Minnesota and Wisconsin

Geology of the Upper Mississippi Valley and Western Superior Basin

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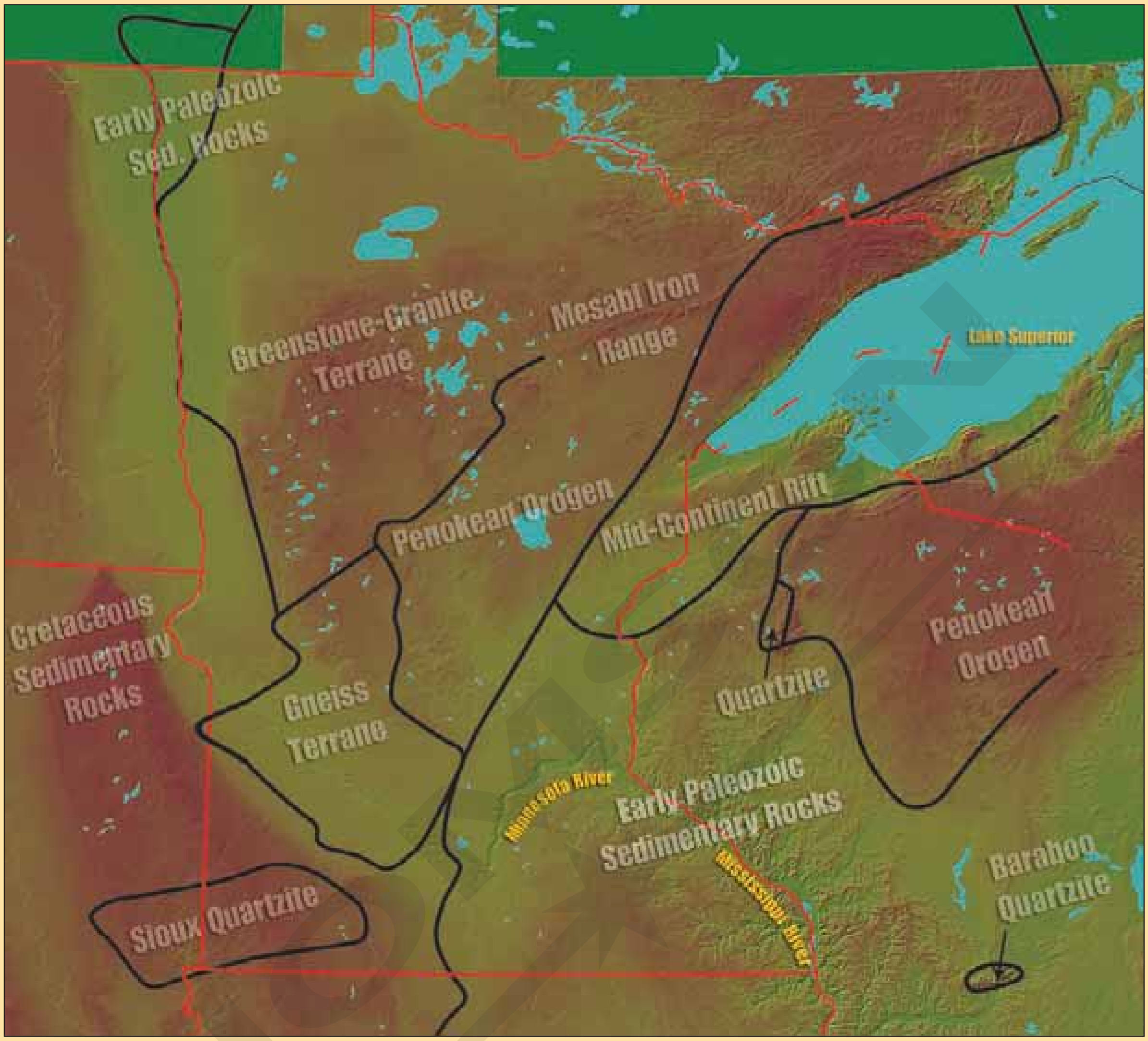
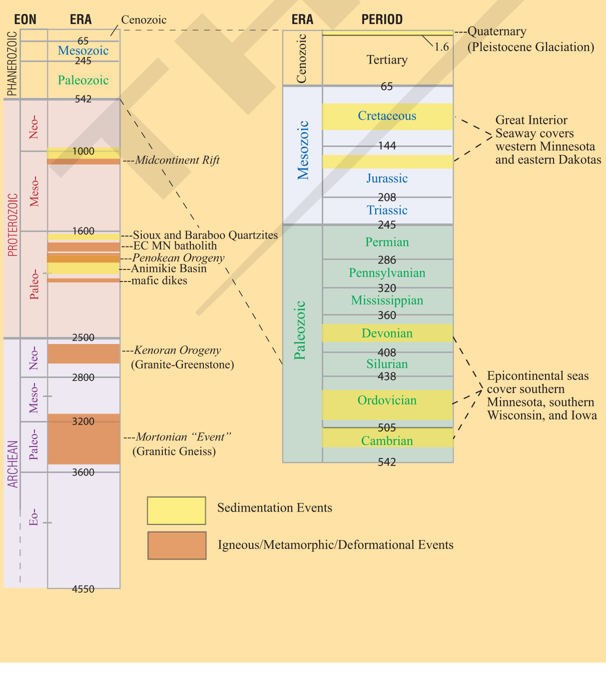
Split Rock Lighthouse sits atop a cliff of anorthosite, a resistant rock made almost entirely of plagioclase feldspar. This and other anorthosite blocks are embedded in intrusive mafic rocks (diabase) of the Beaver Bay Complex that was emplaced during rifting of the midcontinent. The diabase magma plucked the anorthosite blocks from somewhere near the base of the earth's crust and carried them upward nearer to the surface.





The landscape of the Upper Mississippi Valley and Western Superior Basin is primarily a landscape shaped by continental glaciation. Although pre-glacial topography controlled patterns of glaciation and deposition, glacial deposits cover much of the bedrock in the region and obscure the original fluvial landscape. Major areas of bedrock are exposed primarily along the Mississippi and Minnesota River Valleys, the area north and west of Lake Superior, northern Wisconsin, and the pseudo-driftless area of southeastern Minnesota, western Wisconsin, and northeastern Iowa. In order to study the history written in the Precambrian and Phanerozoic bedrock, subsurface data from wells, together with aeromagnetic and gravity surveys must be used to supplement observations made in outcrops.

Geologic patterns in bedrock beneath surficial deposits reveal the history of the Precambrian Archean and Proterozoic Eons, and the Phanerozoic Eon. The major geologic terranes that tell the story of the geology of this region are the Minnesota Valley Gneiss Terrane, the Greenstone-Granite Terrane, the Penokean Orogen, the Midcontinent Rift, the Early Paleozoic Sedimentary Basin, and the Cretaceous foreland basin. The accompanying map of the major geologic terranes and the geologic time scale are useful for keeping this history in perspective.

ESSENTIAL QUESTIONS TO ASK

Upper Mississippi Valley and Western Superior Basin (UMV-WSB).1 Introduction

- *What are the aspects of the geologic record that allow us to interpret the geologic history of the Upper Mississippi Valley and Western Superior Basin?*

UMV-WSB.2 The Archean: Creating Kenoraland—The Nucleus of North America

- *What do turbidites and pillow lavas in the Archean rocks of the Greenstone-Granite belt tell us about the environment in which these rocks formed?*
- *Describe the events that formed Kenoraland, the nucleus of North America.*

UMV-WSB.3 The Early Proterozoic: The Penokean Mountains and the Making of Laurentia

- *What do the banded iron formations and the stromatolitic structures they contain tell us about the nature of the Early Proterozoic atmosphere?*
- *Describe the ways in which the formation of Laurentia were similar to the formation of Kenoraland.*

UMV-WSB.4 Erosion of the Penokean Mountains—The Baraboo Interval 1750–1630 ma

- *What conditions and processes are necessary for supermature quartz sandstone to form in a single cycle of derivation, transport and deposition?*
- *What do the Sioux and Baraboo Quartzites lack that makes it so difficult for geologists to determine if they were formed at the same time?*

UMV-WSB.5 Middle Proterozoic: The Mid-continent Rift—An Attempt at Unmaking Laurentia

- *What features of the mid-continent rift and the rocks it contains tell us that it was most likely formed atop a mantle plume?*
- *Why did continental rifting cease before a full-fledged ocean basin could form?*

UMV-WSB.6 Phanerozoic: Periodic Flooding and Exposure of North America's Stable Interior

- *Why has the craton of North America been tectonically stable during Phanerozoic time?*
- *How do we know that cycles of rise and fall of sea level took place during the Cambrian and Ordovician of this region?*
- *How do we know that most of the Cambrian and Ordovician sedimentary rocks of this region are marine?*

UMV-WSB.7 Pleistocene: The Laurentide Ice Sheet and Shaping of the Landscape

- *How do we know that several advances and retreats of glacial ice occurred in the region during the Pleistocene Epoch?*
- *Describe three ways in which glaciation altered the pre-glacial topography.*

UMV-WSB.8 A Most Precious Resource—Surface Water, Ground Water, Landscape Evolution, and Water Quality

- *Why is groundwater especially susceptible to pollution in areas directly underlain by carbonate rocks?*
- *Describe three landforms common in the area that are formed by groundwater solution.*

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Upper Mississippi Valley and Western Superior Basin.1

Overview of Geology of the Upper Mississippi Valley and Western Superior Basin

The geologic history of the construction of the North American continent is revealed through the rocks and landscapes of the upper Mississippi Valley and the western Superior Basin (UMV and WSB, respectively). From some of the oldest rocks in the continent, through the aborted rifting of the continental crust, the region's first 3-billion-year history is a story of periodic dramatic upheaval and leveling of the Precambrian crust. The story tells of formation of enormous submarine volcanoes, collision of great volcanic island chains, assembling of plates of continental crust, development of economically important iron formations coincident with the appearance of photosynthesizing organisms, uplift of an Alpine-scale mountain range, the subsequent destruction of these mountains by erosion, and the aborted rifting of the continent.

The story continues through the last 550 million years of geologic time, with periodic flooding and retreat of vast seas atop the Precambrian crust, and deposition of a widespread blanket of sedimentary rocks, which has only been mildly deformed. A great diversity of marine fossils is preserved in these deposits, and great reservoirs of groundwater are stored in the sandstone and carbonate aquifers. During the past 2 million years, great sheets of ice advanced southward from Canada to sweep clean and expose the basement rocks of the Lake Superior region, and to deposit several hundred feet of glacial deposits elsewhere. This glacial drift has become the source of the rich soils that nurture the region's agriculture.

Section Geology of the Upper Mississippi Valley and Western Superior Basin (UMV-WSB).1 Summary

- The geology of any region is the product of a complex interaction of internal processes (generally understood in terms of plate tectonics) and external processes, both of which create and modify earth materials.
- The Precambrian evolution of North America can be understood by studying the rocks of the UMV-WSB. These rocks contain a record of primitive oceanic crustal material, the granitic nucleus of the continent, and the aborted rifting of the continental crust.
- The Phanerozoic evolution of the UMV-WSB was dominated by deposition of a blanket of sedimentary rocks, formed in seas that periodically advanced and retreated across the stable continental interior.
- The finishing touches were applied to the surface by continental glaciation, stream erosion and deposition, and the work of groundwater.

Upper Mississippi Valley and Western Superior Basin.2

The Archean: Creating Kenoraland—The Nucleus of North America

The Archean rocks of the Minnesota River Valley Gneiss Terrane of southwestern Minnesota and the Wawa Subprovince of northern Minnesota and adjacent Wisconsin tell the story of how the core of North America was created (Table 1).

▶ **Table.1** Chronology of Archean Events in the Superior Province.

Age (Ma)	Event
3600	Primary crystallization of gneisses
3370–3285	Granodiorite intrusions
3300–3250	Metamorphic event
3140–3080	Mafic intrusions followed by metamorphic event
2620–2590	Granite intrusions and deformation of terrane—metamorphism, shearing, and mafic intrusions along northeast-oriented shear zones

The Minnesota River Valley Gneiss Terrane contains some of the oldest rocks in North America. While the Acasta Gneiss Complex near Great Slave Lake in Canada and the Isua supracrustal rocks in West Greenland are older (4.03 Ga and 3.7 to 3.8 Ga, respectively, where Ga is billions of years before the present), the Morton Gneiss in the Minnesota River Valley has been dated at 3.6 Ga.

▶ **Figure UMV-WSB.1** Montevideo Gneiss, part of the Minnesota River Valley Archean Gneiss Terrane.

Photo by J. Meyers

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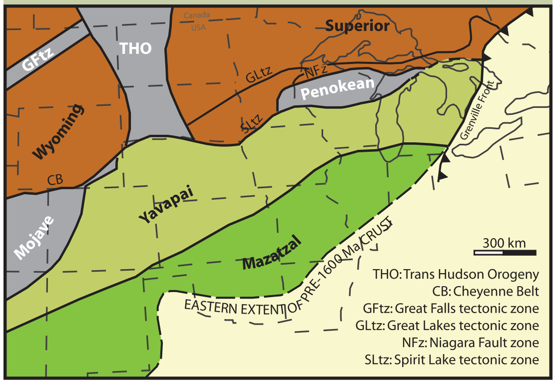
▶ Figure UMV-WSB.2 Precambrian basement provinces of the United States portion of the North American craton.



This map is taken from Holm, D.K., et al, "Reinterpretation of Paleoproterozoic accretionary boundaries of the northcentral United States based on a new aeromagnetic-geologic compilation," *Precambrian Research*, (in press). Copyright *Precambrian Research*. Used with permission

The Minnesota River Valley gneisses form the basement of the southern part of the Superior Province, which is one of the major Archean terranes of the North American craton (see Figure 2). These gneisses lie south of the Great Lakes Tectonic Zone, which is the structural boundary between the Gneiss Terrane and the granite-greenstone Terrane of the Wawa Province to the north.

The origin of these highly metamorphosed rocks is difficult to discern because of the intense temperatures and pressures to which they were subjected. However, their granitic composition implies that they represent the early creation of continental crust. The presence of rafts of basalt-like amphibolite in the granite gneiss could be interpreted as remnants of the primary mafic oceanic crust that preceded the formation of secondary granitic crust.

