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The Geologic History of Minnesota

The geologic history of southern Minnesota is defined by its inclusion of formations such as mesas and valleys that demonstrate the impact of Pleistocene glaciation.

Quite near to this location, we saw an outcrop of 3.5-billion-year-old metamorphic Archean gneiss in an abandoned mining town, the formation of which I will talk about in a moment. Some of this gneiss was heavily weathered during the Cretaceous period as it rested underneath tropical plants at the time (and we saw this near a river). The gneiss exhibits numerous colors and lines that one can follow – the pink color is potassium feldspar, the shiny bits are biotite mica, and the gneiss also contains amphibole and quartz. The banding (foliation) of the gneiss, while its specific causes are unexplainable, is known to be the result of metamorphosis, or the changing of minerals under heat and pressure.

The foliation of the gneiss is due to the deformation / squeezing of flat or elongate minerals (such as amphibole and pyroxene) within granite that align it in the direction that the pressure was applied in (some rocks such as limestone will not align)[1]. The amphiboles and plagioclases precipitate first – they can be in any shape they want to be. The quartz doesn't crystallize until the last moment, so it has to assume the shape of what is left. Quartz looks like a collection of baby teeth in granite (the rock granite itself is a "derived

[1] "USGS Geology in the Parks," Geology and Geophysics, December 15, 2014, accessed November 15, 2016, http://geomaps.wr.usgs.gov/parks/rxmin/rock3.html.

distilled buoyant froth”. We know from paleomagnetists’ analysis that the gneiss originated in the ______ latitude during the _____ time period.

There exists Archean age Morton gneiss in the Minnesota River Valley. This gneiss, being 3.5 billion years old, is the oldest exposed rock that can be seen in the state, and is a resource for paleomagnetists and allows us to study metamorphosis and the extreme impact of weathering.

The state itself was a peninsula during the late Cambrian period, and this led to the formation of its stratigraphy as sea levels initially rose and then dropped. During this period, the sea deposited sand, clay minerals, and limestone per each particle’s size and weight; the quartz sand was deposited proximal to shore due to its greater weight, and the water carried the limestone the furthest distance offshore due to its lighter mass (thus, the water should be muddier in deeper water, but this is not always the case – in tropical areas, there are often organisms that enjoy making carbonate sediment that use up the fine limestone). Eventually, these particles were lithified into stone. This process, coupled with the rise and fall of sea levels between long spans of constant sea levels, formed the stratigraphic units that we studied in class. In addition, it left numerous artifacts such as stromatolite and banded iron formations.

So the history of the area went like this: 500 million years ago, the ocean came in and inundated the basalt with sandstone. But before then, we had 600 million years to make an ancient landscape – boulders & gravel – before the ocean came in. The ocean rose, and the waves stripped weathering rind off of the basalt, transporting it to lower elevations and forming the conglomerates. After this, when the ocean left, the landscape was once again eroded by natural processes resulting in the disjointed formations of sandstone and basalt that we see today.

The dense deposits of basalt are due to the eruption of effervescent mafic lava flows from a continental rift – more specifically, three aulacogens - that occurred 1.1 Ga (billion) years ago. During our visit to the Interstate State Park, we saw various forms of basalt that represented the way in which the landscape was formed; the lower-level basalt was smooth, monolithic and weathered in place, whereas as we moved up the landscape, the basalt exhibited scoria-like characteristics and presented itself as boulders within a conglomerate of pebbles, quartz sand, and fossils. Basalt weathers to clay. Also, the basalt that was weathered in situ was more monolithic and retaining of its sharp angles, and the basalt that was not weathered in place was more well-rounded.

The Interstate State Park shows the impact of the mid-continental rift. We saw glacial potholes, river eddies, and the glacial river St. Croix that allowed the glacial lake Duluth to drain in the past. On the other side of the St. Quarry river was Wisconsin, so we were right next to the border. The basalt was 1.1 billion years old, and iron stained. How did people discover the age of the basalt? It was radiometrically dated; igneous rocks lock uranium into the lattice better than sedimentary rocks do (and metamorphic rocks & stalactites). Carbon-14 dating, by contrast, is used on sedimentary rocks that are less than 50,000 years old. The basalt was the second-oldest rock we saw. The oldest one was the 3.8 billion year old Archean gneiss. On the basalt, bands of pock marks increase as you go upward. These are gas bubbles that couldn't rise all the way out to the top. The density of basalt is 2.9 g/cm^3, so basalt is dense. The dense basalt – 20 km thick – in the middle of sedimentary and granitic rocks creates a greater gravitational field. What happens is that the plume stays still and the crust moves (ex. Hawaii). Plate tectonics were unsuccessful at ripping North America apart, and instead we have aulacogens. Flood basalts came out of the rift, creating sags in the continental lithosphere. This is the reason for the existence of the Great Lakes. The fault that we saw at Red Wing was a minor expression of what was going on with the basalts. Referring to physical weathering, rolling is more efficient at rounding the basalt. When we walked up to ~800 meters, we saw calcium phosphate brachiopods that were thin-shelled, and smooth, rounded, heavily weathered and cracked basalt. Some of the basalt was angular and not rounded. The boulders had a conglomerate with some sort of material (matrix) between them. According to Clint, amongst what is between the boulders are fossils and pebbles in quartz sand with brachiopods in it. An approximation of the truth: The brachiopods are Cambrian dicephalus. The brachiopods are 500 million years old. This outcrop in particular is shaped like half of a bowl. Animals didn't evolve to live in freshwater until _____.

