= History of the Rove Formation =

The Rove Formation is located in the upper northeastern part of Cook County , Minnesota , United States , and extends into Ontario , Canada . It is the youngest of the many Animikie layers , a layer of sedimentary rocks .

Before the Rove sediments were laid down , during the Archean Eon , the Algoman orogeny added landmass along a border from South Dakota to the Lake Huron region ; this boundary is the Great Lakes tectonic zone . Several million years later a thin layer of hypervelocity impact ejecta from the Sudbury impact event was deposited on the older , underlying , Gunflint Iron Formation , and the Rove was then deposited on top of the ejecta ; it is estimated that at ground zero the earthquake generated by the meteor impact would have registered 10 @.@ 2 on the Richter scale .

During the Middle Precambrian a shallow inland sea covered much of the Lake Superior region and formed the Animikie Group , layers of sedimentary rocks overlying 2700 @-@ million @-@ year @-@ old Archean rocks . The Rove Formation is the youngest of the many Animikie layers .

After the Rove sediments were deposited , the Penokean orogeny added more land mass by accretion that occurred from the south . A few hundred million years later the proto @-@ North American continent nearly split in half along the Midcontinent Rift zone , which is a bow @-@ shaped rift extending from northeast Kansas , arcing through the present @-@ day Lake Superior Basin and then angling southeast through Michigan . Then came a period of advancing and retreating glaciers . The more resistant diabase sills and dikes remained , while the softer shales were bulldozed away by the glaciers . The north path of glaciation is transverse to the general trend on the valleys and ridges .

As a result of erosion of sandstone and the erosion @-@ resistant sills and dikes , the topography in Minnesota has repeated parallel hills and valleys . The tightly packed lakes in the narrow valleys are long and narrow , and they orient from the east to west . The cliffs in these narrow valleys are the habitat to several rare plants which prefer living in narrow cliff areas in a sub @-@ Arctic climate . In Ontario the Rove Formation is overlain by a thick diabase cap .

= = Location = =

The Rove Formation is in the Arrowhead Region of northeastern Minnesota , U.S. , and extends into Ontario , Canada . In Minnesota it occurs along the U.S.-Ontario border from Gunflint Lake to Pigeon Point (both in northeastern Cook County) and northward into Canada . Pigeon Point is the most eastern part of Minnesota ; it is a diabase sill about 152 m (500 ft) thick . Both the north and south coasts of the point expose Rove slates under and over the sill . Within the sill , rates of cooling and gravity have created an interesting distribution of rock types .

The visible formation is in Minnesota and contains many east @-@ west oriented ridges and valleys . Many lakes in this 5 to 8 km (3 to 5 mi) wide band along the Canadian border are in the elongated east @-@ west valleys ; included are Caribou , Clearwater , Crocodile , Daniels , Duncan , Dunn , Hungry Jack , Iron , Loon , Moose , Pine , Portage and South . In Ontario the Rove Formation is overlaid by a thick diabase sill .

= = Geologic history = =

= = = Archean Eon = = =

The Archean Eon lasted from 3 @,@ 800 million years ago until approximately 2 @,@ 500 million years ago .

The Algoman orogeny occurred 2800 to 2 @,@ 500 million years ago , and it marks the end of the crust @-@ building Archean Eon . There were several episodes of continental collision , compression and subduction which resulted in mountain building during this time . Orogenic events are characterized by extensive metaphorism , granitic extrusions and unconformities . The Algoman

orogeny added landmass along a border from South Dakota to the Lake Huron region ; this boundary is the Great Lakes tectonic zone (GLTZ) .

Northeast Minnesota has 2700 @-@ million @-@ year @-@ ago exposed rocks formed during volcanic activity that was in the form of seepage of lava from rifts in the sea floor . These lava flows began to rise up out of the ancient ocean to form the Superior craton ; the Superior craton later assembled into the Canadian shield , which became part of the North American craton . The Superior province is the largest preserved fragment of Archean crust , and the Canadian shield is the nucleus of the North American craton .