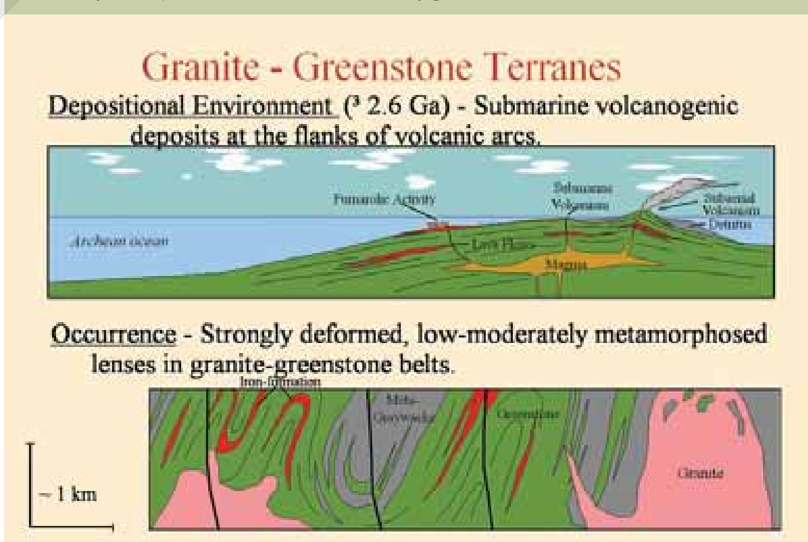
Subhorizontal gneissic banding indicates that metamorphism and deformation of this rock took place in the lower crust. The granitic composition of the gneiss indicates that some form of recycling or remelting of primary oceanic crust occurred early in Earth's history. Whether this recycling was accomplished by melting the bottom of overthickened basaltic crust, or whether ocean crust was forced downward into the mantle by subduction, is unclear. Regardless, the presence of silica-rich granitic rocks tells us that by 3.6 Ga, earth processes were capable of making secondary, continental crust. This crust probably stood as small, isolated microcontinents dotting the ocean-dominated surface of early Earth.

The northern part of the Superior Province in the United States, the Wawa Subprovince, is often referred to as the Granite-Greenstone Terrane. This terrane lies north of the Great Lakes Tectonic Zone and is composed of deformed and metamorphosed volcanic and sedimentary rocks intruded by large bodies of granitic rocks. This complex assemblage represents the tectonic creation and convergence of volcanic island arcs, similar to the modern volcanic archipelagoes of the western Pacific Ocean such as Japan and the Philippians (Figure 3; see Figure 7). Rocks in the Wawa Subprovince are younger than those in the Minnesota River Valley Gneiss Terrane and are dated between 3.0 and 2.7 Ga.

Beginning about 3 billion years ago, a volcanic island arc emerged out of the Archean ocean in what is now northern Minnesota (see Figure 3). Exposed in and around Ely, Minnesota are dark greenish gray outcrops that, when viewed from above, display lobate forms about the size of a pillow. The rock is greenstone, and the lobate patterns are called pillow structures (Figure 4). Greenstone is a mildly metamorphosed basalt, wherein the original igneous minerals have been transformed by heat and water into greenish metamorphic minerals of chlorite and plagioclase feldspar. Pillow structures indicate that the lava flows were erupted into water on the seafloor.

Lenses of banded iron formation are located in the upper part of the volcanic pile of greenstone flows. These rocks are composed of thin alternating layers of microcrystalline silica oxide (chert) and iron oxide (hematite) (Figure 5). Most geologists view these deposits as chemical sediments formed by precipitation in a shallow seawater environment; however, the exact cause of their deposition is not completely understood. One idea is that they represent deposits formed around hot spring vents on the shallow

▶ Figure UMV-WSB.3 Formation of large shield volcanoes on the seafloor of northern Minnesota followed by subsequent deformation and intrusion by granite.



Cross sections by J. Miller, Jr.

► **Figure UMV-WSB.4** Pillow lavas near Ely, Minnesota.

Photo by J. Miller, Jr.

flanks of volcanic island chains. Another idea is that these rocks formed by excessive evaporation of seawater in shallow lagoonal basins between volcanic islands. A third idea is that these deposits are biogenic and were formed by the metabolic activity of early single-celled organisms in a way similar to how limestone is formed today. By whatever means, the presence of these deposits indicates that the Earth's oceans at this time were rich in silica and iron—conditions that are only possible if the earth had an oxygen-poor atmosphere.

Still higher in the Vermillion greenstone belt are sandstones derived from the breakdown of basaltic rocks. The sandstones are composed of quartz, rock fragments, and feldspar and are often called graywacke. Graded bedding, defined by light-colored layers composed of coarse sand grading upward into dark layers composed of fine silt and clay, are characteristic of these sandstones (Figure 6). Each couplet represents deposits from submarine turbidity currents that flowed down the flanks of the volcanic islands. The appearance of this rock type in the greenstone belt heralds the emergence of the volcanic islands from the ocean and the onset of their erosion by surface processes and wave action.

► **Figure UMV-WSB.5** Sudan Iron Formation near Ely, Minnesota. Folds are mainly the result of soft-sediment deformation.

Photo by J. Miller, Jr.

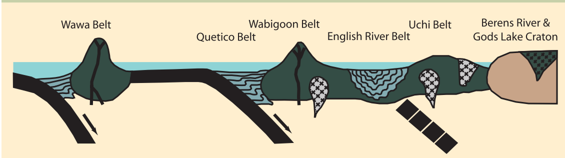
About 2.6 Ga a microcontinent gneiss terrane, which originally formed south of present-day Minnesota and Wisconsin, collided with the series of island arcs to the north and created a continental landmass called Kenoraland (Figure 7). This landmass became the nucleus of the North American Continent. Convergence occurred along the Great Lakes Tectonic Zone and was part of a global event, which involved the greatest rate of continental crust formation in Earth's history.

Collision with the island arcs about 2.6 billion years ago not only caused deformation of the volcanic and sedimentary rocks that formed the arcs, but also caused the crust to become overthickened by compression accompanying the

► **Figure UMV-WSB.6** Turbidites exposed at Pike River Dam in the Vermillion Greenstone Belt, northern Minnesota. The light-colored bands are fine-grained sandstone and the dark-colored bands are rich in mud.

Photo by J. Miller, Jr.

▶ **Figure UMV-WSB.7** South *(left)* to north *(right)* cross section showing a plate tectonic interpretation of deformation of the Granite-Greenstone Terrane, northern Superior Province. The Wawa Belt is north of the Great Lakes Tectonic Zone, which is the boundary between the Minnesota River Valley Gneiss Terrane and the Granite-Greenstone belts (see Figure 2). Note the steep northward-dipping shear zones along which these rocks are deformed. The present-day boundary between Minnesota and Ontario is located between the Quetico and Wabigoon Belts. Cross section is approximately 500 km long.



Modified from a cross section by Charlie Blackburn

▶ **Figure UMV-WSB.8** 2.6 Ga Giants Range Granite intruded into darker-colored mafic rocks of the greenstone belt just north of Virginia, Minnesota. Granite dikes and xenoliths (inclusions) of greenstone are evidence of the timing of these events.

Photo by J. Miller, Jr.

collisions. The deep parts of this overthickened crust were heated to the point of melting, creating granitic magmas. Being lower density than the surrounding rocks, these magmas slowly migrated upward into the middle parts of the greenstone crust, where they cooled and crystallized into granite.

The Great Lakes Tectonic Zone has important implications for residents of the region. Faults reactivated along this Archean zone of crustal suturing are a locus for modern earthquakes. Although the upper Midwest has very low occurrence rates of earthquakes, several historic quakes greater than Richter magnitude 4 have occurred. Perhaps the most notable was the 1975 4.6 magnitude earthquake with an epicenter near Morris in western Minnesota. The Mercalli intensity of this quake was VI. In such an earthquake, everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Plaster in walls might crack. Trees and bushes shake. Damage is slight in poorly built buildings. But there is no structural damage.

Section Upper Mississippi Valley and Western Superior Basin (UMV-WSB).2 Summary

- 3.6 Ga gneisses in the Minnesota River Valley of the southern Superior Province represent the oldest continental crustal rocks of the core of North America in the UMV-WSB. These rocks were formed by recycling of older oceanic crust, perhaps by subduction.
- Pillow lavas in the greenstones of the granite-greenstone belt were formed in a volcanic island arc in the Archean ocean. These rocks were then intruded by granite batholiths around 2.6 Ga, and sutured to the gneiss belt by a collision of plates along the Great Lakes Tectonic Zone.

Upper Mississippi Valley and Western Superior Basin.3 The Early Proterozoic: The Penokean Mountains and the Making of Laurentia

At the dawn of the Proterozoic Eon, about 2.5 Ga, the region sat astride the coastline of Kenoraland. Over the next 800 million years, two events occured that had a profound effect on the face of the Earth. One was the widespread evolutionary appearance of photosynthesizing organisms. The other was doubling the size of the landmass of Kenoraland by collisional plate tectonics, creating a new continent called Laurentia. Both events are recorded in the rocks of the Western Superior Basin. The former event is preserved in the great banded iron formations (BIF'S) of the Mesabi Range of Minnesota; the latter event is preserved in the metamorphic and igneous rocks of the ancient Penokean Mountains, which stretched northeastward across present-day central Minnesota and Wisconsin.

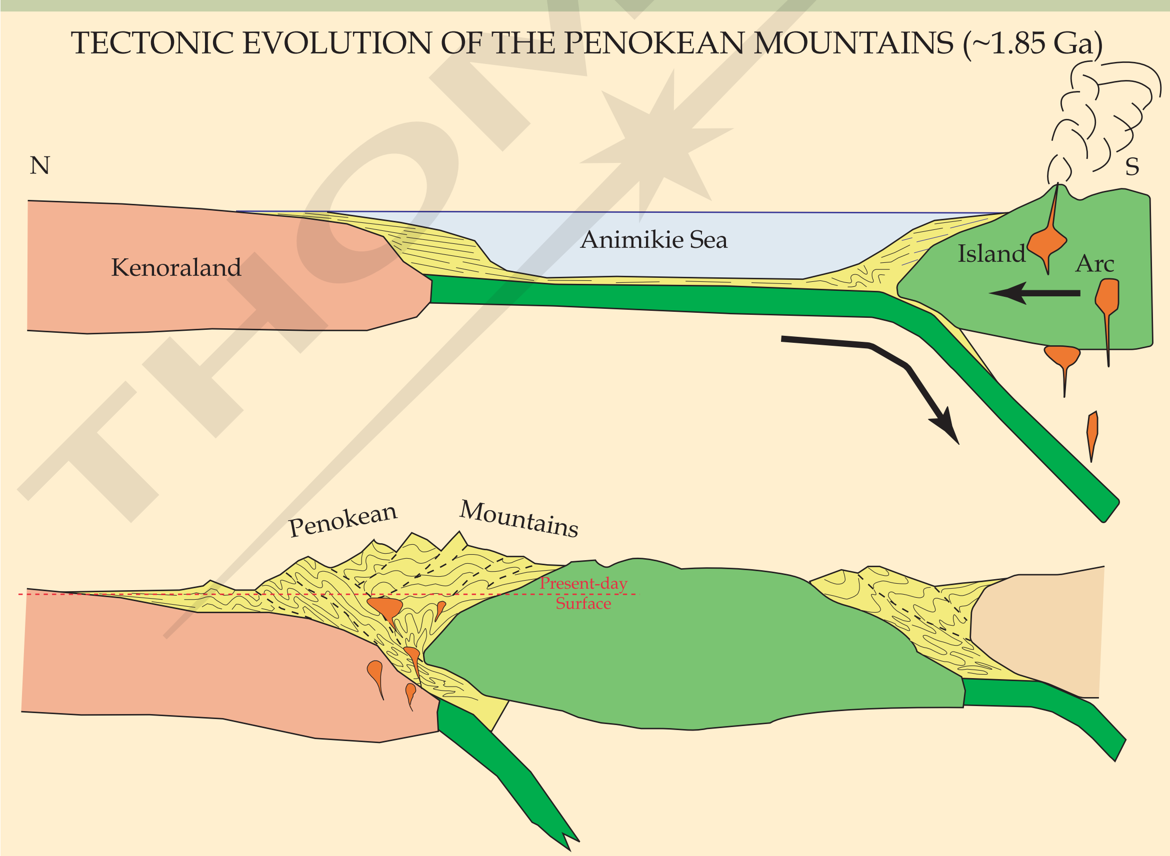
A major unconformity is exposed along the Gunflint Trail in the Arrowhead region of northern Minnesota. This unconformity represents a greater gap in the geologic record (approximately 800 million years) than James Hutton observed at Siccar Point, Scotland. Nearly horizontal rocks of the 1.85 Ga Gunflint iron formation overlie vertically inclined, 2.6 Ga metamorphosed volcanic rock that represents the eroded land surface of the Archean continent of Kenoraland. The unconformity is the record of uplift and erosion of Kenoraland and its subsequent flooding by the Animikie Sea prior to its collision with an island arc system to form Laurentia (Figure 9).

The northeasterly trend of the Mesabi Iron Range approximately traces the coast of ancient Kenoraland where it met the Animikie Sea. The coastline was a barren landscape of low granite and greenstone hills drained by meandering rivers carrying sediment to the sea. Sand, silt and clay were continually redistributed across a vast tidal plain by the rhythmic rise and fall of the tides. These tides were more extreme than anyplace on earth today—a consequence of the moon being 75% closer to earth than the present distance of about 240,000 miles. A moonrise over the Animikie Sea must have been quite a sight. Farther offshore in the clear water, photosynthesizing algae were building reefs that were occasionally exposed at low tide. Upwelling currents brought deep reducing waters rich in iron and silica to the surface to mix with the oxygenated waters of this shallow water reef environment. Thin deposits of silica and iron oxide were precipitated and deposited as an iron formation on the seafloor. The tidal flat deposits of sand and silt are found in the Pokegama Quartzite Formation. The banded chert and magnetite deposits of the offshore reef environment make up the Biwabik Iron Formation.

Stromatolitic iron formations were deposited in the Animikie Sea that flooded the margin of Kenoraland (Figures 9, 10 and 11). The stromatolites were formed when sticky filaments of cyanobacteria colonies (similar to today's algae) trapped sediment on their surfaces to create a variety of wavy laminated to finger-like and dome-shaped structures in the sedimentary deposits (Figure 10). The stromatolites, together with widespread appearance of the world's iron formations at the same time in the geologic record, provide evidence for the role of newly evolved photosynthesizing organisms in the worldwide deposition of Mesabi-type iron formations and ultimately the oxygenation of the Earth's atmosphere.

Iron ore has been mined on the Mesabi Range of northern Minnesota since the 1880s (Figure 12). Until the 1950s the type of ore that was mined was "natural ore." This ore is actually altered iron formation formed by the

► **Figure UMV-WSB.9** North *(left)* to south *(right)* cross section showing a plate tectonic and paleogeologic reconstruction of the Animikie Sea and its closure by the collision of Kenoraland with an island arc system to form the Penokean Mountains and the continent of Laurentia.

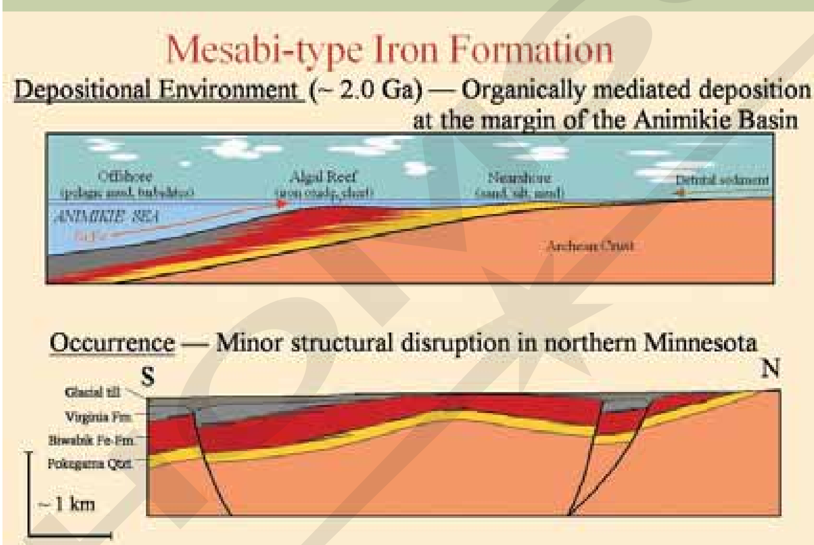


Cross section by J. Miller, Jr.

