10-2015

North-Central Nebraska Geology: Niobrara River Valley in Brown, Cherry, and Keya Paha Counties

R. M. Joeckel
University of Nebraska-Lincoln, rjoeckel3@unl.edu

L. M. Howard
University of Nebraska-Lincoln, lhoward3@unl.edu

S. T. Tucker
University of Nebraska-Lincoln

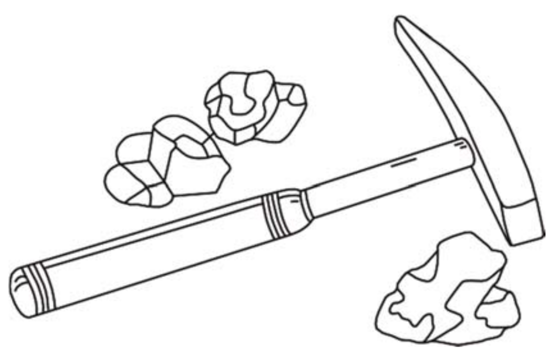
FIELD TRIP GUIDE

(for the Nebraska Well Drillers Association)

NORTH-CENTRAL NEBRASKA GEOLOGY:
Niobrara River Valley in Brown, Cherry, and Keya Paha Counties

R. M. Joeckel
L. M. Howard
Conservation and Survey Division
(Nebraska Geological Survey)
School of Natural Resources

S. T. Tucker
University of Nebraska State Museum



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

Guidebook No. 17

October 30, 2015

Field Guide for North-Central Nebraska Geological Field Trip
Nebraska Well Drillers Association
and
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Itinerary
North-Central Nebraska Geological Field Trip
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Begin at Ainsworth, Nebraska (schedule is approximate: note that tour may run as much as one hour over scheduled time of completion)

7:30	Registration and check-in @ Rodeway Inn. Brief introduction to trip
8:00 (1 hr)	Leave Ainsworth and proceed westward to Valentine, discussing Geology and ecology of the region on U.S. Highway 20.
9:00-10:30 (1.5 hr)	STOP 1: Vicinity of Valentine, Nebraska: overview of Niobrara River Valley and examination of stratigraphy of Ogallala Group (Valentine and Ash Hollow Formations). Discuss composition of High Plains aquifer, as well as depositional history and fossil record of regional Cenozoic stratigraphic succession. Proceed to Fort Niobrara National Wildlife Refuge (discussion of Nebraska Sand Hills on bus *en route*).
10:30-12:00 (1.5 hr)	STOP 2: Fort Niobrara National Wildlife Refuge: examine Fort Falls and Rosebud Formation (Oligocene), discuss surface hydrology, and examine lower part of Ogallala Formation (Miocene) and groundwater seepage along its basal contact with the Rosebud Formation. Brief discussion of ecological significance of modern Niobrara River Valley.
12:00-12:30	Lunch at Fort Niobrara National Wildlife Refuge. Following lunch, proceed eastward from Valentine on Nebraska Highway 12 to Sparks and Smith Falls State Park
13:00-15:00 (2 hr)	STOP 3: Smith Falls State Park: examine sediments of Ogallala Group and underlying Rosebud Formation, visit waterfall and Niobrara River. Proceed eastward to Springview, Nebraska on Nebraska Highway 12 and turn south on U.S. Highway 183 at Springview.
15:00-15:30 (0.5 hr)	STOP 4: South of Springview, Nebraska: overlook of Niobrara River Valley and examine sediments of White River Group along U.S. Highway 183.
15:50-16:50 (1 hr)	STOP 5: Vicinity of Long Pine, Nebraska: examine Long Pine gravels (Broadwater Formation) and discuss local stratigraphy and hydrogeology. Return to Ainsworth on U.S. Highway 20.
17:00 (0.50 hr)	Return to Ainsworth and conclusion of tour. Completion of tour and sign out. Note that tour may run as much as one hour overtime.

Objectives of tour: The primary objective of this tour is to examine upper Eocene through Pleistocene strata in the contexts of regional stratigraphy, geological history, paleogeography, depositional environments, and geohydrology. An outline of regional stratigraphy and the High Plains aquifer will be presented in the process, as well as a brief discussion of upper Cretaceous strata (Pierre Shale) underlying the Cenozoic stratigraphic succession. The secondary objective of this tour is to elucidate regional geomorphology (including fluvial and eolian landforms), surface hydrology, and ecology during the course of the tour.

Tour leader: This tour will be led by Dr. 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.

1. Introduction

This field trip (Fig. 1) explores the middle Niobrara River Valley, which is among the most scenic and scientifically interesting features on the Great Plains. Biologists have long been aware of the uniqueness of the valley, but it is of particular interest to geologists and vertebrate paleontologists since the first scientific expedition to the area in 1857 because of the Cenozoic strata exposed along its length and their rich content of vertebrate fossils (Skinner and Johnson, 1984; Voorhies, 1987). Cenozoic strata within the valley (Figs. 2, 3) record more than 35 million years of erosion, deposition, environmental change, and biotic evolution, and the results of research performed in the area contribute substantively to our understanding of the changes in North American mammal communities over geologic time (Skinner and Johnson, 1984; Voorhies, 1987; see also: Tedford et al., 2004, Janis et al., 2008). Moreover, the cropping out of the Upper Cretaceous Pierre Shale in the field area (Fig. 4) means that the course of this trip provides glimpses some 70 million years of Earth history in total. In examining Cenozoic strata of the middle Niobrara River Valley, the observer is presented with a cross-section of the High Plains aquifer as it is expressed in a large part of north-central Nebraska. Likewise, while driving between the field trip stops described herein, the geomorphic and ecological significance of the Niobrara River Valley is readily apparent.

2. Geomorphic and biologic setting of the Niobrara River Valley

The Niobrara River is in many ways a typical Great Plains River, flowing more than 440 miles (715 km) eastward from eastern Niobrara County, Wyoming to the Missouri River. According to Buchanan and Schumm (1990), however, seasonal changes in bed roughness and a nearly constant water-surface elevation through the year, which appear to be related to the

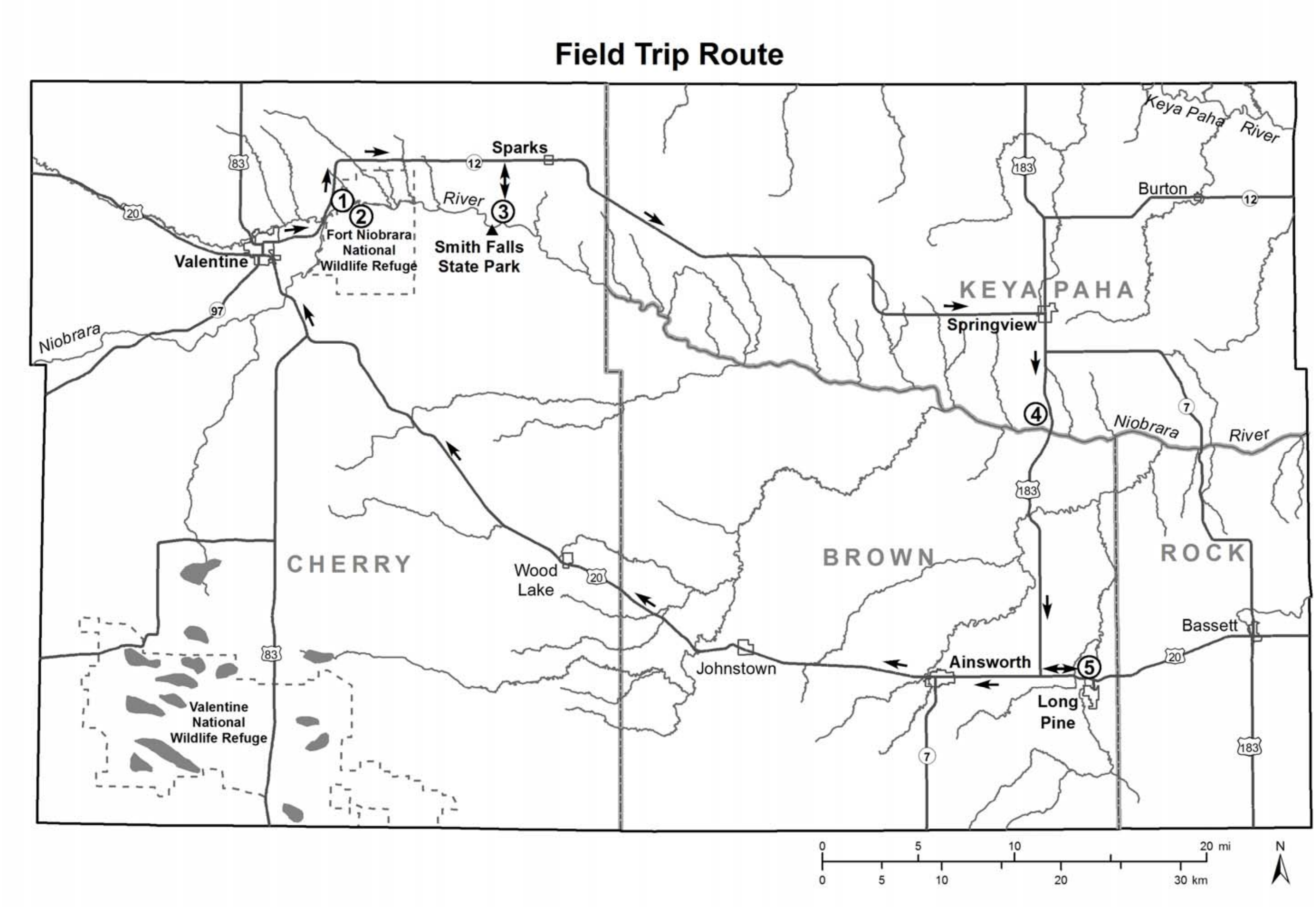

Fig. 1. Area and route of 2015 Nebraska Well Drillers Association field trip.

