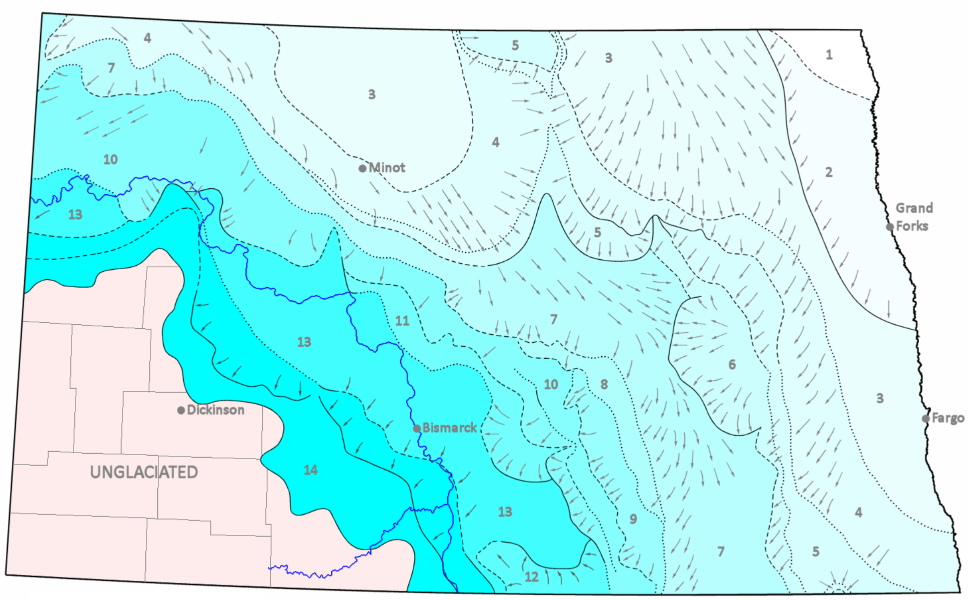
Economic Value of Glacial Stratigraphy

Lorraine Manz

The branch of geology that is concerned with the study of layered rocks and/or sediment is called stratigraphy. The International Subcommission on Stratigraphic Classification (ISSC) of IUGS International Commission on Stratigraphy (1994) defines stratigraphy as: "The science dealing with the description of all rock bodies forming the Earth's crust – sedimentary, igneous, and metamorphic – and their organization into distinctive, useful, mappable units based on their inherent properties or attributes. Stratigraphic procedures include the description, classification, naming, and correlation of these units for the purpose of establishing their relationship in space and their succession in time." In other words, stratigraphy is all about the chronological ordering and age relations of rock units. It is about their distribution, composition, fossil assemblages, physical and chemical properties, and what these attributes infer about a rock's origins and geologic history.

Much of North Dakota's modern landscape was produced by glaciers (fig. 1). Beginning about 2.6 million years ago at the start of what geologists refer to as the Pleistocene Epoch (more popularly known as the "Ice Age") most, or sometimes possibly all, of North Dakota was covered on and off by glaciers. The last ones only exited the state about 10,000 years ago. There is evidence of at least half a dozen distinct glacial episodes, each separated by layers of sediment indicative of periods that were ice-free and the climate warm enough for plants and animals to flourish. These sediments consist of a highly varied and complex succession of material. Broadly categorized, they include till (a chaotic mixture of clay, silt, sand, gravel, and boulders deposited by and beneath a glacier), stratified sand and gravel, deposited as outwash in the channels of meltwater streams flowing out of the glacier, or on beaches along the shores of glacial lakes; finely layered silt and clay that was laid down in the deep, quiet offshore waters of those same lakes, and, more rarely, non-glacial weathering zones, buried soils (paleosols), and organic debris such as wood and other plant matter.

Little remains of the earliest glaciations in North Dakota. What is left is heavily eroded and consists of a scattering of boulders and a few, thin patches of till south and west of the Missouri River.



Approximate ages of ice margin positions (^{14}C years B.P.)