In class, we have studied the upper stratigraphy of Minnesota around the town of Northfield beginning at approximately 250 meters below the surface and extending to the surface. From 250 meters deep to 200 meters, we have the Franconia sandstone (one of the first places that we visited). The Franconia gains its distinctive green coloring due to the presence of the green clay mineral glauconite, which behaves as sand and coats the sand grains. Following this, from about 200 to 185 meters, we have the St. Lawrence formation that is comprised of thick, dolomitic sandy shale and siltstone. The St. Lawrence sandstone, which is by some considered to be part of the Jordan sandstone, is fine-grained to the point that it behaves like shale. Lying on this is the Jordan sandstone from 185 to 160 meters deep, which contains well-rounded light-colored quartz sand of which rust (iron oxide) has been removed by the percolation of methane through the rock. The Jordan sandstone, in particular, is useful as a resource for glass-making as well as proppant for fracking (due to the fact that quartz sand is durable and chemically inert). The Oneota dolomite follows from 160 to 125 meters deep, and presents itself as thick beds of gray dolomite containing desiccation cracks; the dolomite itself is a conglomerate of calcium and magnesium (and it tends to rust, unlike limestone, due to its impurities, which can give it an orange color), and it is a good source of gravel for roads. Following these essential layers we have the Shakopee dolomite (which, as we saw, contains mud cracks, calcium carbonate ooids, and stromatolites to a much greater extent than does the lower Oneota), St. Peter sandstone, Glenwood shale (which does not exist in some places in southern Minnesota), Plattville limestone, Decorah shale (known for being fossil-rich), and Galena limestone, all of which rest underneath a thick layer of glacial deposits. The shale itself is often over-grown. There are Artesian springs in southern Minnesota that come out of the Shakopee dolostone because the Shakopee has fractures that allow the pressurized groundwater to seep through. In many valleys formed as offshoots of the Cannon River, we noted that the thickest soil was at the bottom in part due to the influence of German and Czech settlers who displaced the soil in order to create farms.

Inside the ____ formation, which is known for being fossil-rich, we can find many remnants of the calcareous marine benthos that lived in the ____ period, including phylums such as Echinodermata, mollusks, arthropods, cephalopods, cnidaria, algae, poriferan, bryozoan, brachiopoda, diatoms, rugose coral, trilobites, gastropods, cephalopods, and sea grasses and mangroves. The location in which these fossils are deposited corresponds to the zone in which they live – for example, Echinodermata, mollusks, arthropods, and cnidaria live below the photic zone. According to Wikipedia, the typical euphotic depth in the open ocean is around 200 meters. Brown algae can tolerate more light deprivation than the green algae can and less than the red algae can, so it makes sense that their fossil record (if there is one) would correspond to their preferred depths. Below the carbonate compensation depth, of course, these calcareous marine benthos cannot exist. As for other marine animals, there are also dinoflagellates that life in symbiosis in the gelatinous tissue of coral; when this happens, we refer to them as xanthellae. These dinoflagellates contain a neurotoxin, however, so they produce a "red tide" that can get into our food. The marine benthos without hard exoskeletons, or those with exoskeletons made of aragonite rather than calcite (the two compounds – $CaCO_3$ – differ only in their crystalline structure), will have less of a fossil record (the steinkerns, or sediment casts, of ancient gastropods are examples of the filling of and dissolution of aragonite shells over time).

Banded iron formations formed between 2.5 and 1.8 billion years ago. By 1.8 billion years ago, the banded iron formations were replaced by red beds, with iron solely in its oxidized form because oxygen was able to enter the atmosphere. This reflects the permanent presence of oxygen in the oceans and atmosphere. Once modern photosynthesis evolved in cyanobacteria, aerobic respiration later evolved (consuming oxygen), using oxygen as the terminal electron acceptor in the electron transport chain. Aerobic respiration yields roughly 18 times as much ATP per glucose as does fermentation, hence it gives organisms an advantage. Banded iron formed during periods of lower oxygen availability when there was much more dissolved iron in the oceans (as iron back then precipitated in large enough quantities to form iron deposits). At the time of the banded iron formations, the seawater is also theorized to have been saturated with silica (120 mg/L) during most of the Archaean-Proterozoic. Currently, seawater contains only less than 10 mg/L because modern oceans are home to several organisms (diatoms, radiolarians, sponges) that extract silica from the water. It has been suggested that the seawater precipitated as so: the evaporation of seawater promoted local silica oversaturation which resulted in silica precipitating as a gel on the seafloor.

