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Geologic Mapping of Nebraska: Old Rocks, New Maps, Fresh Insights

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Geologic Mapping of Nebraska

Old Rocks, New Maps, Fresh Insights

R. M. Joeckel, R. F. Diffendal Jr., P. R. Hanson, and J. T. Korus

ABSTRACT—Geologic mapping in Nebraska and environs is an ongoing endeavor that has spanned more than 170 years, involved dozens of scientists, and evolved through many changes. Digital mapping has risen to dominance in the state only since 1996. Geologic mapping in Nebraska today concentrates on surficial mapping, which emphasizes materials exposed at the land surface and their relationships with landforms, and which is particularly relevant because non-bedrock geologic materials (regolith) lie at the surface across at least 87% of the state. Moreover, surficial geologic maps assist the understanding of groundwater and sand and gravel resources, to name a few applications. The statewide bedrock map of Nebraska, which dates to 1986, remains an important and widely used geologic map, but it needs to be revised. Notwithstanding, when contemplated deeply, Nebraska's statewide bedrock map reveals that (1) effects of gentle geologic structure, mainly those that came to be in the past 80 million years, can be discerned, and (2) some aspects of the map patterns (not the mapped sedimentary rocks per se) probably predate the beginning of the Pleistocene Epoch, about 2.6 million years ago. The geologic mapping of Nebraska, however, is far from completed.

Key Words: bedrock, geologic history, landforms, surficial geology

Introduction

In this article we explore the past, present, and future of geologic maps and mapping in Nebraska and adjacent parts of the Great Plains and Central Lowland. We also describe developments that will improve geologic mapping, contemplate existing maps to achieve new insights, and describe new discoveries that have been made in the process of mapping Nebraska's geology.

Geologic maps are complex, dynamic, and site-specific scientific hypotheses about our physical environment, drawn at an established scale and according to certain technical standards. They are produced today by a combination of field and computer work, the latter aspect having grown markedly in importance merely in the last two decades (e.g., Mookerjee et al. 2015; Chan et al. 2016). Geologic maps can now include laboratory data as well. The execution and evaluation of geologic maps employ scientific methods just as much as any endeavor in the sciences does, even though mapping is not commonly credited in this regard. What is more, geologic maps remain forms of art, so much so that they have been referred to as "the prettiest information resources" (Swoger 2013) of all. Nevertheless, for all that they are and all the insights that they can provide, geologic maps are either unknown to, or underappreciated by, most of society.

Geologic maps convey information about the distribution, nature, and age relationships of Earth materials, which can be subdivided as rock and *regolith*, the latter being the wide range of loose or unconsolidated materials overlying intact bedrock, including heavily weathered bedrock, soils and soil parent materials, and deposits laid down by wind, water, glacial ice, and mass movements such as landslides. Geologic maps can depict either bedrock alone, regolith alone, or both simultaneously. They may also depict or explain:

1. <u>Geologic structures</u>, such as folds, faults, and joints, among others. Indeed, several long faults have been

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mapped in Nebraska, particularly in the southeastern (e.g., Humboldt and Union faults) and northwestern corners of the state, where bedrock exposures are more common. Other mappable faults no doubt exist in the state but are covered by regolith.

2. Energy resources and industrial and ore mineral deposits and their locations. One example relevant in the recent economic development of Nebraska is the Elk Creek carbonatite (Johnson and Pawnee Counties)—a buried igneous rock body containing rare-earth elements and the alloying metal niobium. Likewise, petroleum-producing areas have been mapped in Nebraska and elsewhere across the Great Plains. Industrial mineral resources such as limestone (for aggregate, riprap, cement, agricultural lime, etc.), clays (for brick, tile, and other uses), sand and gravel (for construction, aggregates, and nowadays even hydraulic fracturing), and many other commodities can and should be portrayed on geologic maps. Limestone, clays, and sand and gravel are commodities of specific economic importance in Nebraska.

3. Groundwater conditions, such as the geographic distribution of aquifers and confining units, water-table elevations (relative to unconfined aquifers), the potentiometric surfaces of confined aquifers, and the direction of groundwater flow. Annual maps of water-level changes have proven to be very useful for water management in Nebraska.

4. Geologic hazards, including, but not limited to, seismicity (earthquake potential) and mass movements, such as landslides. There are also hazardous minerals, such as the fibrous zeolite known as erionite ($Ca_5[Si_{26}Al_{10}O_{72}] \cdot 30H_2O$), which exists only in particular kinds of rocks and which is known to cause mesothelioma (Kliment et al. 2009; Van Gosen et al. 2012). Radon gas, naturally produced by the radioactive decay of uranium, qualifies as a geological hazard as well, and its occurrence can certainly be related to the mapped distributions of specific bedrock strata (such as a number of named and regionally correlated thin, black, uranium- and phosphate-bearing shales in the Pennsylvanian and Permian systems, and the thick and widespread Cretaceous Pierre Shale), some surficial sediments, and particular kinds of soils, all of which can produce radon (e.g., Schumann 1993; Lyle 2007). So, too, naturally occurring contaminants in groundwater, such as arsenic and uranium (e.g., Gosselin et al. 2006; Nolan and Weber 2015), have a genetic association with particular bodies of Earth materials, and their distribution is mappable in multiple ways. All of the aforementioned geologic hazards, among others, present some level of risk in various parts of Nebraska and can be represented in some way on geologic maps.

5. Conditions and parameters that are relevant to various forms of waste disposal. Nebraska's controversial, abortive, and ultimately costly participation in the Low-Level Radioactive Waste Compact during the years 1983–2004 (e.g., Benford et al. 1993; Cragin 2007; O'Hanlon 2011) involved extensive geological investigations that emerged from, and contributed to, mapped geological data.

6. Conditions and parameters that are relevant to the siting of infrastructure and facilities. We note that the Keystone XL pipeline extension has been a particularly sensitive issue in Nebraska.

7. Diverse other information (landforms and their relationships with Earth materials, fossil distributions, etc.).

Traditional geologic maps may include, in addition to a narrative, one or more vertical cross-sections downward from the Earth's surface to some key depth, thereby depicting changes in the thicknesses and structural relationships of strata beneath a region that may not be obvious in map view alone. Such protocols in making and presenting geologic maps are rooted in two centuries of tradition. Moreover, the activity of geologic mapping has a rich history in Nebraska and in the North American interior. This history illustrates general trends in the development of the science of geology, in technology, and in societal needs that began before Nebraska was organized as a territory in 1854.

History of Geologic Mapping in Nebraska and Environs

Humans have been utilizing geologic resources for more than three million years (Harmand et al. 2015) and they probably had mental or cognitive maps of the locations of those resources (e.g., Graham 1976). Physical maps depicting geographic and geologic features appeared by 1150 BCE in the circum-Mediterranean region (Harrell and Brown 1992) and, debatably, as early as 6600 BCE (Schmitt et al. 2014).

Pre-Columbian Native Americans in what is now Nebraska collected or quarried chert, flint, jasper, quartz, quartzite, and other hard, durable and knappable materials to make stone tools. Various other Earth materials (pipestone, copper, mica, obsidian, soap-

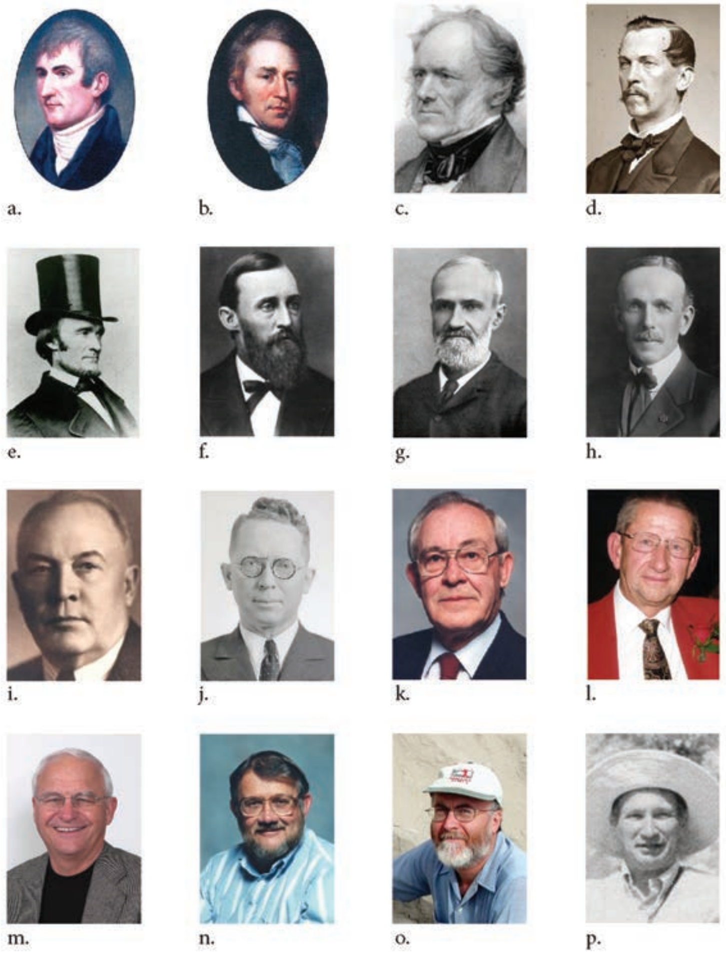

Figure 1. Some geologic mappers of Nebraska and the Great Plains, 1803 to 2003: **(a)** Meriwether Lewis (1774–1809); **(b)** William Clark (1770–1838); **(c)** Sir Charles Lyell (1797–1875); **(d)** Gouveneur K. Warren (1830–1882); **(e)** Fielding B. Meek (1816–1876); **(f)** Ferdinand V. Hayden (1829–1887); **(g)** Samuel A. Aughey (1832–1912); **(h)** Nelson Horatio Darton (1865–1948); **(i)** George E. Condra (1869–1958); **(j)** Alvin L. Lugn (1895–1976); **(k)** Vincent H. Dreeszen (1921–2006); **(l)** Raymond R. Burchett (1935–2015); **(m)** Duane A. Eversoll; **(n)** Vernon L. Souders (1936–2014); **(o)** James B. Swinehart; **(p)** R. F. Diffendal Jr.

stone, etc.) were acquired elsewhere and traded over long distances in the interior of North America. It is difficult to be certain whether Paleoamericans actually drew maps to record the location of these resources, but it is abundantly clear that Native Americans produced physical maps—although certainly not geologic maps—later in history, both before and after Columbian contact (Mundy 1988; Warhus 1997; Lewis 1988). When Europeans began to acquire the lands that ultimately became the United States they began to make maps of the new lands and to note the locations where they found geologic resources. These early maps do not qualify as geologic maps in the modern sense. Beginning in the early 1800s, however, explorers and scientists were publishing detailed notes about geologic features and geologic maps of various kinds began to be drawn in the US. By the end of the same century, maps illustrating the geology of Nebraska and environments with meaningful accuracy had been published.

During their 1804–1806 exploration along the Missouri River and beyond, William Clark and Meriwether Lewis (Fig. 1a–b) marked the locations of coal, grinding stone, fresh- and saltwater springs and other resources on maps of the lands across which the expedition traveled. These were not geologic maps in the modern sense, but the locations were accurate because the geologic resources can still be found today at those places (Diffendal and Diffendal 2003).

Shortly after the Lewis and Clark Expedition, William Maclure produced a rudimentary geologic map of the US, extending to the Mississippi River (Maclure 1809; Library of Congress n.d.). Nevertheless, the archetype for modern geologic maps is widely regarded to be the famous 1815 geologic map of Great Britain produced by the self-taught polymath William “Strata” Smith (Oldroyd 2013). The first geologic map that included part of the Great Plains in the US was probably the one drawn in 1843 by the widely traveled British geologist and lawyer Sir Charles Lyell and published in 1845 (Figs. 1c, 2). Lyell mapped Cretaceous rocks in small parts of what is now northeastern Nebraska and southeastern South Dakota. He also used the written observations of Prince Maximilian of Wied-Neuwied, who noted such strata on his travels across parts of the US and up the Missouri River in 1832–34, to draw the area where these rocks were known to occur. Lyell’s geologic map (Lyell 1845) was published at the very coarse scale of 1:8,446,000, so that 1 cm on the map represents approximately 84.5 km on the actual land surface (1 in = 133 mi).

The new lands of the Louisiana Purchase and other western lands clearly needed to be surveyed for natural resources by the US government. Therefore, federal government–funded scientific surveys, originally under the auspices of the US Army Topographical Engineers, began in the 1850s. The Hayden, Wheeler, King, and Powell surveys, so named for the individuals who led them, are considered to be the "four great surveys of the [American] West." Their work, including the eventual publication of results, extended from the late 1860s into the 1890s (Bartlett 1962; Rabbit 1989). Surveys led by the naturalist, physician, and geologist Ferdinand V. Hayden and military mapping groups led by West Point graduate and brevet major Gouveneur K. Warren (later to gain fame at Little Round Top in the Battle of Gettysburg in 1863) and others produced the first usable geologic maps of large parts of the Great Plains including modern Nebraska (Figs. 1d, 1f, 2). Fossils collected on the several Hayden expeditions were identified and described by Fielding B. Meek, a former businessman who became a famous paleontologist (Fig. 1e). The maps were published after the Civil War in a series of reports by Hayden (1869, 1872, n.d. [probably 1883]). On these maps much of Nebraska was shown to be covered by the "White River Tertiary," a rock unit name he coined that is still used today, although it is now significantly restricted to a few sedimentary rock formations. Federal patronage of science was a critical ingredient in surveys such as those led by Hayden, who has been described as a "public entrepreneur of science," as a "changing environment for science in the United States and the federal government" came to be (Cassidy 2000, 319).

Samuel Aughey, an antislavery Lutheran minister (Aughey 1861), early University of Nebraska professor, and honorary Nebraska state geologist, produced a geologic map of the state dated 1875 that was included in a book about Nebraska written by Edwin Curley in 1876 (Figs. 1g, 3). The map purported to show surface geology and underlying bedrock, including the eastern boundary of the Tertiary (today the Paleogene and Neogene Systems), the boundaries of the Cretaceous, Permian, Upper Carboniferous (Pennsylvanian), and "Potsdam," the name of a sandstone-dominated Cambrian sedimentary-rock unit in New York, Vermont, Quebec, and Ontario. Much of what Aughey showed on his map appears to have been taken from the earlier maps produced by F. V. Hayden, including the usage of "Potsdam." Aughey subsequently published a revised map that showed an area in Dundy County as underlain by the Cretaceous "Laramie" Formation (Aughey 1884), the usage of which is today restricted to northeastern Colorado.

The maps of Lyell, Hayden, and Aughey are historically interesting and set the stage for more refined work. The modern era of geological mapping, which truly began in the field season of 1897 and in 1898, resulted in publication of a report on the groundwaters of southeastern Nebraska and maps by Nelson Horatio Darton (Figs. 1h, 3), a United States Geological Survey (USGS) geologist who had read Lyell's seminal *Principles of Geology* in his youth (Monroe 1949). Maps were done on a topographic base in this and later reports. Darton published a generalized surficial geologic map of Nebraska on a topographic base at a scale of 1:2,500,000 in a report published in 1899 and reprinted with minor corrections in 1903 (Darton 1899, 1903). The report included maps showing groundwater, springs, surface water, irrigation development, and timber resources, as well as photographs taken with a camera using glass plates. Two years later Darton (1905) published a major report on the geology of the central Great Plains that contained even more data and maps from southeastern Wyoming, southern South Dakota, eastern Colorado, Nebraska, and northern Kansas.

Darton and his field crew did their research and mapping under very difficult field conditions, traveling at times by horse-drawn wagon, on horseback or on foot with only a few assistants. In comments he gave at the ceremony where he was awarded the prestigious Penrose Medal by the Geological Society of America in 1940, Darton commented that on one such trip he and his crew were forced to flee a prairie fire set by Native Americans (Darton 1941).