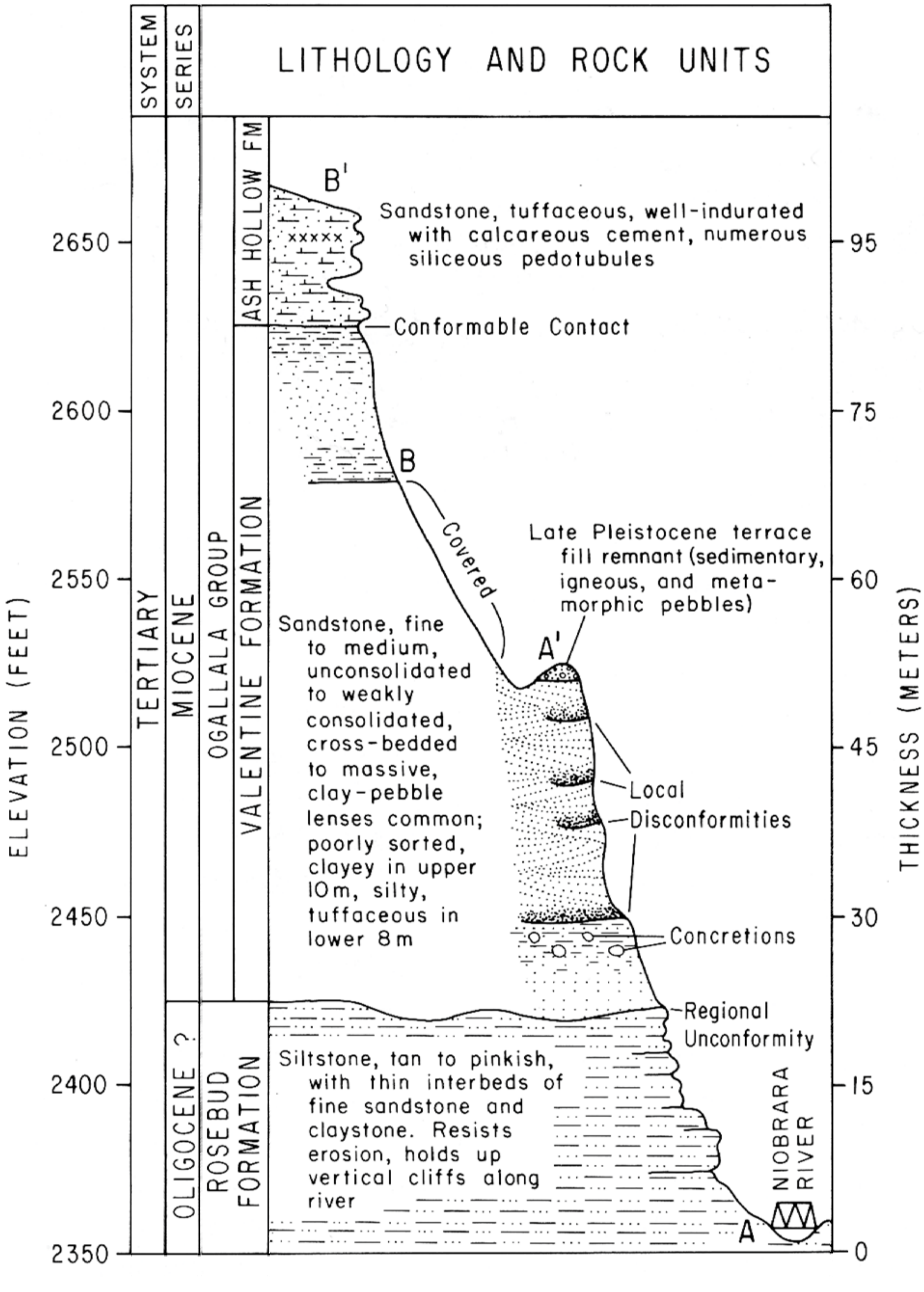

Fig. 2. A) Voorhies (1987) section of strata in Fort Niobrara National Wildlife Refuge.

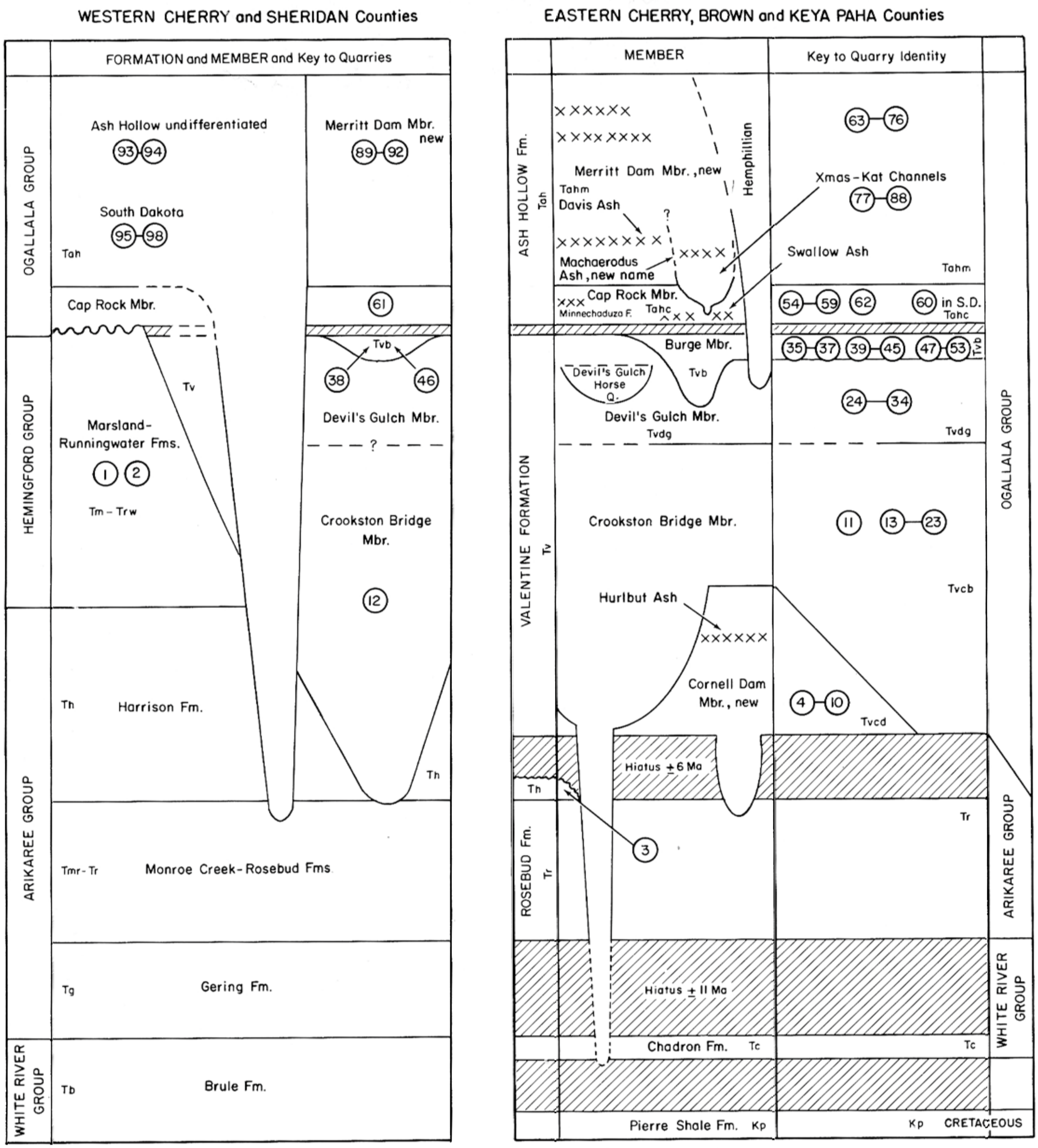

Fig. 2. B) Composite section of exposed Cenozoic strata in middle Niobrara River Valley from Skinner and Johnson (1984)

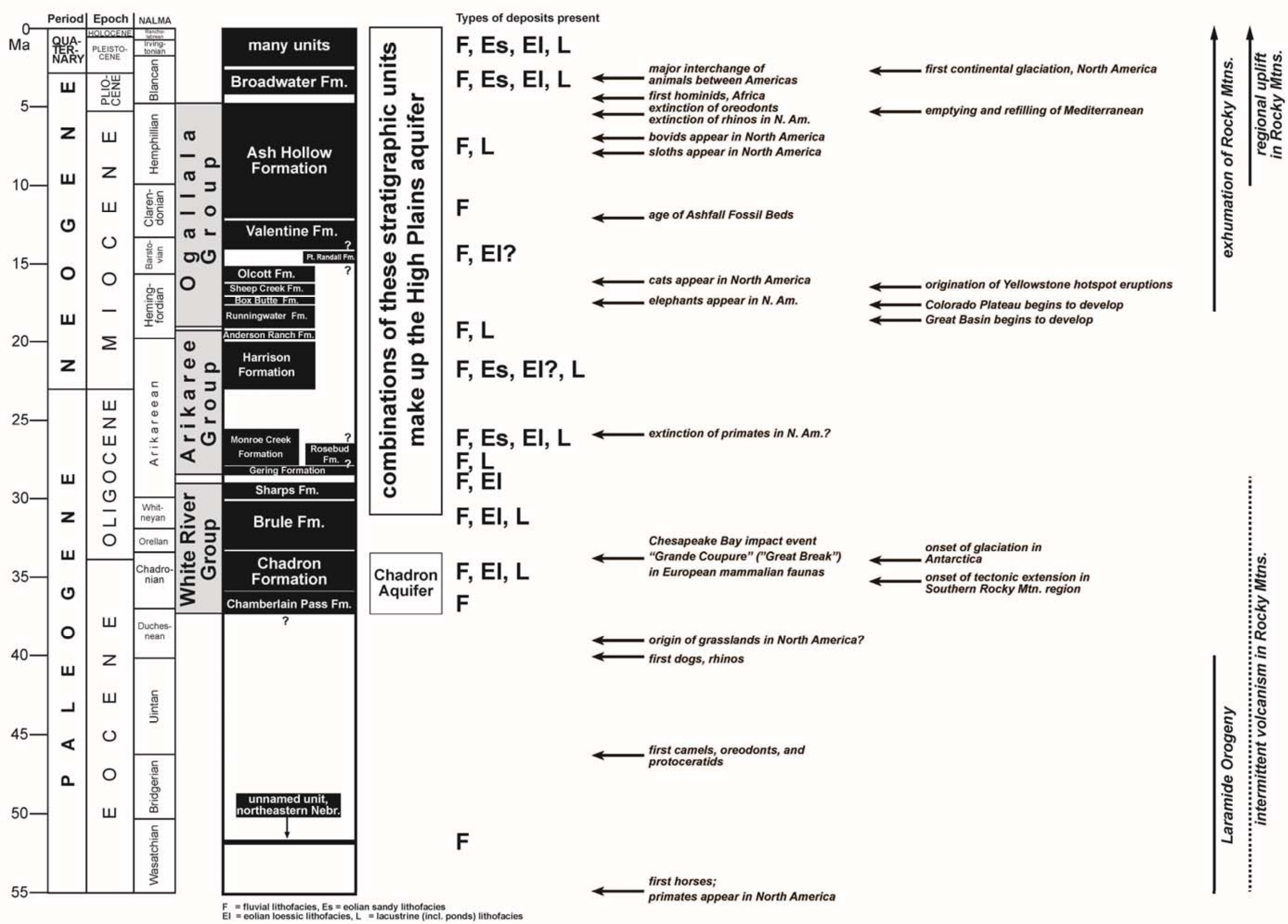

Fig. 3. Composite time-stratigraphic chart of Cenozoic strata in Nebraska, composition of High Plains aquifer, and important events in geologic time. Note that entire composite stratigraphic succession depicted here is not presented in field trip area.