▶ **Figure UMV-WSB.10** Finger-like stromatolitic columns (reddish colored) in the Biwabik Iron Formation.

Photo by J. Miller, Jr.

▶ **Figure UMV-WSB.11** Mesabi-type iron formations in the Western Superior Basin.



Cross section by J. Miller, Jr.

▶ **Figure UMV-WSB.12** Enormous open-pit Hibbing Taconite mine operation viewed from the Hull-Rust mine overlook near Hibbing. Taconite mining takes advantage of the slightly gentle tilt of the iron formation unit. At this location, the Biwabik Iron Formation is about 250 feet thick and dips about 15° to the southeast *(right)*. Of this thickness about 100 feet has enough magnetite in the rock to be considered taconite ore. The non-ore rock and the overlying glacial overburden must be mined and moved to another site. This pit includes many natural ore pits that were mined in the early 1900s. The iron formation between these localized natural ore bodies is now being mined, resulting in one of the largest human-made canyons in the world.

Photo by J. Miller, Jr.

infiltration of oxygenated warm water through the fractured and faulted iron formation bedrock. This alteration, which resulted in oxidation of magnetite (the original iron oxide mineral) to hematite, goethite, limonite, and other oxygen- and water-rich iron minerals, also caused the silica mineral chert to be dissolved from the iron formation. By this "natural" process, the original iron formation, which is composed of about 30% iron and 50% silica, was locally transformed into a high-grade iron ore containing about 50% iron and less than 10% silica. By the nature of their formation, natural ore bodies are limited in size and distribution, usually occurring in narrow zones that correspond to the trend of a fault zone through the iron formation.

By the late 1940s, many of the natural ore mines played out. Because necessity is the mother of invention, a new technology to process iron ore was developed and implemented in the 1950s. This process allowed for the lean, unaltered iron formation, a rock called taconite by miners, to be mined and processed. Taking advantage of the magnetic property of magnetite, the taconite ore is ground to a fine powder and the magnetite is magnetically separated from the silica minerals. The iron oxide is then bound with clay into marble-sized balls called taconite pellets.

Turbidites were deposited in deeper parts of the Animikie Sea, atop and seaward of the iron formations (see Figure 11). The rocks are composed of alternating layers of fine-grained sand, silt, and mud. This sediment formed in the deeper waters of the Animikie Sea from sediment-laden slurries of turbid water that flowed down the continental slope of Kenoraland to the north and off an emerging island arc landmass to the south. Couplets of sand and mud were deposited when each of these turbidity currents slowed and sediment settled according to particle size (largest grains first, smallest grains last).

The spectacular course of the St. Louis River through Jay Cook State Park in Minnesota has exposed deformed and metamorphosed turbidites of the 1.85 Ga Thomson Formation.

▶ Figure UMV-WSB.13 Fins eroded by the St. Louis River along steeply inclined cleavage in the Thompson Formation, Jay Cook State Park, northeastern Minnesota.

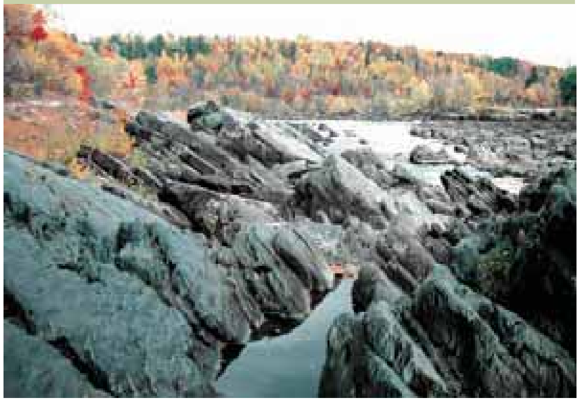


Photo by J. Miller, Jr.

Closely spaced, steeply dipping fractures, which reflect the deformational cleavage in the rock, result in fin-like outcrops over which the river roars in rapids during the high-volume runoff of spring and early summer (Figure 13). The tectonic collision of the island arc landmass with the margin of Kenoraland about 1.8 Ga resulted in the formation of the Penokean Mountains and caused the deformation and metamorphism of these sedimentary rocks (Figures 13 and 14). This mountain building event effectively turned the deep sea floor "inside out" by uplifting this area and creating the northern foothills of the Penokean Mountains.

Precambrian mountain ranges in the Western Superior Basin, like more recent fold-belt mountain ranges including the Appalachians, were produced by plate collisions. These collisions not only resulted in folding and faulting of the bedrock, but were also accompanied by intrusion of large volumes of granitic magma. The intrusion of granites near St. Cloud, Minnesota accompanied the building and erosion of the 1.8-billion-year-old Penokean Mountains, which probably rivaled the Alps in height and grandeur. Processes of crustal thickening and granite formation go hand in hand in mountain belts formed by plate tectonic collisions. When the earth's crust becomes overthickened by plate tectonic collisions, the mountain ranges, which represent the surface expression of that overthickening, are isostatically balanced by the projection of a crustal root into the earth's mantle. The crustal rocks in this deep root are commonly heated to the point of melting, creating granitic magmas. These magmas, which are less dense than the country rock, migrate upward through the crust and typically become frozen into the cooler middle levels of the crust to form large granite intrusions (batholiths). After tectonic uplift ceases, erosion accompanying isostatic rebound exposes the granitic core of the mountain belt.

▶ Figure UMV-WSB.14 Anticline in the Thomson Formation along the St. Louis River, Jay Cook State Park, northeastern Minnesota.

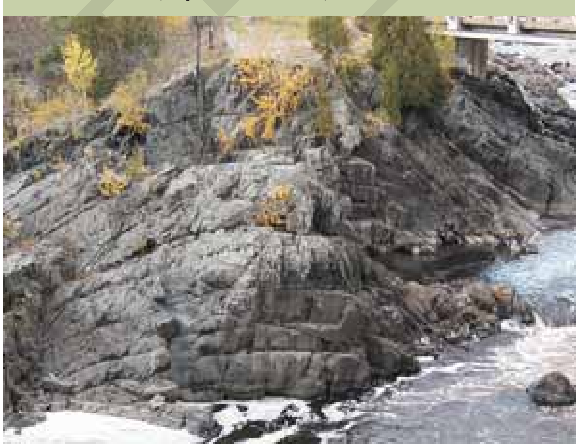


Photo by J. Meyers

Section Upper Mississippi Valley and Western Superior Basin (UMV-WSB).3 Summary

- Banded iron formations of the Mesabi Range are part of a worldwide occurrence about 2.0 Ga and record the global appearance of photosynthesizing organisms. These organisms, called cyanobacteria, created stromatolitic structures that are preserved in the rocks.

- About 1.85 Ga the size of Kenoraland was doubled by a plate tectonic collision that closed the Animikie Sea and created the continent of Laurentia. This collision produced a great fold-belt mountain range (the Penokean Mountains) that must have rivaled the grandeur of the present-day Alps.

Upper Mississippi Valley and Western Superior Basin.4 Erosion of the Penokean Mountains—The Baraboo Interval, 1750–1630 Ma

The tectonic collision and suturing of terranes against the margin of Kenoraland doubled the size of the proto–North American continent and created a new land mass called Laurentia. But by 1.7 Ga, only 100 million years after the Penokean Mountains were created, the alps were eroded to a gently rolling surface with little relief. The 100 million years to bring about the destruction of this great mountain uplift is in agreement with estimates of the rates of erosion of mountains occurring today. However, given the lack of a protective cover of vegetation on the Precambrian landscape, it is likely that the Penokean Mountains may have been eroded even more quickly than modern rates suggest.

Evidence of erosion of the Penokean mountain chain is found in scattered occurrences of gently deformed quartz-rich sandstone over areas of Minnesota and Wisconsin, south of where the Penokean Mountains once stood. Sand grains composed almost exclusively of quartz indicate that the landscape was exposed to prolonged weathering and erosion. The end product of prolonged weathering and erosion is the complete mechanical and chemical breakdown of all original rock-forming minerals to quartz and clay. Both these minerals dominate the composition of mildly metamorphosed conglomerate, sandstone, siltstone, and shale layers that compose the Sioux Quartzite of southwestern Minnesota (Figure 15) and the Baraboo Quartzite of west-central Wisconsin.

The reddish-colored, supermature sediment of the Sioux and Baraboo quartzites contains a population of reworked or detrital zircon grains with a post-Penokean age of 1782–1712 Ma (million years), indicating that deposition of the original sandstone must have occurred after the Penokean orogeny (Figure 16). These late Paleoproterozoic sedimentary rocks are among the most chemically mature detrital sediments in the geologic record, and they rest upon ancient soil horizons that are lacking in unstable silicate minerals such as feldspar. This relationship indicates that the Sioux and Baraboo Quartzites are first-cycle supermature quartz arenites. Studies of supermature quartz-rich sandstones in other parts of the geologic record suggest that conditions of tectonic stability, depositional processes that involve mechanical rigor, and a warm humid climate are prerequisites for their formation. Furthermore, weathering involving microbial processes may have been significant during weathering of the source rocks, hastening the removal of unstable silicate minerals before they could be transported to the basins of deposition.

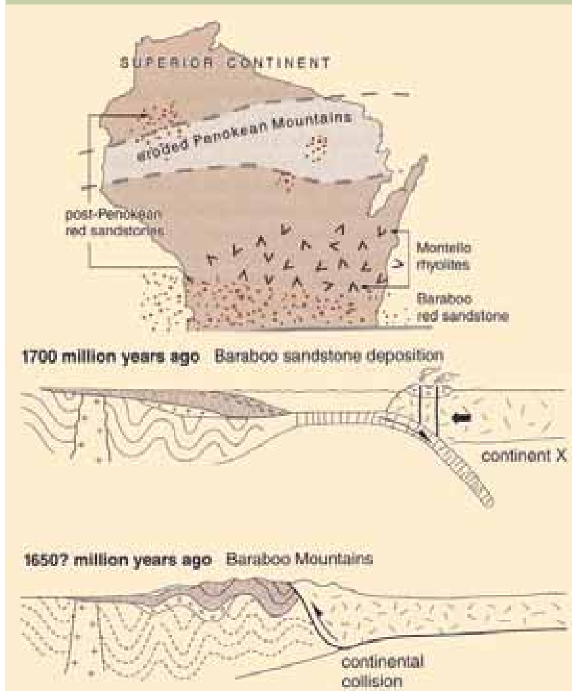
Folding and low-grade metamorphism of the quartzites is thought to reflect 1630 Ma deformation related to the Mazatzal orogeny, and subsequent hydrothermal alteration around 1465 Ma may be related to emplacement of the Wolf River Batholith. The folding event resulted from southward subduction of the plate containing the Sioux and Baraboo depositional basins beneath a northward drifting continent (Figure 16). Folding of the well-known Baraboo syncline occurred during this collision, and the Baraboo Quartzite is now exposed in the uplift of the Baraboo Hills.

The vertical sequence of sedimentary structures and changes in grain size indicate that most of the gravel and sand of the Sioux Quartzite was deposited in channels and bars of a braided river system that drained the eroded landscape of the Penokean Mountains (Figures 17 and 18). Thin layers of clay, including the catlinite that forms the famous pipestone layers of the Sioux Quartzite, were deposited on the floodplains of these same river systems. Paleocurrents are primarily unidirectional and indicate

► **Figure UMV-WSB.15** A nearly 100-foot-high cliff of Sioux Quartzite exposed in Blue Mounds State Park, southwestern Minnesota.

Photo by J. Meyers

► **Figure UMV-WSB.16** Sand deposited as the Baraboo Formation was derived from the Penokean Mountain chain and deposited in a basin to the south. Subsequent collision of the plate containing the Baraboo depositional basin with a northward drifting continent uplifted the Baraboo Mountains. (North is to the *left* in the two cross sections.)



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▶ **Figure UMV-WSB.17** Trough cross-stratification in the Sioux Quartzite, Pipestone National Monument, southwestern Minnesota.

Photo by J. Meyers

generally south-flowing currents from the Penokean Mountains to the north. In the uppermost portion of the Sioux, paleocurrents are bidirectional, suggesting a possible tidal origin for this part of the unit. Basins of deposition for the Paleoproterozoic quartzites are thought to have been fault-bounded basins in the midst of the stable craton.

▶ **Figure UMV-WSB.18** Meter-thick bed of conglomerate deposited in a braided river channel in the lower part of the Sioux Quartzite, New Ulm, Minnesota.

Photo by J. Meyers

Section Upper Mississippi Valley and Western Superior Basin (UMV-WSB).4 Summary

- First-cycle supermature quartz sands of the Sioux and Baraboo quartzites were derived directly from the uplifted Penokean Mountains. Formation of pure quartz sandstone requires intense weathering of the source rocks. Rigorous conditions during transport and depositional history are also necessary for removal of unstable silicate minerals and concentration of the resistant quartz.
- Much of the quartz sand of the Baraboo Interval was deposited in river systems, but evidence of deposition by tidal currents in shallow marine environments is present near the top of the interval in some localities.

Upper Mississippi Valley and Western Superior Basin.5
Middle Proterozoic: The Mid-continent Rift—An Attempt at Unmaking Laurentia

The Middle Proterozoic geology of the Upper Mississippi Valley and Western Superior Basin tells the story of aborted rifting of the North American continent about 1.1 Ga. Continental rifting is a common and recurring process in the history of the Earth that leads to the breakup of continents and the formation of ocean basins. A geologically recent example is the ongoing expansion of the Atlantic Ocean that began with the breakup of the super-continent Pangea about 250 Ma. The Mid-continent Rift began to form 1109 million years ago along a 2000-km-long arc-shaped break that extended southward in two arms from the Lake Superior region—one to the southwest to Kansas and the other to the southeast to lower Michigan (Figure 19).

As the crust broke and thinned, basaltic magma generated in the mantle at a depth of 50 to 100 km rose to the surface. Most of this magma erupted as layer upon layer of lava flows into an ever-widening and deepening rift valley. Some of these lavas are exposed along the North Shore of Lake Superior and as far south as Taylors Falls, Minnesota along the gorge of the St. Croix River in Interstate Park.