Darton completed an astounding body of work during his career with the USGS (King 1949; Monroe 1949). He drew detailed geologic maps of Minnesota, Iowa, South Dakota, Nebraska, Kansas, a sliver of Oklahoma, Texas, eastern Colorado, Wyoming, southeastern Montana, New Mexico, Arizona, and small parts of southern California in the West, as well as maps of New York and other eastern states. Darton also named or renamed new geologic formations and described them in detail. Among these names of formations are Ogalalla (spelling later changed to Ogallala), Arikaree, Gering, Brule, and Chadron, all of which are still used today by geologists in Nebraska and elsewhere. Anyone who uses Darton's reports can still find a site on one of his maps and go there to see the geologic materials that he described.

After the creation of the Conservation and Survey Division (CSD) of the University of Nebraska by the

Figure 2. Pre-statehood early geologic maps of Nebraska. (Top) Excerpt from geologic map by Charles Lyell (1845), showing Cretaceous bedrock strata in small part of present Nebraska (dashed outline). (Bottom) Excerpt of 1857 map by G. K. Warren and F. V. Hayden showing Paleogene and Neogene (yellow, labeled “Tertiary”), Cretaceous (green), and Pennsylvanian (blue, labeled “Carboniferous”) bedrock strata in present Nebraska (dashed outline). Already apparent are rudiments of patterns expressed in latest statewide bedrock map (Burchett 1986).

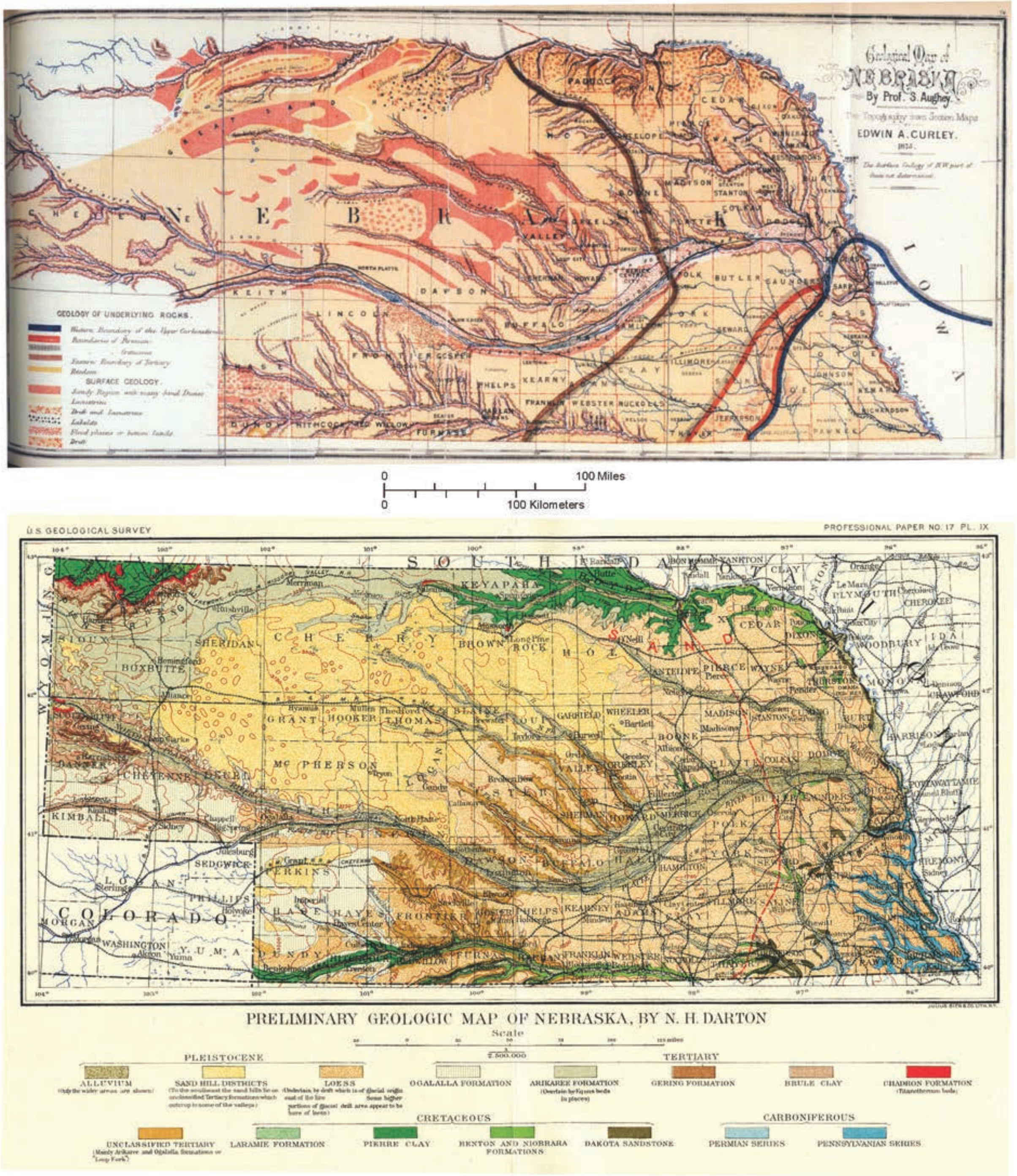

Figure 3. Post-statehood early geologic maps of Nebraska. (Top) Geologic map by S. A. Aughey, published by Curley (1875). It is fundamentally a surficial geologic map, on which the approximate geographic limits of outcrops and subcrops of Cretaceous and Pennsylvanian bedrock strata are superimposed. (Bottom) Preliminary geologic map by Darton (1899). It is also a surficial geologic map, representing both exposed or very shallow bedrock and regolith.

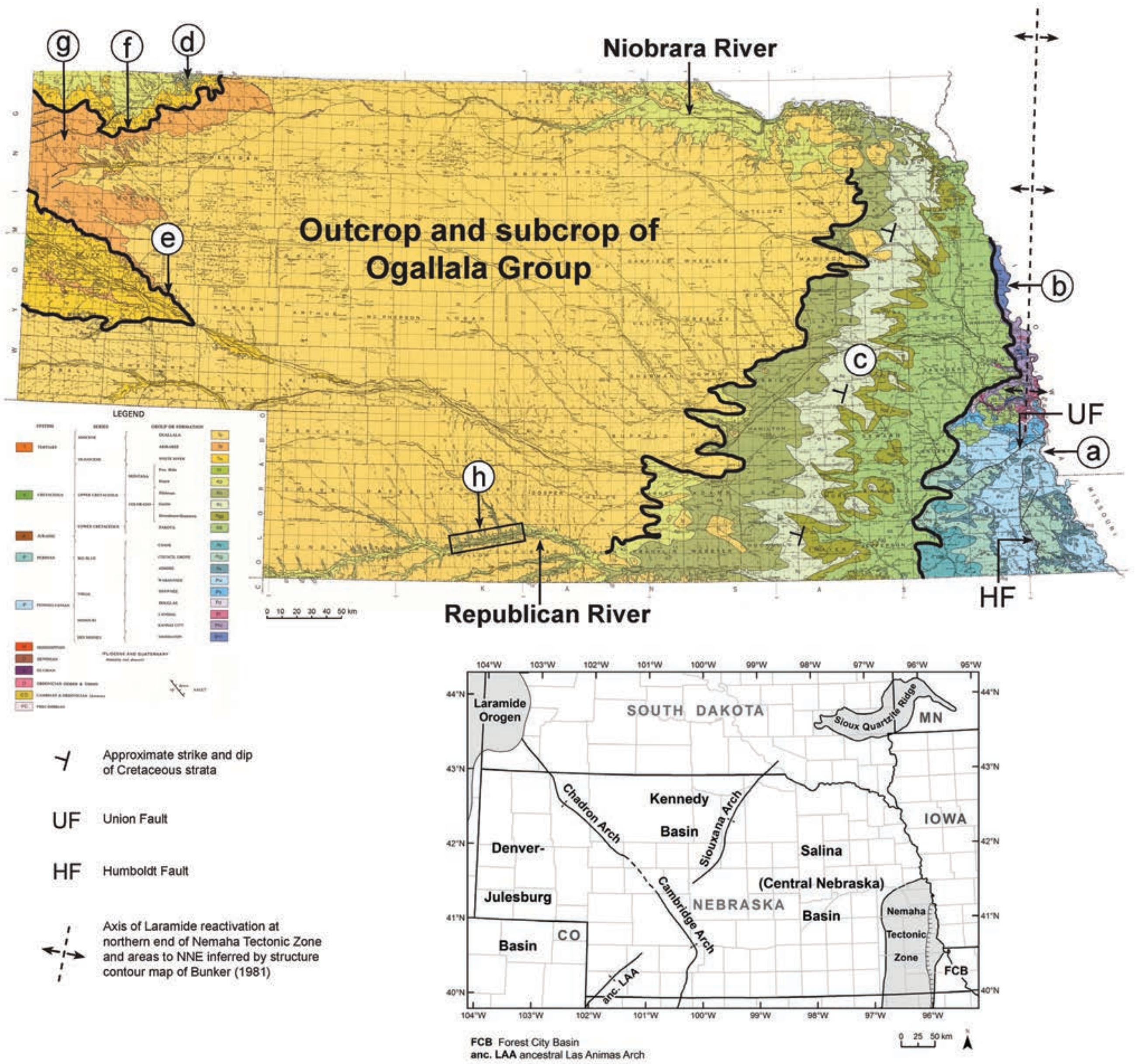

Figure 4. Most recent statewide bedrock geologic map of Nebraska (Burchett 1986). See text for discussion of features identified by lowercase letters. Smaller map at lower right shows major structural features in and around Nebraska that influenced pattern on bedrock geologic map. Note that such structures are discernible chiefly in Nebraska's subsurface geology, and their direct effects are generally not visible at the land surface. Laramide Orogen is area directly affected by mountain-building during Laramide orogeny (about 80 to 45 million years ago) and includes present Black Hills and Rocky Mountains. Gentle, far-field Laramide uplift also occurred in the Nemaha Tectonic Zone, on the Sioux Quartzite Ridge, and Chadron and Cambridge arches, but those areas experienced much less vertical movement of Earth's crust. Nevertheless, Laramide reactivation of those structures contributed significantly to the present bedrock-map pattern in eastern Nebraska. Trend of the ancestral Las Animas Arch (anc. LAA) in southwestern Nebraska is based on maps by Rascoe (1978). See text for additional explanation.

Nebraska legislature in 1921, George E. Condra, its director (Fig. 1i), and other researchers, including A. L. Lugn (Fig. 1j), mapped the geology of many parts of the state. Unlike recently made geologic maps, these state and county maps were not drawn on a topographic base. Nevertheless, they are an important historical resource and they are preserved in the map files of CSD for use by stakeholders. CSD produced a statewide bedrock geologic map of Nebraska in 1950 (Condra and Reed 1950) and a revised and colored version in 1969 (Burchett 1969). The latest version of the statewide bedrock map was issued more than three decades ago (Burchett 1986; Fig. 4). Digital map products at smaller scales were first produced at CSD around 1996 and onscreen digital mapping was initiated there in 1998.

Starting in the 1950s and continuing to today, faculty and students from the University of Nebraska's Department of Geology (now Earth and Atmospheric Sciences) and the University of Nebraska State Museum periodically prepared geologic maps of parts of Nebraska. These maps are useful, but most of them went unpublished and they are difficult to access.

USGS geologists have continued to the present day, often in cooperation with geologists of state geological surveys such as the CSD, to prepare maps and reports on the groundwater and other geologic resources across the Great Plains. In 1963, for example, the CSD began a long-term cooperative mapping program across the state with the USGS to prepare regional geologic maps of the bedrock surface of Nebraska. Eleven maps at a scale of 1:250,000 covering all of Nebraska were proposed to be prepared using data from surface mapping and all borehole data available. Outcrops of rock formations on these maps were to be shown using a darker overprint on the maps with a topographic base. Other information, such as thickness variations in regolith covering the bedrock, were to be included. Only a few researchers were available from the USGS and the CSD at any one time to go to the field, obtain permission from property owners to survey their lands, and then prepare the detailed maps on topographic base maps available at the time.

Only five of the 11 proposed 1:250,000 geologic maps were published in the style originally proposed (in 1972 the Lincoln and part of the Nebraska City 1° × 2° quadrangles; in 1973 the Grand Island 1° × 2°quadrangle; in 1975 the Fremont 1° × 2° quadrangle; in 1988 the McCook 1° × 2° quadrangle and the Sioux City 1° × 2°quadrangle).

In federal fiscal year 1985 a new program of the USGS was initiated, called COGEOMAP. Accordingly, all subsequent 1:250,000 geologic maps were to show geology at the land surface. Mapping surficial geology can be a more challenging task than mapping bedrock in Nebraska, however, because of the complex mix of surface deposits of windblown, river, glacial, and lake sediments, mostly covering isolated exposures of bedrock, that are required to be shown.

In 1992 a new cooperative mapping program of the USGS replaced COGEOMAP. This program has three components (federal or FEDMAP; state or STATEMAP; and university or EDMAP) and resulted in the production of printed and digital geologic maps. In Nebraska, the North Platte 1° × 2° and Scottsbluff 1° × 2° quadrangles followed the COGEOMAP model described above. More recently, the Broken Bow and O'Neill quadrangles were published (in 2000 and 2008, respectively). Authors of these two maps eliminated the explanatory text used on the borders of the previously published paper maps and replaced it with expanded booklets that allow for more detailed explanations of the geologic and other features depicted on the maps.

Nine of the originally proposed 1° × 2° maps had been published up to October 2017. Only the Valentine and Alliance quadrangles remain uncompleted, but many field maps for these two projects are available. These field maps cover much of the areas of both maps and are in the files of CSD.

The CSD research geologists who were mainly responsible for work on these 11 maps included V. H. Dreeszen, R. R. Burchett, D. A. Eversoll, V. L. Souders, J. B. Swinehart, and R. F. Diffendal Jr. (Fig. 1k–p). Others who contributed to the research for some of the maps include C. Timperley, H. LaGarry, M. Rebone, S. T. Tucker, M. R. Voorhies, and E. J. Voorhies, and USGS geologist George Pritchard.

Finally, Swinehart and Diffendal proposed and received funding from STATEMAP and COGEOMAP grants to compile and publish a 1:63,360-scale map of Morrill County, Nebraska, which was completed and published in 1995. They found that Morrill County had the most interesting and structurally complicated geology of any of the counties in the southern half of the Nebraska Panhandle that could be best and most usefully published on a single map with a larger scale.

CSD geologists who have recently worked on surficial geologic maps include P. R. Hanson, L. M. Howard, R. M. Joeckel, J. T. Korus, and A. Young. J. S. Dillion of the Department of Geography at the University of Nebraska at Kearney and S. T. Tucker of the Highway Paleontology Program at the University of Nebraska State Museum have also assisted in recent mapping projects, as have multiple students. All maps are available at the offices of the CSD. Geologic maps of Nebraska produced in the past few decades are also available in the form of full downloads, whether at the USGS website and/or at the University of Nebraska–Lincoln's Digital Commons website (http://digitalcommons.unl.edu).

Geologic Mapping Today

Dimensions and Digitality

Traditional two-dimensional geologic maps (on paper or in digital format) are the only "official" geologic maps that have yet been produced in Nebraska. The continued use of two-dimensional geologic maps on paper, the original form of the inclusive genre as well as its chief standard until recent memory, might easily be dismissed by some non-mappers as evidence for the static nature—or, worse yet, stagnation—of geologic mapping as a scientific endeavor. Some authors have declared that traditional geologic maps—and perhaps even those in digital format—are experiencing a decline in use and perceived relevance (e.g., Broome 2005), a problem that others attribute to the public's limited ability to decipher maps (Brick 2013). None of this predicament can be considered more the fault of geology or geologists than that of larger society. Monmonier (1998, 16) opined of seismic-hazard maps, a type of geologic map, that "voters who have trouble balancing a checkbook have little interest in arcane claims." His statement identifies a major disconnect between the evaluation of information by scientists and the general public, yet a low level of public awareness and concern about geology-related issues may also be at work.

Moreover, it is erroneous to assume that geologic mapping has lost its relevance anywhere, much less in Nebraska. To the contrary, geologic mapping is experiencing a technological renaissance. Digital geologic mapping came to the fore with improvements in computer software, specifically geographic information systems (GIS) programs, and hardware near the end of the 20th century, and it is "now a fully mature technology that dramatically improves . . . problem-solving capabilities" (Pavlis and Mason 2017). In Nebraska, the development of digital geologic maps began around 1996 and it is now the only manner in which maps are produced by the CSD.