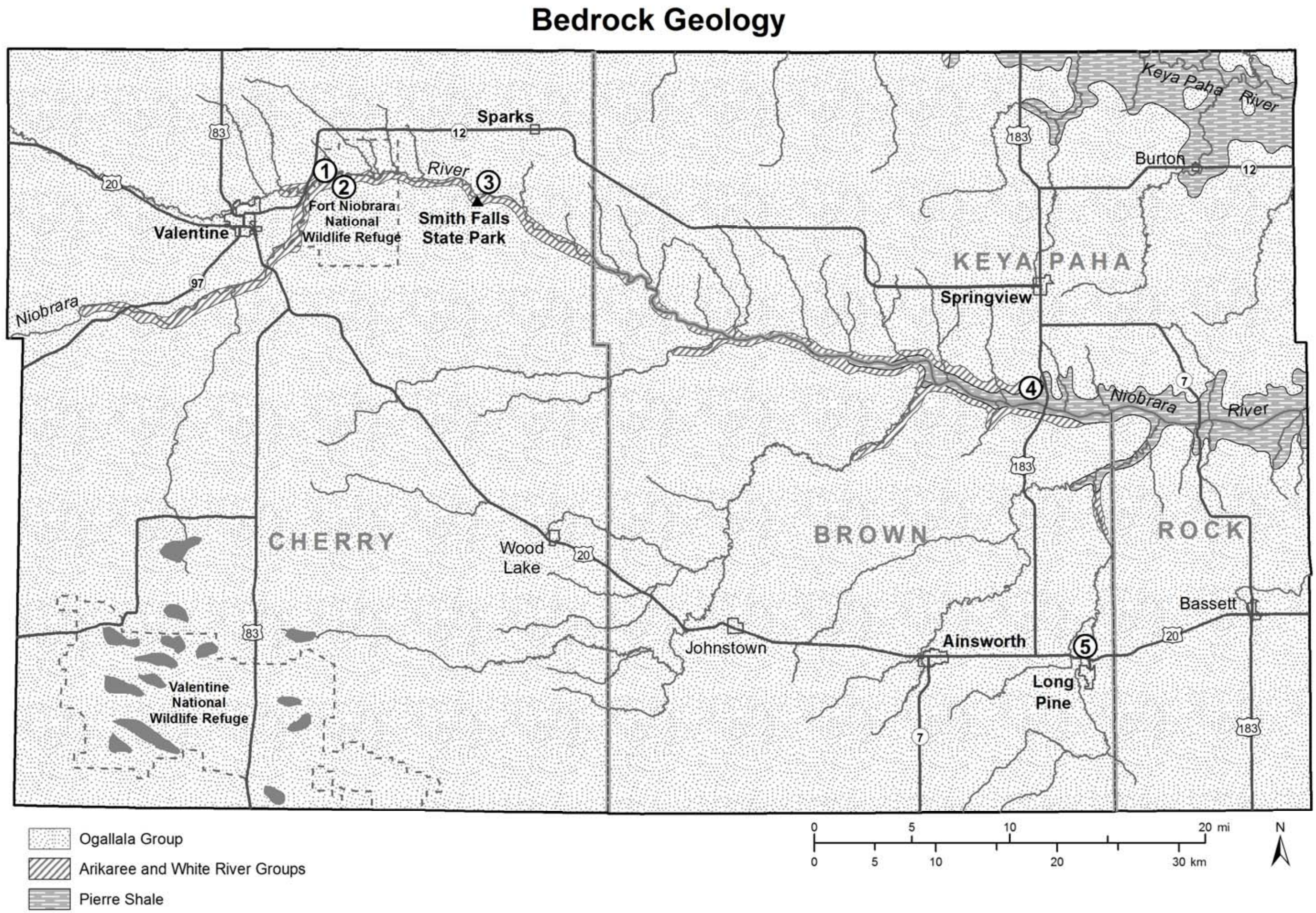

Fig. 4. Bedrock geology of field trip area.

dynamics of winter ice and the river's fine-sand-dominated bedload, make the Niobrara River unique in comparison with many other streams on the plains. The Niobrara River has a drainage basin of some 12,800 mi^2 (33,150 km^2) and it receives only a few large tributaries, although steady year-round baseflow in the river is evidence for a persistent hydrologic connection with the High Plains aquifer (Buchanan and Schumm, 1990). Channel width has decreased in many places on the Niobrara River since the 1870s and the braided aspect of the river is now less prominent than it was in the early 20th century. Near its mouth, the dynamics of the Niobrara River has also been greatly affected in the course of a few to several decades by the impoundment of Lewis and Clark Lake on the Missouri River (Bristow et al., 1999). Groundwater irrigation in the Niobrara Basin began in 1938 and increased considerably in succeeding decades, but the impact of groundwater withdrawal appears to be comparatively minimal in the field trip area. The few surface-water engineering projects along the length of the Niobrara River have had little effect in comparison with the many more heavily regulated river basins on the Great Plains (Buchanan and Schumm, 1990).

The valley of the Niobrara River attains a maximum depth of approximately 460 ft (140 m), although in the field trip area its maximum depth is approximately 300 ft (91 m). The mouth of the Niobrara River, at the town of Niobrara in Knox County, Nebraska, lies very close to the western limit of Laurentide glaciation, which is approximated by the present course of the Missouri River in southern South Dakota and then by a line trending southward through the middle of Knox County, Nebraska and beyond. The Niobrara River eroded through unconsolidated sediments and eventually became incised into underlying bedrock strata during geologically recent times: in the least after 27,000 years ago, and possibly much more recently (Larson, 2001; Jacobs et al., 2007).

Today's young, steep-sided Niobrara River Valley with its bedrock outcrops contrasts starkly with the Nebraska Sand Hills to the south, the largest dune field in the Western Hemisphere. Although currently stabilized, Sand Hills dunes were actively migrating as recently as ~700 years ago, and did so multiple times during the past 10,000 years, in response to severe drought (Miao et al., 2007). The Pleistocene and Holocene histories of the Niobrara River and the Sand Hills are indirectly linked by climate change and geomorphic processes operating on a regional scale, but also by more direct interactions. Immediately west of the field trip area, south of Cody and Merriman in Cherry County, Nebraska and at the northern edge of the Nebraska Sand Hills, lie the elongate Cobb and Wobig basins, which were parts of the ancient Niobrara River blocked by migrating sand dunes (*dune dams*) and filled with lake sediments beginning approximately 45,000 years ago and ending before 27,000 years ago (Jacobs et al., 2007). The sedimentary deposits of these large lakes are now perched at the edge of the Niobrara River Valley, high above present river level.

The United States Department of Agriculture Natural Resources Conservation Service (2006) recognizes three Major Land Resource Areas within the area of the field trip (Fig. 5): (1) the Nebraska Sand Hills, (2) the Dakota-Nebraska Eroded Tableland, and (3) the Southern Pierre Shale Plains (of these, only #1 and #2 will be viewed during the trip). The Nebraska Sand Hills are widely recognized as a unique area, with slight variations in mapped extent, by many geologists and other scientists. The other two MLRAs are not widely recognized among geologists, but their definition is scientifically sound from the perspective of regional geology and geomorphology. Soils in the field trip area range in texture from clayey to sandy and parent materials are likewise diverse, ranging from weathered Upper Cretaceous Pierre Shale to Pleistocene-Holocene dune sands (Fig. 6). The most widespread soil parent material in the field

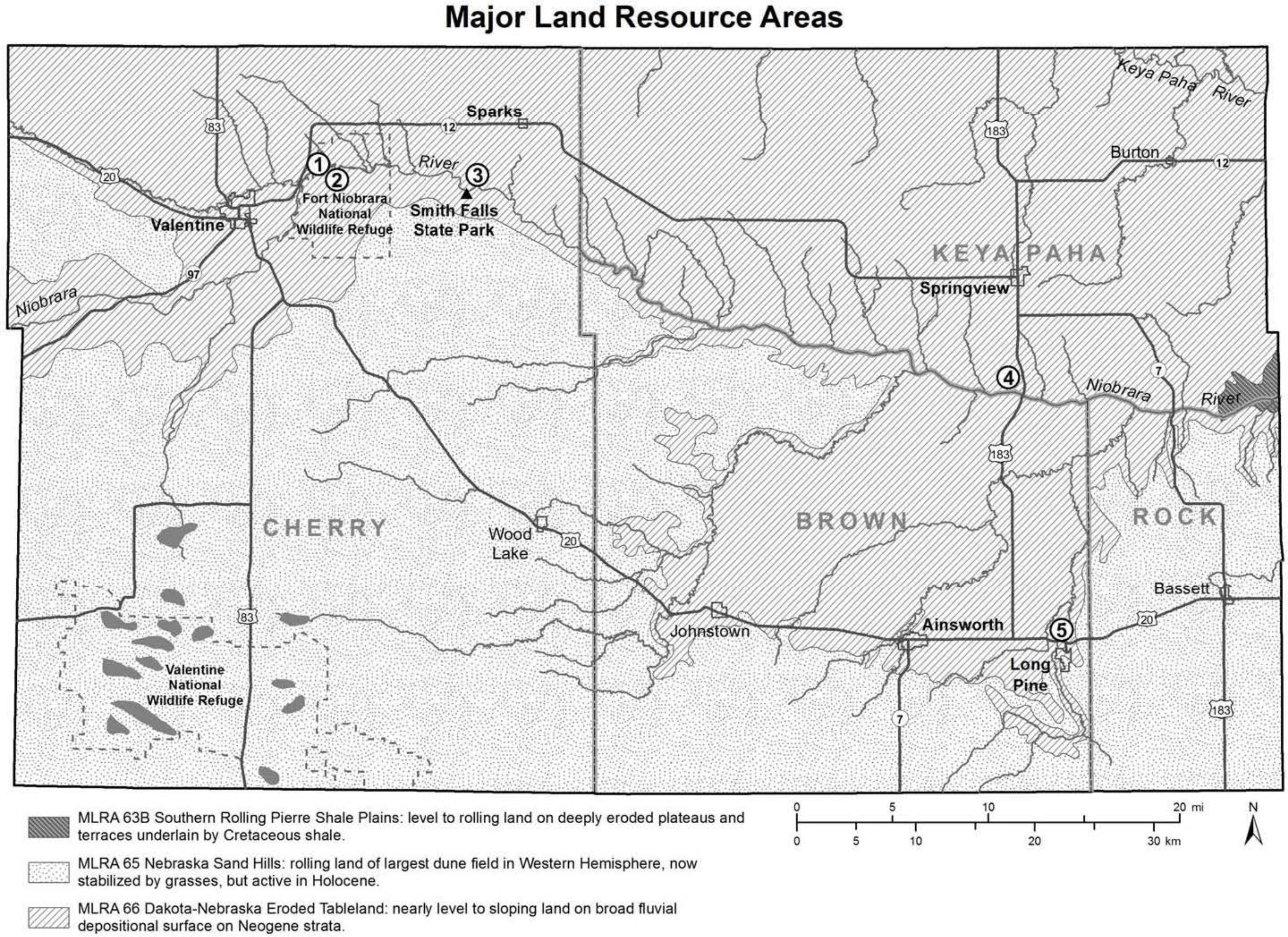

Fig. 5. Major Land Resources Areas (MLRAs) in field trip area (see United States Department of Agriculture Natural Resources Conservation Services 2006)

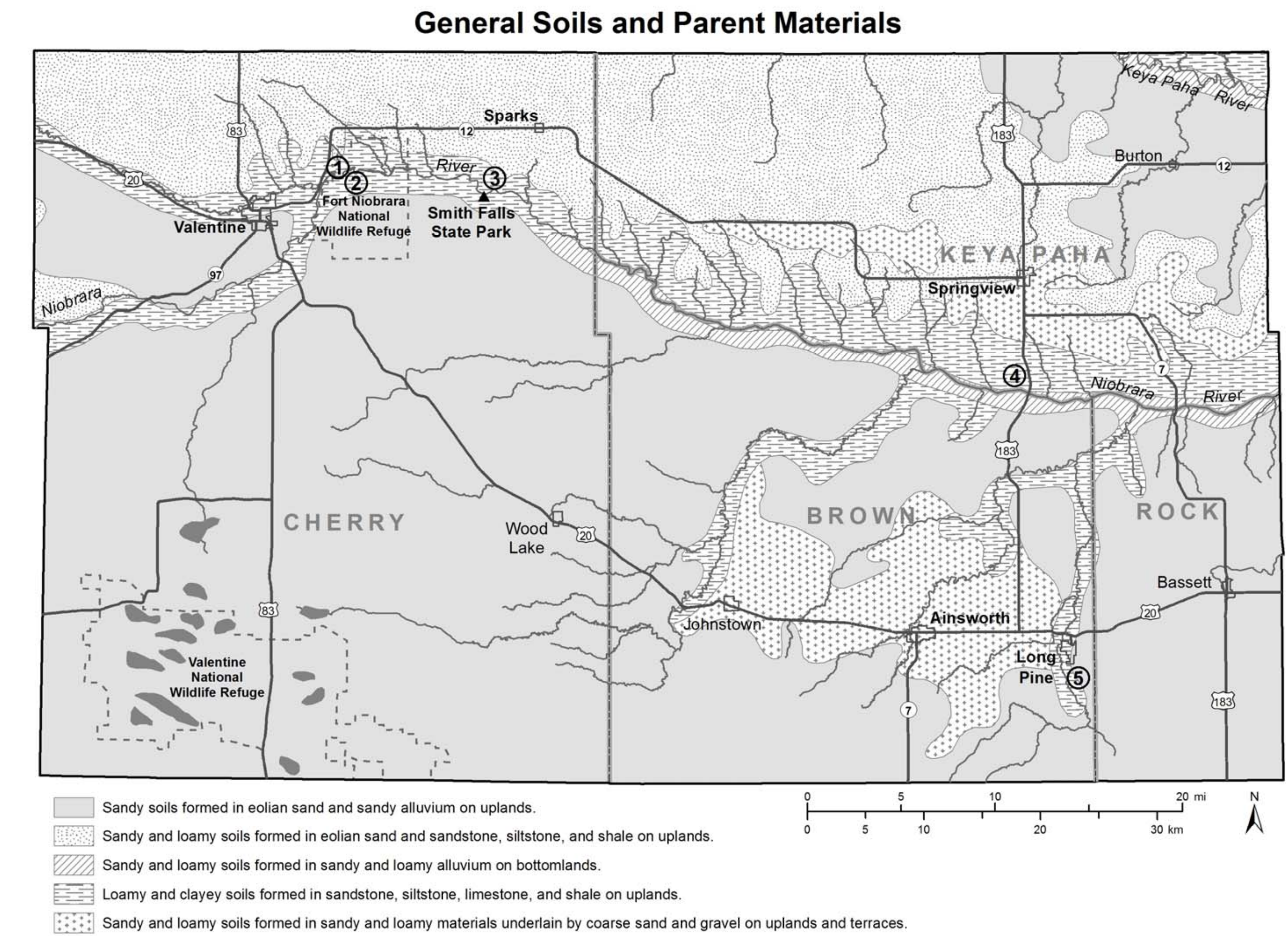

Fig. 6. General soil and parent-material map of field trip area.