1	< 11,900	8	?
2	11,900	9	12,400
3	?	10	12,700
4	12,000	11	12,900
5	12,100	12	15,000 Limit of most recent (Late Wisconsinan) glaciation
6	12,200	13	> 40,000 Limit of Early Wisconsinan glaciation
7	?	14	> 40,000 Maximum known limit of Pleistocene glaciation in North Dakota

0 20 40 60 miles
0 20 40 60 kilometers
N

Figure 1. Limits of Pleistocene glaciation in North Dakota. The boundaries mark the outer margins of several glacial advances although not all necessarily record major events. Some may record a minor readvance – a few miles or so – of an existing glacier, or a period of stagnation when the ice margin was virtually stationary. The glacial deposits associated with each margin are color-coded by their approximate age. Arrows indicate the direction of ice movement. Note that (a) the deposits become progressively younger towards the north and east and (b) glaciers advanced into North Dakota from more than one direction. Modified from Clayton and others, 1980.

In northern and eastern North Dakota the sediments are younger and much, much thicker, averaging about 150 to 200 feet except on the Missouri Coteau and Turtle Mountains where thicknesses of 500 to 600 feet are not uncommon and in places exceed 700 feet. These sediments were deposited towards the end of the Pleistocene during the latter part of the last major glacial episode - the Wisconsinan Stage. Most of them are less than 20,000 years old.

Within this great pile of layered sediments is a record of North Dakota's most geologically recent biological, climatic, and environmental history. Understanding the stratigraphic relationships between the different layers and the nature of their sedimentary components enables geologists to piece those histories together and add that knowledge to the global picture. But the reasons for studying our state's glacial stratigraphy go beyond pure scientific curiosity; there are some very good economic ones as well.

The first is groundwater. Although they are generally smaller than most bedrock aquifers, the unconsolidated sands and gravels deposited by glacial meltwater streams are the most productive aquifers and providers of the best fresh water in North Dakota (fig. 2). These glacial aquifers account for about half of the developed fresh water use in the state (more than 400,000 acre feet [about 130 billion gallons] in 2017; North Dakota State Water Commission, 2018) and reserves are estimated at about 60 million acre feet (19.5 trillion gallons).

Finding an aquifer that is buried beneath tens or hundreds of feet of impermeable (clay-rich) glacial sediment means drilling a well. To determine the size and shape of the aquifer once it has been located means drilling more wells. Regardless of their purpose, most wells are logged during construction. The log is a record of the physical characteristics (lithology) of the rock and/or sediment types penetrated as the well is drilled, plotted against the depth interval of origin beginning at the top of the well and proceeding, in sequence, all the way to the bottom. It may be descriptive, compiled from the examination of drill cuttings and core samples, or electronic (e.g. gamma ray or resistivity). Either way, well logs are one of stratigraphy's most fundamental and powerful tools. Among the wealth of information they provide, a good log allows geologists to identify specific rock/sediment units and by comparing logs from nearby wells, how far a particular unit extends laterally, in which direction it thickens or thins, if it is compositionally homogeneous, and by "connecting the dots" between adjacent wells obtain a cross sectional (2D) or three-dimensional view of the locale's stratigraphy.

Besides facilitating the location and delineation of glacial aquifers, these views into the subsurface are very helpful in assessing their development potential, recharge rates, and understanding the mechanisms of groundwater flow through glacial sediments, which is important from the standpoint of pollution control and the siting of landfills and other waste disposal facilities. Stratigraphy will also probably be of consideration in aquifer storage and recovery, a process under evaluation by the State Water Commission as a means of storing excess surface water generated during periods of high stream flow by diverting it into glacial aquifers depleted by overuse (North Dakota Water Education Foundation, 2018).

Not all glacial sands and gravels are aquifers. Large surface and near-surface glacial sand and gravel bodies are important sources of aggregate for road construction, building, and other applications (fig. 3). As a commodity, sand and gravel is cheap. The average free-on-board plant price in 2017 was about $8.60 per ton (U.S. Geological Survey, 2018). Transportation costs add significantly to this figure, especially over distances of 20 miles or more, so it makes good economic sense to have the sand and gravel source as close as possible to its point of use. This is why NDGS geologists have been eyeing local sand resources as potential alternatives to the much pricier out-of-state proppant sands that are a vital component of the hydraulic fracturing of oil and gas wells in the Williston Basin (Anderson, 2011, 2018).