Today's digital geologic maps are finding new applications in association with cyberdata. Thus, they should be thought of as societally and scientifically critical "Big Data," because they are "not just a lot of data, but different types of data handled in new ways" (Lohr 2013). The range, precision, and sheer volume of data associated with geologic maps still expands, and all the more so as older maps are revised while new maps are produced. Likewise, the means by which map data are collected, shared, and compiled—smartphones, tablets, and other handheld electronic instruments; satellite, aerial, and unmanned aerial systems (UAS) imagery; Structure-from-Motion (SfM) photogrammetry (e.g., Westby et al. 2012); LiDAR (light detection and ranging—the imaging of the land surface with ultraviolet, visible, or near-infrared light); other forms of geomatics; and associated cyberinfrastructure (e.g., Mookerjee et al. 2015; Chan et al. 2016)—show no signs of becoming less diverse, less technologically complex, or less tied to the immense and pervasive information economy.

Three-dimensional digital geologic maps, perhaps the most striking evidence of technological advances in the mapping field, developed late in the 20th century to address issues in petroleum exploration and development, groundwater supply and protection, geologic hazards assessment, planning, and other needs. Unfortunately, although it may come to transform geologic mapping in the near future (Pavlis and Mason 2017), the practicability of true three-dimensional mapping is not universal, and therefore its application remains limited. True three-dimensional geologic mapping has yet to be done in Nebraska, and the emergence of statewide three-dimensional mapping in the near future seems very unlikely, although it has been pursued elsewhere in the interior of North America, such as parts of Illinois, Minnesota, and Manitoba.

Despite the widening horizons of geologic mapping and the now-absolute imperative of "digital language" as a means of production, archiving, and dissemination under conditions of accelerating technological change, and the primacy of numeracy in other science and engineering disciplines notwithstanding, we observe that the fundamental "visual language" of maps and diagrams (Rudwick 1976) persists as the lingua franca of geology everywhere. This visual language has dominated geology for more than two centuries, perhaps inescapably, considering the spatial data and concepts that must be presented by geologists. Therefore, we feel confident that the production of, and demand for, geologic maps will continue. At the same time, however, we are mindful of political, societal, and fiscal issues that almost certainly will shift the imperative and affect the rate and means of production of such maps over time.

Bedrock vs. Surficial Geologic Maps

Geologic maps assume multiple forms depending on the need and the particular data sets to be emphasized in any given case. Geologic mapping, in turn, is a set of diverse skills, practices, applications, and philosophies that must be adapted carefully to needs, goals, and to the local setting. We contrast two very common kinds of geologic maps that have dominated mapping in Nebraska (and elsewhere) from the onset: surficial and bedrock geologic maps.

Bedrock geologic maps depict bedrock alone, whether it is exposed at the surface as outcrops or buried at depth under regolith as a part of a particular bedrock body's *subcrop*. Bedrock is defined for the purposes of two-dimensional mapping as the first layer of consolidated (hard) Earth material encountered at or below Earth's surface—in the latter case, underneath a cover of regolith of some thickness. Defining what constitutes bedrock is not always a simple matter because Earth materials are indurated, cemented, or consolidated to widely varying degrees.

The most recent statewide geologic map of Nebraska (Burchett 1986) is a bedrock map that was produced at the scale of 1:1,000,000 without the benefit of GIS. Active geologic mapping in Nebraska is currently limited to the production of 1:24,000-scale digital (GIS-based), two-dimensional surficial geologic maps, which depict many types of regolith at the land surface, as well as any bedrock that happens to be exposed thereon, especially in the context of extant landforms. The association between particular kinds of surficial sediments and particular kinds of landforms is a critical part of surficial geologic mapping, and therefore, digital elevation models (DEMs) and LiDAR (light detection and ranging) data, which offer detailed perspectives on the landscape, are extremely important. The statewide geologic map of Iowa (Witzke et al. 2010), like that of Nebraska (Burchett 1986), is a bedrock map, and Minnesota has a statewide bedrock map as well (Jisra et al. 2011). The statewide geologic map of Kansas is a surficial geologic map (State Geological Survey of Kansas 2008), showing both bedrock and regolith. The official geologic map of South Dakota (Martin et al. 2004) accurately depicts the dominance of exposed bedrock in the unglaciated part of the state west of the Missouri River, but it also depicts the dominance of Quaternary sediments (chiefly glacial sediments), as regolith at Earth's surface on the glaciated eastern side of the river. Thus, it too qualifies as a surficial geologic map. Interestingly, then, the geologic maps of five contiguous states are not fully comparable.

Kansas, South Dakota, Iowa, and Minnesota all have official geological statewide maps at a finer scale of resolution (1:500,000) than Nebraska's, and all were produced in the recent digital age of geologic mapping, rather than being digitized from a preexisting paper version, as was the Nebraska statewide geologic map about a decade after its publication in 1986. In the process of comparing the five statewide geologic maps, we also observe that it is vital that the title of any geologic map accurately describe what the map is intended to represent: bedrock geology, surficial geology, or some other aspect. Considering the lack of complete comparability between the maps of five aforementioned states alone (not to mention potential differences between the geologic maps of all 50 US states), this comparison also illustrates the necessity of specifying what kind of geologic map is to be made prior to actually engaging in mapping, and even before that, determining the actual scientific and societal needs that can or must be served by mapping.

Understanding Geologic Maps of Nebraska

Processes (erosion, movements of Earth's crust, and deposition) that were at work during the geologic history of Nebraska produced the patterns visible on any kind of geologic map of the state. Nebraska is comparatively unique in its possession of particular geologic attributes and also in its conspicuous lack of others. This comparative uniqueness of Nebraska has shaped the practice, process, and products of geologic mapping in the state, and its influence is apparent on both bedrock and surficial geologic maps. Geologic maps, such as the bedrock geologic map of Nebraska, also yield important, and even unexpected, perspectives when they are viewed creatively (e.g., the "down structure" method of Mackin 1950, and others) and contemplated deeply in broader contexts. We do so in the following subsections.

Statewide Bedrock Map: A Story in Stone

Only 13% or less of Nebraska's surface area is underlain by very shallow or exposed bedrock. Furthermore, almost seven-tenths of the total area of very shallow or exposed bedrock is in the Panhandle alone. The remaining three-tenths of the total area of very shallow or exposed bedrock lies mostly near the north-central, northeastern, and southeastern boundaries of the state, leaving a vast interior in which bedrock is rarely, if ever, encountered except by comparatively deep drilling. These observations underscore the relevance of, and societal need for, surficial geologic mapping in the state (see forthcoming discussion), even though a statewide bedrock map remains a critical scientific and decision-making asset. In turn, these observations also point to the technical and procedural difficulties associated with producing a bedrock map in a region with very limited exposures of bedrock.

The bedrock geologic map of Nebraska is somewhat abstract in that it was compiled mostly from indirect observations—subsurface data, rather than the direct observations of Earth materials across the land surface—at data points (scattered boreholes). The bedrock map depicts more than the geographically limited bedrock exposures; it further represents the pattern of bedrock strata across the state were all the overlying regolith removed.

As in many states in the interior US, the production of the present statewide bedrock map of Nebraska (Burchett 1986) relied heavily on subsurface data of various origins—CSD test holes logged by professional geologists, logs from water wells logged by drillers with highly variable levels of experience and education, and miscellaneous other borehole data. These data were first plotted by hand on paper US Geological Survey 7.5-minute (1:24,000) quadrangles. Quality assessment and control are an endemic problem whenever such different data sources are employed. How, exactly, quality assessment and control were practiced when the statewide bedrock map was produced has largely been lost from institutional memory. Unfortunately, two-thirds of the individuals who were involved in the making of the map are now deceased, and the philosophical approach in producing the map, not to mention the actual day-to-day procedures involved, cannot now be fully documented.

Inasmuch as we are aware, there has never before been a comprehensive explanation of the pattern portrayed by the bedrock geologic map of Nebraska (Burchett 1986; Fig. 4). Nebraska lies on the platform of the ancient North American craton, and the characteristics of this setting over the past billion years have influenced the larger-scale pattern in the bedrock geologic map in many ways. The platform is part of the old central "core" of the continent that has been comparatively stable in terms of crustal movements and volcanism for more than the last one-fifth of geologic time. The North American platform is characterized by (1) a succession of nearly flat-lying sedimentary rock strata that overlie old basement crystalline rocks of the craton; (2) broad and gentle up- or downwarping of Earth's crust (epeirogeny) as arches and sag basins (Fig. 4), but only localized, more abrupt, bedrock uplift by tectonics; and (3) consequently, a simple bedrock geologic map pattern in comparison to those in other parts of the continent, even the Canadian Shield, which is the part of the craton exposed at the present land surface. These characteristics contrast with the western, southern, and eastern parts of the continent, including parts of states as nearby as Colorado and Wyoming to the west and Arkansas and Oklahoma to the south, all of which were subjected to intense geologic activity related to plate-tectonic interactions during various intervals in the Phanerozoic Eon, or the last 541 million years since the beginning of the Cambrian Period. In Phanerozoic times, most of the deposition of the sedimentary-rock cover occurred during particular intervals of geologic time in response to slow upwelling and downwelling in Earth's mantle, plate tectonics, erosion, deposition, and global changes in sea level (e.g., Sloss 1988; Miller et al. 2005; Burgess 2008).

That which is lacking in Nebraska's geology bears major consequences in the practice of mapping and in geologic maps themselves. Nebraska and only five other states, including the companion Great Plains state of North Dakota, have no exposure of bodies of igneous or metamorphic rocks (collectively known as crystalline rocks) at the land surface. Actually, all the states surrounding Nebraska have some surface exposure, however small or large, of rocks that qualify either as igneous or metamorphic types. The genetic diversity of geologic features, rocks, minerals, and resources is, as a consequence, lesser in Nebraska than in most of the other states, and only unconsolidated sediments and sedimentary rocks can be mapped at its land surface. Evidence is also lacking for the subcrop of crystalline rocks under regolith in Nebraska. Rather, the nearest that any crystalline basement rocks come to the surface in Nebraska is approximately 150 m—still buried under Upper Pennsylvanian sedimentary rocks—atop the Nemaha Uplift in southeastern Nebraska. In the southwestern Panhandle of Nebraska, the depth to basement rocks approaches 3,000 m.

Likewise, Nebraska is one of perhaps six of the 50 states that lacks definitive karst topography, that is, caves, sinkholes, and related features developed by the progressive natural dissolution of the carbonate-mineral-bearing sedimentary rocks limestone and dolostone (or even the evaporate sedimentary rocks gypsum or anhydrite). There is, however, some ambiguity about the occurrence of karst in Nebraska in at least one published report (e.g., Weary and Doctor 2014). Karst areas and features are frequently mapped on geologic maps, in part because they represent significant hazards (groundwater contamination, engineering and construction problems, sudden ground collapse, etc.). Once again, all the states surrounding Nebraska have significant examples of karst somewhere within their boundaries. In Kansas, karst is developed even in some of the same Pennsylvanian and Permian limestones that crop out and are mapped in Nebraska (Young and Beard 1993). The lack of karst terrain in Nebraska sets it apart from states such as Indiana, Kentucky, Missouri, Texas, and Florida, which have sizeable regions of karst. Nebraska's lack of true karst is related to multiple factors, including the typically widespread nature of thick regolith, the comparatively limited area of exposure of limestone in the state, and local and regional hydrogeologic conditions.

Additionally, and perhaps most relevant to geologic mapping, only one-fifth of the states in the US—including Nebraska, Kansas, North Dakota, and Iowa—encompass neither (1) true, structural or volcanic mountains that have present positive relief, nor (2) even the exposed, eroded remnants of very ancient mountains, as on the Canadian Shield in northern Minnesota (Jisra et al. 2011), northern Wisconsin (Mudrey et al. 1982), and the Upper Peninsula of Michigan (Reed and Daniels 1987). Overall, few faults are mapped at the surface in Nebraska, although it is all but certain that more are present but undetected in an area in which bedrock exposure is so minor. Geologic processes were certainly more dramatic during Nebraska's distant geologic past. Between approximately 1.8 and 1.1 billion years ago the area now encompassed by Nebraska experienced plate-tectonic collision and accretion, orogeny (mountain building) by crustal folding and thrusting, as well as rifting and volcanism (e.g., Van Schmus and Hinze 1985; Sims and Peterman 1986; Hutchinson et al. 1990). Any direct signature of these long-past events and the complicated patterns of bedrock relationships that they produced, however, are now deeply buried beneath younger sedimentary rocks. As a result, the pattern on the bedrock geologic map of Nebraska is much less complicated than those of Rocky Mountain states such as Colorado and Wyoming, those of states in the Appalachian region (e.g., Pennsylvania), those of certain states that lie partially on the Great Plains (e.g., Oklahoma, South Dakota, and Texas), or even those of some states that would seem to be geographically similar, such as Minnesota, Wisconsin, and Michigan, where erosion has removed any once-overlying bedrock from atop the very old, deformed rocks on the southern margin of the Canadian Shield.

In discussing aspects of geology that are absent in Nebraska, we observe that no evidence has yet been put forward for the existence of any bedrock impact structures (craters and associated features) produced by large meteorites, asteroids, or even comets. Large impact structures influence the patterns on bedrock geologic maps in various places on Earth. Such structures typically appear as partial or complete, concentric, round to oval signatures on bedrock geologic maps. The two-million-year-old Vredefort Crater/Dome in South Africa and the slightly younger, mineral-rich Sudbury Basin in Ontario (e.g., Riller 2005) are prominent examples of impact structures many tens of kilometers in diameter that confer distinctive patterns on geologic maps. But to consider impact structures in a discussion of the bedrock geologic map of Nebraska is by no means unwarranted: bedrock impact structures of geologically ancient ages have been identified, whether under regolith or buried within successions of rock strata, in many midwestern states, including Illinois, Indiana, Iowa, Missouri, North Dakota, Ohio, Oklahoma, and Wisconsin, as well as in Wyoming to the west (Koeberl and Anderson 1996). The Manson Crater in the north-central part of adjacent Iowa (Hartung and Anderson 1996; Koeberl and Anderson 1996) produces an especially striking pattern on the bedrock map of that state (Witzke et al. 2010).

Even though multiple types of geologic features are absent in Nebraska, and despite the shortcomings of its pre-digital origin, the existing statewide bedrock map of Nebraska (Fig. 4) still yields important insights. In an utterly abstract sense, Nebraska's bedrock geologic map is a patchwork recording of geologic processes over the past 300+ million years. Sediments were deposited during particular intervals of geologic time, buried, and lithified to produce strata of sedimentary rock. Those rock strata were subsequently offset by faulting, very gently warped by movements in Earth's crust, and eroded during different later intervals of geologic time. The actual surface or "top" of bedrock in Nebraska, both where it is exposed at the land surface and where it is buried under regolith, is akin to a palimpsest manuscript that was written upon several times and partially erased, such that traces of earlier writing are preserved along with the present text. To understand the palimpsest nature of the bedrock surface in Nebraska one need only envisage a river eroding its bed through surficial sediments and into flat-lying bedrock, while simultaneously considering that the same bedrock remains uneroded below regolith in the uplands adjacent to the river's valley. Shifts in the course of the hypothetical river and the position of its valley may later lead to the partial or complete erosion of the bedrock in other places. As time goes by, bedrock erosion will have occurred to different degrees and depths—and possibly not at all in some places—at different times, yet there is a single surface that represents the top of all bedrock within the enclosing region. It only stands to reason, then, that the geometric pattern exhibited by the bedrock surface on a bedrock geologic map and the actual rocks represented by that pattern typically record vastly different information about the geologic history of a region. This maxim is abundantly true in Nebraska.