Sometimes the magma ponded and slowly solidified in chambers within the lava pile to form coarse-grained igneous intrusions, including the Duluth Complex and, higher in the volcanic pile, the Beaver Bay Complex. Emplacement of the mafic intrusives was also accompanied by formation of metallic deposits, including copper and platinum, whose future development may hold the key to

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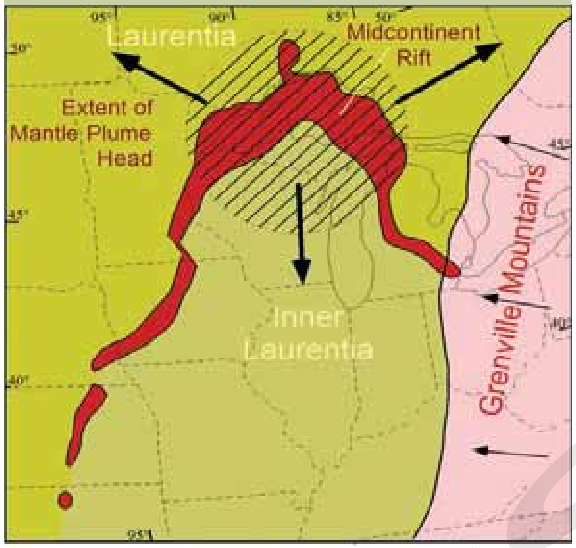
▶ **Figure UMV-WSB.19** The Mid-continent Rift, centered above a mantle plume beneath the upper peninsula of Michigan.



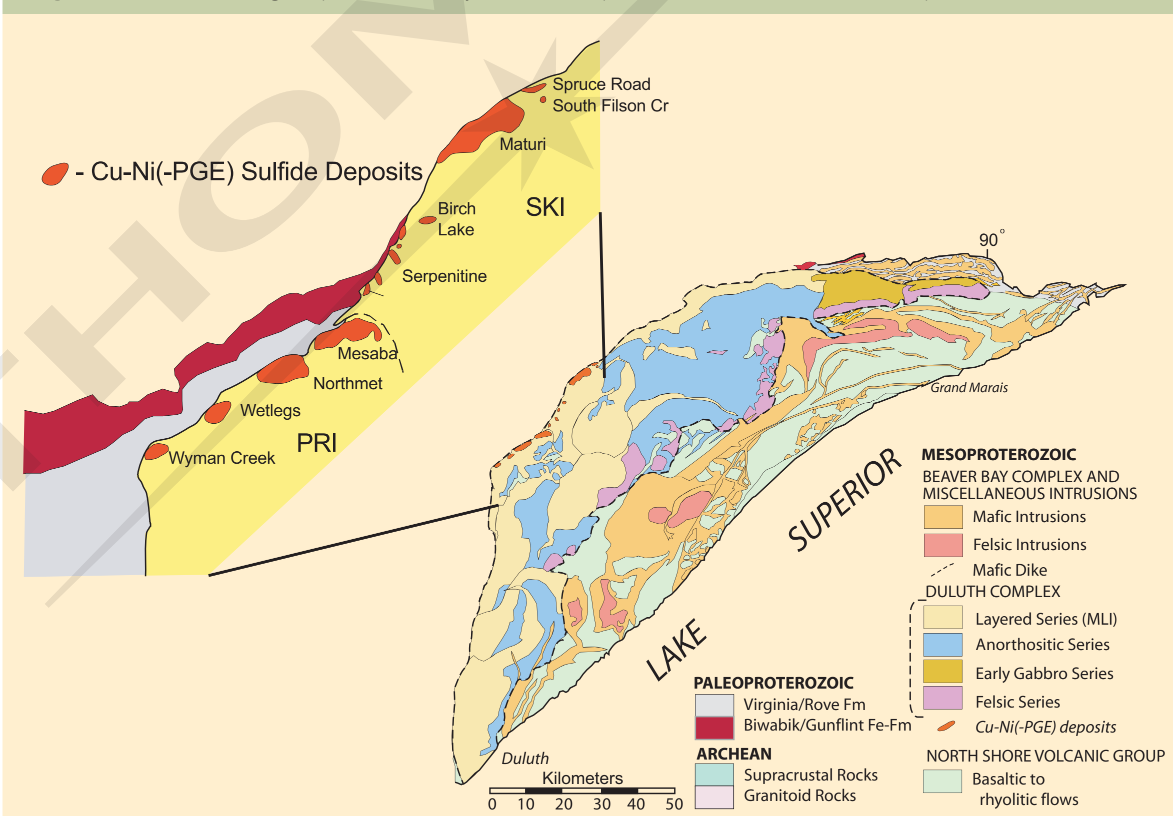
Map by J. Miller, Jr.

the ongoing success of the mining industry in this region. After almost complete rifting and separation of the originally 40-km-thick granitic continental crust, and following filling of the rift with basaltic oceanic crust, rifting and magmatic activity abruptly ceased about 1086 Ma.

The thick wedge of dense basalt caused continued down warping of the rift valley and led to its infilling with sediments dominated by fluvial and aeolian sandstones in east-central Minnesota and the Bayfield Peninsula of northwestern Wisconsin. The last chapter of the Mid-continent Rift's story was compression of the rift, resulting in uplift of a central block of basalt flanked by sandstone. Compression was caused by the Grenville mountain-building event that occurred about 1 Ga along the eastern margin of Laurentia (Figure 19). This event not only prevented Laurentia from breaking up but also added a new terrane to the edge of the growing continent.

The highway along the north shore of Lake Superior reveals excellent examples of the nature of the lava flows that were erupted into the rift (Figure 20). Outcrops along the north shore of the lake expose an approximately 10-km-thick pile of lava flows near the top of the North Shore

▶ **Figure UMV-WSB.20** Geologic map of the Beaver Bay and Duluth complexes and the North Shore Volcanic Group.



Map prepared by J. Miller, Jr.

► **Figure UMV-WSB.21** Lava flows of the North Shore Volcanic Group at Gooseberry Falls State Park, Minnesota. Each of the cascades tumbles downward over the edge of a lava flow.

Photo by J. Meyers

► **Figure UMV-WSB.23** Columnar joints formed perpendicular to the cooling surface at the top of a basalt lava flow of the North Shore Volcanic Group.

Photo by J. Meyers

Volcanic Group. The numerous waterfalls along rivers flowing southward into Lake Superior have many steps that are formed at the boundaries of individual lava flows within the sequence (Figure 21). And the surfaces of these flows often display features that one expects to find in more recent basalt flows in Craters of the Moon National Park (Idaho) or in Hawaii. Ropy pahoehoe surfaces occur at many flow contacts (Figure 22) and indicate more fluid flows, while blocky and jumbled aa structures indicate more viscous flows. Columnar joints that formed perpendicular to cooling surfaces in the basalt flows are common (Figure 23). Other flow-contact features such as reddish oxidation surfaces (see Figure 22), upper zones of gas-escape holes (vesicles), and lower zones of pipe-like mineral-filled vesicles (amygdules), allow an astute observer to determine the number of flows in any one exposure. Many vesicles are filled with silica (Figure 24), some of which weather into individual pebbles of agate that are rounded by wave action along the shore of the lake.

Eruption of lava flows into the rift must have been episodic, because sedimentary rocks are interbedded within the sequence. Just south of Grand Marais, Minnesota, is a road cut where the massive black rock of the Terrace Point basalt flow, one of the major cliff-formers of the "Sawtooth Range," overlies a thick (40-meter) section of brick red, interflow sedimentary rock (Figure 25). The basalt flow is approximately 50 meters thick and can be traced inland for 23 km. The sedimentary rock is thinly bedded fine sandstone and shale. The sand grains are made up exclusively of fragments of broken-up volcanic and intrusive rock. This implies that the source of the sediment was confined to the rift basin and was not from older quartz-bearing rocks outside the basin. The fine grain size of the sediments indicates deposition in a low-energy river system or lake. The occurrence of such a thick sequence of sediment implies a protracted hiatus in volcanic activity, perhaps on the order of 1 million years or more.

► **Figure UMV-WSB.22** Pahoehoe (ropy lava) and oxidized flow surface exposed at the top of one of the basalt flows of the North Shore Volcanic Group along the north shore of Lake Superior.

Photo by J. Meyers

► **Figure UMV-WSB.24** Agate formed by hydrothermal precipitation of silica in vesicles (holes formed by escaping gas) in basalt of the North Shore Volcanic Group.

Photo by J. Miller, Jr.

The overlying Terrace Point basalt contains large blocks of older basalt that have a very discolored and broken appearance. Such characteristics are typical of basalts that flow into water. These lavas may have been the earliest eruptions into the shallow lake basin into which the sediments were being deposited. When the main overwhelming eruption of the Terrace Point basalt occurred, it apparently incorporated some of these early basalt eruptions and carried them along as large inclusions.

Although the dominant type of lava flow in the North Shore Volcanic Group is basalt, it is not the only type. Rhyolite flows are also present. The Palisade rhyolite (Figure 26) is a 100- to 150-meter-thick lava flow that holds up many prominent topographic features in the vicinity of Tettegouche State Park (Minnesota). Rhyolites are silica-rich lava flows that make up about 10% to 25% of the North Shore Volcanic Group. Rhyolite lava is thought to form by partial melting of the base of the crust by the heat of intruded basaltic magmas. Because of their high silica content, rhyolitic lavas are very viscous and therefore tend to form very thick lava flows compared with basaltic lavas. Rhyolite flows are also more gaseous than basalt flows and therefore tend to erupt more explosively. Evidence of this explosive eruption can be seen in the fragmental and flow-banded lava and ash preserved in the base of the flows. The interior of the Palisade rhyolite flow is generally massive but contains small crystals of pink feldspar and clear quartz. This texture indicates that the magma was slowly crystallizing in a deeper staging chamber before it erupted.

The thick wedge of dense basalt caused continued down warping of the rift valley and subsequent infilling with sediments. These sediments are now preserved as the Late Proterozoic sandstones of east-central Minnesota and northwestern Wisconsin (Bayfield Peninsula). The end of

► **Figure UMV-WSB.25** Cut Bank Sandstone interbedded with the Terrace Point basalt flow near Grand Marais, Minnesota, on the north shore of Lake Superior.

Photo by J. Meyers

► **Figure UMV-WSB.26** Rhyolite flow in the North Shore Volcanic Group at Palisade Head.

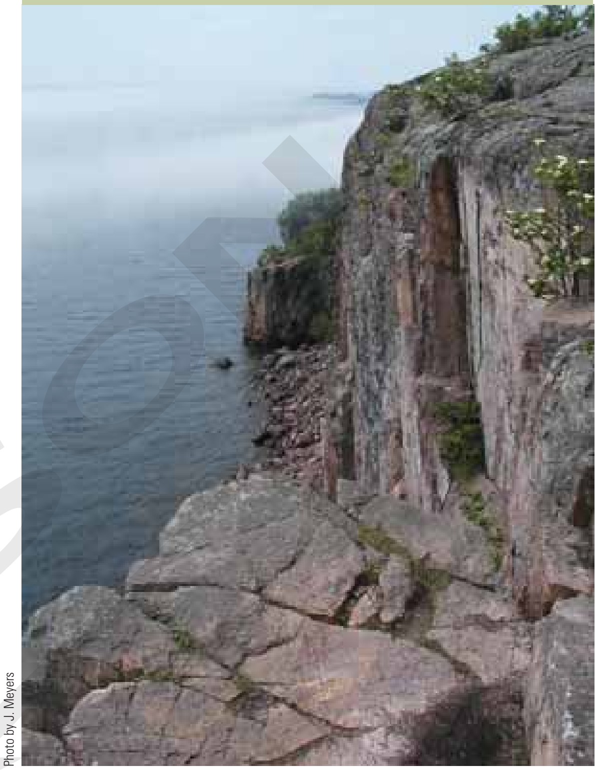
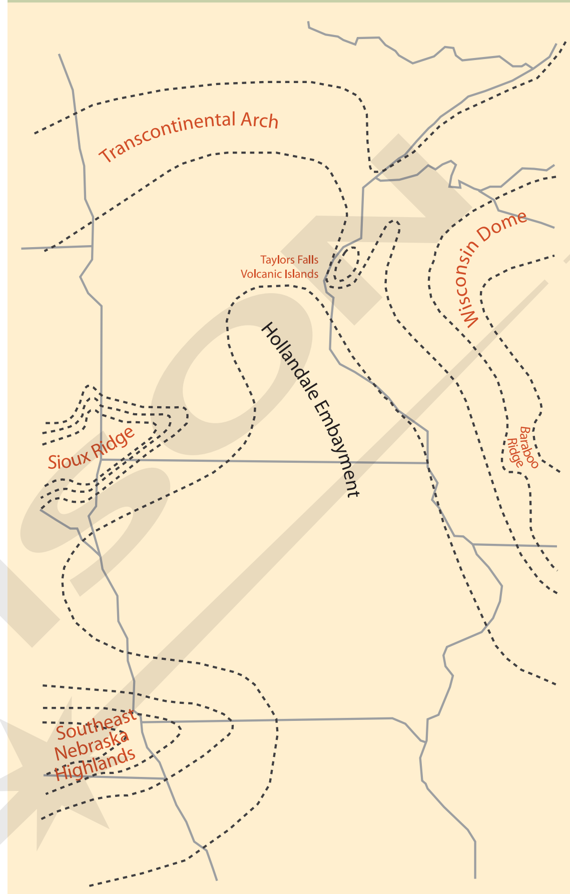


Photo by J. Meyers

the history of rifting of the mid-continent was brought about by compression of the rift caused by the Grenville mountain-building event that occurred about 1 billion years ago along the eastern margin of Laurentia (see Figure 19). This compressional event not only prevented Laurentia from breaking apart but also added a new terrane to the eastern margin of the new continent.

▶ **Figure UMV-WSB.27** Cambrian structural features of the Upper Mississippi Valley and Western Superior Basin.



Map by J. Miller, Jr.

Section Upper Mississippi Valley and Western Superior Basin (UMV-WSB).5 Summary

- Rifting of the continental crust of Laurentia occurred atop a mantle plume around 1.1 Ga. Rifting was aborted when the rising Grenville Mountains to the east caused compression of the rift.
- Episodic outpouring of basaltic magma filled the rift with basalt lava flows. Two major intrusive complexes, whose magma solidified before reaching the surface, are also present. Lesser volumes of rhyolite flows occur in the North Shore Volcanic Group, along with sedimentary rocks that formed during pauses in igneous activity.

Upper Mississippi Valley and Western Superior Basin.6 Phanerozoic: Periodic Flooding and Exposure of North America's Stable Interior

Following the tumultuous events of Precambrian time, the crust beneath the upper Midwest ceased its restless behavior and became the nucleus of the stable core (craton) of the North American continent. Only broad, gentle warping and minor faulting of the crust was to take place through the next 550 million years. The Wisconsin Dome and Transcontinental Arch (Figure 27) were uplifted early in Cambrian time, when the region was located in tropical latitudes (Figure 28). Uplands developed on these arches provided a source of sediment that was eroded by rivers and carried southward into the sea that occupied the adjacent Hollandale Embayment of the Forest City basin, which was centered in Iowa.

Sediment deposited in the shallow seas that flooded the continental platform became the sandstones, shales, limestones and dolostones of the Cambrian and Ordovician Systems. Minor intrabasinal uplift and subsidence along northeast-trending faults and associated folds also occurred (Figure 29). Some of these minor structural movements of the crust controlled the finer details of the distribution of depositional environments and thereby influenced the dispersal and distribution of sediment.

The pattern of transport and deposition of these sediments was strongly governed by the geographic arrangement of uplifts around the northern margins of the basin, and by water depth, tides, storms, and circulation patterns in the shallow seas. Superimposed on these controls was the history of global (eustatic) rise and fall of sea level (controlled in part by global climate change and associated fluctuations in ice cap volume) and the history of uplift of the crust beneath the arches and subsidence of crust beneath the basin.