trip area is eolian sand, which dominates south of the Niobrara River in the Nebraska Sand Hills (Figs. 5, 6). Sandy to loamy soils on a variety of parent materials dominate north of the river.

Biologists have been aware that the Niobrara River Valley is ecologically distinctive for more than 120 years (Bessey, 1887). Dozens of species of animals and vascular and non-vascular (e.g., mosses) plants found in the valley are absent from the surrounding grasslands, strongly suggesting that the valley is a "biological crossroads," that is, both: (1) a *refugium* (the location population of organisms that are rare or geographically isolated due to environmental changes) from Pleistocene glacial times, and (2) an important migration corridor across the plains, chiefly for species that are normally associated with boreal and cool-temperate forests in North America (Kaul et al., 1988; Kantak and Churchill, 1993). Perhaps the most obvious of the seemingly "out-of-place" organisms in the valley are the Ponderosa pine (*Pinus ponderosa*), the range of which is chiefly to the west, and the paper or white birch (*Betula papyrifera*), the range of which lies chiefly to the far north. The close relationship between plant communities and local physical conditions within the Niobrara River Valley is compelling: slope aspect (e.g., north- vs. south-facing slopes, the presence of permeable or impermeable strata, and soil characteristics clearly determine where species (e.g., the paper birch and associated cool-forest understory species) thrive at a fine spatial scale (Hearty, 1978, Kantak, 1995).

3. Geologic setting, stratigraphy and hydrogeology of the middle Niobrara River Valley

The field trip lies on the North American *platform*, that being the comparatively stable part of the continent under which a relatively thin cover of sedimentary rocks overlies Precambrian *basement* (old, deep rocks, generally igneous and metamorphic, that are a billion years old or older). The basement of North America is a large-scale patchwork of crust ranging in age from older than 2.5-1.0 billion years ago. Under the field trip area lies the Central Plains Orogen (Sims and Petermar, 1986), an association of various basement rock types that was added to the North American continent by *orogeny* (collectively, the tectonic processes that build mountains) more than 1.6 billion years ago. Thus, there were once mountains in north-central Nebraska. The Central Plains Orogen abuts other large associations of older basement rocks in northern Nebraska.

The structural and tectonic setting of north-central Nebraska and adjacent South Dakota has been established in broad terms by studies of regional geology. The field trip area lies atop the eastern side of the southern part of the somewhat poorly defined Kennedy Basin, which itself lies between two areas that experienced broad uplift during the Paleozoic and possibly intermittently thereafter: the Chadron Arch (or Chadron-Cambridge Arch) to the west and the Siouxana Arch to the east, which barely extends into the southeastern part of the field trip area (Fig. 7). All of these features lie along the very broad, northeast-to-southwest feature known as the Transcontinental Arch, and the basinal region between the Chadron and Siouxana arches is referred to as the Nebraska Sag by some authors (Carlson, 1999). The #1 Borman Cattle well, a dry hole located immediately southeast of Valentine, Nebraska (NE¼ NW¼ SW¼ of sec. 5, T. 33 N., R. 27 W.) encountered Precambrian basement rocks at 631 ft (192 m) below sea level, after penetrating Cretaceous, Jurassic, Permian, and Pennsylvanian strata; Paleozoic strata older than Pennsylvanian appear to be absent. On the basis of stratigraphic logs from a very few fully-penetrating petroleum bores in the area, some 3000-3200 ft (914-975 m) of Phanerozoic sediments and sedimentary rocks overlie Precambrian basement in the field trip area. Several weak earthquakes have been recorded in the area in historic times, and specifically from the

Historical Earthquakes and Subsurface Structural Features

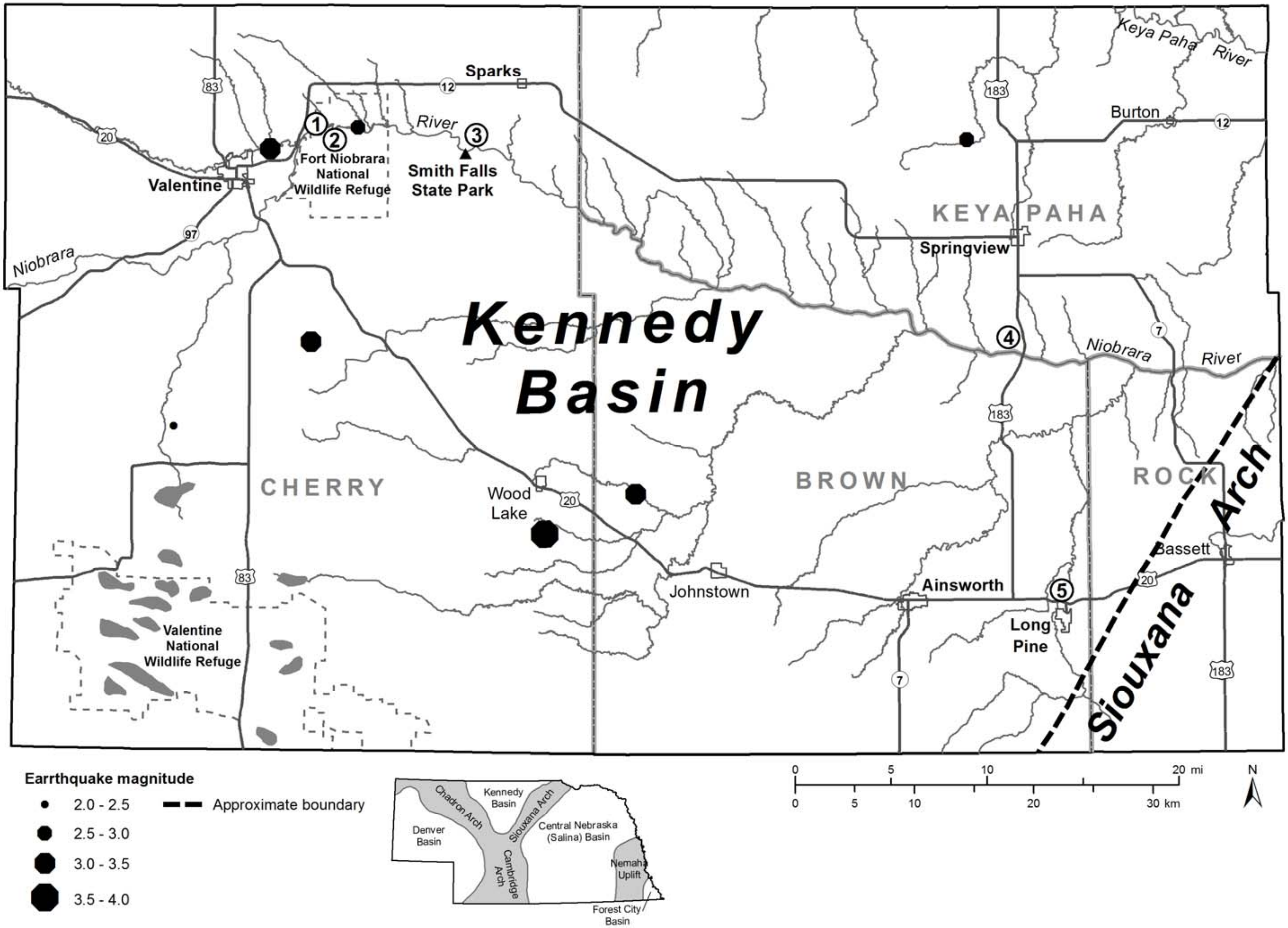

Fig. 7. Historical earthquakes in field trip area and approximate boundary between two major structural features (Kennedy Basin and Siouxana Arch), with inset map of large-scale structural features in Nebraska.

1930s onward (Fig. 7), indicating ongoing tectonism associated with structural features in Phanerozoic sedimentary rocks at depth and in the basement. A magnitude 5.1 earthquake with an epicenter near Merriman, Nebraska, 58 mi (93 km) west of Valentine occurred on March 28, 1964. This earthquake was felt in parts of four states and caused minor damage (United States Geological Survey, undated).

Sediments and sedimentary rocks ranging from Late Eocene to Holocene in age are exposed in the middle Niobrara River Valley (Figs 2, 3, 8). The Upper Cretaceous Pierre shale is exposed at the eastern end of the field trip area Figs. 4), being visible south of Springview, Nebraska in the lower slopes of the Niobrara River Valley (Fig. 8), and it underlies the aforementioned Cenozoic deposits to the west. According to Skinner et al. (1968), Skinner and Hibbard (1972), and Skinner and Johnson (1984) the composite Paleogene-lower Pleistocene succession in north-central Nebraska (including all of Cherry County) is, in ascending stratigraphic order: (1) the upper Eocene-lower Oligocene White River Group, consisting of the Chadron and Brule formations; (2) the middle Oligocene-lower Miocene Arikaree Group, consisting of the Gering Formation plus the Monroe Creek and Rosebud formations, which may be, in part, laterally equivalent (Skinner and Johnson, 1984); (3) the middle to upper Miocene Ogallala Group, consisting of the Valentine and Ash Hollow formations, and (4) the Pliocene (?) and lower Pleistocene Keim and Long Pine formations, the latter of which, at least, is considered to be equivalent to the Broadwater Formation recognized in western Nebraska, if not a direct extension thereof (Swinehart and Diffendal, 1998). The significance of this succession is discernible in the composite Cenozoic section for Nebraska (Fig. 3). In the field trip area, however, local stratigraphic successions are less complete, although the Rosebud, Valentine, and Ash Hollow formations are widespread in the field trip area, and the Chadron Formation may be

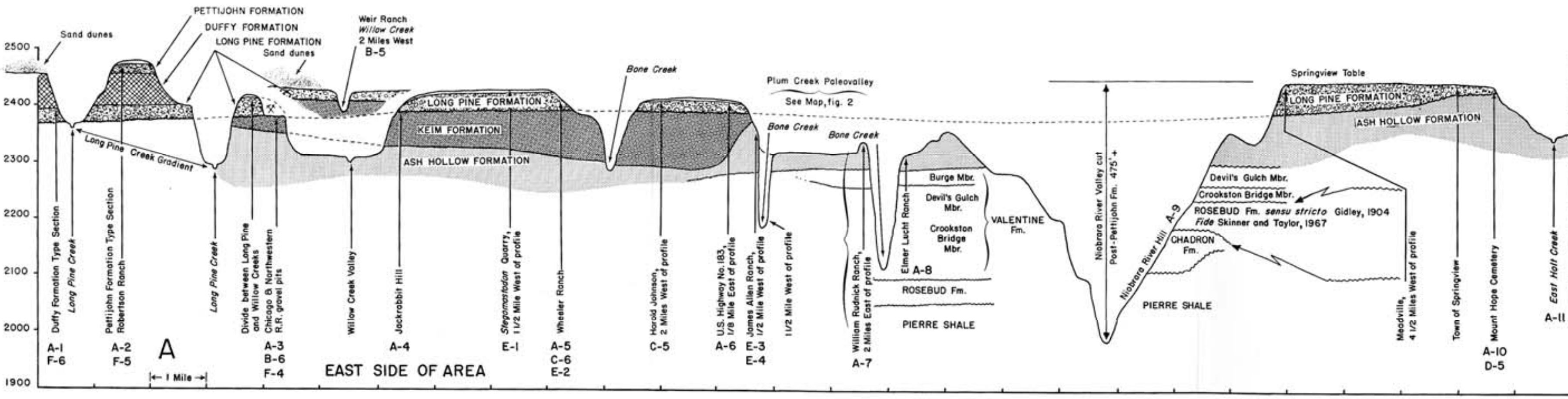

Fig. 8. A) Cross-section from Skinner and Hibbard (1972, fig. 3) showing Springview Table at right and stratigraphy of Niobrara River Valley south of Springview (Stop 4) along U. S. Highway 183.