Although the pattern that is graphically presented on a bedrock geologic map (that is, where rocks are present versus where they may have been present and were then eroded) is typically younger than the rocks it portrays, the conceptual origins of at least one part of Nebraska's bedrock map is even older than the rocks portrayed in the map. The Midcontinent Rift System (e.g., Stein et al. 2016), which stretches from Lake Superior into southeastern Nebraska and Kansas, and is an old geologic structure that is now completely buried by younger bedrock underneath southeastern Nebraska, including the Lincoln and Omaha metropolitan areas (as well as the metropolitan areas of Council Bluffs and Des Moines, Iowa, and Minneapolis–St. Paul, Minnesota). The fault zone at the southern boundary of the Midcontinent Rift System was reactivated more than once in the past 1.1 billion years ago, and definitely after Upper Pennsylvanian and Lower Permian strata were deposited, by stresses within Earth's crust much later in geologic time, long after rifting ceased, as the Thurman-Redfield Fault Zone in Iowa, the southwestward extension of which has been called Union Fault in southeastern Nebraska (Fig. 4, "UF"). The mapped relationships of rock strata along this fault zone (Burchett 1986; Witzke et al. 2010) indicate that this reactivation occurred after the deposition of Pennsylvanian and Lower Permian strata in the region (Fig 4, "a"). This reactivation played a role in determining the bedrock map pattern (Burchett 1986) in southeastern Cass, Otoe, and southwestern Lancaster Counties in southeastern Nebraska, as well as in neighboring southwestern Iowa (Witzke et al. 2010).

Other parts of the pattern on the bedrock map in Nebraska are also related to geologic structures and tectonic activity. Many aspects are ultimately related to the building of geographically distant mountains—a mechanism commonly referred to as far-field tectonics—in the geologic past. The Nemaha Uplift or, in a broader sense, the Nemaha Tectonic Zone (NTZ) of Berendson and Blair (1995), is a 500-km-long, 40-km-wide uplift of Earth's crust, bounded on the east by the near-vertical Humboldt Fault or Fault Zone (Fig. 4, "HF"), which extends into Richardson, Pawnee, Johnson, Nemaha, and Otoe Counties in southeastern Nebraska (Burchett 1986). Bedrock strata are offset by hundreds of meters in some places on faults along the eastern margin of the NTZ (Stander 1989). Analyses indicate that the northern end of the NTZ was uplifted at least three times during the past 300+ million years by movements of crustal rocks along faults and in response to mountain building hundreds of kilometers away, whether in the area of the present Rocky Mountains in Colorado (the Ancestral Rockies) or in the Ouachita Mountains of present Oklahoma and Arkansas (Burberry et al. 2015). A later phase of fault reactivation in the NTZ appears to have taken place during the Laramide orogeny (Burberry et al. 2015), which occurred in western North America but had far-field effects well east of the Front Range. The Laramide orogeny spanned an interval from the time of deposition of the youngest Cretaceous strata in the eastern half of Nebraska to as recently as about 45 million years ago (Cather et al. 2012) and uplifted the Rocky Mountains, the Black Hills, and certain smaller ranges (Fig. 4), some of which are close to the western border of Nebraska. During Laramide times, much subtler, far-field uplift of the crust occurred in present Nebraska. This uplift played a role in determining the current pattern of Pennsylvanian, and Lower Permian strata in southeastern Nebraska (Fig. 4, "a" and "b") as well, in that (1) even a slight uplift at the northern end of the NTZ would have facilitated the erosion of any younger strata that once lay atop it (see forthcoming discussion), thereby exposing the Lower Permian and Pennsylvanian rocks underneath; and (2) movements along reactivated faults appear to have changed the geometric relationships between some of the latter strata (Fig. 4, "a").

The map pattern of younger Cretaceous bedrock strata in the eastern one-third of Nebraska (Burchett

1986; Fig. 4, "c") indicates a north-northeastward strike (the intersection of a structural plane or rock layer with a horizontal plane) along an azimuth of about 20° to 30° and a strong westward component of dip across almost all of that area. A similar pattern is also apparent in northern and central Kansas (State Geological Survey of Kansas 2008), indicating a common control of this geologic trend. Also, part of the same succession of Cretaceous strata continues northeastward on the geologic bedrock map of adjacent Iowa (Bunker 1981; Witzke et al. 2010) and eventually terminates in southern Minnesota (Jisra et al. 2011). Some part of westward aspect of the dip of Cretaceous strata across Nebraska must be due to the primary (depositional) basinward dip of Cretaceous sedimentary strata as they were laid down in and around the Western Interior Seaway between 100 and 70 million years ago (cf. Miall et al. 2008), but that aspect alone does not explain the present map pattern. Rather, the bedrock map pattern of Cretaceous strata in eastern Nebraska and eastern Kansas, like that of Pennsylvanian and Permian strata, appears to be related chiefly to the Laramide reactivation (gentle uplift) at the northern end of the Nemaha Tectonic Zone (NTZ). Laramide reactivation of the NTZ would have uplifted, however gently, all Cretaceous strata that were once present in eastern Kansas and southeastern Nebraska, prompted their eventual erosion by streams, and produced the present pattern of strike and dip. Similarly, uplift along the north-northeast-striking axis of the NTZ would have led to the erosion of Cretaceous strata above the Dakota Formation in northwestern Iowa. A hypothetical north-northeast-trending axis (continuous with the trend of the Humboldt Fault in southeastern Nebraska) for the uplift associated with this Laramide reactivation was implied in a structure contour map of the Greenhorn Limestone, a formation within the regional Cretaceous succession, presented by Bunker (1981, fig. 8; Fig. 4).

The effects of Laramide and later movements of Earth's crust on the bedrock map pattern in Nebraska's Panhandle are also striking. The feature historically referred to as "Chadron Dome" in northeastern Dawes County and northwestern Sheridan County in Nebraska has a distinctive, local pattern on bedrock maps (Fig 4, "d"). It is uplifted Cretaceous sedimentary strata at one end of the elongate, gentle crustal upwarping known as the Chadron Arch (Fig. 4), which was reactivated during Laramide times (Swinehart et al. 1985; Burchett 1986; Bunker et al. 1988; Diffendal 1994; Tikoff and Maxson 2001; Welch and Leite 2014). The same geologic structure even may have influenced the geography of dunes and other features near the western edge of the Sand Hills (Loope and Swinehart 2000).

In southwestern Nebraska, the Cambridge Arch, which is essentially continuous with the Chadron Arch (Moore and Nelson 1974), was also reactivated during Laramide times. Evidence for such reactivation can be seen in the pattern of Upper Cretaceous strata on Nebraska's bedrock geologic map in the Republican River valley in Red Willow and Furnas Counties. A 60-km-long stretch of that valley between McCook and Edison, Nebraska, is underlain by the Niobrara Formation, whereas parts of the same valley immediately to the west and east are underlain by the younger—and normally superjacent—Pierre Shale. This map pattern indicates that both stratigraphic units had been gently uplifted in the area after the Cretaceous Period and that the formerly continuous Pierre Shale was then eroded from atop the arch by the Republican River, thereby exposing the underlying Niobrara Formation. A similar, but less clear, bedrock-map pattern is exhibited in the valley of Beaver Creek to the south of the Republican River. Furthermore, Stanley and Wayne (1972) proposed that gentle uplift of the Chadron and Cambridge Arches has occurred not only in Laramide times, but "spasmodically" into recent geologic times.

At a large scale, the obvious east–west increase in elevation across the Great Plains today and the evident geologically recent, broad (long-wavelength, low amplitude, sensu Flament et al. 2013) uplift of much of the western part of that region has long intrigued geologists. There are aspects of Nebraska's bedrock map that appear to be related to such uplift (Fig. 4, "d" through "g"). Crustal tectonics and mantle dynamics, and even the wholesale hydration of minerals in the lower crust, have been invoked at times to explain the regional uplift and elevation of the western Great Plains (e.g., Hinze and Braile 1988; McMillan et al. 2002; McMillan et al. 2006; Nereson et al. 2013; Jones et al. 2015). Mantle-driven processes have been invoked to explain present relief in the nearby southern Rocky Mountains (e.g., Karlstrom et al. 2011). Regional uplift in the western Great Plains (High Plains), whatever the ultimate causes, must relate to much younger, post-Laramide, and even post-Miocene, events, because it appears to have affected the present distribution of Miocene strata of the Ogallala Group.

Various authors have proposed multiple episodes of uplift and movement along faults, from Laramide times onward, in the vicinity of the North Platte valley in eastern Wyoming and far western Nebraska (Thomas 1971; Merin and Moore 1986; Ahlbrandt and Groen 1987; McMillan et al. 2002). On the statewide bedrock map of Nebraska (Burchett 1986), there is a prominent, relatively sharp, eastward (downstream) "veeing" of strata in the North Platte valley in Scotts Bluff, Banner, and Morrill Counties (Fig 4, "e") which would be expected if those strata were structurally elevated to the west and dipping gently eastward (cf. Lisle 2004, 12–13). Furthermore, the Pine Ridge (Fig. 4, "f"), a present-day positive relief feature, is an escarpment on lower Miocene sedimentary strata that Swinehart et al. (1985) interpreted to be the result of local activation of geologic structure in post-Laramide times, although Nixon (1995) considered it to have a genetic relationship with the uplift of the Black Hills. Likewise, it appears likely that Ogallala Group sediments were once present on, then eroded from, the Box Butte Tableland and surrounding areas in Sioux and Box Butte Counties, between the Pine Ridge and the North Platte valley (Fig. 4, "g"). Deep or widespread incision by streams may have begun in the greater Rocky Mountain region as early as late Miocene times, but it was mostly post-Miocene in its timing, exposing the older Miocene, Oligocene, and upper Eocene sedimentary strata that were affected by Laramide and post-Laramide uplift in Nebraska's Panhandle (Swinehart et al. 1985; Ahlbrandt and Groen 1987; McMillan et al. 2002).

Stream erosion played a large role in determining the pattern on Nebraska's bedrock map, in large part by accentuating the preexisting gentle structural deformation discussed previously. Pennsylvanian and Lower Permian strata appear only in the southeastern part of the state (Burchett 1986; Fig. 4, "a" and "b"). In adjacent Kansas, however, such strata are exposed or lie at very shallow depths across the entire eastern one-third of that state, exhibiting northward to north-northeastward strikes (State Geological Survey of Kansas 2008), and thereby forming the prominent escarpments and bedrock-dominated topography of the hilly terrain known as the Flint Hills and Osage Cuestas (e.g., Frye and Schoewe 1953). The Kansas statewide geologic map also shows these bedrock strata partially buried by Pleistocene glacial sediments in the northeastern corner of that state, as they are in most of southeastern Nebraska immediately to the north, where bedrock-dominated topography is not the norm. Although the aforementioned ancient uplift of the northern end of the Nemaha Tectonic Zone, as well as the reactivation of faults along the Midcontinent Rift Zone, set up gentle structural trends that contributed to the appearance of the present map pattern of Pennsylvanian and Lower Permian strata in southeastern Nebraska, stream erosion still had to remove any younger rock strata that almost certainly had overlain them in the distant past. The prior existence of overlying Cretaceous sedimentary rocks in this area (albeit in an eastward-thinning trend) is supported by multiple observations: (1) the Dakota Formation, the oldest and stratigraphically lowest formation in the Cretaceous succession, is still present eastward into central Iowa (Witzke et al. 2010); (2) several Cretaceous formations underlie a large part of southwestern and far west-central Minnesota, some 500 km to the north-northeast (e.g., Merewether 1983; Jisra et al. 2011); (3) thin Cretaceous sediments are present in western Illinois (Frye et al. 1964), more than 400 km to the east-southeast of southeastern Nebraska; and (4) isolated outliers of Cretaceous sedimentary rocks exist in northeastern Iowa, northern Minnesota, and even 600 km northeastward in Wisconsin (Andrews 1958; Mudrey et al. 1982; Witzke et al. 2010; Jisra et al. 2011). Accordingly, we propose that eastward-thinning middle and late Cretaceous sedimentary rock strata were formerly widespread eastward of the present outcrop and subcrop of Cretaceous strata in eastern Nebraska, at one time covering all of Nebraska and most of Kansas and Iowa, and that they were later eroded from southeastern Nebraska, southern Iowa, and a large part of eastern Kansas (cf. Cross 1986; Bunker et al. 1988; Cobban et al. 1994).

If they originally extended farther eastward, as we hypothesize, then when were Cretaceous strata eroded in eastern Nebraska and Kansas? Aber (1997) hypothesized that streams incised (eroded into bedrock) the landscape of eastern Kansas by as much as 80 m during the Pleistocene and Holocene epochs (i.e., the past 2.6 million years or less), and that the Flint Hills were not a topographically higher region or drainage divide in Kansas prior to that time. Ancient stream gravels, now perched as eroded remnants on topographically high locations, are the basis of Aber's (1997) argument; these gravels are not age-dated, although they may have been deposited as long ago as the Pliocene Epoch. Aber (1997), however, referred only to the incision of Pennsylvanian and Lower Permian bedrock strata, and not to the widespread erosion of any once-overlying Cretaceous strata. In any event, combined thickness of those hypothetical Cretaceous strata alone probably exceeded 80 m (cf. Zeller 1968)—a sizeable amount of bedrock to be eroded in a low-relief continental-interior setting. Furthermore, the remnant stream gravels described by Aber (1997) directly overlie Pennsylvanian and Lower Permian rocks, making it abundantly clear that any Cretaceous strata that might have once overlain those rocks had long since been eroded by the time the gravels were deposited. The burial of Pennsylvanian and Lower Permian strata by pre-Illinoian (older than about 0.6 million years) glacial sediments in northeastern Kansas and southeastern Nebraska indicates that the basic form of Upper Pennsylvanian and Lower Permian strata on the bedrock map pattern of southeastern Nebraska and northeastern Kansas had already been established by the time of the last glacial advance during the early Middle Pleistocene at the very latest, and it may well have been established prior to the *first* advance of the Laurentide ice sheet into the area during the earliest Pleistocene.

Additional evidence for a pre-glacial, or even pre-Pleistocene, origin of the stream-eroded pattern of Cretaceous strata mapped in eastern Nebraska (Burchett 1986) is the westward-pointing "vees" or large-scale crenulations represented on it, particularly near the middle of the Cretaceous outcrop and subcrop belt (Fig. 4, "c"). Some artistic license may have been taken in rendering these features by hand in hand-drafted maps on the basis of subsurface data, but they were recognized in some form decades ago (Condra and Reed 1950), and they continue to appear when both old and new data are plotted using GIS methods (e.g., Divine et al. 2016). Such "vees" would be expected to form through the erosion of extremely gently westward-dipping strata by past and present erosion by generally eastward-flowing subparallel drainages. It is undeniable that drainages with a strong eastward component of flow have characterized the Great Plains for tens of millions of years since the earliest Paleocene Epoch (e.g., Stanley and Wayne 1972; Swinehart et al. 1985; Galloway et al. 2011). Additionally, ancient and now-sediment-filled eastward-trending stream valleys lie underneath Pleistocene glacial sediments in southeastern Nebraska—making those ancient valleys and the sediments filling them older than about 640,000 years at least, and possibly older than the first advance of the Laurentide ice sheet near the beginning of the Pleistocene (Divine et al. 2009; Korus et al. 2013). There are some indications that drainages flowing eastward from the Great Plains extended into present Iowa, before the current course of the middle Missouri River was established (Witzke and Ludvigson 1990).

Two exceptions to the general pattern of Cretaceous strata on Nebraska's bedrock map are related to both stream erosion and gentle geologic structure. One is that the Niobrara Formation and the Pierre Shale have been mapped along the Republican River and some of its tributary valleys in Dundy, Hitchcock, Red Willow, Furnas, and Harlan Counties in southernmost Nebraska (Fig. 4). This pattern resulted, overall, from the deep incision of the river and its tributaries during the Pleistocene Epoch, and there is indirect evidence that the present Republican River may be older than many of the other major rivers in Nebraska (cf. Joeckel et al. 2007). Locally, the pattern was influenced by the Cambridge Arch in the manner described previously. Another exception to the general pattern of Cretaceous strata in Nebraska is a much broader, and more irregular, pattern exhibited by the Pierre Shale on Nebraska's bedrock map around the Niobrara River and some of its tributaries in Knox, Holt, Boyd, Brown, Rock, and Keya Paha Counties in the northeastern to north-central part of the state (Burchett 1986; Fig. 4). Two observations probably explain the latter map pattern: (1) Cretaceous strata have a strong southward component in their dips in northwestern Knox County, if not in some of the aforementioned counties farther to the west as well (Bunker 1981, fig. 8; Divine et al. 2016, figs. 5, 6). This aspect of regional dip in northeastern Nebraska is related to the gentle Laramide uplift of the Sioux Quartzite Ridge (Fig. 4) in southeastern South Dakota and southwestern Minnesota (e.g., Koch, 1986), which also uplifted Cretaceous sedimentary strata around it. Second, it appears that the Niobrara River, likely in contrast to the Republican River, incised its valley very rapidly during the Late Pleistocene (cf. Larson 2001; Jacobs et al. 2007). Stream erosion by tributaries in the surrounding area would have accelerated and therefore widened the outcrop and subcrop belt of the Pierre Shale. In comparison to these two exceptions, there is no equivalent westward extension of the bedrock map pattern (Burchett 1986) of the same Cretaceous strata around the Platte River in east-central Nebraska.