The Cambrian and Ordovician Systems exposed in southeastern Minnesota and western Wisconsin consist in the most general terms of a thick pile of sand overlain by a thick blanket of carbonate sediment, totaling approximately 2000 feet (Figure 30). This succession of deposits reflects an overall rise of global sea level from the Cambrian through Ordovician periods, which flooded the sources of sand to

▶ **Figure UMV-WSB.28** Paleotectonic reconstruction of Laurentia (NAM) during Late Ordovician time (~450 Ma). The interior of Laurentia was far removed from the convergent plate boundary along the eastern edge of the early Appalachian Mountains. The craton of Laurentia was flooded by the highstand of the global ocean at the end of the Ordovician.

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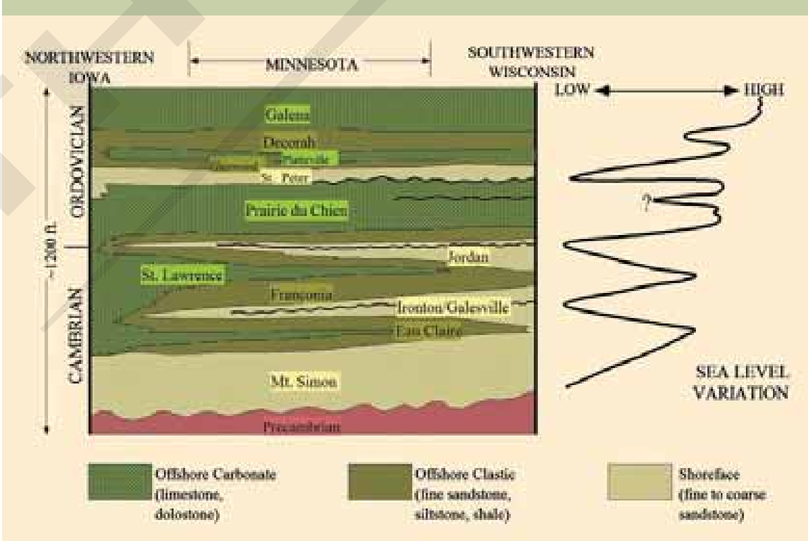
▶ **Figure UMV-WSB.29** The steeply dipping Red Wing Fault along U.S. Highway 61, on the south edge of Red Wing, Minnesota. The older Franconia (Lone Rock and Mazomanie) Formation is uplifted in the footwall and is now adjacent to the younger Jordan Sandstone in the down-dropped hanging wall.

Photo by J. Meyers

the north of the depositional basin (see Figure 30). Without a significant influx of detritus to the basin, carbonate-secreting organisms flourished, resulting in the formation of limestone and dolostone.

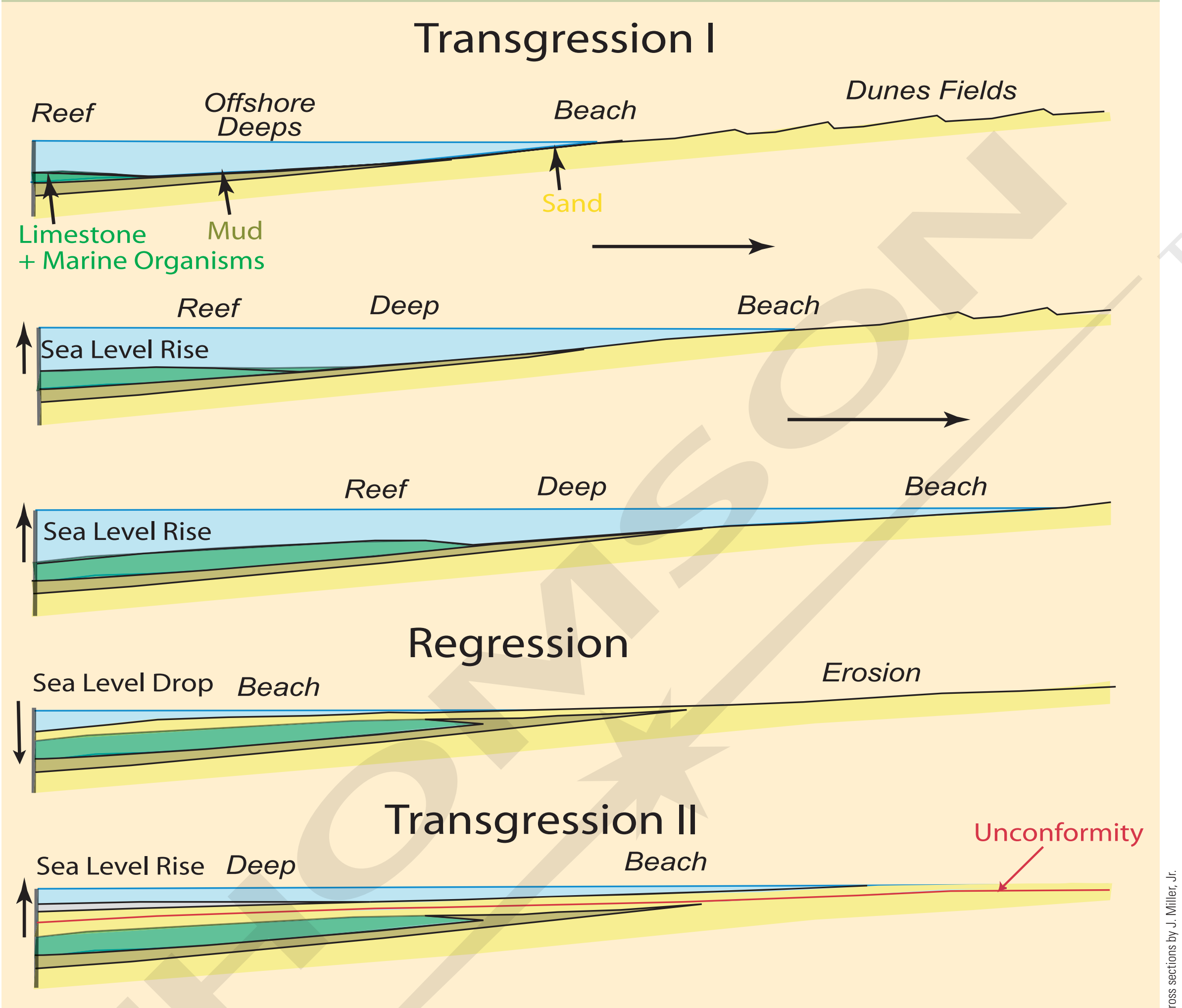
The global or eustatic sea-level curve also shows smaller order fluctuations in sea level that governed smaller-scale vertical variations in sediment accumulation. These smaller-scale transgressions and regressions resulted in cyclic deposition of sediment (Figures 31–34). With each transgression and subsequent highstand of the sea, several very significant changes take place (see Figure 31). Conglomerate and sandstone deposited in a terrestrial or nearshore location are buried by accumulation of finer grained sediment deposited in deepening water under conditions of lower energy. If sea level continues to rise, the amount of sand and mud delivered to the basin diminishes; as the source area is flooded. Ultimately the sea becomes less turbid, carbonate-secreting organisms flourish, and limestone and dolostone may be deposited. A good example of such a cycle is the Mt. Simon–Eau Claire package of sediment, which represents terrestrial to shoreface conglomerate and sandstone overlain by offshore shale and thin carbonate rocks (see Figure 30). This same cycle is present in the lowermost Cambrian sediments throughout the North American continent. Furthermore, this cycle appears to be symmetrical, in that a regression (retreat of the sea and retreat of the shoreline toward the basin center) is also recorded in the Eau Claire–Galesville part of the package (see Figure 30).

▶ **Figure UMV-WSB.30** Cambro-Ordovician stratigraphy in northwestern Iowa, Minnesota, and southwestern Wisconsin and interpretation of global (eustatic) variation in sea level. According to recently proposed terminology, the Ironton-Galesville sandstones are members of the Wonewoc Sandstone, the lower Franconia Formation is referred to as the Lone Rock Formation, and the upper Franconia is the Mazomanie Formation.



Restored cross section by J. Miller, Jr.

▶ **Figure UMV-WSB.31** Transgression and regression of the sea in a cratonic setting and the resulting facies distribution that produces different vertical stacking patterns of sedimentary rock types.



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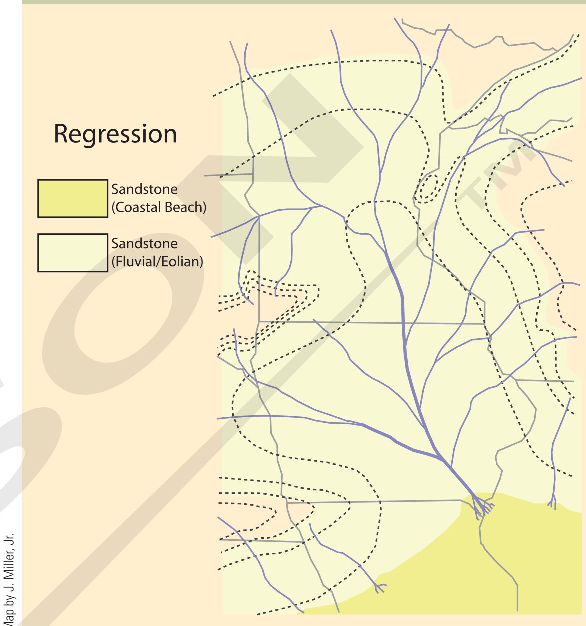
Another classic transgressive interval in the Upper Mississippi Valley is the Ordovician St. Peter Sandstone, Glenwood Shale, and Platteville Limestone. This sequence is especially well exposed in the Twin Cities Basin of Minnesota, particularly along the north bank of the Mississippi River in St. Paul (Figure 32).

But not all the sandstone-carbonate successions represent transgression of the sea from basin center to basin margin. For many years geologists interpreted the Jordan Sandstone and the overlying Oneota Dolostone of the Prairie du Chien Group as a transgressive sequence. But more recent work has shown that an unconformity is present between the two units. When an unconformity is present within an interval of sedimentary rocks such as the Jordan-Oneota, Walther's "Law" cannot be used across that gap in the record to interpret the history of transgression and regression. The most recent interpretation of the Jordan Sandstone indicates that the Jordan Formation lies at the top of a depositional sequence with carbonates of the St. Lawrence Formation at its base. The carbonate to sandstone sequence of the St. Lawrence–Jordan formations indicates that the Jordan Sandstone was formed during regression (Figure 34). The St. Lawrence Formation, which is underlain by a surface of maximum flooding, represents farther offshore, deeper water deposition compared with the Jordan, which was deposited in nearshore to shoreface environments.

▶ **Figure UMV-WSB.32** Exposure of the St. Peter Sandstone, Glenwood Shale, and Platteville Limestone at the Wabasha Street bridge, north bank of the Mississippi River, in downtown St. Paul, Minnesota.

Photo by J. Meyers

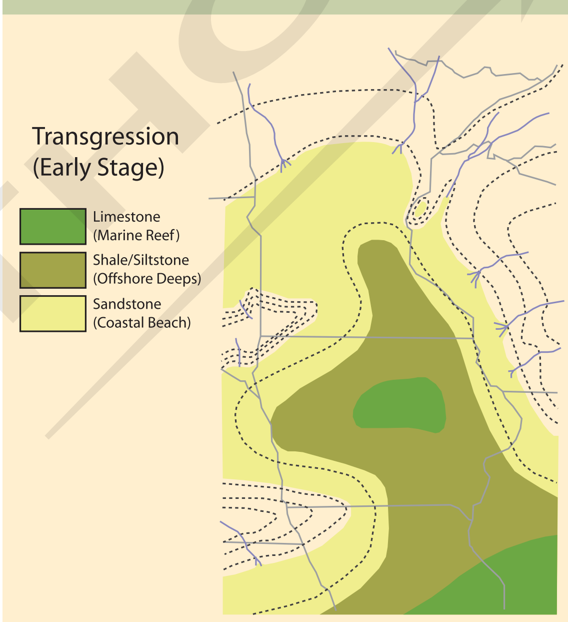
▶ **Figure UMV-WSB.34** During regression, the shoreline advanced toward the basin center and the area of marine accumulation of sediment shrank dramatically. At times of maximum regression, much of the region was undergoing erosion and surfaces of unconformity developed over which the next transgression took place.



Map by J. Miller, Jr.

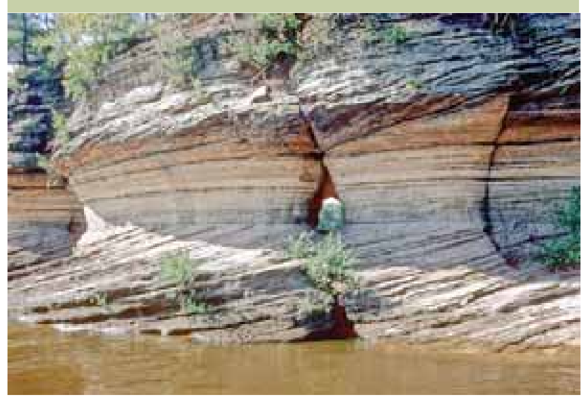
Cambro-Ordovician sedimentary rocks of the Upper Mississippi Valley were deposited in both terrestrial and shallow marine environments (Figures 35 through 38). Some sandstones at the base of depositional sequences were deposited in aeolian dunes (see Figure 35) and braided rivers. Other sandstones accumulated in beach and shoreface settings or in tidal flats and tide-dominated nearshore settings (see Figure 37). Finer-grained siliciclastic sediments and carbonates accumulated in offshore environments below normal wave base. These deeper water environments were occasionally influenced by storm waves, resulting in deposition of finer grained sediments

▶ **Figure UMV-WSB.33** Early stage of transgression of the sea outward from the center of the Forest City Basin in Iowa. Environments in which carbonates and mudrocks accumulated expanded outward from the basin center and ultimately covered much of southeastern Minnesota.



Map by J. Miller, Jr.

▶ **Figure UMV-WSB.35** Large-scale cross bedding formed by the migration of aeolian dunes, Cambrian Wonewoc Formation, Wisconsin Dells.



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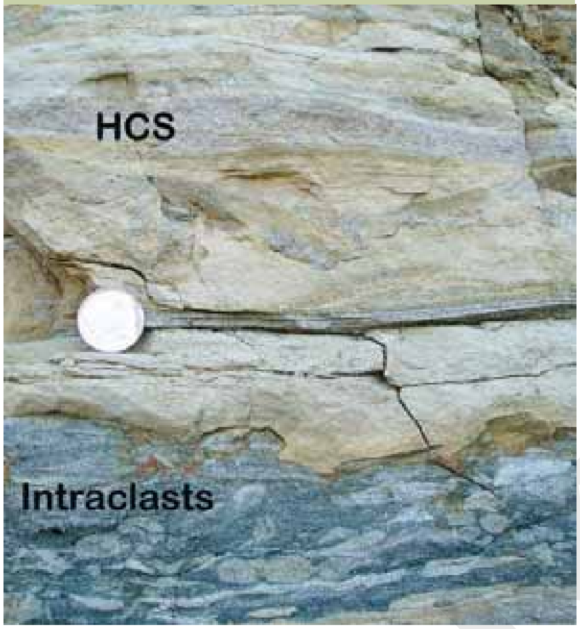


Photo by J. Meyers

▶ **Figure UMV-WSB.36** Greensand in the Cambrian Franconia Formation near Rollingstone, Minnesota. The green color is caused by high abundance of glauconite grains. Layering in the upper third of the photo is hummocky cross stratification (HCS), which forms in the offshore under the influence of storm waves. Intraclasts in the lower third of the photo were formed by ripping up of semiconsolidated sediment by storm waves.

containing pebble-sized fragments of semiconsolidated sediment ripped up from the bottom and redeposited nearby (see Figure 36).