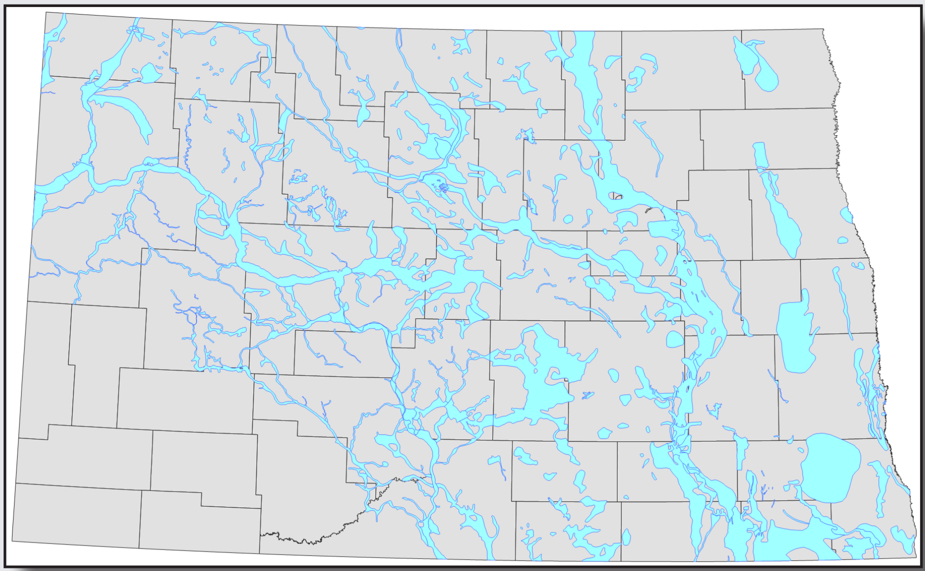


Figure 2. Major glacial aquifers in North Dakota. Many occupy former river channels wholly or partly buried by glacial sediment, which explains their resemblance to a surface drainage system. Data provided by the State Water Commission.

The clay-rich lake sediments that underlie the Red River Valley of North Dakota and Minnesota have some very poor engineering qualities (Arndt, 1977). Deposited in the deep, offshore waters of glacial Lake Agassiz at the very end of the Pleistocene and into the beginning of the Holocene (the current epoch), they contain large amounts of smectite – the general name for one of several groups of clay minerals capable of absorbing exceptionally large volumes of water. Increasing the moisture content of fine-grained (silt

Figure 3. A large sand and gravel operation just south of I-94 in Stutsman County. Most of this material will be sold as crushed stone or construction aggregate.

and clay) sediments compromises their engineering properties, so the effect on smectites and smectitic clays, with their huge affinity for water, is considerable. The low compressive strength and load-bearing capacity of these so-called "fat" clays (owing to their tendency to swell when wet) means that bridges, large buildings and other heavy structures must be supported by caissons or pilings anchored to more robust geologic units like till or bedrock, which may be as much as 100 feet below the surface, to prevent them from sinking or collapsing (fig. 4). Fat clays, when wet, are also highly plastic, and if unconfined will lead to slope failure – a recurrent problem along the banks of the Red River and its tributaries (fig. 5). Another potential problem facing construction engineers in the Red River Valley is quick sand conditions. This is associated with bodies of confined, water-saturated sand that is under high pressure as a result of upward (artesian) groundwater flow. They are commonly found in the former stream channels in the