Nevertheless, deep incision of the present Platte River system in western Nebraska (particularly the North Platte River), as well as that of the Niobrara River to the north, must have occurred after the deposition of the fluvial sediments of the Broadwater Formation in western and northern Nebraska during the Pliocene Epoch (5.3–2.6 million years ago), and possibly into the early Pleistocene Epoch (Stanley and Wayne 1972; Swinehart et al. 1985; Swinehart and Diffendal 1998). This conclusion is supported by the observation that partially eroded sediments of the Broadwater Formation lie at elevations well above those of major modern streams in both of these areas. Moreover, the present middle Missouri River, between Nebraska and Iowa, is a product of Pleistocene changes in continental drainage. The development and eventual incision of the middle Missouri River, which formed its present trough-like valley, must have contributed to the erosion of bedrock along its course and the courses of tributaries.

Stream deposition, rather than erosion, has also played a significant role in the development of the pattern on Nebraska's statewide bedrock map. The extensive distribution of the Ogallala Group on Nebraska's statewide bedrock map is due primarily to the widespread deposition of sediments by Miocene streams that flowed generally eastward from the Rocky Mountains down the slope of the Great Plains (e.g., Swinehart et al. 1985; Galloway et al. 2011), even though those sediments too have experienced local erosion after the end of the Miocene Epoch. Considering that the Ogallala Group can be mapped in northeastern Nebraska, due north of areas where they and even some of the Cretaceous succession of strata are absent in southernmost Nebraska, it is likely that Ogallala Group sediments were deposited over a larger area than that over which they are mapped today, perhaps across present eastern Nebraska and even into Iowa (cf. Witzke and Ludvigson 1990). The present north-northeastward strike of the Ogallala Group in the eastern half of Nebraska (Burchett 1986) more or less parallels that of Cretaceous formations, suggesting a relationship between the two patterns, whether it is related directly to the reactivation of geologic structures (less likely) or is merely the result of post-Miocene stream erosion along preestablished trends of very gentle bedrock geologic structure (more likely).

Although wholesale bedrock erosion in Nebraska's past is chiefly and most logically related to streams, the Laurentide ice sheet and strong winds also eroded bedrock during the Pleistocene Epoch. Barbour (1900) described prima facie evidence for the local abrasion of bedrock by one or more of the multiple advances of the Laurentide ice sheet in southeastern Nebraska, yet the actual extent to which glacial erosion contributed to the present bedrock map pattern is still unknown nearly 12 decades later. Perhaps surprisingly, the effects of past wind erosion are easier to identify, although chiefly at finer scales of map resolution (e.g., 1:24,000 and less). There is abundant evidence for wind erosion of soft bedrock during the Pleistocene Epoch in parts of Nebraska. In extreme northeastern to north-central and northwestern Nebraska—north of the Pine Ridge in northernmost Sioux and Dawes Counties, and in Knox, Boyd, Keya Paha, and Cherry Counties—oriented landforms eroded from the Pierre Shale and less so from the Ogallala Group can only be attributed to strong northwesterly winds (Joeckel et al. 2010; Joeckel and Howard 2018). Nevertheless, the importance of wind erosion in shaping Nebraska's landscapes remains underappreciated.

Quandaries associated with bedrock geologic mapping in Nebraska remain unresolved. One example is whether the strata of the Ogallala Group—which underlie fully 63% of the state's land area—should even be mapped as bedrock sensu stricto at all. These strata have, of course, long been mapped as such, but a surfeit of borehole data suggests that a significant amount of the Ogallala Group consists of loose sand and silt, rather than cemented sedimentary rocks, although there are layers of cemented sedimentary rocks within the Ogallala Group in the subsurface. The "mortar beds" or calcium-carbonate-cemented ledges of sedimentary strata that were frequently considered to be characteristic of the Ogallala Group across the Great Plains (e.g., Frye et al. 1956), although qualifying as rock sensu lato when they are encountered in outcrops, appear in some cases at least to be the products of geologically recent, geographically localized case-hardening around the contours of slopes at and near the land surface. Such a scenario differs manifestly from that of deep-seated and long-term geological processes (collectively known as burial diagenesis) that change unconsolidated sediments wholesale into thick, continuous layers of sedimentary rocks in the subsurface. The distinction of what is and what is not to be mapped as bedrock is not merely an esoteric matter, because it has practical implications in the assessment of regional hydrology and groundwater supply (e.g., reduction of porosity, permeability, and hydraulic conductivity in consolidated materials), land use and planning, waste disposal, construction, and engineering. We suspect that the Ogallala Group will continue to be mapped as bedrock in the future by long-term convention.

Surficial Geologic Maps: A Saga in Sediment

Surficial geologic mapping has special relevance in Nebraska because at least 87% of its land area is underlain by significant accumulations of regolith, almost exclusively in the form of transported sediments such as dune sand and other deposits of eolian sand, loess (wind-deposited silt), alluvium (stream sediments), glacial till, and colluvium (sediments deposited by shallow, unconfined flows of rainwater and mass movements on hillslopes). Accordingly, the lives and livelihoods of almost all Nebraskans intersect only with regolith, rather than with bedrock, making surficial geologic maps a societally relevant product. Agricultural soils in Nebraska typically have regolith parent materials, most of the sand and gravel mined in the state comes from regolith, and a large part of the groundwater extracted for agricultural, domestic, and municipal uses comes from regolith. Unlike the statewide bedrock geologic map (Burchett 1986), an official statewide surficial geologic map per se of Nebraska has yet to be produced. Surficial geologic mapping in the state has proceeded at the much finer scale of 1:24,000 on a quadrangle-by-quadrangle basis, as part of the STATEMAP Cooperative Geologic Mapping program, for two decades, and the task is far from being completed.

The surficial geology of Nebraska is unique in multiple ways that impact the conduct of mapping and the nature of map products. The Sand Hills, which lie almost entirely within the boundaries of the state, are the largest dune field in the Western Hemisphere (Loope and Swinehart 2000). Consequently, the identification of several types of dunes and other wind-deposited sediments and associated landforms, such as dune types (e.g., Swinehart 1998), is important in surficial geologic mapping. The morphology and history of formation of Sand Hills dunes is not fully understood and the matter needs critical reexamination with a mapping approach. Pleistocene loess deposits from the last glacial period (approximately 110,000–11,700 years ago), chiefly the Peoria Loess, are notably thick along a narrow, diagonal trend along the southern to eastern margin of the Sand Hills from southwestern to north-central Nebraska. The Peoria Loess, which can be identified from eastern Colorado to Ohio and from North Dakota to Louisiana, attains its maximum thickness of about 48 m at Bignell Hill in Lincoln County, Nebraska (Bettis et al. 2003). Where loess deposits are so thick, loess dominates the landscape, soil parent materials, and also the map pattern on surficial geologic maps. The deposition, mass movement, erosion by wind and running water, and volumetric collapse of loess, as well as its ancillary properties and behaviors, produce unique landforms, geomorphic effects, and geologic hazards (e.g., Bariss 1968, 1977; Leger 1990; Derbyshire et al. 1995; Derbyshire 2001; Lukić et al. 2009; Yan et al. 2014; Wang et al. 2015), the full spectrum of which in Nebraska has yet to be described and quantified. In the eastern quarter of the state, the presence of multiple glacial tills exerted significant influence on soil characteristics, surface-water and groundwater hydrology, landscape evolution, and land use and engineering, yet it has proven difficult to name, consistently identify, and satisfactorily map, discrete till sheets of different ages and characteristics.

Having conceded that the bedrock geologic map of Nebraska is less complicated in its pattern than those of many states in which geologic structure is common and complex, we discern concurrently that most surficial geologic maps of modest scale (e.g., 1:24,000) in Nebraska—and in many other places, for that matter—have inherently complex patterns. This statement is only true, of course, if geologic mappers opt to adequately represent the diversity of surficial materials in terms of origin, age, and landscape or geometric relationships, rather than merely representing undifferentiated Quaternary sediments, as was once common in some circles devoted to bedrock mapping. Two of the forthcoming examples of new discoveries made through surficial geologic mapping in Nebraska illustrate how important it is to scrutinize Quaternary sediments and differentiate them as multiple mapping units.

New Discoveries from Geologic Mapping in Nebraska

Several new discoveries have been made in the recent production of 1:24,000 surficial geologic maps in Nebraska, and we are confident that they will continue to be made. These discoveries cast a new light on local to regional geology and increase our understanding of Nebraska's changing landscapes through deep time. We describe only a few of them in the following paragraphs.

Structural Bedrock Landforms in Southeastern Nebraska

Recent mapping in parts of southeastern Nebraska (Korus et al. 2014; Korus and Howard 2015) was augmented by high-resolution LiDAR and LiDAR-based digital elevation models. This technique provided novel information about the Nemaha Tectonic Zone (NTZ). Much of what had already been known about this structural feature anywhere along its length emerged not from surficial mapping but from subsurface data (boreholes and downhole geophysical logs, as well as geophysical surveys). Prior geologic maps of southeastern Nebraska provided little, if any, direct evidence of structural features associated with the NTZ. Recent mapping, however, demonstrated that distinct steps on hillslopes within the area of the NTZ in southeastern Nebraska are produced by individual erosion-resistant limestone strata that can be meticulously traced along hillsides and through areas not accessible by foot (Fig. 5b–d). Tracing these limestone steps along hillslopes demonstrates that the limestone strata, which were originally flat, now have structural dips of 3° to 7°, decreasing in elevation at the land surface by at least 34 m over a distance of 305 m. Furthermore, particular landforms—sharp-crested structural ridges and small, low-relief cuestas (Fig. 5b–d)—have been produced by the differential erosion of a succession of these structurally inclined strata.

By connecting scattered locations in which these structurally controlled landscape features are present, it is possible to delineate a north–south zone of eastward-dipping beds corresponding to the eastern margin of the NTZ in easternmost Pawnee County and westernmost Richardson County. Structural complexity is manifest in these subtle features. The orientations and dip angles change abruptly in several locations, suggesting that the fault zone may consist of a series of fault blocks with varying structural attitudes. Regardless, the landforms described in the process of surficial mapping are the only small-scale, structurally controlled bedrock landforms yet to be described from Nebraska. In a general sense, they are miniature subdued versions of structurally controlled ridges in the far-off foothills of the Colorado Rockies.

Eolian Sand Sheets in the Western Platte Valley

For the first time, mappers of the area directly west of the town of North Platte, Nebraska, have identified several elongate and "tonguelike" eolian (windblown) sand sheets (Fig. 6). Eolian sand sheets are low relief (<3 m) deposits of sand that typically lack dune morphologies and slipfaces (steep surfaces down which wind-transported sand cascades). Sand sheets form where sand availability is limited or where environmental conditions have not persisted for an adequate time period to allow for the formation of actual dunes.

The sand sheets in the western Platte Valley were first mapped in the Hershey West Quadrangle (Young et al. 2013) and the abutting Hershey East Quadrangle (Hanson et al. 2015). Individual sand sheets are as much 2,200 m long and 600 m in width. They overlie alluvial terraces of the North Platte River, which are approximately 3–4 meters above the present floodplain of the Platte River. Sand sheets mostly exhibit 2 m or less of relief, but locally they exceed 5 m in relief. Nearby and much larger dunes in the Nebraska Sand Hills lie 25–40 m higher than the river's terraces, and they were mapped as dome or domelike dunes (Swinehart 1998). The sand sheets are connected to the dunes, and the intimate geographic relationship between the two kinds of features indicates that the sand sheets were sourced from the dunes. In other words, sand from the dunes of the Sand Hills was blown onto the terraces in the river valley. It is not yet known whether the sand sheets formed in one or multiple events, but it is likely that sand was moving the last time the Nebraska Sand Hills were an active dune field, approximately 1,000 years ago, during the Medieval Climatic Anomaly (Miao et al. 2007).

Sand Ridges in the Eastern Platte River Valley

Numerous unusual sand ridges (Fig. 7) have been identified in multiple places along the Platte River Valley from Duncan, Nebraska, eastward to South Bend through surficial geologic mapping. Sand ridges lie on the Platte River's present floodplain or on low-lying terraces in the valley. Although they are quite striking, they had not been described in the scientific literature prior to surficial geologic mapping at the turn of the 21st century (Mason and Joeckel 2001a, 2001b). They are obvious topographic anomalies, having been utilized by people in various ways, most impressively as high-ground locations for homes on the floodplain. Sand ridges were first identified between Fremont and Ashland in the eastern Platte Valley by Mason and Joeckel (2001a), and they are particularly prominent on surficial geologic maps of Schuyler (Young et al. 2010), Silver Creek SE (Hanson and Young 2008), and Valley (Mason and Joeckel 2001b).

Most sand ridges in the Platte Valley are oriented

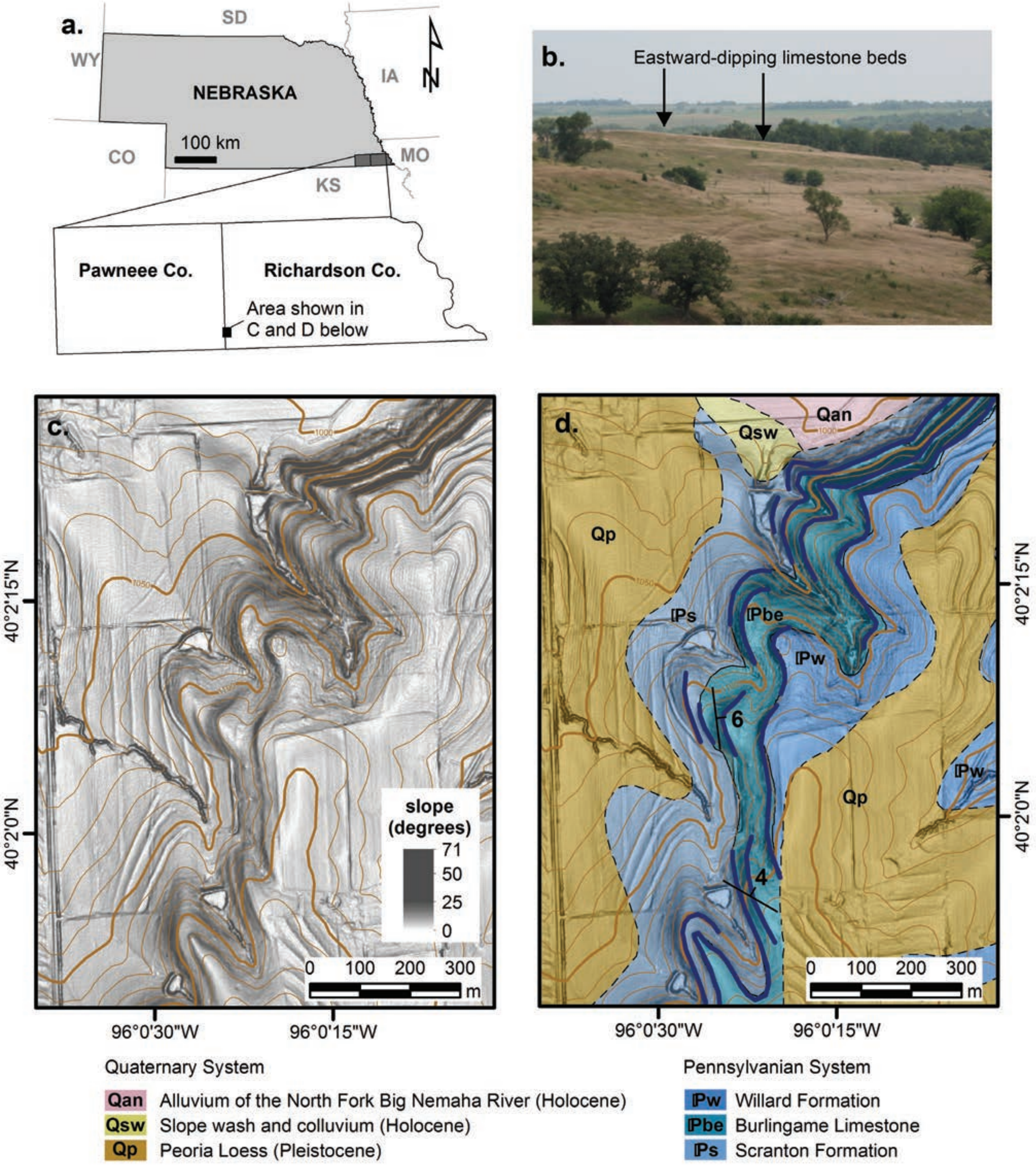

Figure 5. A new discovery from surficial mapping in southeastern Nebraska. Examples of structurally controlled landscape features associated with gently deformed Pennsylvanian bedrock strata (Willard Formation, Burlingame Limestone, and Scranton Formation) in US Geological Survey Dubois 7.5-Minute Quadrangle. **a.** Location map. **b.** View toward east-southeast in Pawnee County showing gently dipping, resistant limestone beds forming distinct benches in the hillside. Field of view at midrange is approximately 500 m. **c.** Slope map and topographic contours (intervals of about 3 m, or 10 ft) derived from LiDAR (light detection and ranging); dark linear bands in slope map were identified as limestone beds through field mapping. Note discordance between limestone beds and topographic contours. **d.** Portion of surficial geologic map (Korus et al., 2014) showing changes in elevation on as much as 30 m of contacts between mapped strata. Dark blue lines are Pennsylvanian limestone beds identified in slope map. Numbers indicate slope in degrees.

roughly parallel to either existing or abandoned channels of the river. Most of the ridges range from 30 to 120 meters in width and have lengths of 500 to 4,000 m. Many ridges are lower than 2 m in height, but a few ridges attain heights of as much as 6 m above the present floodplain. Coring indicates that ridges consist mostly of fine- to medium-grained sand, but also that they contain a few thin beds of coarse-grained sand and granules.