During Late Cretaceous-Paleocene time, tectonic convergence of crustal plates at the western edge of North America resulted in uplift of the Rocky Mountains. An extensive basin (the Rocky Mountain Foreland Basin) formed east of the mountains, as a counterpart to the mountain uplifts (Figure 39).

Photo by J. Meyers

▶ **Figure UMV-WSB.37** Exposure of the upper part of the Cambrian Jordan Sandstone near Homer, Minnesota. Opposing orientations of cross bedding and thickening and thinning of the millimeter-scale cross lamination in the tidal bundles indicate deposition by tidal currents.

Photo by J. Meyers

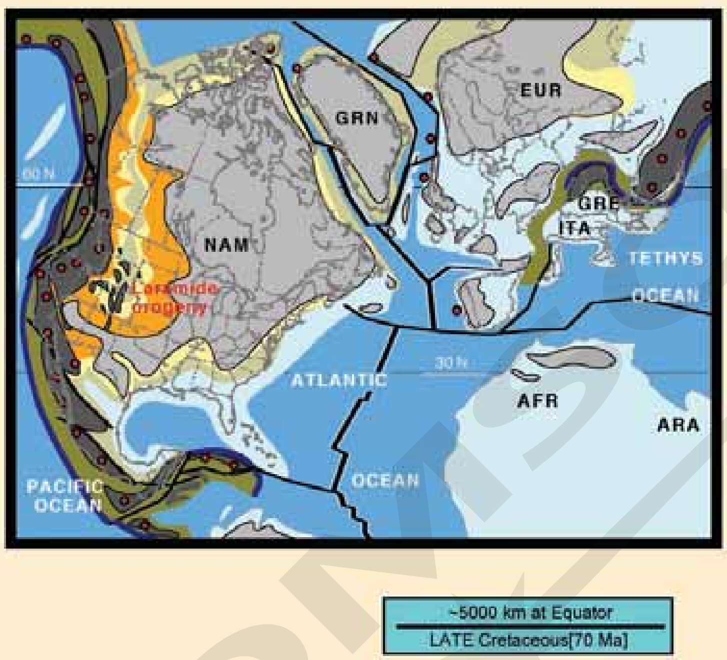
▶ **Figure UMV-WSB.38** Dome-shaped stromatolites in the upper part of the Ordovician Prairie du Chien Group south of Chatfield, Minnesota. The stromatolites were formed by trapping of sediment by cyanobacteria in shallow subtidal offshore environments.

Dinosaurs roamed the western lands, and great sea serpents, including mososaurs, prowled the depths of the shallow sea that lay to the east of the Rockies. From time to time, this shallow sea flooded parts of Minnesota, northwestern Iowa, and the adjacent Dakotas, and sandstone and black shale were deposited in beach and offshore warm, stagnant waters respectively. Because the depositional environments were primarily marine, no terrestrial dinosaur fossils are found in these rocks in Minnesota; but marine fossils, including ichthyosaurs, sharks' teeth, and a variety of mollusks, are present.

Section Upper Mississippi Valley-Western Superior Basin (UMV-WSB).6 Summary

- Cambro-Ordovician siliciclastic-carbonate sequences of sedimentary rocks were deposited in marine environments as a thin blanket atop the basement of the stable craton. These sequences were formed in response to patterns of global sea level change. Tide- and wave-dominated environments controlled the patterns of grain size and sedimentary structures in the rocks.
- Marine sandstone and black shale were deposited in the western part of the region during Late Cretaceous time. Deposition occurred in a basin that formed in response to the uplift of the Rocky Mountains far to the west.

▶ **Figure UMV-WSB.39** Paleogeographic and paleotectonic map of North America during Late Cretaceous time. The orange color is the Rocky Mountain Foreland Basin. When eastward-directed thrust faults stacked slices of the crust upon one another, the lithosphere subsided, creating the basin. Late Cretaceous rise in sea level caused marine transgression in this basin across the continental interior. Seas advanced from the Arctic and from the Gulf of Mexico. The Late Cretaceous seaway then encroached eastward, covering the Dakotas and reaching as far as southwestern and northern Minnesota.



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Upper Mississippi Valley and Western Superior Basin.7

Pleistocene: The Laurentide Ice Sheet and Shaping of the Landscape

The landscape of the upper Midwest owes its form primarily to the repeated advance and retreat of the Laurentide ice cap from its centers of accumulation in the vicinity of Hudson Bay, Canada. At various times during the interval from ~2 million years to 10,000 years before the present (the Pleistocene Epoch), lobes of ice moved southward into the region through the Winnipeg Lowland and the Red River Valley, and southwestward through the Superior Basin and Green Bay (Figure 40). The glacial landforms that we see throughout much of Minnesota and Wisconsin are mainly from ice advances during the last 80,000 years (the Wisconsin Episode) of this much longer interval of glacial history. Landforms in the Western Superior Basin are mainly erosional and were formed when glaciers carved out less resistant rocks and left more resistant rocks standing at higher elevations. The result in the Arrowhead region of northeastern Minnesota is a wonderful array of lakes that bedeck the Boundary Waters Canoe Area and Voyageurs National Park. These lakes are oriented northeast-southwest, reflecting the "grain" of structures in the Precambrian bedrock.

As many as six advances and retreats of the Laurentide ice sheet occurred in Minnesota and Wisconsin during the Wisconsin Episode, and each one left its mark on the glacial deposits and glacial landforms developed on these deposits. Till deposited by the succession of Wisconsin advances can be differentiated based upon its color and the abundance of boulders versus clay content. Bedrock in the Superior Basin is mainly composed of crystalline Precambrian igneous and metamorphic rocks, along with iron formations. As a result, when the Superior and Rainey Lobes advanced to the southwest from their center of accumulation in Canada, reddish stony tills were deposited (Figure 41). Bedrock in the Winnipeg and Red River Lowland is mainly composed of Ordovician shale and carbonate rocks. Consequently, when the Wadena and Des Moines lobes advanced southward through the Red River Lowland from their center of accumulation in Canada, lighter colored, less stony, and more clay-rich tills were deposited. In Wisconsin, tills associated with the Green Bay and Lake Michigan lobes are brownish and sandy, and brown to red-brown and sandy, silty and clay-rich respectively, reflecting the Precambrian crystalline rocks and Paleozoic sandstones and carbonate rocks over which these glaciers advanced.

A variety of glacial landforms are developed on the Wisconsin till and outwash of this region: broad ridges of till deposited at the margins of the ice (end moraines); gently rolling to hummocky terrain behind these ridges (ground moraine); streamlined elongate hills within this rolling landscape (drumlins); serpentine ridges (eskers) and cone-shaped hills (kames) developed in sand and gravel deposited by running water atop, within, and beneath the ice; and broad plains and valley trains underlain by outwash deposited beyond the margins of the ice. The Alexandria Moraine Complex in west-central Minnesota (Figures 42 through 44) and the Kettle Moraine in southeastern Wisconsin are excellent examples of glacial topography developed on till and outwash. In both these areas, touring

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► **Figure UMV-WSB.40** Map of the maximum advance of Pleistocene glaciation in the mid-continent of the United States. The pseudo-driftless area and the Paleozoic plateau are also shown. The pseudo-driftless area was probably glaciated one or more times during the Middle Glaciations (~300,000–1,000,000 years ago), and deposition and erosion of residual tills probably occurred during the Early Glaciations (~2.2 Ma to 1.0 Ma), but no landforms survive from these pre-Wisconsin glacial advances. And only scattered, thoroughly weathered deposits and erratics are present to suggest that these glaciers once covered this area. The Paleozoic Plateau in western Wisconsin was most likely never covered by glacial ice. The various provenances refer to individual directions of ice advance, generally as lobes moving outward from the edge of the ice sheet.

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routes have been established to enable viewing of these beautiful glacial landscapes (the Glacial Ridge Trail Scenic Byway in Minnesota and the Ice Age National Scenic Trail in Wisconsin).

Morainal topography is arguably the most interesting assemblage of landscape features formed by the Wisconsin Episode glaciation. But deposition of glacio-fluvial sand and gravel in outwash plains, kames, and eskers resulted in creation of the most economically important geologic resource in the region. Sand and gravel quarried from these deposits (Figure 45) is used in road building and other construction projects. And important aquifers in these sand and gravel deposits provide a significant source of groundwater for the region.

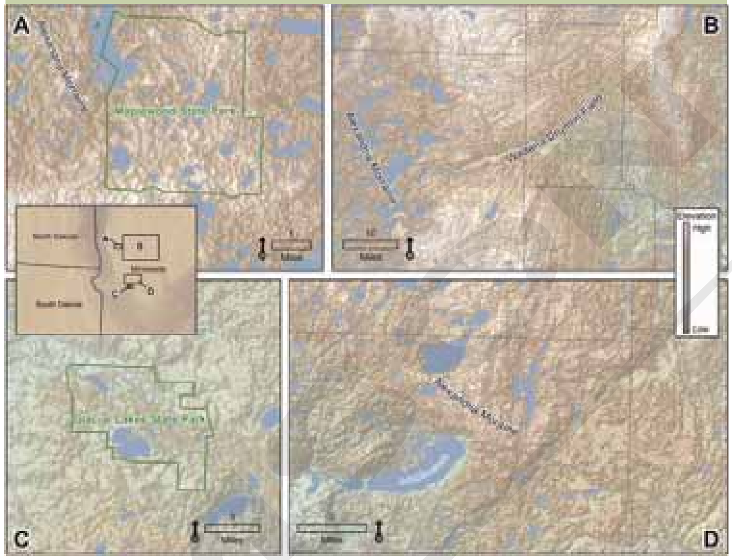
After retreat of the last of the Laurentide ice from the region (about 12,000 years ago), an immense lake, Glacial Lake Agassiz, formed in western and northwestern Minnesota, easternmost North Dakota, and southern Canada (Figure 46). Lacustrine deposits of mud on the bottom of the lake form the flat landscape in the present-day Red River Valley drainage basin of northwestern Minnesota and eastern North Dakota. Sandy beaches, best developed along the eastern shores of the lake because of prevailing westerly winds, stand slightly higher than the lake bottom to form elongated north-south–oriented beach ridges.

When the water of this lake broke its dam, torrential floods coursed through the Minnesota River Valley, then down the Mississippi from its confluence with the Minnesota River. During this River Warren Phase of the Wisconsin Episode (11,500 to 10,000 years ago), erosion by floods of Glacial River Warren scoured and deepened the Minnesota and Mississippi River valleys and resulted in the formation of waterfalls along tributary rivers that were left standing higher than the new base level. Terraces were also formed along the rivers during episodic downcutting events related to the flooding (Figures 47, 48, and 50C). And high energy flows and associated downcutting by the Mississippi River during the River Warren flood events caused

► **Figure UMV-WSB.41** Reddish-colored stony till deposited by the Superior Lobe, North Shore of Lake Superior.

Photo by J. Meyers

► Figure UMV-WSB.42 **A.** The Alexandria Moraine in Maplewood State Park, Minnesota. The topography is dominated by kames and kettles. **B.** The Wadena Drumlin Field east and northeast of the Alexandria Moraine in west-central Minnesota. **C.** Glacial Lakes State Park in west-central Minnesota. The landscape is dominated by kames and kettles, formed during stabilization and stagnation of the Wadena Lobe. **D.** Alexandria Moraine Complex. Lake Minnewaska occupies a tunnel valley formed by west-southwestward subglacial erosion.



Maps prepared by Ross Hoffmann

► Figure UMV-WSB.43 Alexandria Moraine Complex viewed to the east from Inspiration Peak (el. ~1750 feet). The topography includes kames and kettles formed in the midst of a broad, arc-shaped ridge developed at the margin of the Wadena Lobe during stabilization and stagnation of the ice front.

Photo by J. Meyers

► Figure UMV-WSB.44 Kame and kettle topography in the Alexandria Moraine Complex, Maplewood State Park.

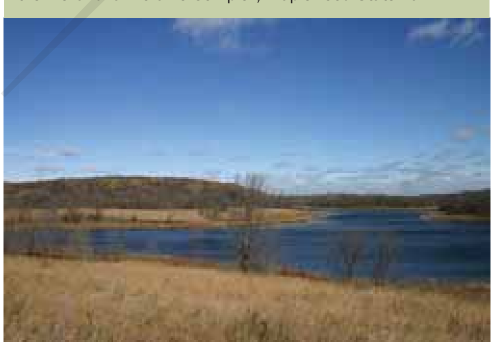


Photo by J. Meyers

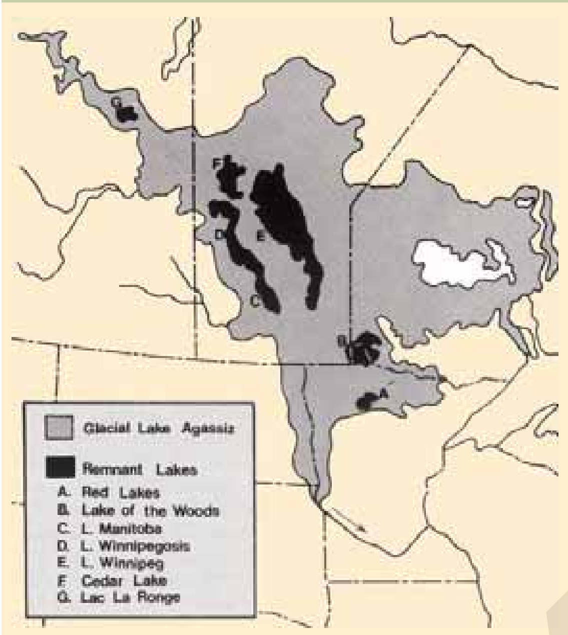
► Figure UMV-WSB.45 Outwash exposed in gravel pit on the outskirts of Maple Grove, Minnesota. The channel form at the top of this sand and gravel deposit is typical of fluvial transport.

Photo by J. Meyers

older courses of the river to be abandoned and new channels carved in the bedrock of the pseudo-driftless area (Figures 49 and 50A).

Another spectacular deluge during the River Warren Phase occurred when Glacial Lake Duluth, a larger predecessor of present-day Lake Superior, drained catastrophically southwestward and southward through the St. Croix River Valley, carving the spectacular gorge and potholes, some as deep as 50 feet, in basalt of the Midcontinent Rift near Taylor's Falls, Minnesota.

► **Figure UMV-WSB.46** Glacial Lake Agassiz.



Courtesy University of Minnesota Press

► **Figure UMV-WSB.47** Bedrock terrace along the north side of the Minnesota River Valley near Ortonville, Minnesota.