How did the banded iron formations gain their layers? It seems likely that there was biological mediation and that the changes in BIF composition reflect the cyclical changes in the number of respective organisms. The process goes as follows: Iron accumulates in seawater from erosion as well as mid-ocean spreading ridges. Photosynthesizing cyanobacteria produce O_2 and oxidize the iron, the iron precipitates, and O_2 continues to build until the population of oxygen-generating cyanobacteria crashes due to oxygen's toxicity. This crash in population allows the iron to accumulate once more in the absence of oxygen. This whole process accounts for the rhythmic nature of deposition. After the Sudbury impact, we see that there was still a period in which BIFs were forming. These Rapitan-type BIFs seem to be associated with global ice age (Snowball Earth). At the time, the world ocean was almost completely covered by ice and therefore was isolated from the atmosphere. That reintroduced reducing conditions in the water column similar to those that existed before the oxygenation of the atmosphere. This near global anoxia in seawater is generally believed to be the reason why BIFs reappeared as iron accumulated in the water and were later deposited with the ice age receded and the ocean was once again oxygenated.

In general, the appearance of red beds in the geologic record indicates an oxidizing atmosphere and the lack of an ozone layer.

Banded iron formations consist of layers of iron oxides (typically either magnetite or hematite) separated by layers of chert (silica-rich sedimentary rock). Each layer is usually narrow (millimeters to a few centimeters). BIF is a chemogenic sedimentary rock. Because of old age, BIFs generally have metamorphosed to various degrees (especially older types), but the rock has largely retained its original appearance because its constituent minerals are fairly stable at higher temperatures and pressures. The first supercontinent that formed in the Proterozoic was Rodinia.

Within Minnesota's mesas are dolostone outcrops, with sandstone comprising the lower section of the bluffs. Approximately 10 to 8 thousand years ago, the glacial ice sheets melted and produced glacial outflow, creating the valleys between the mesas. The Mississippi River as well as the sod farms rest on the glacial sediment that was deposited by those same glaciers.

Four miles south of Franklin, Minnesota on County Road II, we saw a rock outcrop that contained 1.15 million year old gabbro – an igneous rock that was, from our observation, coarse-grained, black, containing shiny bits, with a translucent gray-greenish-white crystalline rock embedded in the darker gray matrix (these crystals were allegedly crystallized 10 to 15 kilometers into the Earth). The gabbro was 1.15 million years old.

On one of our trips, we went to Red Wing Memorial Park and saw an example of the Franconia sandstone being pushed up by a fault.

[TALK ABOUT THE GEOLOGIC TIME SCALE – LAURENTIA, BALTICA, AVALONIA… & THE GEOTHERMAL GRADIENT & POSSIBLE HISTORY OF EARTHQUAKES & MENTION BOWEN'S REACTION SERIES & METAMORPHOSIS OF CLAY MINERALS]

After this outcrop, we continued up the slope to about ~900 meters, where we saw an outcrop of sandstone, basalt, and granite boulders. Unlike the first outcrop, for which the weathering rind was included in the matrix between the boulders, this outcrop has had the weathering rind stripped away. 600 million year old basalt, 10,000 years of weathering.

You need pure and clean water to get limestone in the ocean. Creatures in the shaley zone make $CaCO_3$ shells and have a "tolerance" for sands & clays.

Rains, speed and volume influence the amount and types of sediment in rivers. There is paleological evidence for droughts that last either decades or 100s of years. It typically takes 100s of kms to transition from sand to shale to limestone, but in this one particular Monkey River case it was very sudden and fast.

An example of isostatic rebound is this: Antarctica will not resemble its underlying continental mass due to isostatic rebound. The rebound area is greater than the sag area. Glacial rivers, due to isostatic rebound, become lakes, and are cut off from the ocean. Glacial plucking transports rocks. The firn line is the lowest elevation where snow survives the summer. Ice crystals can shear past one another when compacted, and this must be what enables glacial transport. The arrival of ice (flow) is balanced by the removal of ice by melting. For a terminal moraine we have "till": it can have a huge range of sediment size, it is unsorted, and can contain exotic rocks from hinterlands. Glacial outwash in contrast, is: water-carried material, sorted, organized, and stratified (i.e. sorted by water). Glaciers do not push sediment – in order to get a moraine, a glacier has to stay in place for a while; glaciers do not push material. There is evidence for 230 million year old Gondwanan glaciation evidence. When rocks contact bedrock, they can scratch it and polish it. Other effects of glaciers include glacial striations, and glacial chatter marks. [map of gravel resources for roads].