The genesis of the Platte Valley sand ridges is still a mystery. They may be unique to the Platte River or at least uncommon in similar river systems worldwide. In fact, we have not yet found parallel examples of these features in literature describing diverse other braided river systems. Hypotheses of eolian and fluvial (river) origins for the ridges have undergone some preliminary scientific testing, and the results seem to favor the latter. Assuming that the sand ridges were produced by river processes—rather than eolian ones—further research on them will assist in the reconstruction of past flow conditions on the Platte River.

Conclusion

Geologic maps and mapping of Nebraska continue to provide information to the scientific community and the greater public. The statewide bedrock map of Nebraska reveals a pattern that formed over millions of years in response to far-off and regional movements of Earth's crust (mountain-building events to the west and south) and long-term erosion, chiefly by streams. In effect, it tells a long and complicated story about time and place, about which we still know little. Surficial geologic maps tell other stories. Such maps now being produced in Nebraska help us understand how the landscape upon which we live evolved in more recent geologic times, especially since the beginning of the Pleistocene Epoch. Surficial geologic maps are also valuable in the understanding of soils, the assessment of sand, gravel, and construction-fill resources, in land management and water resources, and in characterizing geologic hazards such as landslides and the potential for ground motion and shaking during earthquakes.

More than 170 years were required to attain the present state of geologic mapping in Nebraska, but much more work remains to be done. Major directives that should be addressed include (1) continued detailed digital mapping of surficial geology at the scale of 1:24,000 and the compilation of those results into larger-scale maps; (2) the production of a new digital statewide bedrock geologic map, preferably at the scale of 1:500,000 (thus comparable in important ways with maps in some adjacent states); and (3) the production of a "working" digital statewide map of surficial geology at the same scale. The revised bedrock geologic map of Iowa required more than 12 years of work by multiple geologists, and it is substantively different from earlier versions because new data sources, scientific research, and digital technology were incorporated (Anderson and Witzke 2010; Witzke et al. 2010). A new digital bedrock map of Nebraska would require similar investments of time, effort, and technology. Progress in surficial geologic mapping in Nebraska remains at an early stage. At the present rate of production, surficial geologic mapping in Nebraska at the scale of 1:24,000 could continue for decades, yielding important scientific results all the while. Yet other kinds of geologic maps of Nebraska require revision or even complete remaking, particularly in digital formats. Examples include the statewide map of the basement rock surface, as well as basement rock types, structure-contour maps of key stratigraphic levels, and various kinds of hydrogeologic maps.

The quantum jump that mapping technology has made in the past two decades has set geologic mapping on a seemingly auspicious trajectory around the world, including in Nebraska. Unfortunately, there are practical constraints on the implementation of new geologic mapping, which apply almost universally as well. These constraints can be summarized in three questions: (1) Who—in a position of authority—will recognize and decide that geological mapping should to be done and promulgate its importance? (2) Who is qualified to do the mapping—in whose purview does the activity lie—and who, specifically, will actually do the mapping? (3) Who will pay for the mapping? These questions are all open in nature, and somewhat beyond the scope of this article, but we offer some opinions. Regarding the first and second questions, we believe that a significant part of the prioritization and performance of geologic mapping should remain in the hands of state geological surveys (e.g., the Conservation and Survey Division) in cooperation with the US Geological Survey, as it is today in the STATEMAP program. As long as a state geological survey can employ qualified, dedicated geologists, it will be the best source of local to regional earth science knowledge. The third question, however,

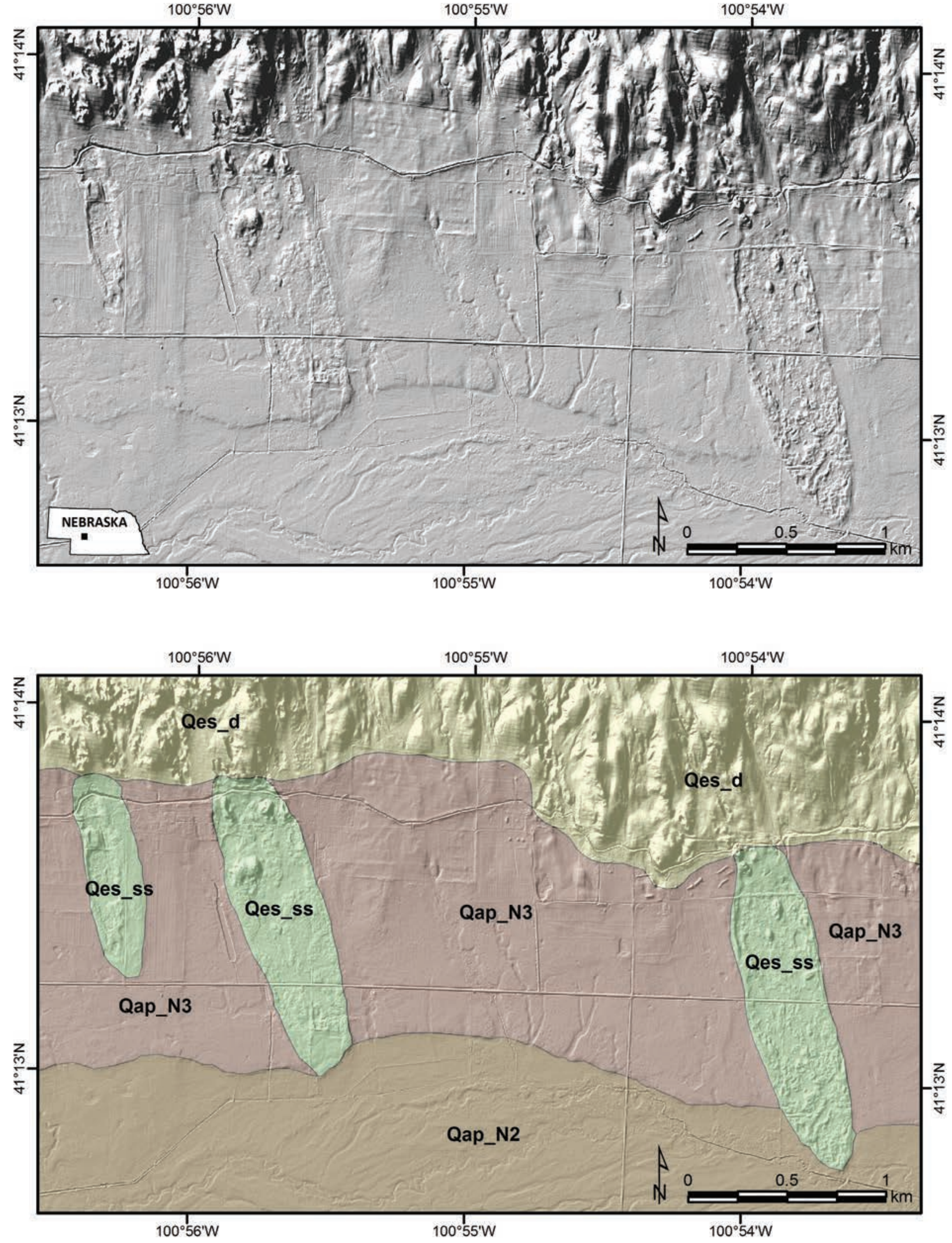

Figure 6. A new discovery from surficial mapping in the Platte Valley in US Geological Survey Hershey East 7.5-Minute Quadrangle. (Top) Digital elevation model showing three small, tonguelike sand sheets consisting of sand blown from the Sand Hills southward onto a terrace of the Platte River. (Bottom) Portion of surficial geologic map (Hanson et al. 2015) showing same area; sand sheets (Qes_ss) extend from dune deposits (Qes_d) onto middle to late Holocene alluvium of Platte River (Qap_N3) that is slightly higher in elevation relative to slightly younger alluvium (Qap_N2)

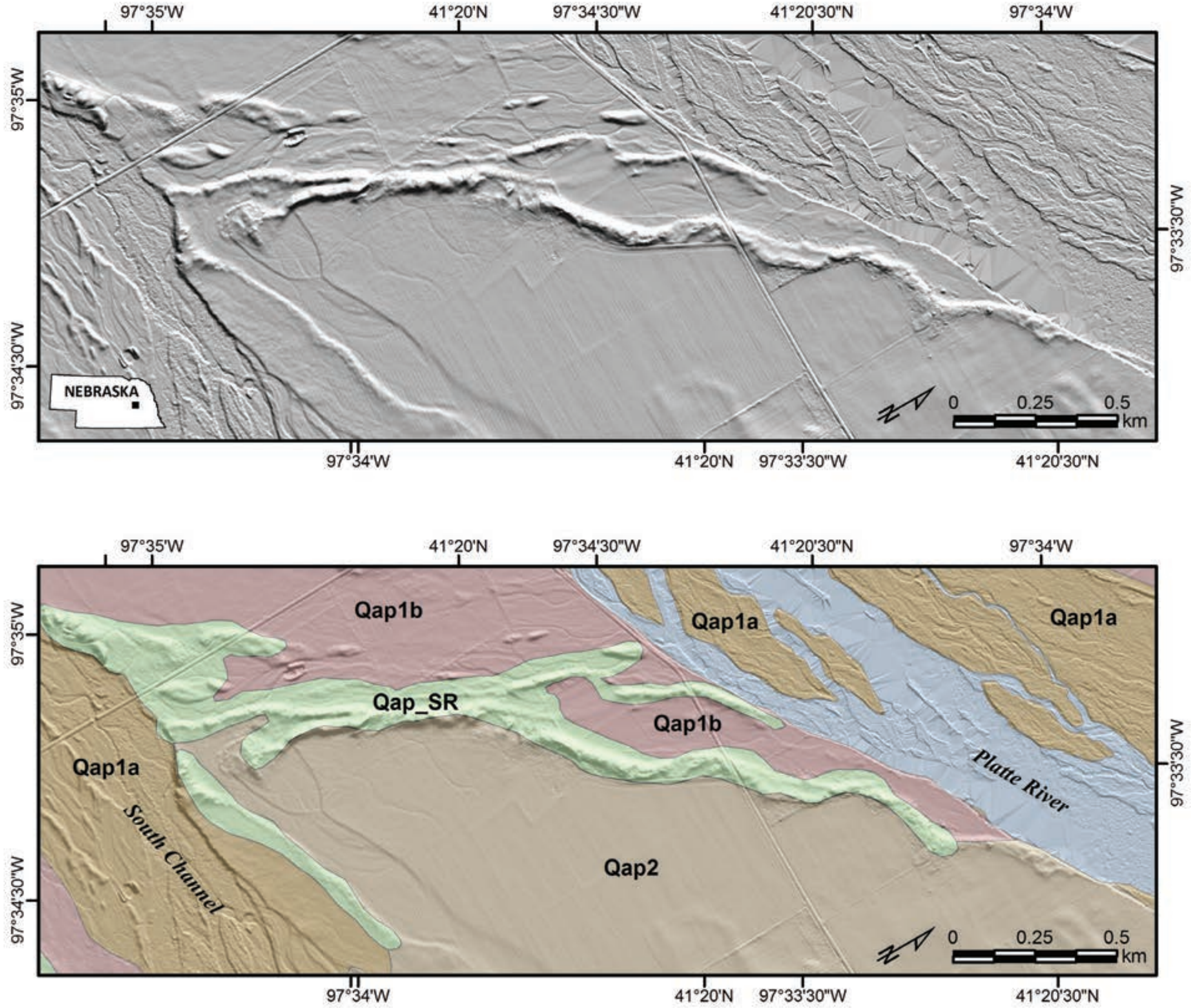

Figure 7. Another new discovery from mapping in the Platte Valley in US Geological Survey Silver Creek Southeast 7.5-Minute Quadrangle. (Top) Digital elevation model showing prominent sand ridge between Platte River (right) and South Channel Platte River (left). (Bottom) Portion of surficial geologic map (Hanson and Young 2008) showing same area; sand ridge (Qap_SR) extends between areas mapped as Holocene alluvium of Platte River (Qap1b, Qap2).

reflects the most powerful constraint of all on the practice of geologic mapping. It is all the more relevant in an era of reorganizations, downsizing, and budget cuts in state geological surveys in the US (Buchanan 2016) and at a moment in time—that during which this article was written—when funding for the US Geological STATEMAP Cooperative Mapping Program faces potential reduction.

We are compelled to admit that geologists can be introverted and that they do not uniformly excel at communicating the relevance of what they do with other scientists, much less with the general public. These shortcomings may be at the root of some of the poor societal understanding and lack of general appreciation for geologic maps. Nevertheless, there are “teachable moments,” like the public concern over the Keystone XL pipeline extension that has emerged in Nebraska, which should be embraced as opportunities to inform the public about geologic maps and their value. These events should also cause geologists to reflect on whether or not geologic mapping is appropriately and adequately serving the public interest. Nevertheless, there is ample evidence that geologic mapping in general remains a scientifically sound and societally relevant endeavor.

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References

Aber, J. S. 1997. “Chert Gravel and Neogene Drainage in East-Central Kansas.” *Kansas Geological Survey Bulletin* 240:30–41.

Ahlbrandt, T. S., and W. Groen. 1987. “The Goshen Hole Uplift: A Brief Review of its Geologic History and Exploration Potential.” *The Mountain Geologist* 24 (2): 33–43.

Anderson, R. R., and B. J. Witzke. 2010. “New Digital Bedrock Geologic Map of Iowa” [abstract]. *Geological Society of America Abstracts with Programs* 42 (2): 89–90.

Andrews, G. W. 1958. “Windrow Formation of Upper Mississippi Valley Region: A Sedimentary and Petrographic Study.” *Journal of Geology* 66 (6): 597–624.

Aughey, S. 1861. *The Renovation of Politics; A Discourse Delivered in St. Paul's Evangelical Lutheran Church, Lionville, Chester County, Pa., on the Evening of January 4th, 1861*. West Chester, PA: E. F. James. https://catalog.hathitrust.org/Record/009604699.