Photo by J. Meyers

► **Figure UMV-WSB.48** Langdon and Grey Cloud Terraces developed in Mississippi River outwash along U.S. Highway 61 at Kellogg, Minnesota. The Langdon Terrace is the older, and represents a former level of the Mississippi River. Increased discharge related to flooding of Glacial River Warren resulted in downcutting to the level of the Grey Cloud Terrace. Subsequent downcutting caused by increased discharge in the Mississippi River related to Glacial River Warren left the Grey Cloud Terrace standing above the subsequent floodplain.

Photo by J. Meyers

► **Figure UMV-WSB.49** Abandoned channel of the Mississippi River, viewed downstream from Barn Bluff on the south side of Red Wing, Minnesota.

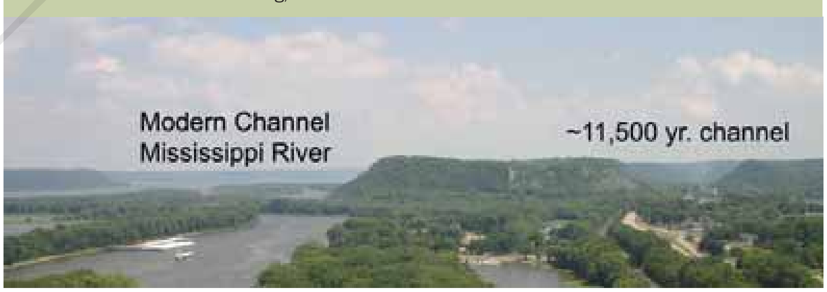
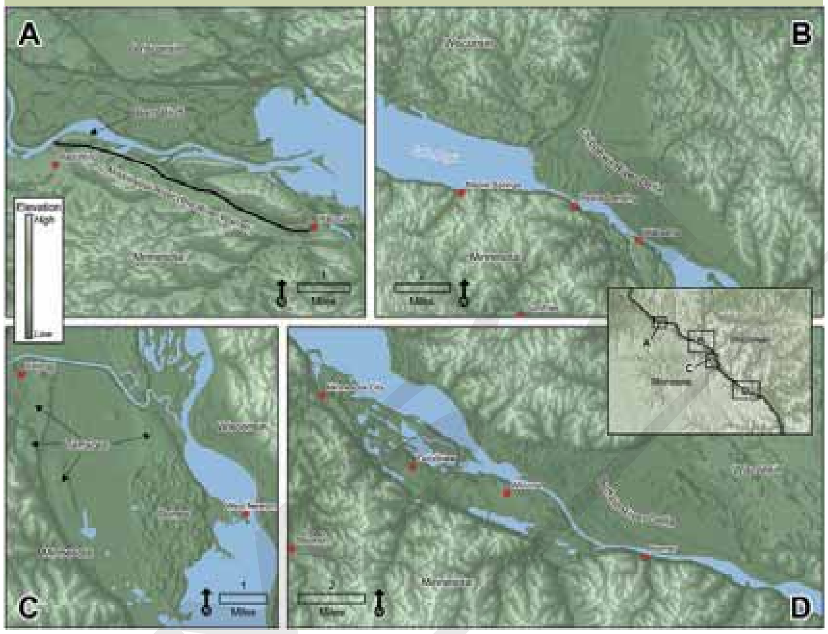


Photo by J. Meyers

► **Figure UMV-WSB.50** **A.** Abandoned course of the 11,500-year-old Mississippi River on the south side of Barn Bluff, Red Wing, Minnesota. **B.** Delta of the Chippewa River, which dammed the Mississippi River, forming Lake Pepin. **C.** Terraces along the Mississippi River valley near Kellogg, Minnesota. Pleistocene dunes are developed on the youngest (and, hence, the lowest) terrace. **D.** Delta of the Buffalo River damming the Mississippi River near Winona, Minnesota.



Maps prepared by Ross Hoffmann

Section Upper Mississippi Valley and Western Superior Basin (UMV-WSB).7 Summary

- Much of the landscape of the Upper Mississippi Valley and Western Superior Basin is the result of advance and retreat of glaciers from the Laurentide Ice Sheet during the past 80,000 years. Deposits left behind by the glaciers obscure much of the bedrock of the region, except for the area north and northwest of Lake Superior, the Minnesota River Valley, the Paleozoic Plateau and the Pseudo-Driftless Area.

- The sequence of advance and retreat of ice during the Wisconsin Episode of the Pleistocene Epoch can be understood by a study of the characteristics of deposits laid down by the ice (till) and the succession of glacial tills that are piled atop one another.

- Advance and retreat of ice during the Wisconsin Episode brought about major drainage changes throughout the region. Drainage courses were reorganized, great floods sculpted the landscape during catastrophic draining of glacial lakes, and a system of terraces was formed along many valleys. The Great Lakes also took on their present form as a consequence of glaciation.

Upper Mississippi Valley and Western Superior Basin.8

A Most Precious Resource—Surface Water, Groundwater, Landscape Evolution, and Water Quality

The most precious resource in the upper Mississippi Valley and the western Superior Basin is water. As long as the water supply is plentiful and clean, the region can prosper and flourish. Both surface water and groundwater are important in the development of the landscape and in creation of water reservoirs for household, agricultural, and industrial use.

The Mississippi River and its tributaries are the major surface water drainage system in the United States. In its present form, the Upper Mississippi River system has evolved since the retreat of the last Pleistocene ice sheet. But the glacial history also played a very significant role in the evolution of the fluvial landscape of the region. Terraces along river valleys are attributed to cycles of climate change related to advance and retreat of glacial ice and to catastrophic flooding from glacial lakes. And cycles of erosion and deposition in river valleys, carving new valleys, and abandonment of old ones are also related to these glacial cycles. Mass wasting associated with steepening of valley walls by fluvial erosion is especially prevalent along the Mississippi River and its tributaries. Downslope earth movements are also initiated by oversteepening of slopes by construction of roads and buildings.

The Great Lakes are the major reservoir of fresh water in the world. Their evolution is inextricably tied to glacial history. The basins that hold these lakes, while controlled by bedrock patterns established as early as Precambrian time, were ultimately sculpted by lobes of ice advancing to the south and southwest from the Laurentide Ice Sheet in Canada (see Figure 40). Drainage of these basins was originally through the proto-Mississippi Valley drainage system. But blocking of drainage outlets by glacial deposits and deepening of the eastern outlets of these lake basins by glacial erosion resulted in the present-day drainage of the Great Lakes to the Atlantic Ocean. The shorelines of the Great Lakes are especially vulnerable to wave erosion, especially in places where development has taken place in these fragile landscapes.

Groundwater is the most important source of fresh water in the region. Aquifers include Precambrian crystalline rocks, Lower Paleozoic sandstones and carbonate rocks, and Pleistocene sands and gravels. Each of these aquifers presents special problems in the maintenance of abundant, clean supplies of groundwater. Threats to this water supply include the potential for pollution from industrial, agricultural, and municipal sources.

The sand and gravel aquifers in glacial deposits are vulnerable to pollution from a variety of sources, especially from agricultural land use and from industrial waste. Aquifers in Precambrian crystalline rocks are especially sensitive to mining of the metallic resources in the Arrowhead Region of northeastern Minnesota, northern Wisconsin, and the adjacent Upper Peninsula of Michigan.

Sandstone and carbonate aquifers are a significant part of the geology of southeastern-most Minnesota and western Wisconsin in the pseudo-driftless area and the Paleozoic Plateau (see Figure 40). This region is an excellent example of the way in which geologic processes interact with human activities to affect water quality in these aquifers. The lack of a cover of glacial sediments makes these aquifers especially vulnerable to pollution because a thick cover of glacial sediment acts as a filter that helps to remove pollutants from water as it infiltrates to the water table.

In addition, groundwater solution of the carbonate bedrock, which is at the surface in much of this region, produces an assemblage of landforms called karst topography, dominated by interconnected sinkholes, fractures (joints) enlarged by solution, and cavern systems. During storms, pollutants introduced at the surface reach the water table in a matter of hours to days. Infiltrating surface water moves very rapidly through a system of surface sinkholes connected to underground caverns through a system of joints enlarged by solution. Karst landscapes are very much like a sieve through which surface water moves very rapidly to the groundwater system.

► **Figure UMV-WSB.51** Fountain sinkhole plain, Fillmore County, southeastern Minnesota. Sinkholes are the circular features occupied by trees *(red)*. Note the northward headward erosion of the upland in the southern part of the photo by small tributaries of the Middle Fork of the Root River.

With permission of the Minnesota Department of Natural Resources

An excellent example of karst topography in the region is the sinkhole plain surrounding Fountain, Minnesota (Figure 51). This area is underlain by Ordovician bedrock dominated by limestone and dolostone. The Root River is incised below this sinkhole plain, providing a gravitational head for groundwater that infiltrates the plain on its way to emergence as base flow in the valley bottoms. Increased rate of groundwater flow increases the rate of solution of bedrock, forming well-developed karst topography. But these increased flow rates also carry pollutants such as nitrates from manure and fertilizer, and pesticides and herbicides from intensely cultivated uplands to the water table in very short time. During storms, some springs emerging in valley bottoms carry water that was at the surface of the upland mere hours ago. In a karst groundwater system such as this, aquifers in the near-surface carbonate rocks are quickly polluted, so wells must be drilled to lower aquifers at greater expense in order to obtain potable sources of water.

Features of the karst plain near Fountain include solution and collapse sinkholes (Figure 52), rises (springs that are the source for surface water streams) (Figure 53), dry valleys, sinks (sinkholes where surface streams disappear to subsurface courses), and cavern systems (Figures 54 and 55).

One of the main cavern systems south of the Fountain sinkhole plain is Mystery Cave, a unit within Forrestville State Park. The cave is developed in Ordovician limestone and dolostone, and the shape of the passages is strongly

► **Figure UMV-WSB.52** Collapse sink near Cherry Grove, Fillmore County, Minnesota. Collapse sinkholes have characteristically steep and rocky sides and form by the collapse of the roofs of cavern systems.

Photo by J. Meyers

► **Figure UMV-WSB.53** Karst spring northwest of Fountain, Minnesota.

Photo by J. Meyers

► **Figure UMV-WSB.54** Low, flat-topped ceiling in passageway of Mystery Cave.

Photo by J. Meyers

► **Figure UMV-WSB.55** Joint-controlled passage in Mystery Cave.

Photo by J. Meyers

controlled by rock type and structure. Where the bedrock consists of limestone with thin, well-developed interbeds of shale, passages have generally low flat ceilings, reflecting the control of bedding on their morphology (see Figure 54).

Where bedrock is more homogenous and a vertical set of intersecting joints is well developed, passages are generally narrow and ceilings are high, reflecting structural control of the fracture system on passage development (see Figure 55).

While global reserves of oil and natural gas dominate today's headlines, water may be the most important worldwide resource of the twenty-first century. The Upper Mississippi Valley and Western Superior Basin has been blessed with a plentiful supply of water. And although Minnesota is indeed the "land of 10,000 lakes" and the birthplace of the Mississippi River, the United States Geological Survey has determined that more than 79% of the state's population uses groundwater as the main domestic water supply. Minnesotans withdraw nearly 720 million gallons of groundwater every day for all uses. Consequently, protection of groundwater, as well as surface water sources, is of extreme importance if the region is to continue to grow and prosper.

Section Upper Mississippi Valley and Western Superior Basin (UMV-WSB).8 Summary

- Water is the resource of the twenty-first century in the Upper Mississippi Valley and Western Superior Basin.
- Groundwater is especially vulnerable to pollution from surface sources, especially where glacial deposits are absent and karst topography has formed atop soluble carbonate bedrock.

Review Workbook

ESSENTIAL QUESTIONS SUMMARY

Upper Mississippi Valley and Western Superior Basin (UMV-WSB).1 Introduction

■ *What are the aspects of the geologic record that allow us to interpret the geologic history of the Upper Mississippi Valley and Western Superior Basin?*
The geologic history of this region can be interpreted by a study of the rocks and the landforms.

UMV-WSB.2 The Archean: Creating Kenoraland—The Nucleus of North America

■ *What do turbidites and pillow lavas in the Archean rocks of the Greenstone belt tell us about the environment in which these rocks formed?*
Turbidites are formed when sedimentary particles of various sizes are deposited quickly in water, according to their size. Pillow lavas are formed when lava flows are erupted in water. These features therefore confirm that many of the rocks in the Greenstone belt were formed in a subaqueous environment.

■ *Describe the events that formed Kenoraland, the nucleus of North America.*
Kenoraland was formed when a micro-continent gneiss terrane collided with a series of island arcs along an ancient subduction zone approximately 2.6 billion years ago.

UMV-WSB.3 The Early Proterozoic: The Penokean Mountains and the Making of Laurentia

■ *What do the banded iron formations and the stromatolitic structures they contain tell us about the nature of the Early Proterozoic atmosphere?*
BIF's and stromatolites in Early Proterozoic rocks tell us that by this time the atmosphere contained free oxygen.

■ *Describe the ways in which the formation of Laurentia was similar to the formation of Kenoraland.*
Like Kenoraland, Laurentia was formed along a subduction zone where a continental mass collided with an island arc. The intervening ocean basin (the Animike Sea) was closed and a great mountain range (The Penokean Mountains) was formed.

UMV-WSB.4 Erosion of the Penokean Mountains—The Baraboo Interval 1750–1630 Ma

■ *What conditions and processes are necessary for supermature quartz sandstone to form in a single cycle of derivation, transport and deposition?*
To create a deposit of well rounded and well sorted resistant quartz grains, intense weathering in the source is required. In addition, rigorous conditions involving significant and prolonged abrasion in a high-energy transport medium is necessary. Tectonic stability favors these conditions.

■ *What do the Sioux and Baraboo Quartzites lack that makes it so difficult for geologists to determine if they were formed at the same time?*
Without fossils, correlation of the Sioux and Baraboo Quartzites is difficult.

UMV-WSB.5 Middle Proterozoic: The Mid-continent Rift—An Attempt at Unmaking Laurentia

■ *What features of the mid-continent rift and the rocks it contains tell us that it was most likely formed atop a mantle plume?*
The geometry of the rift includes two well-developed arms, and a third that is poorly developed. Such a "triple junction" suggests a centralized cylindrical shaft of heat, such as that which exists atop a mantle plume. In addition, the predominant rocks of the rift are mafic rocks (basalt and gabbro). Such rocks suggest a source of magma in the upper mantle.

■ *Why did continental rifting cease before a full-ledged ocean basin could form?*
Plate tectonic collision at the eastern margin of Laurentia produced compression that stopped the extensional opening of the rift.

UMV-WSB.6 Phanerozoic: Periodic Flooding and Exposure of North America's Stable Interior

■ *Why has the craton of North America been tectonically stable during Phanerozoic time?*
The craton has been stable since the end of the Precambrian because the region has been far-removed from a plate boundary.

■ *How do we know that cycles of rise and fall of sea level took place during the Cambrian and Ordovician of this region?*
The vertical stacking patterns of different types of sedimentary rocks can be interpreted in terms of transgression and regression. For example, a succession of sandstone overlain by shale, then carbonate rocks, indicates an advance of the sea across the edge of the land. Conversely, a succession of carbonate rocks, overlain by shale, then sandstone, indicates a retreat of the sea from the edge of the land.