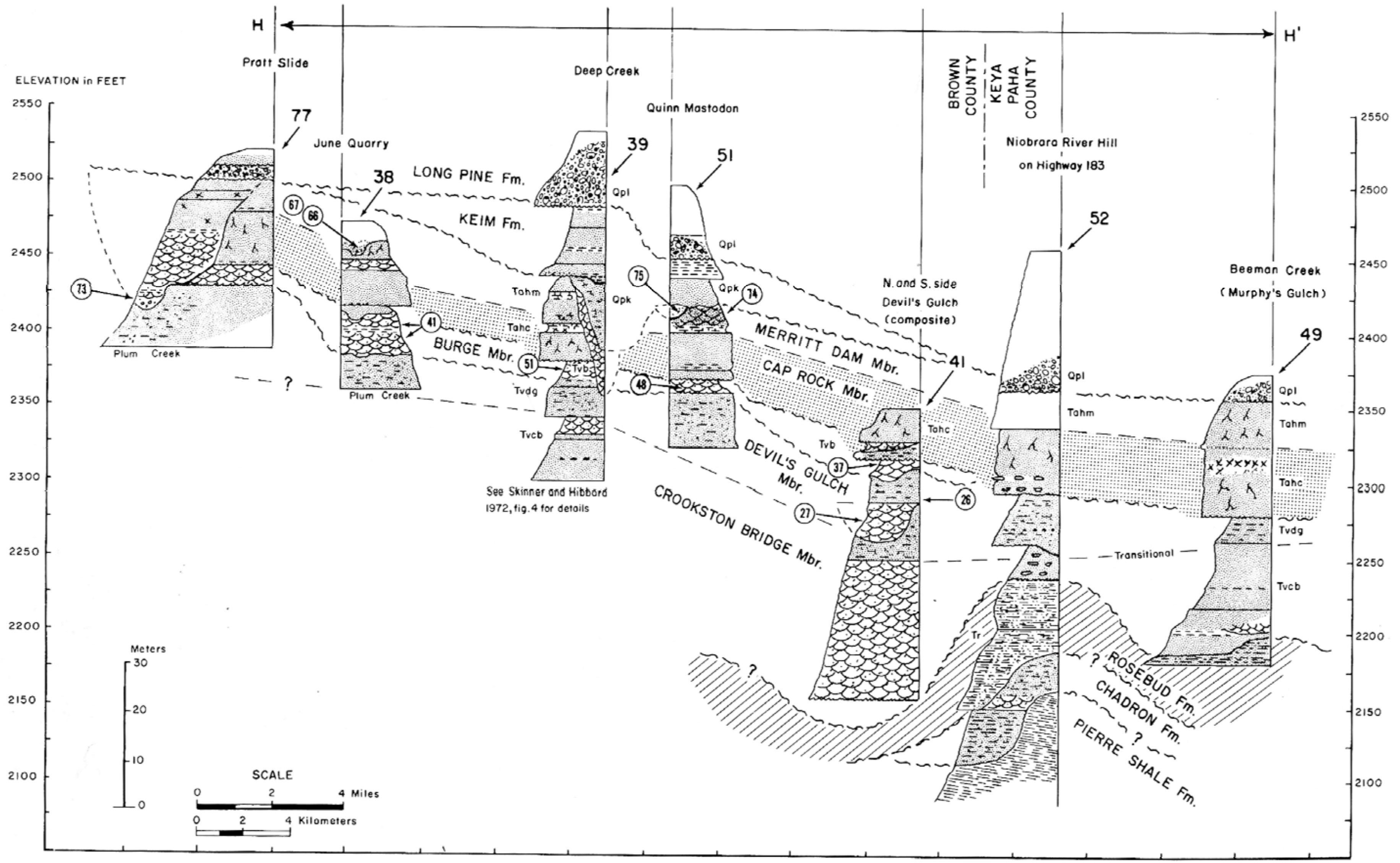

Fig. 8. B) Cross-section from Skinner and Johnson (1984, fig. 37) showing detailed section (#52 in figure) at of stratigraphy at Stop 4 on north side of Niobrara River Valley south of Springview along U. S. Highway 183.

more widespread in the subsurface than the sparseness of outliers suggest. The local Paleogene-Neogene section, as specified above, is dominated by sandy fluvial deposits, but the Chadron, Brule, and Rosebud formations are widely considered to have a significant component of eolian sediments.

The High Plains aquifer in the field trip area (Fig. 9) is hosted chiefly by the Ogallala Group and Quaternary fluvial and eolian sediments, although there may also be groundwater in the upper Brule, Gering, Rosebud, and Monroe Creek formations (Figs. 2, 3). The role of the Rosebud Formation in regional hydrogeology should be investigated in the future, because sands within that formation bear water but its massive siltstones may function as aquitards. The water table in the field trip area declines generally east-northeastward and, although the saturated thickness of the High Plains aquifer is less and more variable north of the Niobrara River, within 15 mi (24 km) south of Valentine, Nebraska, saturated thickness attains values of 400 ft (122 m) or greater under the Sand Hills (Fig. 10). Registered irrigation wells are distributed throughout the area and exhibit some degree of clustering in the vicinity of Ainsworth, Nebraska (Fig. 11). For the most part, there has been no significant change in water levels since pre-development times in the field trip area, but long-term groundwater-level declines have occurred in very small areas both north and south of the Niobrara River (Fig. 12). Areas of slight water-table rise within the field trip area (e.g., north of Ainsworth and east of Springview, Nebraska) are actually greater in aggregate size (Fig. 12). The High Plains aquifer is easily visualized in the middle Niobrara River Valley not merely because its host strata are exposed therein, but also because of the presence of extensive seeps along the valley walls at the contact between the Rosebud Formation and the overlying Valentine Formation. These seeps frequently freeze in wintertime to form ice falls, which have, in themselves, become a minor recreational draw.

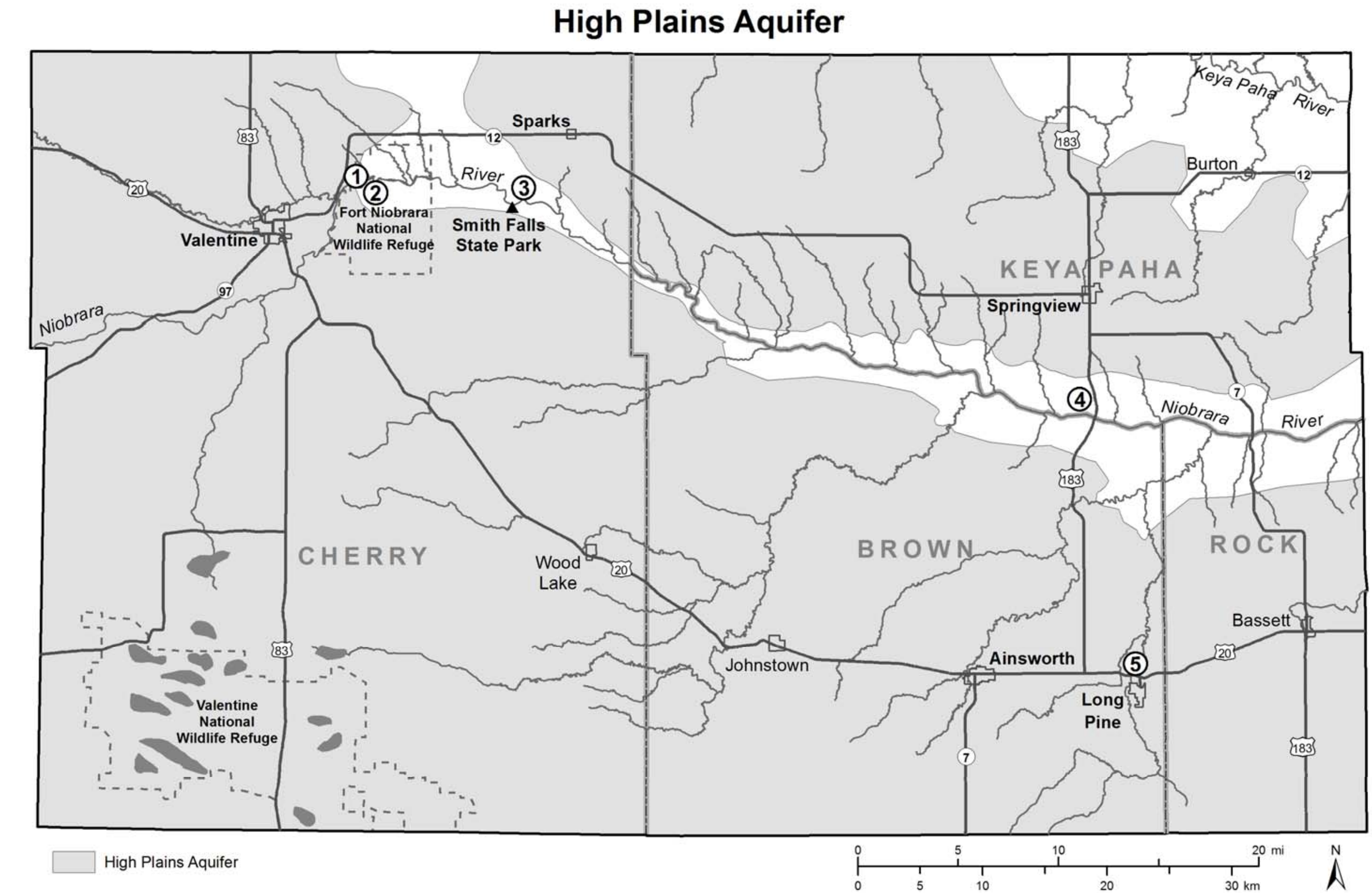

Fig. 9. Distribution of High Plains aquifer in field trip area.