Aughey, S. 1884. “Geological Map of Nebraska.” https://upload.wikimedia.org/Wikipedia/commons/b/b6/EB9_Nebraska_-_geological_map.jpg.

Barbour, E. H. 1900. “Glacial Grooves and Striae in Southeastern Nebraska.” *Journal of Geology* 8 (4): 309–12.

Bariss, N. 1968. “Comparative Landscape Study of Selected Loess Areas in the Missouri River Basin.” In *Loess and Related Eolian Deposits of the World*, Proceedings, 12:81–99, International Association for Quaternary Research, 7th Congress, Boulder-Denver, Colorado, 1965. Lincoln, NE: University of Nebraska Press.

Bariss, N. 1977. “Gullying in Semi-Arid Loess Region of North America.” *Great Plains-Rocky Mountain Geographical Journal* 6:125–32.

Bartlett, R. A. 1962. *Great Surveys of the American West*. Norman: University of Oklahoma Press.

Benford, R. D., H. A. Moore, and J. A. Williams Jr. 1993. “In Whose Backyard?: Concern About Siting a Nuclear Waste Facility.” *Sociological Inquiry* 63 (1): 30–48.

Berendsen, P., and K. P. Blair. 1995. “Structural Development of the Nemaha Tectonic Zone in Kansas.” In *Structural Styles in the Southern Midcontinent*, ed. K. S. Johnson, 208–14. Oklahoma Geological Survey Circular 97.

Bettis, E. A. III, D. R. Muhs, H. M. Roberts, and A. G. Wintle. 2003. “Last Glacial Loess in the Coterminous USA.” *Quaternary Science Reviews* 22:1907–46.

Brick, G. 2013. “‘Water Flowing Uphill Is One of the Commonest Facts of Nature’: The Emergence of a Visual Language for Groundwater Geology.” *Groundwater* 51 (6): 968–72.

Broome, J. 2005. “The Future of Geosciences in the 21st Century: Art, Science, or Resource?” In *The Current Role of Geological Mapping in Geosciences*. NATO Science Series IV: *Earth and Environmental Science*, ed. S. R. Ostaficzuk, 56:51–58. Dordrecht, Netherlands: Springer.

Buchanan, R. 2016. “State Budgets, Geological Surveys, and the New Reality.” *Eos* 97, doi.org/10.1029/2016EO059893.

Bunker, B. J., 1981. “The Tectonic History of the Transcontinental Arch and Nemaha Uplift and their Relationship to the Cretaceous Rocks of the Central Midcontinent Region.” In *Cretaceous Stratigraphy and Sedimentation in Northwest Iowa, Northeast Nebraska, & Southeast South Dakota,* 1–23. Iowa Geological Survey Guidebook Series Number 4. Iowa City: Iowa Geological Survey Bureau.

Bunker, B. J., B. J. Witzke, N. L. Watney, and G. A. Ludvigson. 1988. “Phanerozoic History of the Central Midcontinent, United States.” In *Sedimentary Cover—North American Craton: U.S.*, ed. L. L. Sloss, 243–60. Geological Society of America, Geology of North America D-2. Boulder, CO: Geological Society of America.

Burberry C. M., R. M. Joeckel, and J. T. Korus. 2015. “Post-Mississippian Tectonics of the Nemaha Tectonic Zone and Mid-Continent Rift System, SE Nebraska and N Kansas.” *Mountain Geologist* 52:47–73.

Burchett, R. R., compiler. 1969. “Geologic Bedrock Map of Nebraska,” scale 1:1,000,000. Nebraska Geological Survey, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln.

Burchett, R. R., compiler. 1986. “Geologic Bedrock Map of Nebraska,” scale 1:1,000,000. Nebraska Geological Survey, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln.

Burgess, P. M. 2008. “Phanerozoic Evolution of the Sedimentary Cover of the North American Craton.” In *Sedimentary Basins of the World*, ed. A. D. Miall, 5:31–63. Amsterdam: Elsevier.

Cassidy, J. G. 2000. *Ferdinand V. Hayden: Entrepreneur of Science.* Lincoln: University of Nebraska Press.

Cather, S. M., C. E. Chapin, and S. A. Kelley. 2012. “Diachronous Episodes of Cenozoic Erosion in Southwestern North America and Their Relationship to Surface Uplift, Paleoclimate, Paleodrainage, and Paleoaltimetry.” *Geosphere* 8 (6): 1177–206. doi:10.1130/GES00801.1.

Chan, M. A., S. E. Peters, and B. Tikoff. 2016. "The Future of Field Geology, Open Data Sharing and CyberTechnology in Earth Science." *Sedimentary Record* 14 (1): 4–9.

Cobban, W. A., E. A. Merewether, T. D. Fouch, and J. D. Obradovich. 1994. "Some Cretaceous Shorelines in the Western Interior of the United States." In *Mesozoic Systems of the Rocky Mountain Region, USA*, ed. M. V. Caputo, J. A. Peterson, and K. J. Franczyk, 393–414. Denver: Rocky Mountain Section SEPM (Society for Sedimentary Geology).

Condra, G. E., and E. C. Reed. 1950. "Geologic Map of Nebraska," scale 1:500,000 (approximate). Nebraska Geological Survey, Conservation and Survey Division, University of Nebraska–Lincoln.

Cragin, S. 2007. *Nuclear Nebraska: The Remarkable Story of the Little County That Couldn't Be Bought*. New York: American Management Association.

Cross, T. A. 1986. "Tectonic Controls of Foreland Basin Subsidence and Laramide Style Deformation, Western United States." In *Foreland Basins*, ed. P. A. Allen and P. Homewood, 15–39. International Association of Sedimentologists Special Publication 8. Oxford: Blackwell Scientific.

Curley, E. A. 1875. *Nebraska, Its Advantages, Resources, and Drawbacks.* New York: American News Company.

Darton, N. H. 1899. "Preliminary Report of the Geology and Water Resources West of the One Hundred and Third Meridian." Nineteenth Annual Report, Part 4. Washington, DC: US Geological Survey.

Darton, N. H. 1903. "Preliminary Report of the Geology and Water Resources West of the One Hundred and Third Meridian." US Geological Survey Professional Paper 17. Washington, DC: US Geological Survey.

Darton, N. H. 1905. "Preliminary Report of the Geology and Underground Water Resources of the Central Great Plains." US Geological Survey Professional Paper 32. Washington, DC: US Geological Survey.

Darton, N. H. 1941. "Response of Dr. Darton." In *Presentation of the Penrose Medal to Nelson Horatio Darton, Medalist*. Anonymous, 84–88. Proceedings of the Austin Meeting. Boulder, CO: Geological Society of America.

Derbyshire, E. 2001. "Geological Hazards in Loess Terrain, With Particular Reference to the Loess Regions of China." *Earth-Science Reviews* 54 (1–3): 231–60.

Derbyshire, E., X. Meng, J. Wang, Z. Zhou, and B. Li. 1995. "Collapsible Loess on the Loess Plateau of China." In *Genesis and Properties of Collapsible Soils*. NATO ASI Series 468, *Earth and Environmental Science*, ed. E. Derbyshire, T. Dijkstra, and I. J. Smalley, 56:267–93. Dordrecht, Netherlands: Springer.

Diffendal, R. F. Jr. 1994. "Geomorphic and Structural Features of the Alliance 1° × 2° Quadrangle, Western Nebraska, Discernible from Synthetic Aperture Radar Imagery and Digital Shaded-Relief Maps." *Contributions to Geology, University of Wyoming* 30 (2): 137–47.

Diffendal, R. F. Jr., and A. P. Diffendal. 2003. "Lewis and Clark and the Geology of the Great Plains," Conservation and Survey Division, University of Nebraska–Lincoln, Educational Circular 17.

Divine, D. P., R. M. Joeckel, J. T. Korus, P. R. Hanson, and S. Olafsen Lackey. 2009. "Eastern Nebraska Water Resources Assessment (ENWRA): Introduction to a Hydrogeologic Study." Bulletin 1 (New Series), Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln.

Divine, D. P., R. M. Joeckel, and S. Olafsen Lackey, 2016. "Aquifers of Nebraska I: The Codell Aquifer in Northeastern Nebraska." Bulletin 7 (New Series), Conservation and Survey Division, University of Nebraska–Lincoln.

Flament, N., M. Gurnis, and R. D. Müller. 2013. "A Review of Observations and Models of Dynamic Topography." *Lithosphere* 5 (2): 189–210. https://doi.org/10.1130/L245.1.

Frye, J. C., B. Leonard, and A. Swineford. 1956. "Stratigraphy of the Ogallala Formation (Neogene) in Northern Kansas." Kansas Geological Survey Bulletin 118.

Frye, J. C., and W. H. Schoewe. 1953. "The Basis for Physiographic Subdivision of Kansas." *Transactions of the Kansas Academy of Science* 56:246–52.

Frye, J. C. Jr., H. B. Willman, and H. D. Glass. 1964. "Cretaceous Deposits and the Illinoian Glacial Boundary in Western Illinois." *Illinois Geological Survey Circular* 364:3–28.

Galloway, W. E., T. L. Whiteaker, and P. Ganey-Curry. 2011. "History of Cenozoic North American Drainage Basin Evolution, Sediment Yield, and Accumulation in the Gulf of Mexico Basin." *Geosphere* 7:938–73.

Gosselin, D. C., L. M. Klawer, R. M. Joeckel, F. E. Harvey, A. R. Reade, and K. McVey. 2006. "Arsenic in Groundwater and Rural Public Water Supplies in Nebraska, U.S.A." *Great Plains Research* 16 (2): 137–48.

Graham, E. 1976. "What is a Mental Map?" *Area* 8 (4): 259–62.

Hanson, P. R., Bruihler, J., and L. M. Howard. 2015. "Surficial Geology of the Hershey East 7.5-Minute Quadrangle, Nebraska," scale 1:24,000. Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln. http://snr.unl.edu/data/geologysoils/STATEMAP/index.aspx.

Hanson, P. R., and A. R. Young. 2008. "Surficial Geology of the Silver Creek SE 7.5-Minute Quadrangle," scale 1:24,000. Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln. http://snr.unl.edu/data/geologysoils/STATEMAP/index.aspx.

Harmand, S., J. E. Lewis, C. S. Feibel, C. J. Lepre, S. Prat, A. Lenoble, X. Boës, R. L. Quinn, M. Brenet, A. Arroyo, N. Taylor, S. Clément, G. Daver, J.-P. Brugal, L. Leakey, R. A. Mortlock, J. D. Wright, S. Lokorodi, C. Kirwa, D. V. Kent, and H. Roche. 2012. "3.3-Million-Year-Old Stone Tools from Lomekwi 3, West Turkana, Kenya." *Nature* 521:310–15.

Harrell, J. A., and V. M. Brown. 1992. "World's Oldest Surviving Geological Map: The 1150 BC Turin Papyrus from Egypt." *Journal of Geology* 100 (1): 3–18.

Hartung, J. B., and R. R. Anderson. 1996. "A Brief History on Investigations of the Manson Impact Structure." In *The Manson Impact Structure, Iowa: Anatomy of an Impact Crater*, ed. C. Koeberl and R. R. Anderson, 31–43. Special Paper 302. Boulder, CO: Geological Society of America.

Hayden, F. V. 1869. "Geological Report of the Exploration of the Yellowstone and Missouri Rivers (1859–60)." Washington, DC: US Government Printing Office.

Hayden, F. V. 1872. "Final Report of the United States Geological Survey of Nebraska and Adjacent Territories." Washington, DC: House of Representatives, 42nd Congress, 1st Session, Ex. Doc. No. 19.

Hayden, F. V. n.d. (probably 1883). "General Geologic Map of the Area Explored by F. V. Hayden and Surveys Under His Charge, 1869–1880." http://1.bp.blogspot.com/-VAnXFaAUZIc/VLkWf-eS6WI/AAAAAAAAKQA/091CZtNPjTM/s1600/HaydenOverallGeoMapFig.jpg.

Hinze, W. J., and L. W. Braile. 1988. "Geophysical Aspects of the Craton: U.S." In *Sedimentary Cover—North American Craton: U.S.*, ed. L. L. Sloss, 5–24. Geological Society of America, Geology of North America D-2. Boulder, CO: Geological Society of America.

Hutchinson, D. R., R. S. White, W. F. Cannon, and K. J. Schulz. 1990. "Keweenaw Hot Spot: Geophysical Evidence for a 1.1 Ga Mantle Plume Beneath the Midcontinent Rift System." *Journal of Geophysical Research* 95:10869–84.

Jacobs, K. C., S. C. Fritz, and J. B. Swinehart. 2007. "Lacustrine Evidence for Moisture Changes in the Nebraska Sand Hills During Marine Isotope Stage 3." *Quaternary Research* 67 (2): 246–54.

Jisra, M. A., T. J. Boerboom, V. W. Chandler, J. H. Mossler, A. C. Runkel, and D. R. Setterholm. 2011."Geologic Map of Minnesota—Bedrock Geology." Minnesota Geological Survey Map Series S-21. http://conservancy.umn.edu/handle/11299/101466.

Joeckel, R. M., J. S. Dillon, P. R. Hanson, L. M. Howard, and M. S. Kuzila. 2010. "The Ridges of Boyd County: Oriented Landforms and Late Quaternary Eolian Processes in North-Central Nebraska, USA" [abstract]. *Geological Society of America Abstracts with Programs* 42 (5): 417.

Joeckel, R. M., and L. M. Howard 2018. "The Ups and Downs of Nebraska: Recognizing Gilgai Microrelief in the State." *Great Plains Research* 28:51–63.

Joeckel, R. M., H. M. Loope, K. D. Wally, and J. E. Hellerich. 2007. "Late Cenozoic Geomorphology of a Bedrock-Dominated Landscape Adjacent to the Laurentide Glacial Limit, Southeastern Nebraska, USA." *Zeitschrift für Geomorphologie* 51:469–86.

Jones, C. H., K. H. Mahan, L. A. Butcher, W. B. Lewandowski, and G. L. Farmer. 2015. "Continental Uplift through Crustal Hydration." *Geology* 43 (4): 355–58.

Karlstrom, K. E., D. Coblentz, K. Dueker, W. Ouimet, E. Kirby, J. Van Wijk, B. Schmandt, S. Kelley, G. Lazear, L. J. Crossey, R. Crow, A. Aslan, A. Darling, R. Aster, J. MacCarthy, S. M. Hansen, J. Stachnik, D. F. Stockli, R. V. Garcia, M. Hoffman, R. McKeon, J. Feldman, M. Heizler, M. S. Donahue, and the CREST Working Group. 2011. "Mantle-Driven Dynamic Uplift of the Rocky Mountains and Colorado Plateau and Its Surface Response: Toward a Unified Hypothesis." *Geosphere* 4:1–22.

King, P. B. 1949. "Memorial to Nelson Horatio Darton." *Proceedings of the Annual Report of 1948*, 145–70. Boulder, CO: Geological Society of America.

Kliment C. R., K. Clemens, and T. D. Oury. 2009. "North American Erionite-Associated Mesothelioma with Pleural Plaques and Pulmonary Fibrosis: A Case Report." *International Journal of Clinical and Experimental Pathology* 2 (4): 407–10.

Koch, N. C. 1986. "Post-Cretaceous Uplift of the Sioux Quartzite Ridge in Southeastern South Dakota." US Geological Survey Open-File Report 86-419W. Huron, SD: US Geological Survey.

Koeberl, C., and R. R. Anderson. 1996. "Manson and Company: Impact Structures in the United States." In *The Manson Impact Structure, Iowa: Anatomy of an Impact Crater*, ed. C. Koeberl and R. R. Anderson, 1–30. Special Paper 302. Boulder, CO: Geological Society of America.

Korus, J. T., L. M. Howard, M. S. Kuzila, and R. M. Joeckel. 2014. "Surficial Geology of the Table Rock 7.5-Minute Quadrangle," scale 1:24,000. Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln.http://snr.unl.edu/data/geologysoils/STATEMAP/index.aspx.

Korus, J. T., and L. M. Howard. 2015. "Surficial Geology of the DuBois 7.5-Minute Quadrangle," scale 1:24,000. Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln. http://snr.unl.edu/data/geologysoils/STATEMAP/index.aspx.