= = = Proterozoic Eon = = =

The Proterozoic Eon lasted from 2 @,@ 500 million years ago until 570 million years ago

= = = = Animikie Group = = = =

The Animikie Basin , measuring 700 x 400 km (420 mi x 240 mi) , is an elongated oval straddling the North Shore of Lake Superior , mainly in Minnesota . Approximately the northwestern two @-@ thirds lies to the northwest of the shoreline ; the southeastern third lies to the southeast of the shoreline (so is under Lake Superior 's waters) .

During the Middle Precambrian a shallow inland sea covered much of the Lake Superior region and formed the Animikie Group , which are layers of sedimentary rocks which unconformably overlies 2700 @-@ million @-@ year @-@ old Archean rocks . This group contains both the Rove and Gunflint Iron formations . The Rove Formation is the youngest of the many Animikie layers ; it consists of gently tilted fine @-@ grained sediments . It is composed of greywackes and black shale , and contains lower concentrations of iron and taconite than the underlying Gunflint Iron Formation does .

The Rove Formation consists of a lower argillite unit , a middle transition unit and an upper thin @-@ bedded greywacke unit . The lower argillite unit is about 150 m (490 ft) thick ; this layer contains fine @-@ grained greywacke , and silty and graphitic argillites . Greywacke is a sedimentary rock composed of a mixture of poorly sorted grains of sand , silt and clay particles . Argillite is a fine @-@ grained sedimentary rock composed primarily of clay particles ; they are essentially lithified muds and oozes . Greywacke is abundant in the middle unit and dominates the upper unit . The complete thickness of the upper two units is about 900 m (3 @,@ 000 ft) .

Gunter Faure and Jack Kovach , using Rb @-@ Sr dating , determined the age to be 1635 ± 24 million years old . The Resident Geologist Program , Geology of the Thunder Bay South District , reports an age of 1800 million years old .

= = = = Penokean orogeny = = = =

The Penokean Mountain Range formed in the Penokean orogeny 1880 to 1830 million years ago , when an oceanic island arc called the Pembine ? Wausau terrane collided with the southern margin of the Superior craton . From 1880 to 1850 million years ago , the region was volcanically active . This volcanism ceased 1850 million years ago when a fragment of Archean crust arrived from the South at the subduction zone . Collision of this Archean crust in the south with the Superior craton in the North caused a period of intense crustal shortening . Rocks of the Pembine ? Wassau terrane were thrust up over and onto the Superior craton , forming a mountain range that covered all but the northernmost portion of Lake Superior , crossed parts of three US states (south @-@ central Minnesota , northern Wisconsin , and the Upper Peninsula of Michigan) , and continued to the southernmost tip of Ontario , Canada . Loading of the lithosphere by these thrust sheets caused it to flex downwards , forming a foreland basin at around 1850 million years ago in the south and 1835 million years ago in the north . The Rove Formation was deposited in the northern basin . In the southern basin , crustal thickening caused high @-@ grade metamorphism of the sedimentary fill by 1830 million years ago . A series of post @-@ orogenic plutons intruded into the overlying rocks

1830 million years ago , ; these plutons mark the end of the Penokean orogeny .

= = = = Sudbury impact ejecta = = = =

At the base of the Rove Formation , between the Rove and the underlying Gunflint Iron Formation , there is a lateral layer of shocked quartz and feldspar grains found within accretionary lapilli , accreted grain clusters and spherule masses . These pieces of debris indicate that the layer contains hypervelocity impact ejecta . Zircon geochronologic data shows that this layer formed 1878 to 1836 million years ago ; the Sudbury Impact event occurred 1 @,@ 850 ± 1 million years ago . Because of the closeness in dating and the nearness of the crater , the Sudbury Impact event is the likely source for the ejecta ; these are the oldest ejecta linked to a specific event on Earth . In the Rove area this layer is about 7 @.@ 6 m (25 ft) thick ; this thin layer very likely represents the catastrophic events of a single day nearly 1 @,@ 850 million years ago .