We saw glacial porphyry at the terminus that we went to. The striations between the layers of the hills of detritus were evident both in miniature and applied on a bigger scale form: there was evidence of the finest alternation being between day/night, then summer/winter, then hot years/cold years. The changes in temperature drove the speed of the water to increase or decrease (depending on whether the temperature was hot or cold respectively). In sorting, fine rocks get carried further. Streams go faster as the day heats up. The small layering could in fact be due to rain. But overall, the presence of water was due to the melting of the glaciers. We also saw some orange rock that contained what appeared to be fractals.

The ice ages themselves were governed by variations in Earth's orbital parameters that systematically and rhythmically changed the distribution of incoming solar radiation over long time spans (1000s of years). Basically, when the summer solstice happens at aphelion – i.e. the summers are cooler and the winters are warmer – you get an ice age. The ice sheets always start at 65 degrees of latitude in the Northern Hemisphere. Isotopic analysis of the oxygen in the remains of plankton indicates when these ice ages occurred through an understanding of the concept of Rayleigh fractionation. This is called stable isotopic mass spectrometry.

The modern-day Minnesotan landscape is defined by what are called Kettle lakes and Came hills. The Kettle lakes were formed when ice chunks broke off of the glaciers (this process is known as calving) as they were receding and then subsequently melted. The Came hills formed when sediment that was deposited on top of the glacier was gradually lowered and contributed to as the ice melted. This Kettle and Came topography is direct evidence for Pleistocene glaciation, as are the moraines and physical scratches that present themselves in some parts. The very ancient ice ages, however do not leave such readily visible evidence; they leave no landscapes (though striations on bedrock can persist) and no ocean sediment cores. We must rely on rocks interpreted as glacial deposits such as "diamictite" and ancient dropstones. All that we know about the continents' arrangements before Pangaea is from paleomagnetism, because we can close ocean basins to get Pangaea but can't predict the movement of continents past that. Also, "belt worlds" where every continent is near the equator trigger severe glaciation.

In the process of formation of BIFs, iron was transported by upwelling of water to the surface; when the wind blows parallel to the coast in the southern hemisphere, then Ekman transport can produce a net movement of surface water 90 degrees to the direction of the wind.

The CCD is on average 4500 meters in depth. Below this depth, calcareous plankton dissolve. Sedimentary rocks are those rocks made up of pieces of other rocks (clasts). Most limestone and chert are grown by living organisms rather than broken from other rocks. The hardness of basalt is 6 on the Moh's hardness scale.

We also saw an outcrop a short distance into the Arboretum that displayed stromatolites (created by a variety of bacteria and plankton) and ooids. The outcrop was made of dolostone.

Subduction tends to felsic volcanism. The supercontinent Pangaea was formed by subducting all the ocean basins.

Minnesota exists on Laurentia, or the North American Craton (the nucleus/stable portion of North America).

Aside from the glaciated area, we have in the south-eastern portion of Minnesota what is called the Driftless Area – the topographically dramatic region of land that escaped glaciation not only during the last glacial maximum but escaped previous glaciations as well[2]. Due to the lack of glaciation and hence lack of glacial deposits, the Paleozoic stratigraphy of the area is exposed – these exposures typically occur in the steep ravines, and are primarily Ordovician dolomite, limestone, and sandstone with Cambrian sandstone, shale, and dolomite exposed along the valley walls of the Mississippi River (against which the greatest amount of relief occurs)[3]. Although the region was originally a plateau underlain by flat sedimentary Paleozoic era rocks[4], the landscape has been heavily dissected by streams and rivers (eroded into large bluffs and narrow valleys) over the past 10,000 years of geologic time[5]. The region is covered by loess – loosely compacted wind-

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[2] "The Driftless Area: Fewer Glaciers but More Topography Than the Rest of Minnesota," All-geo: The best of Geology and Earth Science on the web, November 30, 2010, accessed November 14, 2016, http://all-geo.org/highlyallochthonous/2010/11/the-driftless-area-fewer-glaciers-but-more-topography-than-the-rest-of-minnesota/.

[3] "Regional Landscape," Northern Research Station - USDA Forest Service, February 18, 2004, accessed November 14, 2016, http://www.nrs.fs.fed.us/pubs/gtr/other/gtr-nc178/sec4.htm.

[4] "ECS: Paleozoic Plateau Section: Minnesota DNR," Minnesota Department of Natural Resources: Minnesota DNR, July 28, 2006, accessed November 14, 2016, http://www.dnr.state.mn.us/ecs/222L/index.html.

[5] "The Driftless Area".

blown silt and clay – that varies in thickness depending partly on the steepness of the slope on which it rests.

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