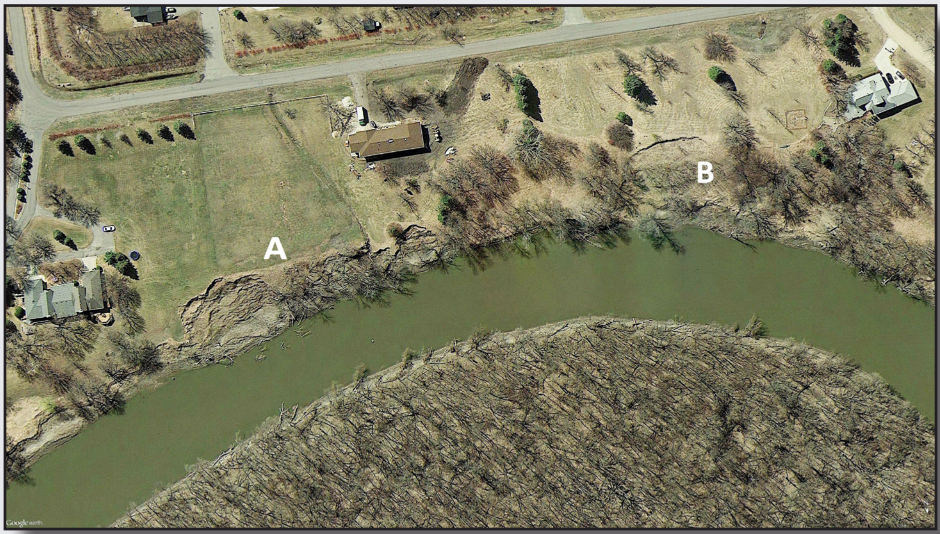


Figure 5. This GoogleEarth image, dated April 2014, shows a series of landslides along the Red River near 76th Avenue South in Fargo. The disturbed area labeled A extends for 500 feet and is up to 100 feet wide. The scarp of another landslide (120 x 160 feet in area) is visible at B. Nine homes in this area, including the one between A and B eventually had to be abandoned because of persistent slope instability. The inherent weakness of the lake clays exposed along the banks of the Red River means that slope failure is a common and inevitable result of the river's natural behavior. The effect was likely intensified by the additional stress induced on the clayey subsurface by the weight of the nearby housing development.

Figure 4. The FargoDome on the campus of North Dakota State University is supported by more than 240 caissons (concrete piers) that transmit the weight of the building into a till unit 100 to 130 feet below the surface (Schwert, 2005). Photo by Bobak Ha'Eri, CC BY SA 3.0.

Poplar River Formation that lies sandwiched between the Sherack and Brenna Formations (fig. 6), as well as in buried nearshore lake and beach deposits. Left unmitigated, structures built on or above such material are likely to sink.

Unstable ground pervades the entire central Red River Valley corridor but it is the southern end, and the Fargo-Moorhead area in particular, that is most affected because this is where the weakest lake sediments, the Brenna and Argusville Formations, are thickest. The stratigraphy in this part of the valley is fairly straightforward and laterally consistent for the most part (fig. 6) but if a high-load structure is to withstand the local subsurface conditions, it must be properly designed; and in order to do that a detailed stratigraphic study is essential. The Northern Pacific Railway Company learned this the hard way when, in 1906, with only a general idea of the local stratigraphy and the field of soil mechanics in its infancy, a decision was made to go ahead with the construction of an enormous embankment along a 7.3-mile-long stretch of track beginning about 10 miles east of Moorhead, MN. The roughly $2.8 million (about $78.5 million in 2018 currency) project was finally shut down in 1909 with virtually nothing achieved as large sections of the embankment continued to settle uncontrollably into the underlying wet clays and water-saturated sand (Schwert and Piehl, 1996). Four years later, in 1913, a grain elevator in Transcona near Winnipeg, Manitoba underwent foundation failure as it was being filled. In 1955 the Fargo Grain Terminal elevator collapsed shortly after being filled with a large amount of grain for the first time since its construction in 1954 (fig. 7). Both elevators were constructed on Agassiz lake clay.

It would be unfair to blame the failure of all these structures on poor engineering or a disregard for the geologic setting. Even in the 1900s, the inherent instability of Red River Valley lake sediments was well known – it was the mechanics that were then only just beginning to be understood. Engineering geology has come a long way in the last 100 years and these examples serve only to illustrate what can happen if we choose to ignore the importance of understanding the local stratigraphy, for without