Korus, J. T., R. M. Joeckel, and D. P. Divine. 2013. "Three-Dimensional Hydrostratigraphy of the Firth, Nebraska Area: Results from Helicopter Electromagnetic (HEM) Mapping in the Eastern Nebraska Water Resources Assessment (ENWRA)." Bulletin 3 (New Series), Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln.

Larson, C. 2001. "Provenance, Distribution, and Sand Hills Dune Sand Source Potential Connely Flat Beds, (Latest Wisconsin), Niobrara River, Ainsworth to Merriman, Nebraska." Master's thesis, University of Nebraska–Lincoln.

Leger, M. 1990. "Loess Landforms." *Quaternary International* 7–8:53–61.

Lewis, G. M. 1988. "Maps. Mapmaking, and Map Use by Native North Americans." In *The History of Cartography*. Vol. 2, Book 3, *Cartography in the Traditional African, American, Arctic, Australian, and Pacific Societies*, ed. D. Woodward and G. M. Lewis, 51–182. Chicago: University of Chicago Press.

Library of Congress. n.d. "Maclure's Geologic Map of the United States." https://www.loc.gov/resource/g3701c.ct003944/.

Lisle, R. J. 2004. *Geological Structures and Maps: A Practical Guide*, 3rd ed. Amsterdam: Elsevier.

Lohr, S. 2013. "The Origins of 'Big Data': An Entomological Detective Story." *New York Times* (blog), February 1. https://bits.blogs.nytimes.com/2013/02/01/.

Loope, D. B., and J. B. Swinehart. 2000. "Thinking Like a Dune Field: Geologic History in the Nebraska Sand Hills." *Great Plains Research* 10:5–35.

Lukić, T. S., B. Marković, T. Stevens, D. A. Vasiljević, B. Machalett, N. Milojković, B. Basarin, and I. Obrecht. 2009. "The Loess 'Cave' Near the Village of Surduk—An Unusual Pseudokarst Landform in the Loess of Vojvodina, Serbia." *Acta Carsologica* 38 (2–3): 227–35.

Lyell, C. 1845. *Travels in North America in the Years 1841–2: Geological Observations on the United States, Canada, and Nova Scotia*, vol. 2. New York: Wiley and Putnam.

Lyle, S. 2007. "The Geology of Radon in Kansas." Public Information Circular 25. Lawrence: Kansas Geological Survey Geology Extension.

Mackin, J. H. 1950. "The Down-Structure Method of Viewing Geologic Maps." *Journal of Geology* 58 (1): 55–72.

Maclure, W. 1809. "Observations on the Geology of the United States, Explanatory of a Geologic Map." *Transactions of the American Philosophical Society* 6 (2): 411–28.

Martin, J. E., J. F. Sawyer, M. D. Fahrenbach, D. M. Tomhave, and L. D. Schulz. 2004. "Geologic Map of South Dakota," scale 1:500,000. South Dakota Geological Survey General Map 10. http://www.sdgs.usd.edu/pubs/pdf/G-10.pdf.

Mason, J. A., and R. M. Joeckel. 2001a. "Surficial Geology of the Platte River Valley, Fremont to Ashland (Fremont East, Arlington, Valley, Wann, and Ashland East 7.5-Minute Quadrangles)." Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln, Open-File Report 68.

Mason, J. A. and R. M. Joeckel. 2001b. "Surficial Geology of the Valley Quadrangle, Nebraska," scale 1:24,000. Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln. http://snr.unl.edu/data/geologysoils/STATEMAP/index.aspx.

McMillan, M. E., C. L. Angevine, and P. L. Heller. 2002. "Postdepositional Tilt of the Miocene-Pliocene Ogallala Group on the Western Great Plains: Evidence of Late Cenozoic Uplift of the Rocky Mountains." *Geology* 30 (1): 63–66.

McMillan, M. E., P. L. Heller, and S. L. Wing. 2006. "History and Causes of Post-Laramide Relief in the Rocky Mountain Orogenic Plateau." *Geological Society of America Bulletin* 118 (3/4): 393–405.

Merewether, E. A. 1983. "Lower Upper Cretaceous Strata in Minnesota and Adjacent Areas: Time-Stratigraphic Correlations and Structural Attitudes, Stratigraphy and Paleontology of Mid-Cretaceous Rocks in Minnesota and Contiguous Areas." *US Geological Survey Professional Paper 1253-B*, 27–52.

Merin, I. S., and W. R. Moore. 1986. "Application of Landsat Imagery to Oil Exploration in Niobrara Formation, Denver Basin, Wyoming." *American Association of Petroleum Geologists Bulletin* 70 (4): 351–59.

Miall, A. D., O. Catuneanu, B. K. Vakarelov, and R. Post. 2008. "The Western Interior Basin." In *Sedimentary Basins of the World*, ed. A. D. Miall, 5:329–62. Amsterdam: Elsevier.

Miao, X., J. A. Mason, J. B. Swinehart, D. B. Loope, P. R. Hanson, R. J. Goble, and X. Liu. 2007. "A 10,000-Year Record of Dune Activity, Dust Storms, and Drought in the Central Great Plains." *Geology* 35:119–22.

Miller , K. G., M. A. Kominz, J. V. Browning, J. D. Wright, G. S. Mountain, M. E. Katz, P. J. Sugarman, B. S. Cramer, N. Christie-Blick, and S. F. Pekar. 2005. "The Phanerozoic Record of Global Sea-Level Change." *Science* 310:1293–98.

Monmonier, M. 1998. *Cartographies of Danger: Mapping Hazards in America*. Chicago: University of Chicago Press.

Monroe, W. H. 1949. "Memorial; Nelson Horatio Darton (1865–1948)." *Bulletin of the American Association of Petroleum Geologists* 33 (1): 116–24.

Mookerjee, M., D. Vieira, M. Chan, Y. Gill, T. L. Pavlis, F. Spear, F, and B. Tikoff. 2015. "Field Data Management: Integrating Cyberscience and Geoscience." *Eos* 96, doi: 10.1029/2015EO036703.

Moore, V. A., and R. B. Nelson 1974. "Effect of Cambridge-Chadron Structural Trend on Paleozoic and Mesozoic Thickness, Western Nebraska." *American Association of Petroleum Geologists Bulletin* 58:260–68.

Mudrey, M. G. Jr., B. A. Brown, and J. K. Greenberg. 1982. "Bedrock Geologic Map of Wisconsin." University of Wisconsin Extension, Geological and Natural History Survey.

Mundy, B. F. 1988. "Mesoamerican Cartography." In *The History of Cartography*. Vol. 2, Book 3, *Cartography in the Traditional African, American, Arctic, Australian, and Pacific Societies*, ed. D. Woodward and G. M. Lewis, 183–256. Chicago: University of Chicago Press.

Nereson, A., J. Stroud, K. Karlstrom, M. Heizler, and W. McIntosh. 2013. "Dynamic Topography of the Western Great Plains: Geomorphic and ^{40}Ar/^{39}Ar Evidence for Mantle-Driven Uplift Associated with the Jemez Lineament of NE New Mexico and SE Colorado." *Geosphere* 9 (3): 521–45.

Nixon, D. A. 1995. "The Structure of the Pine Ridge of the Tri-State Region of Wyoming, Nebraska, and South Dakota and Its Relationship to the Black Hills Dome" [abstract]. *Abstracts with Programs, Geological Society of America* 27 (3): 77.

Nolan, J., and C. Weber. 2015. "Natural Uranium Contamination in Major U.S. Aquifers Linked to Nitrate." *Environmental Science and Technology Letters* 2 (8): 215–20.

O'Hanlon, K. 2011. "Epilogue: Nuke Dump Battle Peaked 10 Years Ago This Month." *Lincoln Journal Star*, July 4. http://journalstar.com/special-section/epilogue/epilogue-nuke-dump-battle-peaked-years-ago-this-month/article_8fe7f462-7662-5c03-8d03-7f4cc4729a0f.html.

Oldroyd, D. 2013. "Maps as Pictures or Diagrams: The Early Development of Geological Maps." In *Rethinking the Fabric of Geology,* ed. V. R. Baker, 41–101. Special Paper 502. Boulder, CO: Geological Society of America.

Pavlis, T. L., and K. A. Mason. 2017. "The New World of 3D Geologic Mapping." *GSA Today* 27, doi: 10.1130/GSATG313A.1.

Rabbitt, M. C. 1989. "The United States Geological Survey: 1879–1989." US Geological Survey Circular 1050.

Rascoe, B. Jr. 1978. "Late Paleozoic Structural Evolution; The Las Animas Arch." In *Energy Resources of the Denver Basin*, ed. J. D. Pruitt and P. E. Coffin. 113–27. Denver: Rocky Mountain Association of Geologists.

Reed, R. C., and J. Daniels, compilers. 1987. "Bedrock Geology of Northern Michigan," scale 1:500,000. Geological Survey Division, Michigan Department of Natural Resources.

Riller, U. 2005. "Structural Characteristics of the Sudbury Impact Structure, Canada: Impact-Related Versus Orogenic Deformation—A Review." *Meteoritics and Planetary Science* 40 (11): 1723–40.

Rudwick, M. J. S. 1976. "The Emergence of a Visual Language for Geological Science, 1760–1840." *History of Science* 14:149–95.

Schmitt, A. K., M. Danišík, E. Aydar, E Şen, İ. Ulusoy, and O. M. Lovera. 2014. "Identifying the Volcanic Eruption Depicted in a Neolithic Painting at Çatalhöyük, Central Anatolia, Turkey." *PLoS ONE* 9 (1): e84711. https://doi.org/10.1371/journal.pone.0084711.

Schumann, R. R. 1993. "Preliminary Geologic Radon Potential Assessment of Nebraska." In *Geologic Radon Potential of EPA Region 7*, ed. R. R. Schumann, 125–42. US Geological Survey Open-File Report 93-292-G.

Sims, P. K., and Z. E. Peterman. 1986. "Early Proterozoic Central Plains Orogen: A Major Buried Structure in the North-Central United States." *Geology* 14:488–91.

Sloss, L. L. 1988. "Tectonic Evolution of the Craton in Phanerozoic Time." In *Sedimentary Cover—North American Craton: U.S.*, ed. L. L. Sloss, 25–51. Geology of North America D-2. Boulder, CO: Geological Society of America.

Stander, T. W. 1989. "Structural Nature of the Humboldt Fault Zone in Northeastern Nemaha County, Kansas." In *Geophysics in Kansas*, ed. D. W. Steeples, 117–28. Kansas Geological Survey Bulletin 226.

Stanley, K. O., and W. J. Wayne. 1972. "Epeirogenic and Climate Controls of Early Pleistocene Fluvial Sediment." *Geological Society of America Bulletin* 83:3675–90.

State Geological Survey of Kansas. 2008. "Geologic Map of Kansas," scale 1:500,000. Kansas Geological Survey Map M-118.http://www.kgs.ku.edu/General/Geology/gifs/M118_150dpi.pdf.

Stein, S., C. Stein, J. Kley, R. Keller, M. Merino, E. Wolin, D. Wiens, M. E. Wysession, G. Al-Equabi, W. Shen, A. Fredriksen, F. Darbyshire, D. Jurdy, G. Waite, W. Rose, E. Vye, T. Rooney, R. Moucha, and E. Brown. 2016. "New Insights into North America's Midcontinent Rift." *Eos* 97, https://doi.org/10.1029/2016EO056659.

Swinehart, J. B. 1998. "Wind-Blown Deposits." In *Atlas of the Sand Hills*, 3rd ed., ed. A. Bleed and C. Flowerday, 43–56. Resource Atlas 5b. Lincoln: Conservation and Survey Division, University of Nebraska–Lincoln.

Swinehart, J. B., and R. F. Diffendal Jr., 1998. "Geology of the Pre-Dune Strata." In *Atlas of the Sand Hills*, 3rd ed., ed. A. Bleed and C. Flowerday, 29–42. Resource Atlas 5b. Lincoln: Conservation and Survey Division, University of Nebraska–Lincoln.

Swinehart, J. B., V. L. Souders, H. M. DeGraw, and R. F. Diffendal Jr. 1985. "Cenozoic Paleogeography of Western Nebraska." In *Cenozoic Paleogeography of the West-Central United States*, ed. R. M. Flores and S. S. Kaplan, 209–29. Denver: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists.

Swoger, B. 2013. "The Prettiest Information Resources: Geologic Maps." *Scientific American* (blog). https://blogs.scientificamerican.com/information-culture/the-prettiest-information-resources-geologic-maps/.

Thomas, G. E. 1971. "Continental Plate Tectonics: Southwest Wyoming." In *Wyoming Tectonics*, ed. A. B. Renfro, 103–24. Wyoming Geological Association 23rd Annual Field Conference Guidebook.

Tikoff, B., and J. Maxson. 2001. "Lithospheric Buckling of the Laramide Foreland During Late Cretaceous and Paleogene, Western United States." *Rocky Mountain Geology* 36:13–35.

Van Gosen, B., T. Blitz, G. Plumlee, G. Meeker, and M. P. Pierson. 2012. "Geologic Occurrences of Erionite in the United States: An Emerging National Public Health Concern for Respiratory Disease." *Environmental Geochemistry and Health* 35 (4): 419–30.

Van Schmus, W. R., and W. J. Hinze. 1985. "The Midcontinent Rift System." *Annual Reviews of Earth and Planetary Science* 13:345–85.

Wang, G., T. Li, X. Xing, and Y. Zou. 2015. "Research on Loess Flow-Slides Induced by Rainfall in July 2013 in Yan□an, China." *Environmental Earth Science* 73:7933–44.

Warhus, M. 1997. *Another America: Native American Maps and the History of Our Land.* New York: St. Martin's Press, 1997.

Weary, D. J., and D. H. Doctor. 2014. "Karst in the United States: A Digital Map Compilation and Database." US Geological Survey Open-File Report 2014-1156. Reston, VA: US Geological Survey.

Welch, S., and M. B. Leite. 2014. "Northwest Nebraska's Chadron Dome Is Not a Dome." *Geological Society of America Abstracts with Programs* 46 (4): 58.

Westby, M. J., J. Brassington, N. F. Glasser, M. J. Hambreu, and J. M. Reynolds. 2012. "'Structure-from-Motion' Photogrammetry: A Low-Cost, Effective Tool for Geoscience Applications." *Geomorphology* 179:300–314.

Witzke, B. J., R. R. Anderson, and J. P. Pope, compilers. 2010. "Bedrock Geologic Map of Iowa" scale 1:500,000. Iowa Geological and Water Survey Open-File Map 2010-01.

Witzke, B. J., and Ludvigson, G. A., 1990. "Petrographic and Stratigraphic Comparisons of Sub-till and Inter-till Alluvial Units in Western Iowa; Implications for Development of the Missouri River Drainage." In *Holocene Alluvial Stratigraphy and Selected Aspects of the Quaternary History of Western Iowa*, 119–43. Midwest Friends of the Pleistocene 37th Field Conference. Iowa Geological Survey Guidebook Series 9.

Yan, M.-J., Q.-Y. He, N. Yamanaka, and S. Du. 2014. "Location, Geology, and Landforms of the Loess Plateau." In *Restoration and Development of the Degraded Loess Plateau, China*, ed. A. Tsunekawa, G. Liu, N. Yamanaka, and S. Du, 3–21. Ecological Research Monographs. Tokyo: Springer.

Young, A. R., P. R. Hanson, and L. M. Howard. 2010. "Surficial Geologic Map and Interpretive Geological Cross-Section of the Schuyler, Nebraska 7.5-Minute Quadrangle," scale 1:24,000. Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln. http://snr.unl.edu/data/geologysoils/STATEMAP/index.aspx.

Young, A. R., P. R. Hanson, and L. M. Howard. 2013. "Surficial Geologic Map of the Hershey West, Nebraska 7.5-Minute Quadrangle," scale 1:24,000. Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln. http://snr.unl.edu/data/geologysoils/STATEMAP/index.aspx.

Young, J., and J. Beard, J. 1993. "Caves in Kansas." Kansas Geological Survey, Educational Series 9.

Zeller, D. E., ed. 1968. "The Stratigraphic Succession in Kansas." *Kansas Geological Survey Bulletin* 189.