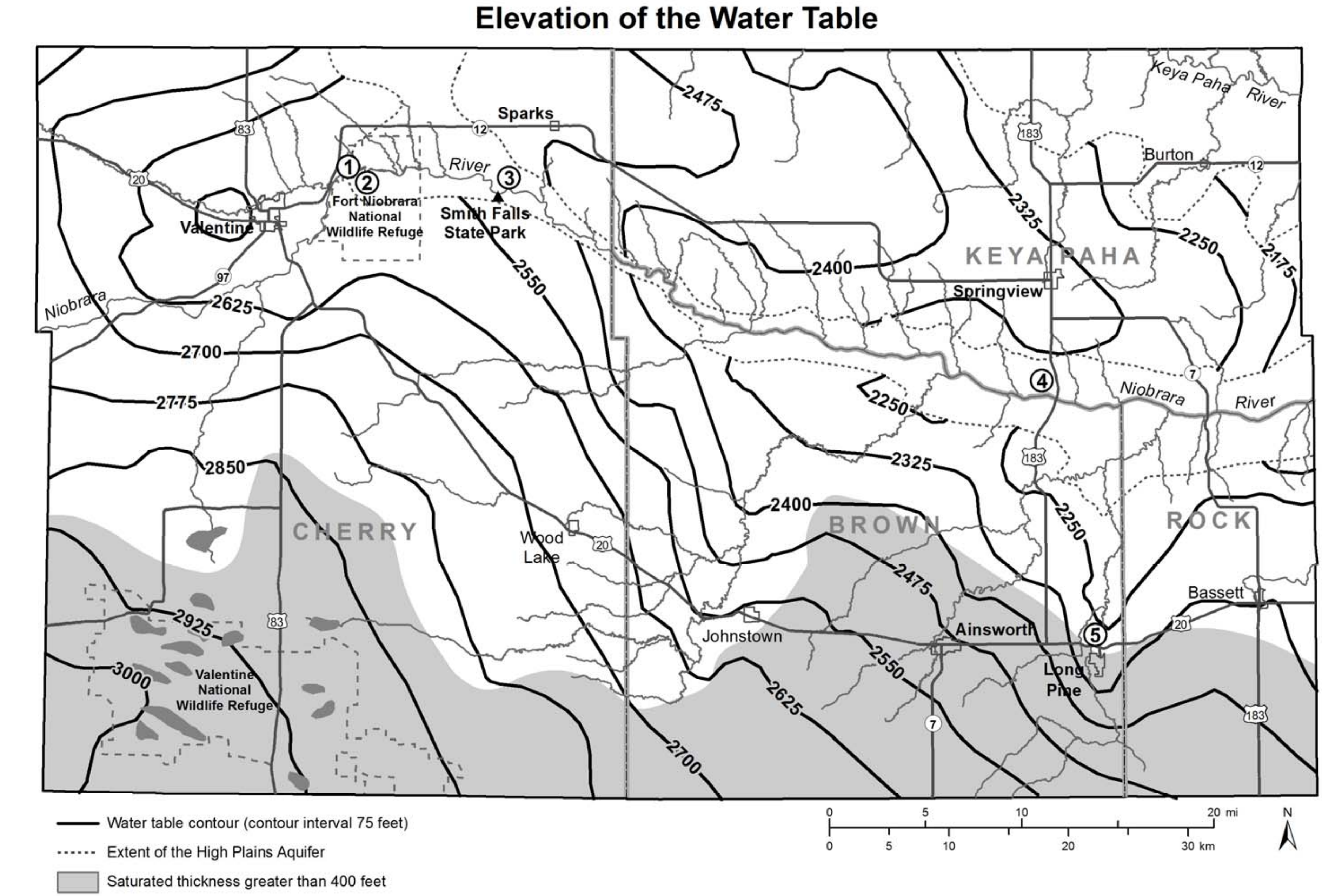

Fig. 10. Elevation of water table in High Plains aquifer in field trip area and distribution of saturated thickness in excess of 400 ft (122 m) within that aquifer.

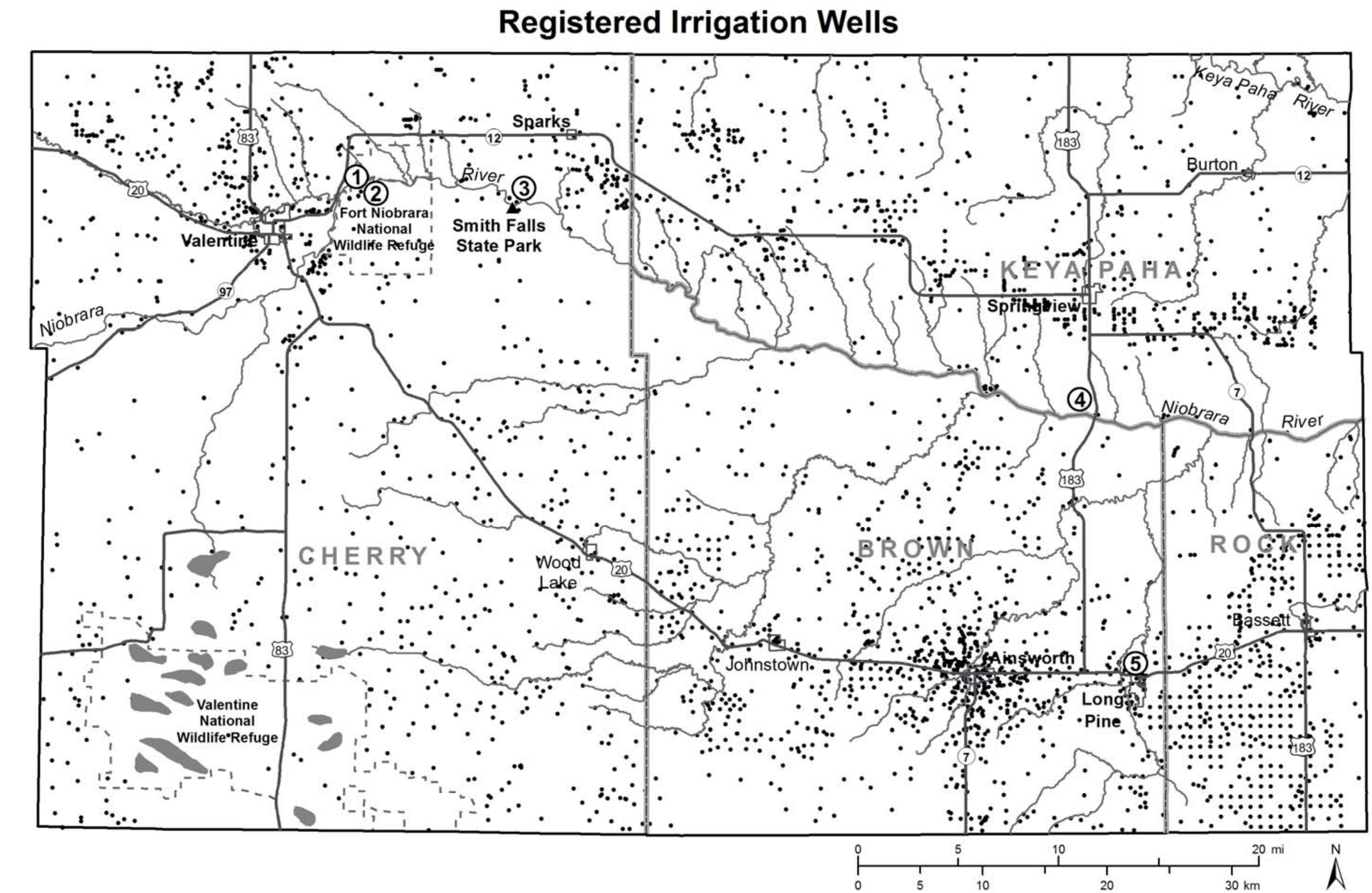

Fig. 11. Distribution of registered irrigation wells within field trip area.

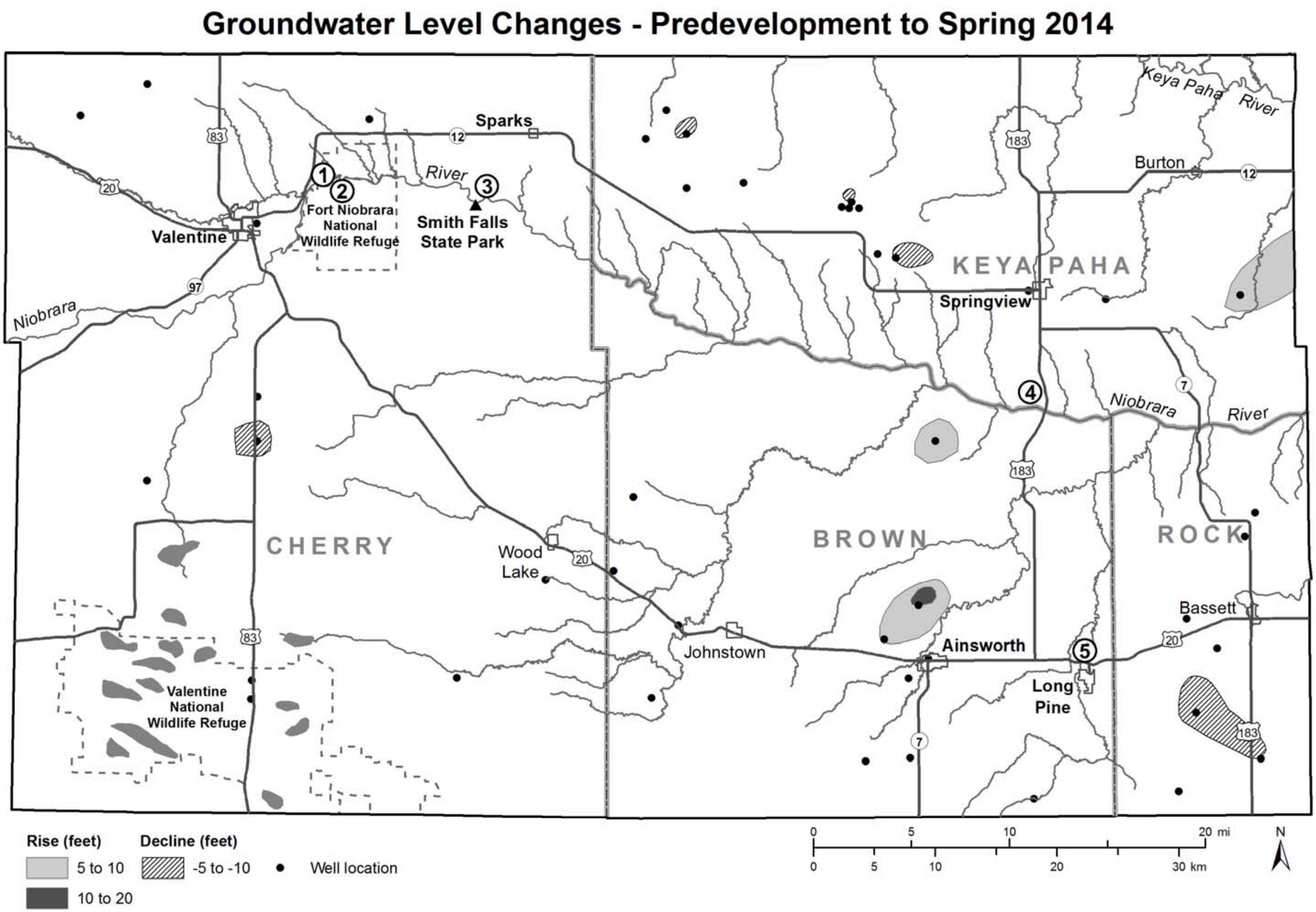

Fig. 12. Long-term groundwater level changes to 2014 within field trip area.

It should be noted that other aquifers lie deeper below the base of the High Plains aquifer in north-central to northeastern Nebraska. The Upper Cretaceous Codell Sandstone of the Carlile Shale yields groundwater locally east of the field trip area and, likewise, a few wells are developed in the fractured upper part of the overlying Niobrara Formation as well. Much more extensive in area, however, are the Great Plains and Western Interior Plains aquifer systems (Jorgenson et al., 1996). The extents, recharge areas, potentiometric surfaces, and other characteristics of these deeper and more extensive aquifers are related to regional geologic structure and the geologic history of deposition, uplift, and erosion.