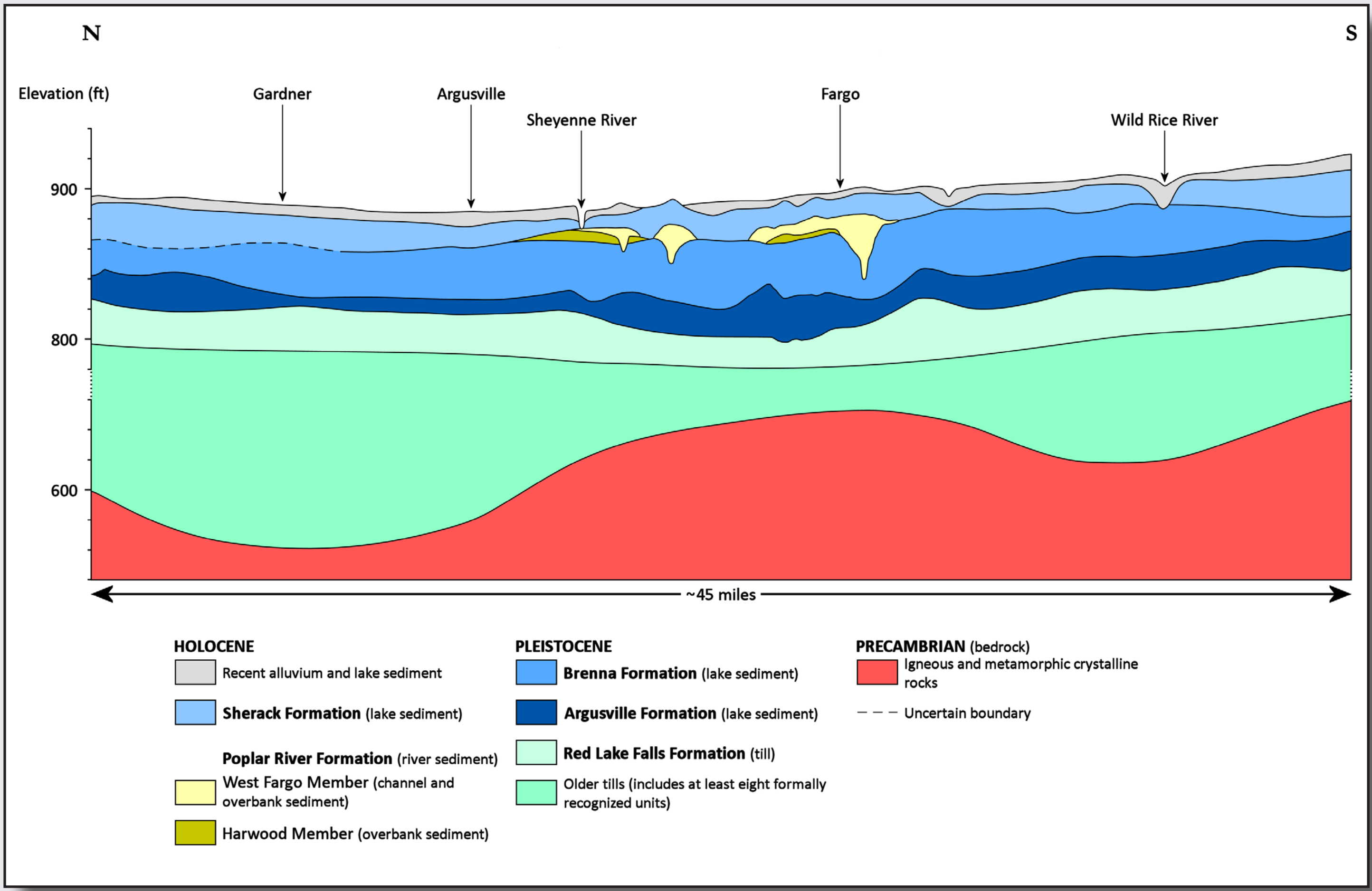


Figure 6. A north-south cross section of Cass County along I-29 showing the general stratigraphy and bedrock surface, which consists of igneous and metamorphic rocks of Precambrian age in this part of the Red River Valley. The eastern half of Cass County (and western half of Clay County on the opposite side of the river in Minnesota) is underlain by as much as 100 feet of lake sediment, including the smectite-rich clays of the Brenna and Argusville Formations. The combined thickness of these two geotechnically weak units is about 85 feet in the Fargo-Moorhead area and large, heavy structures must be supported by caissons or pilings anchored into the underlying till to prevent their collapse.

Figure 7. The Fargo Grain Terminal elevator collapsed around midnight on June 12, 1955, spilling 600,000 bushels of wheat and other grains. Image from the Institute for Regional Studies, North Dakota State University, Fargo, North Dakota.

it an accurate assessment of the engineering properties of each geologic unit would be impossible. Moreover, to assume that the glacial stratigraphy in one part of the Lake Agassiz basin is the same as in another is oftentimes a risk not worth taking and could end up costing far more than the money saved by foregoing a geotechnical survey.

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