Evidence indicates a 16 km (10 mi) diameter meteorite collided with Earth in the current @-@ day vicinity of Sudbury , Ontario , Canada , about 1 @,@ 850 million years ago . The meteorite vaporized and created a 240 km (150 mi) wide crater (this is the second @-@ largest impact depression on Earth) . This impact is 770 km (480 mi) east of the Minnesota @-@ Ontario border of the Rove Formation . Earthquakes shattered the ground hundreds of miles away and within seconds ejecta (cloud of ash , rock fragments , gases and droplets of molten rock) began to spread around the globe . It is estimated that at ground zero the earthquake would have registered 10 @.@ 2 on the Richter scale . Seas covered the Rove Formation area and the Sudbury impact generated huge tsunamis .

To put the Sudbury meteorite impact in perspective , the Chicxulub impact on the Yucatán Peninsula occurred 66 million years ago from an object perhaps 60 % the size of the Sudbury impactor ; the results of this impact caused the worldwide extinction of many species (including dinosaurs) .

The Sudbury Impact would have had global ramifications ; it is conjectured that this caused the end of the iron deposits . The impact fundamentally affected concentrations of dissolved oxygen in the sea ; the accumulation of marine sediments (known as banded @-@ iron formations) were almost instantaneously shut down . Banded @-@ iron formations are massive deposits rich in iron oxides ; they accumulated at several periods in the Earth 's geologic past . One extended episode of banded @-@ iron formation buildup suddenly ended about 1 @,@ 850 million years ago . In northeastern Minnesota these banded @-@ iron formations lie immediately under the ejecta layer . Minnesota 's Iron Range is composed of this layer of banded @-@ iron formation .

Most of the impact layer in the Rove area consists of beccia , a mixture of rock fragments which ripped loose from the sea floor during the earthquakes . The tsunamis jumbled the loosened bedrock and ejecta together ; over time this layer was buried by younger sediments , cemented together and fused by molten rock to form a solid layer . Ejecta from the Sudbury Impact was found in May 2007 on the Gunflint Trail in Cook County , Minnesota . Geologists Mark Jirsa and Paul Weiblen from the University of Minnesota took advantage of the burnt @-@ over landscape resulting from the intense , hot Ham Lake fire to explore the newly exposed geology along the Gunflint Trail . Jirsa picked up some rocks which turned out to be ash and debris from the 1 @,@ 100 km (680 mi) distant impact site ; this is the farthest distance that Sudbury detrita has been found .

= = = = Midcontinent Rift = = = =

The Midcontinent Rift (also known as the Keewenawan Rift) began about 1 @,@ 100 million years ago ; it lasted for about 20 million years . After the Penokean Mountains had eroded away , the proto @-@ North American continent nearly split in half along this rift zone . The 2 @,@ 000 km (1 @,@ 200 mi) bow @-@ shaped rift extended from northeastern Kansas , through the southeastern corner of Nebraska , diagonally northeast through Iowa , through Minnesota along the current Minnesota @-@ Wisconsin border , arced through the present @-@ day Lake Superior basin and

angled southeasterly through Michigan .

The Midcontinent Rift is the largest @-@ known continental rift in the world . The rift began as a hot spot of basaltic magma underneath the Lake Superior region ; it extruded layers of lava up to 20 km (12 mi) thick and extending up to 100 km (60 mi) on either side of the rift . The deposited lava along the North Shore of Lake Superior is 7 @,@ 620 m (5 mi) thick .

This was a fast @-@ spreading rift ; the resulting basalts show little interaction with the then @-@ existing rock . These immense volumes of mafic lava were generated in two major pulses , mostly via a hot mantle plume . Along the North Shore of Lake Superior , one can see the solidified lava (igneous rock) most everywhere . In the Rove region the magma didn 't reach the surface ; it intruded into fractures in the formation and slowly cooled to become diabase (rather than basalt) . These solidified bodies are the Pigeon River and Logan Intrusion diabases .

The continent didn 't split into two because the Grenville province (a microcontinent) was converging with the proto @-@ North American continent to the east . This convergence applied compressional forces to the rift , preventing the complete splitting apart of the proto @-@ North American continent .