4. Road narrative and field trip stops

4.1.1. Ainsworth to Valentine, Nebraska and Stop 1 (Niobrara River Valley overlooks)

4.1.1.1 Ainsworth to Valentine, Nebraska on U.S. Highway 20

Ainsworth, Nebraska lies atop the broad, nearly flat-topped feature known as Ainsworth Table, which attains elevations of more than 2500 ft (762 m), and which is dissected to depths in excess of 200 ft (61 m) by Bone Creek approximately 6 mi (10 km) to the northeast. Ainsworth Table has large areas of loam to fine sandy loam soils because it is mantled with Late Pleistocene loess, unlike the Sand Hills immediately to the south and west (Figs. 5, 6, 10-12. There are numerous center-pivot irrigation systems atop the table; water-well bores in the immediate vicinity of Ainsworth penetrate to depths of as little as 60 ft (18 m) to as much as 480 ft (146 m).

The stabilized dunes of the Nebraska Sand Hills first become prominent to the west and south of U.S. Highway 20 approximately 8 mi (13 km) west of the intersection of Nebraska Highway 7 and U.S. Highway 20 in Ainsworth. Multiple types of dunes, as well as eolian sand sheets, are present in the surrounding area. *Domal* and *domal-ridge dunes*, the latter trending northwest-to-southeast, are prominent along the highway from just east of the Brown-Cherry county line northwestward to the vicinity of Wood Lake, Nebraska, where some domal dunes attain relief of 80-140 ft (24-43 m) and diameters in excess of 1 mi (1.6 km). Domal dunes are mound-shaped and may, in this area, be modified barchan dunes (Swinehart, 1998). Domal-ridge dunes are continuous, coalesced dome-like dunes that may, in certain cases, may be modified *barchanoid ridge dunes* (Swinehart, 1998). Between Wood Lake and a point approximately 3 mi (4.9 km) northwest of Arabia, Nebraska, similarly large and comparatively widely spaced *barchan dunes* (crescent-shaped, slip-faced dunes with horns pointing downwind). North of U. S. Highway 20 near the Niobrara River, domal, domal ridge, and barchan dunes give way to *linear dunes* (Swinehart, 1998, fig. 3-19). South of Valentine, Nebraska, barchanoid ridge dunes, the most common and perhaps the most striking dunes in the Sand Hills, dominate.

U. S. Highway 20 enters the Niobrara River Valley approximately 41 mi (66 km) west-northwest of Ainsworth. In Valentine, proceed north on Main Street and turn east onto Nebraska Highway 12.

4.1.1.2 Stop 1: Overlook of Niobrara River Valley and descent of Nebraska Highway 12

The U. S. Fish and Wildlife service maintains two overlooks on the northern rim of the Niobrara River Valley at the northern edge of the Fort Niobrara National Wildlife Refuge on the east side of Nebraska Highway 12 approximately 1.8 mi (6 km) northwest of Valentine, Nebraska . These overlooks, as well as the portion of Nebraska Highway 12 that descends the valley wall southward toward the Niobrara River, provide an excellent opportunity to view and discuss the geomorphology and geology of the Niobrara River Valley (looking eastward) and the Nebraska Sand Hills (looking southward).

Looking eastward down the Niobrara River, deep incision is clearly apparent relative to the high and rolling uplands immediately to the north, which exhibit approximately 120 ft (37 m) of total relief and the rolling Sand Hills on the skyline to the south. The valley of the Niobrara River is incised approximately two and one-half times as deep as the maximum relief in the uplands north of the river. The northern wall of the Niobrara River Valley in the vicinity of Valentine, Nebraska is distinguished by steep slopes and canyons eroded from upper Oligocene and Miocene sediments and sedimentary rocks, whereas the southern wall of the valley is much lower in elevation and is characterized chiefly by an extensive and very young Pleistocene terrace of the Niobrara River, on which Fort Niobrara was established in 1880. The lower slopes on both sides of the valley tend to be steeper and locally produce cliffs. This break in slope is a result of the outcrop of the siltstone-dominated Rosebud Formation, which, although it is soft, is still more resistant to erosion than the overlying silty sands and sands of the Valentine Formation.

Along the descent of Nebraska Highway 12 from the uplands to the Niobrara River, the northern valley wall exposes the following section in ascending stratigraphic order: (1) Rosebud Formation; (2) Valentine Formation, consisting of the Cornell Dam, Crookston Bridge, Devil's Gulch, and Burge members (Skinner et al., 1968; Sinner and Johnson, 1984); and (3) Ash Hollow Formation, consisting of the Cap Rock and Merritt Dam members (Figs. 2, 3). Almost all of the Valentine Formation is unlithified and much of the Ash Hollow Formation is only weakly lithified or unlithified. The slightly indurated, carbonate-cemented, very fine- to fine-grained sandstone of the Cap Rock Member of the Ash Hollow Formation (Skinner et al., 1968) attains 20-50 ft (6-15 m) in thickness and forms a prominent ledge near the top of the northern valley wall and in nearby road cuts along Nebraska Highway 12. Voorhies (1987) recognized the Cap Rock Escarpment as a regionally persistent geomorphic feature on the north side of the Niobrara River in north-central to northeastern Nebraska. The lower contact of the Cap Rock

Member is also the base of the Ash Hollow Formation in north-central and northeastern Nebraska. The Cap Rock Member can be correlated into the area surrounding Ashfall Fossil Beds State Historical Park, approximately 125 mi (200 km) to the east-southeast. In the vicinity of Valentine, Nebraska, steep slopes and small cliffs have formed on the Cap Rock Member and there are local talus fields of large to very large sandstone blocks on the slopes beneath the Cap Rock Member, which are eroded on unconsolidated sediments of the Valentine Formation. The ledge-forming aspect of the Cap Rock Member appears, at least in the Valentine area, to be a near-surface "case hardening" phenomenon because core drilling within 300 ft (91 m) of its cliff-forming edge at the Fort Niobrara National Wildlife Refuge overlook did not intersect a thick cemented zone below the land surface.

The gently rolling uplands north of the north valley wall are underlain by the Merritt Dam Member of the Ash Hollow Formation (Skinner and Johnson, 1984), which overlies the Cap Rock Member (Fig. 2). In this area, the Merritt Dam Member is covered only by modern soil profiles developed in materials weathered from that member or by soils developed atop a thin veneer of eolian sand deposited during the Late Pleistocene and possibly the Holocene as well. Small dune forms can be identified in the latter setting north of Highway 12 near the South Dakota border. The gently rolling uplands north of the Niobrara River are marked by a strong northwest-to-southeast orientation of elongate and apparently streamlined hill summits and of valleys eroded by tributaries of the Niobrara River. The northwest-southeast oriented hill summits are hypothesized to be *yardangs* or streamlined hills eroded by persistent winds (Joeckel et al., 2015). The overall orientation of these putative yardangs is, as would be expected, both parallel to the direction of strong winds during the Pleistocene and roughly perpendicular to the long axes of large dunes, which are depositional features.

Big Beaver Creek, a tributary just east of the overlook area, has at least four levels of Late Pleistocene fill terraces in the northern part of Fort Niobrara National Wildlife Refuge and adjacent areas (Joeckel et al., 2015). These terraces were formed and then abandoned as the creek deepened its valley during the incision of the Niobrara River. Also, there are at least three levels of Quaternary fill terraces along the Niobrara River in the area of the Fort Niobrara National Wildlife Refuge (Joeckel et al., 2015).

Good exposures of Ogallala Group strata (Figs. 2, 3) are limited in size, even on the northern side of the Niobrara River Valley. Photographs in Skinner et al. (1968), Skinner and Johnson (1984), and old photographs reproduced by Voorhies (1987) indicate that these strata were much better exposed in the early to middle 20th century, and astoundingly so. The contact between the silty sands of the Cornell Dam Member and overlying sands of the Crookston Bridge Member of the Valentine Formation is exposed along Nebraska Highway 12 approximately 0.13 mi (0.20 km) north-northwest of the entrance to Fort Niobrara National Wildlife Refuge. Also, there are good exposures of the Cap Rock Member of the Ash Hollow Formation approximately 0.7 mi (1.1 km) farther north-northwest on the highway and upslope, approximately 0.15 mi (0.24 km) south-southwest of its intersection with the access road leading to the aforementioned overlooks.

The field trip route proceeds from Nebraska Highway 12 through the entrance of Fort Niobrara National Wildlife Refuge and along marked access roads to the Fort Falls parking area. Note exposures of the Rosebud Formation at and above road level on the north side of the refuge access road, between the Highway 12 entrance and the Niobrara River, and then again on the upslope grade on the opposite bank of the river. Note also that the refuge headquarters and other buildings lie atop two Quaternary terraces of the ancient Niobrara River.

4.1.2. Stop 2 (Fort Falls and Rosebud Formation outcrops, Fort Niobrara National Wildlife Refuge).

Fort Falls is a scenic highlight of the Fort Niobrara National Wildlife Refuge. Its location indicates a *knickpoint* (comparatively abrupt change in the gradient of a stream) where a small tributary of the Niobrara River descends into the steep lower part of the valley. There are several falls of varying sizes on the outcrop of the Rosebud Formation (Figs. 2, 3) in the field trip area. These knickpoints result from both the cropping out of the more erosion-resistant Rosebud Formation and from the geologically recent incision of the Niobrara River. Knickpoints along the valley walls will gradually migrate upstream (away from the river) on tributaries as erosion proceeds into the distant future.

Immediately downstream of the confluence of the falls and the Niobrara River are large outcrops of the late Oligocene Rosebud Formation, over which groundwater discharges in extensive seeps (ice falls in wintertime) from the overlying Valentine Formation. These seeps were even more prominent in the early 20th century before vegetation spread over the lower valley slopes of the Niobrara River (Voorhies, 1987). The contact between siltstones of the Rosebud Formation and sands of the overlying Valentine Formation is visible in the Fort Falls area. The basal part of the Valentine Formation here and elsewhere exhibits large, irregular masses of light gray to greenish gray opaline silica-cemented sandstone ("quartzite" or "orthoquartzite") that are resistant to weathering.

The exact identity and age of all of the strata grouped under the name "Rosebud" in Nebraska and South Dakota, however, have been debated for some time (Martin, 2011), but the strata referred to as the Rosebud Formation in the field trip area form a coherent package in the context of regional stratigraphy and they are likely to be of Oligocene age (Skinner et al., 1968; Skinner and Johnson, 1984; Martin, 2011). In the middle Niobrara River Valley, the Rosebud Formation contains distinctive sedimentary rock types. Massive siltstones with blocky soil structure and frequently also with unusual banding of unknown origin, may be floodplain fines, loessic deposits, or a combination of both. The distinctive banding present in many of exposures of Rosebud Formation siltstones can easily be discerned in the outcrops downstream from Fort Falls. Cut-and-fill within sequences of thin siltstones, sparse sands, and siltstone-clast conglomerates are prominent in a few exposures. These sequences are interpreted to be gully-fill deposits or the deposits of small streams. One exposure of the upper Rosebud Formation in the area of Fort Niobrara National Wildlife Refuge exhibits a comparatively thick (> 3 m) sheetlike sand body with macroform accretion surfaces indicates bar accretion within a fluvial channel of modest depth. The stratigraphic architecture, lithofacies composition, and depositional origins of the Rosebud Formation are stimulating ongoing research.

Waterfalls on the outcrop of the Rosebud Formation tend to be convex in shape rather than concave. Darryll Pederson, his student Len Mason, and other researchers in the Department of Earth and Atmospheric Sciences at the University of Nebraska-Lincoln examined waterfalls in the Niobrara River Valley in detail during the early 2000s. Pederson et al. (2003) emphasized freeze-thaw weathering and Mason et al. (2004) implicated *salt weathering* (precipitation and hydration of salt efflorescences) as potentially important differential weathering agents in the development of waterfalls on the Rosebud Formation in the Niobrara River Valley.

