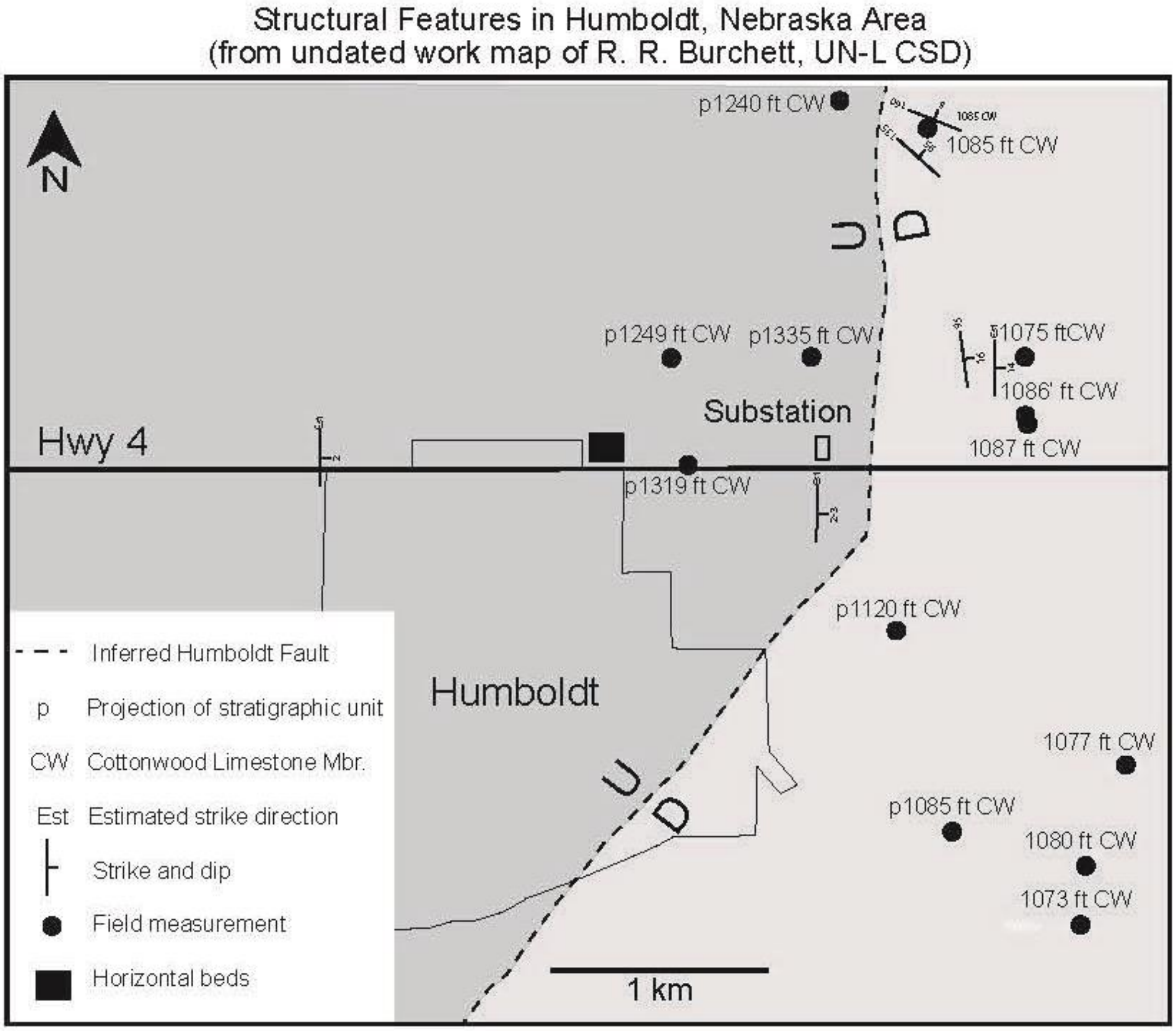


Fig. 16. Flight lines in the Shubert, Nebraska block survey. Coarse aquifer material (indicated by yellow and brown) is limited. Fourteen new test holes were drilled to provide physical geologic information along the flight lines.