■ *How do we know that most of the Cambrian and Ordovician sedimentary rocks of this region are marine?*
Most of the Cambrian and Ordovician sedimentary rocks of this region contain fossils of organisms that exclusively lived in a marine habitat. Also, sedimentary structures such as tidal bundles can be used to reveal marine origins.

UMV-WSB.7 Pleistocene: The Laurentide Ice Sheet and Shaping of the Landscape

■ *How do we know that several advances and retreats of glacial ice occurred in the region during the Pleistocene Epoch?*
The vertical stacking of glacial sediments can be used to indicate advances and retreats of the ice. For example, if a till derived from one source, such as the Winnipeg Lowland, is overlain by a second till derived from the Superior Basin, then two separate advances of the ice must have occurred. Also, if a till is overlain by outwash or lake sediments or an ancient soil, then covered by a second till, more than one advance of the ice must have occurred.

■ *Describe three ways in which glaciation altered the pre-glacial topography.*
Pre-glacial landscapes were covered by glacial deposits, river courses were changed, and landforms such as end moraines, ground moraine, outwash plains, and drumlins were formed.

UMV-WSB.8 A Most Precious Resource-Surface Water, Ground Water, Landscape Evolution, and Water Quality

■ *Why is groundwater especially susceptible to pollution in areas directly underlain by carbonate rocks?*

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Carbonate rocks are soluble. Solution by chemically active water enlarges fractures; consequently groundwater can move very rapidly from the surface zone, where pollutants can be introduced, to the water table.

■ *Describe three landforms common in the area that are formed by groundwater solution. What is such a landscape called?*
Sinkholes, springs and cavern systems are formed. Assemblages of these landforms are called karst topography.

ESSENTIAL TERMS TO KNOW

Aeolian Referring to wind-blown origin.

Amphibolite A metamorphic rock consisting mainly of hornblende; because hornblende has elongate crystal form, amphibolites often lack good foliation (layering formed by metamorphism involving both higher temperature and pressure).

Animike Sea A body of water that flooded a basin created by subsidence along the shores of Kenoraland.

Aquifer An underground layer of water-bearing permeable rock or unconsolidated materials (usually gravel or sand) from which groundwater can be usefully extracted using a water well.

Archean The eon or interval of time before 2.5 Ga (billion years).

Banded iron formation Rock composed of interlayered centimeter-thick bands of chert (microcrystalline silica) and hematite (iron oxide), common world-wide during the Early Proterozoic.

Cambrian and Ordovician Systems Rocks deposited during the Cambrian and Ordovician Periods of time.

Carbonate sediment (sedimentary rock) A major group of sediment or sedimentary rock composed of calcium carbonate (calcite) or calcium magnesium carbonate (dolomite).

Chemical maturity of sediment The chemical composition of sediment that represents the end stage of chemical weathering; generally rich in oxides of silica and alumina.

Craton The stable interior of a continent, far removed from plate boundaries and not susceptible to effects of earthquakes, volcanism and mountain building.

Cyanobacteria A phylum (or "division") of Bacteria that obtain their energy through photosynthesis. They are often referred to as blue-green algae, although they are in fact prokaryotes (organisms without a cell nucleus), not algae.

Deformational rock cleavage Fractures in a rock produced during folding.

Depositional sequence A package of sedimentary rocks bounded below and above by unconformities; rock formations in a sequence share a common history of deposition during rises and falls of sea level relative to the land.

Detritus Sedimentary particles derived by weathering and erosion of rocks that are exposed on land.

Driftless and pseudodriftless areas An area of southeastern Minnesota and western Wisconsin that was either never glaciated, or whose landscape does not bear the imprint of glaciation.

Dry valley In our context, a valley found in carbonate bedrock in karst areas that no longer has a surface flow of water because of diversion of flow to underground routes through a sinkhole.

Duluth Complex Largest and most important of the layered intrusions in the mid-continent rift, composed largely of gabbro derived from periodic tapping of an upper mantle magma source.

Dunes Features developed on a bed of sediment, either below water or on the surface of the land; their forms generally consist of crests and troughs that have relatively high ratios of height (measured from trough to crest) compared to length (measured between successive crests).

Eustatic Referring to global rise or fall of sea level; independent of local uplift or subsidence of the land.

Facies Literally "aspect" of a body of sediment, formed under a uniform set of conditions; a facies exists side-by-side and contemporaneous with other facies; for example, a sandstone facies (formed on a beach with high energy waves) exists side-by-side at the same time with the shale facies (formed offshore where currents are weak and mud can settle from suspension). Facies that exist side-by-side can stack vertically when the environments in which they are formed move laterally, such as during a transgression of the sea.

First-cycle sediment Sediment derived directly from igneous or metamorphic rocks; not reworked from a previous sedimentary rock; such sediment often contains unstable silicate minerals and fragments of the original source rock, because weathering has not had the opportunity to remove the unstable minerals and concentrate stable quartz.

Fluvial Referring to river origin.

Fold-belt mountain range A linear belt of mountains characterized by folded and thrust-faulted sedimentary rocks, and a core of metamorphic rocks and granite batholiths; formed at convergent plate margins where compressive forces are dominant.

Foreland basin Formed adjacent to an uplifted fold-belt mountain range, where slabs of the lithosphere stacked upon one another by thrust faulting result in subsidence of the adjacent crust.

Glauconite A green pellet-shaped sand-sized, silicate mineral rich in aluminum; formed by chemical processes in marine environments; often reworked by tide- and wave- generated currents.

Glacial Lake Agassiz A large lake formed at the end of the Pleistocene Epoch, when south-flowing drainage from rapidly retreating ice was dammed by a glacial moraine in the present-day Red River Valley.

Glacial Lake Duluth A lake formed at the end of the Pleistocene Epoch, when southwest-flowing drainage from the retreating Superior Lobe was dammed by a glacial moraine west of present-day Lake Superior.

Graded bedding A bed with an erosional base, and characterized by coarse sediments at the base, grading upward into progressively finer particle sizes.

Graywacke A first-cycle dark-gray sandstone containing unstable rock fragments and mica or clay between the sand grains.

Greenstone belt Zone of variably metamorphosed mafic to ultramafic volcanic rocks and associated sedimentary rocks that occur within Archaean and Proterozoic cratons between granite and gneiss bodies. The belts have been interpreted as having formed at ancient oceanic spreading centers and island arc terranes.

Grenville The Grenville orogeny was a Late Proterozoic episode of mountain-building (1300-1000 Ma), associated with the assembly of the ancient supercontinent Rodinia by collision of smaller continental masses.

Highstand A time of maximum flooding of a continent by transgression of the sea, marked by accumulation of sediment from the continent that builds outward into the sea.

Hummocky cross stratification (HCS) A type of layering in sediment characterized by mounds and intervening swales or depressions with relief on the order of magnitude of centimeters to tens of centimeters; formed when oscillating flow associated with the passage of storm waves is combined with unidirectional flow associated with the seaward rush of retreating storm surge.

Hydrothermal alteration Alteration of surrounding rocks in contact with high-temperature groundwaters, involving the formation of new minerals.

Intraclast A fragment derived from semi-consolidated sediment within the basin, often when storm waves or currents rip up material from the bottom.

Isostasy The mechanism whereby areas of the crust rise or subside until the mass of their topography is buoyantly supported or compensated by the thickness of crust below, which "floats" on the denser mantle. The theory that continents and mountains are supported by low-density crustal "roots."

Isostatic rebound Uplift of continental crust associated with removal of a weight that formerly depressed the surface, such as would occur with the melting of an ice cap.

Kame and kettle topography An assemblage of landforms produced by uneven glacial deposition, especially during a standstill of the ice front, and consisting of conical hills and intervening depressions.

Karst topography An assemblage of landforms produced by groundwater solution, and consisting of sinkholes and cavern systems and associated features.

Kenoraland The continental nucleus of North America, formed approximately 2.65 billion years ago by collision of island arcs and small protocontinents to form the Algoman Mountains.

Laurentia The nucleus of the North American continent, formed by collision of Kenoraland with an island arc to the south around 1.85 billion years ago.

Laurentide Ice Cap (Ice Sheet) The ice cap that formed in the vicinity of Hudson Bay during the Pleistocene Epoch.

Lobes of ice (glaciers) Tongues of ice that advance outward from the center of accumulation of an ice cap toward its edges; lobes often move through lowlands, deepening them and leaving lakes in their place upon melting and retreat of the glaciers.

Mantle plume A hypothetical column of hot, partially molten material that rises from an indeterminate depth in the mantle and is thought by some geologists to provide a driving force for plate movement.

Marine environment An area of the sea defined by conditions and processes on the bottom and in the overlying column of water.

Microbial processes Processes involving the activity of microorganisms, especially bacteria.

Nearshore The area of a coastal marine environment extending from the backshore (landward of the beach) to the offshore (the area of the shallow sea below normal wave base).

Normal wave base The depth to which normal wind-driven waves are able to affect the bottom; A depth equal to one half the wave length of waves in deep water, below which stirring due to wind is negligible.

North Shore Volcanic Group A thick pile of basalt lava flows and associated mafic intrusive rocks that formed in the Superior Basin of the mid-continent rift around 1.1 Ga.

Offshore That part of the marine environment below normal wave base.

Orogeny A mountain building episode involving subduction and collision of plates.

Outwash Sediment originally transported by glaciers, but washed from the ice by melt water and deposited by running water; stratified and well sorted and rounded compared to sediment deposited directly by the ice.

Paleoproterozoic The first of the three sub-divisions (eras) of the Proterozoic occurring between 2500 Ma and 1600 Ma (million years ago).

Paleotectonic and paleogeographic maps Maps showing ancient configurations of continental and oceanic environments and the large-scale geologic structural patterns associated with plate tectonics.

Penokean Mountains Formed by the closing of the Animike Sea and collision of Kenoraland with an island arc.

Phanerozoic The most recent eon of geologic time beginning 543 million years ago and continuing to the present.

Pillow structures A structure observed in igneous rocks, especially basalts, extruded into water; characterized by discontinuous, close-fitting, pillow-shaped masses, commonly up to a meter across.

Pleistocene Epoch Interval of time from ~2 Ma to 10,000 years before the present; includes the most recent "ice age" composed of at least 7 identifiable glacial intervals.

Pothole A hole or basin cut into bedrock of a stream by the abrasive action of pebbles and sand swirled by turbulent flow.

Provenance Referring to source, generally of sediment.

Reactivation When ancient faults in the Earth's crust become active at a later time, in response to the prolonged build-up of stress, usually caused by plate tectonic forces.

Rifting of a continent The breakup or splitting apart of continental crust by extensional or pull-apart forces generally associated with development of divergent plate margins.

River Warren (Phase) Interval of the Pleistocene Epoch marked by formation and draining of Glacial Lake Agassiz and

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downcutting by Glacial River Warren, 11,500 to 10,000 years ago. Major terraces in the Upper Mississippi drainage basin below the junction of the Minnesota River formed during this interval.

Shear zone A fault zone where rocks slide past one another in opposite directions along a lateral surface; rocks in a shear zone are often deformed in complex ways.

Shoreface A shallow near shore marine environment in the zone of the breaking waves.

Siliciclastic sediment (sedimentary rock) Grains of sediment composed of silica-bearing minerals, derived from weathering of bedrock in a terrestrial source area.

Stromatolites Layered structures in sedimentary rocks produced by shallow water colonies of microbial organisms that trap sediment on their sticky surfaces.

Subduction The plunging of a more dense plate of the lithosphere beneath a less dense plate, along a narrow zone marked by an oceanic trench.

Subtidal The marine environment below the low tide, and always submerged.

Supermature sediment Particles of sediment that have been extensively weathered and reworked by transporting agents, so that they are at the end of their compositional and textural evolution. This generally means that the sediment will consist of resistant and stable quartz grains that are well rounded (smooth corners), well sorted (of uniform size), and have no finer-grained material trapped between the particles.

Spracrustal Rocks formed in upper levels of the crust, especially sedimentary and volcanic rocks; Archean examples are often metamorphosed and form part of the basement in cratons.

Surface of maximum flooding Widespread marine flooding surface that separates the underlying sediments deposited during transgression from the overlying sediments building out into the sea during the highstand. The surface also marks the deepest water sediment deposited in the pile of sediment.

Suture zone The boundary between two continents that have collided in a subduction zone; marked by a fold-belt mountain range where the rocks are complexly folded and faulted by compressional forces.

Taconite A banded iron formation in which very finely dispersed iron is present as magnetite in amounts generally 25 to 30%. In the late 19th and early 20th centuries, iron ore was of such high quality that taconite was considered an uneconomic waste product.

Terrace A generally broad flat surface above the floodplain of a river; left standing high when the stream downcut into the floodplain, either because of tectonic uplift of the region, or climate change that increases the discharge of the river.

Terrane A crustal block that preserves a distinctive geologic history different from the surrounding areas and is usually bounded by faults.

Tidal bundles Beds deposited by a single tidal event (rising and falling tide) cluster together to form bundles associated with stronger tides (spring) when the Earth, sun and moon are in alignment, and weaker tides (neap) when the Earth, sun and moon are aligned at right angles to one another.

Tidal flats Broad, essentially horizontal surface over which the tide floods and retreats; often crossed by tidal channels and pockmarked by tidal ponds.

Till Unstratified, very poorly sorted sediment deposited directly by glacial ice; the larger fragments of gravel do not touch one another, but are "floating" in a matrix of finer-grained sediment.

Transgression and regression A transgression is a geologic event during which sea level rises relative to the land and the shoreline moves toward higher ground, resulting in flooding. Transgressions can be caused either by the land sinking or the ocean basins filling with water, often caused by melting of ice caps. The opposite of transgression is regression, in which the sea level falls relative to the land, exposing former sea bottom.

Trough cross stratification (TCS) A type of cross bedding in sediment, where the base of the cross-bedded layer is scoop-shaped or spoon shaped; produced when wind-blown dunes migrate across the surface of the land, or when water-formed dunes migrate across the bed of a river or a submarine surface.

Tunnel valley A tunnel channel is a large cavern, partly in the ice and partly scoured into the bed, extending into and under the ice from the ice margin, from which subglacial water drains. The remnant of a tunnel channel is a scoured, dry valley (tunnel valley), usually half-filled with outwash sand and gravel. The filling with sand and gravel often gives the valley a flat floor.

Turbidity current A density current, where suspended sediment moves along the bottom through the surrounding water; often initiated by storms on the continental shelf, or by earthquakes on the continental slope.

Unconformity A surface in the stratigraphic record (the stack of sediment or sedimentary rocks) along which rocks are missing and the passage of time is not recorded. The rocks are often missing because of uplift and erosion of older rocks, followed by subsidence, flooding and deposition of younger rocks.

Unstable silicate minerals Minerals such as feldspar and iron and magnesium-bearing silicate minerals that are susceptible to chemical weathering.

Volcanic island arc A chain of volcanic islands formed adjacent to a subduction zone.

Walther's "Law" The principle that facies existing side-by-side can stack vertically when the environments in which they are formed move laterally, such as during a transgression of the sea.

Wisconsin Episode The most recent glacial interval of the Pleistocene Epoch from 10,000 to 80,000 years before the present.