After the visit to Fort Falls, the field trip route returns to Nebraska Highway 12 by the same route along which it entered Fort Niobrara National Wildlife Refuge, then it proceeds eastward along that highway to the turn southward to Smith Falls State Park (Stop 3), southwest of Sparks, Nebraska.

4.1.3. Stop 3 (Smith Falls State Park) and route to Stop 4

Along Nebraska Highway 12 east of Valentine, exposures of the Ash Hollow Formation are very common, in contrast to the westward route from Ainsworth to Valentine on U.S. Highway 20. The Ogallala Group is, of course, the most widespread geologic unit classified as bedrock in the entire field trip area (Fig. 4). Thin eolian sands and tracts of dunes are also present on uplands north of the Niobrara River, but the terrain is distinctly different from that of the Sand Hills because bedrock is comparatively shallow. The field trip route proceeds eastward on Highway 12 and then south on the marked access road to Smith Falls State Park. The rim of the Niobrara River Valley is encountered again 2.7 mi (4.3 km) south of Highway 12 on that access road, which descends through the Ash Hollow, Valentine, and Rosebud formations.

Smith Falls, developed on the outcrop of Rosebud Formation, is Nebraska's highest waterfall, approaching 70 ft (21 m) in height. Like Fort Falls, it is developed on the steeper slopes produced by the outcrop of the Rosebud Formation. There are prominent fractures and a few *slickensides* (grooved, polished failure surfaces) within the Rosebud Formation near the falls. The contact between the basal Valentine Formation and the Rosebud Formation is also visible within the park.

After visiting Smith Falls, the field trip will return northward on the park access road to Nebraska Highway 12 and then proceed eastward on that highway through Sparks, Nebraska. Approximately 2 mi (3.2 km) west of Sparks and 3.1 mi (5 km) north of Highway 12 is the topographic feature known as Flattop, an isolated butte developed on strata of the upper Ash

Hollow Formation and standing approximately 100 ft (30.5 m) above the surrounding terrain. Flattop is visible for some distance along Highway 12 during clear weather. There are other prominent erosional remnants of Ogallala Group strata on the north side of the Niobrara River within 80 mi (130 km) to the east, including the Forked Hills or Twin Buttes near Naper, the Harvey Buttes at Butte, and Stony Butte near Verdel, Nebraska. From Sparks, the route proceeds eastward to Springview, Nebraska, then southward on U. S. Highway 183 to Stop 4. Note that the Springview Table, another broad, flat-topped landform similar in overall morphology to the Ainsworth Table, is underlain by sands and gravels of the Long Pine Formation of Skinner and Hibbard (1972), otherwise equivalent to the Broadwater Formation of western Nebraska.

4.1.4. Stop 4 (Bedrock exposures along U.S. Highway 183 and Niobrara River Valley south of Springview, Nebraska)

Skinner and Hibbard (1972, fig. 3) and Skinner and Johnson (1984, Fig. 37) documented the existence of the Chadron Formation of the White River Group (Fig. 3) in road cuts along the east side of U. S. Highway 183 south of Springview and approximately 1.2- 1.6 mi (2-2.5 km) road miles north of the north bank of the Niobrara River (Fig. 8). In the immediate area, massive, blocky weathering claystones of the Chadron Formation are directly overlain by the Rosebud Formation of the Arikaree Group, and the Valentine and Ash Hollow formations of the Ogallala Group are exposed farther upslope. According to Skinner and Hibbard (1972), the existence of a White River Formation outlier was recognized as early as 1955, although the general geological community is unaware that there are multiple small outliers of the Chadron

Formation in the north-central Nebraska. Underneath the Chadron Formation, the weathered upper part of the Upper Cretaceous Pierre Shale is largely covered by vegetation.

Hereafter, the field trip proceeds south on U. S. Highway 183 to its intersection with U. S. Highway 20, and then turns eastward on U. S. Highway 20 and proceeds to Long Pine, Nebraska (Stop 5).

4.1.5. Stop 5 (Long Pine, Nebraska)

Skinner and Hibbard (1972) named the Long Pine Formation for prominent crystalline gravels cropping out in the vicinity of Long Pine, Nebraska (Fig. 8). Swinehart et al. (1985) and Swinehart and Diffendal (1998) consider the gravels that trend north-northeastward from Morrill County in the Nebraska Panhandle into the field trip area and beyond to be sourced from southeastern Wyoming and interpreted them to represent a paleodrainage emerging from the Laramie Mountains, nearly 300 mi (480 km) west-southwest of present-day Long Pine. In effect, the Broadwater Formation (Fig. 3), named in the Nebraska Panhandle, and the Long Pine Formation are the deposits of the same late Pliocene-early Pleistocene fluvial system (Swinehart and Diffendal, 1998).

After Stop 5 the field trip returns westward to Ainsworth on U. S. Highway 20, where the trip ends.

References

Bessey, C.E., 1887. A meeting-place for two floras. Bulletin of the Torrey Botanical Club 14: 189-191.

Bristow, C.S., Skelly, R.L., Ethridge, F.G., 1999. Crevasse splays from the rapidly aggrading, sand-bed, braided Niobrara River, Nebraska: effect of base-level rise. Sedimentology 46: 1029-1047.

Buchanan, J.P., Schumm, S.A., 1990. Niobrara River. In: Wolman, M.G., Church, M., Newbury, R., Lapointe, M., Frenette, M., Andrews, E.D., Lisle, T.E., Buchanan, J.P., Schumm, S.A., Winkley, B.R., The riverscape, pp. 314-321. In: Wolman, M.G., Riggs, H.C. (Eds.) Surface Water Hydrology: The Geology of North America Vo. O-1. Geological Society of America, Boulder, Colorado, pp. 281-328.

Carlson, M.P., 1999. Transcontinental Arch—a pattern formed by rejuvenation of local features across central North America. Tectonophysics 305: 225-233.

Hearty, P.J., 1978. The biogeography and geomorphology of the Niobrara River Valley near Valentine, Nebraska. Unpublished M.S. thesis, University of Nebraska-Omaha.

Jacobs, K.C., Fritz, S.C., Swinehart, J.B., 2007. Lacustrine evidence for moisture changes in the Nebraska Sand Hills during Marine Isotope Stage 3. Quaternary Research 67: 246-254.

Janis, C.M., Gunnell, G.F., Uhen, M.D., 2008. Introduction. In:. Janis, C.M., Gunnell, G.F., Uhen, M.D. (Eds.), Evolution of Tertiary mammals of North America, Vol. 2: Small mammals, xenarthrans, and marine mammals. Cambridge University Press, Cambridge, pp. 1-6

Joeckel, R.M., Tucker, S.T., Howard, L.M. 2015. Surficial Geology of the Cornell Dam 7.5 Minute Quadrangle, Nebraska. Conservation and Survey Division, School of Natural

Resources, University of Nebraska-Lincoln. [URL http://snr.unl.edu/data/geologysoils/STATEMAP/quads.aspx?valentine].

Jorgenson, D.G., Helgesen, J.O., Signor, D.G., Leonard, R.B., Imes, J.L., Christenson, S.G., 1996. Analysis of regional aquifers in the central Midwest of the United States in Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—summary. United States Geological Survey Professional Paper 1414-A, 67 p.

Kantak, G.E., 1995. Terrestrial communities of the middle Niobrara Valley, Nebraska. The Southwestern Naturalist 40: 129-138.

Kantak, G.E., Churchill, S.P., 1993. The Niobrara Valley Preserve: inventory of a biological crossroads. Transactions of the Nebraska Academy of Sciences 10: 1-2.

Kaul, R.B., Kantak, G.E., Churchill, S.P., 1988. The Niobrara River Valley: a postglacial migration corridor and refugium for forest plants and animals in the grasslands of central North America. Botanical Review 54: 44-81.

Larson, C., 2001. Provenance, Distribution, and Sand Hills dune sand source potential, Connely Flat Beds, (Latest Wisconsin), Niobrara River, Ainsworth to Merriman, Nebraska. Unpublished M.S. thesis, University of Nebraska-Lincoln.

Martin, J.E. 2011. The Rosebud problem revisited. Proceedings of the South Dakota Academy of Science 90: 37-50.

Mason, L.J., Pederson, D.T., Goble, R.J., Voorhies, M.R., 2004. Salt weathering of waterfall escarpments along the Niobrara River near Valentine, Nebraska. Geological Society of America Abstracts with Programs 36: 231.

Miao, X., Mason, J.A., Swinehart, J.B., Loope, D.B., Hanson, P.R., Goble, R.J., Liu, X., 2007. A 10,000 year record of dune activity, dust storms, and severe drought on the Great Plains. Geology 35: 119-122.

Pederson, D.T., Mason, L.J., Goble, R.J., 2003. The origin of convex waterfalls along the Niobrara River by Valentine, Nebraska. Eos 84, Issue 46 Supplement.

Sims, P.K., Petermayr, Z.E., 1986. Early Proterozoic Central Plains orogeny: a major buried structure in the north-central United States. Geology 14: 488-491.

Skinner, M.F., Hibbard, C.W., 1972. Early Pleistocene pre-glacial rocks and faunas of north-central Nebraska. Bulletin of the American Museum of Natural History 148: 1-148.

Skinner, M.F., Johnson, F.W. 1984. Tertiary stratigraphy and the Frick Collection of fossil vertebrates from north-central Nebraska. Bulletin of the American Museum of Natural History 178: 217–368.

Skinner, M.F., Skinner, S.M., and Gooris, R.J. 1968. Cenozoic rocks and faunas of Turtle Butte, South-Central South Dakota. Bulletin of the American Museum of Natural History 138: 379-436.

Swinehart, J.B., 1998. Wind-blown deposits. In: Bleed, A.S., Flowerday, C.A. (Eds.), An Atlas of the Sand Hills. Resource Atlas No. 5b (3rd edition), Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, pp. 43-56.

Swinehart, J.B., Diffendal, R.F., 1998. Geology of the pre-dune strata. In: Bleed, A.S., Flowerday, C.A. (Eds.), An Atlas of the Sand Hills. Resource Atlas No. 5b (3rd edition), Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, pp. 29-42.

Swinehart, J.B., Souders, V.L., DeGraw, H.M., Diffendal, R.F., Jr., 1985. Cenozoic paleogeography of western Nebraska. In: Flores, R.M., Kaplan, S.S. (Eds.), Cenozoic Paleogeography of the West-Central United States. Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section Rocky Mountain Paleogeography Symposium 3, pp. 209–229.

Tedford, R.H., L. B. Albright, A.D. Barnosky, Ferrusquia-Villafranca, I., Hunt. R.M., Jr., Storer, J.E., Swisher, C.C., III, Voorhies, M.R., Webb, S.D., Whistler, D.P. 2004. Mammalian biochronology of the Arikareean through Hemphillian Interval (late Oligocene through early Pliocene epochs) in North America. In: M. O. Woodburne, M.O. (Ed.), Late Cretaceous and Cenozoic Mammals of North America, Biostratigraphy and Geochronology. Columbia University Press, New York, pp. 169-231

United States Department of Agriculture, Natural Resources Conservation Service, 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. U.S. Department of Agriculture Handbook 296.

United States Geological Survey, undated. Nebraska: Earthquake history. [URL http://earthquake.usgs.gov/earthquakes/states/nebraska/history.php].

Voorhies, M.R., 1987. Late Cenozoic stratigraphy and geomorphology, Ft. Niobrara, Nebraska. In: Biggs, D.L. (Ed.), Centennial Field Guide Volume 3. North-Central Section of the Geological Society of America, pp. 1-6.