Excerpt from Interpreted Flight Line L202001 with 02-N-19 summarized



Structural Features in Humboldt, Nebraska Area
(from undated work map of R. R. Burchett, UN-L CSD)

Fig. 17. Observations of geologic structure in Humboldt, Nebraska area, from work map by the late R. R. Burchett of the Conservation and Survey Division. These observations were probably made in the 1970s. Upper Pennsylvanian strata are the bedrock on the upthrown (western) side of the Humboldt Fault (actually, a zone of faulting or steep dip); Lower Permian are the bedrock on the downthrown (eastern) side. Note differences between the two sides in terms of the projected (p) or actual elevation of the Cottonwood Limestone Member (CW).

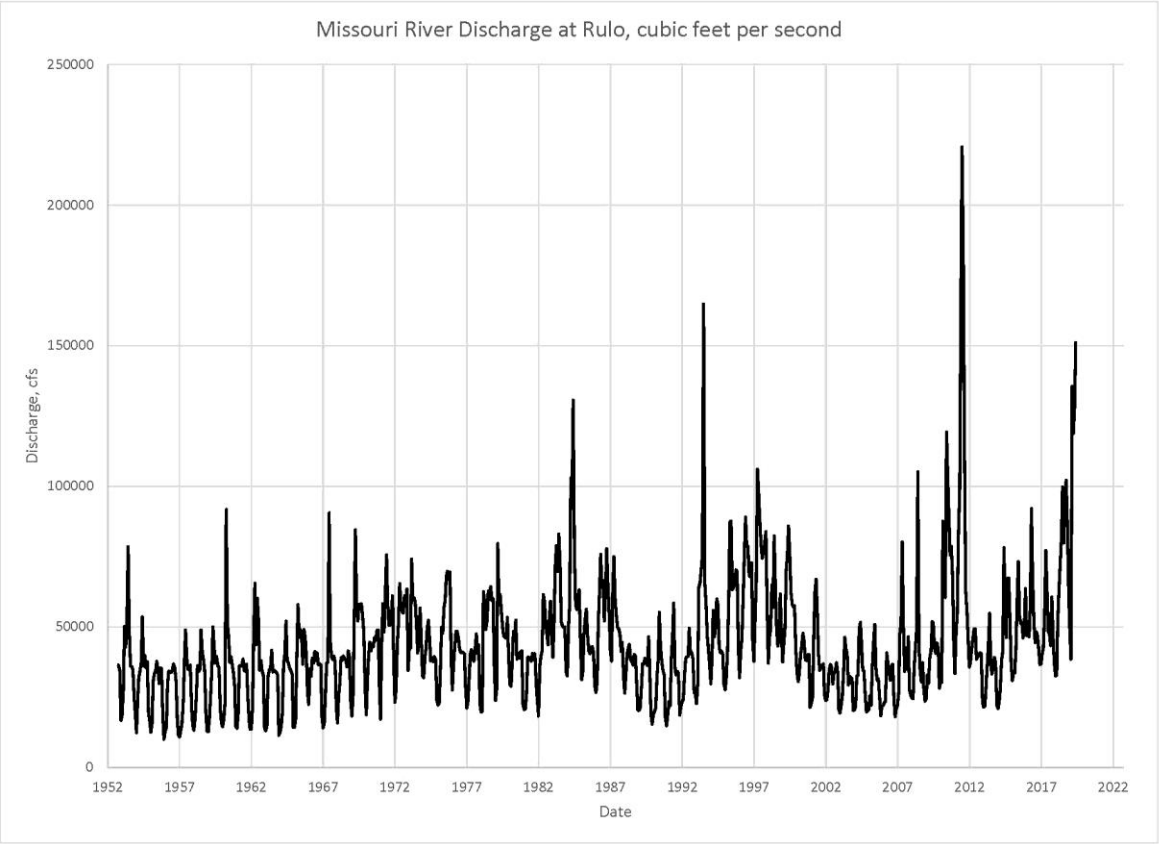


Fig. 18. Historic monthly discharge of the Missouri River at Rulo, Nebraska. Data from the U.S. Geological Survey (undated). Note peaks during 1993, 2011, and 2019 (incomplete).