This rift was the last of volcanic or mountain @-@ building activity in present @-@ day Minnesota . The solidified lava flows have sagged , tilted and faulted ; this created a basin up to 5 @,@ 000 m (16 @,@ 000 ft) deep along the rift zone . Proto @-@ Lake Superior filled the basin .

= = = = Puckwunge Formation = = = =

The Puckwunge Formation has buff to grey sandstone which comes from sediments deposited during the early stages of the Midcontinent rift ; zircon dating shows a time period of 1200 to 1100 million years ago .

Puckwunge sandstone is exposed along an extremely narrow (feet @-@ wide) band on the southwestern border of the Rove formation . The Puckwunge exposure begins at Raspberry Point within the Grand Portage National Monument on Lake Superior , Cook County , Minnesota , and extends for about 40 km (25 mi) inland to the northwest . The Rove Formation is located to the northeast of the Puckwunge sandstone ; none is southwest of the border . The Rove Formation is bisected by several bands of Pigeon River Diabase ; these bands are in a west @-@ to @-@ east orientation . The bands of Pigeon River Diabase do extend southwesterly past the Puckwunge Formation .

= = = Quaternary Period and glaciation = = =

The Quaternary Period began about 2 million years ago and continues today . This is the period of advancing and retreating glaciers . The Rove region has multiple tilted layers of volcanic rocks and easily eroded shale . The more resistant diabase dikes and sills remained , while the softer shales were bulldozed away by the glaciers . These former shale valleys filled with water , forming the many lakes in the region . The character of the slates made them especially well suited for glacial quarrying , much more so than the contiguous sills . A cuesta ? a ridge formed by gently tilted sedimentary rock layers ? topography had developed and was dominated by major east @-@ west valleys with a few pronounced gaps in the intervening ridges .

The Rainy Lobe of the Wisconsin glaciation was the most recent of the glaciation events , and it retreated about 10 @,@ 000 years ago . Glacial scratches and grooves in Rove rocks indicate a north or somewhat east @-@ of @-@ north glacial movement . This direction is transverse to the general trend on the valleys and ridges . The lakes in the Rove Formation area are unique from other well @-@ known linear bedrock lakes in North America because their long axes lie transverse to the general movement of the glaciers .

When continental glaciers moved over the Rove Formation area , the ice was a hundreds of meters thick and its surface sloped gently southward from the Patrician center to the north . The base of the ice sheet encountered the cuesta topography relief of a few hundred feet . Because the ice over the valleys would be thicker than the ice over the ridges , obstructed extrusion flow would operate and

resulted in the removal of the easily quarried slates of the valleys . The ridges would not be appreciably eroded , partly because the ice would be thinner over the ridges and therefore less plastic , and partly because of the resistance of the diabase to both quarrying and abrasion by the ice .

The weight of the ice sheet compressed the land and created depressions . As the glacier retreated , the weight and pressure were relieved from the surface of the land and the land rebounded ; the rebound process continues , and is estimated to be 100 m (330 ft) .

= = Human history = =

The Pigeon River forms the border between Minnesota and Ontario in this area . The first 32 km (20 mi) of the river is crooked , swift , interrupted by rapids and falls , and flows in places through a steep @-@ walled canyon . The High Falls are 37 m (120 ft) high and presents an impassable obstacle to river travel . The Cascade Falls are further up the river . The soft shale erodes easily , leaving the Logan and Pigeon River diabases which create the waterfalls and cascades .

A portage was necessary from the shore of Lake Superior past the High Falls . Southwest of the mouth of the Pigeon River is Grand Portage Bay ; about 1 @.@ 6 km (1 @.@ 0 mi) inland there is a gap through the surrounding hills and bluffs which provides a gradual ascent to Cascade Falls . The river is navigable by canoe beyond the Cascade Falls . The Sioux and Chippewa created a 14 @.@ 5 km (9 @.@ 0 mi) long portage from Grand Portage Bay to bypass the three falls and several kilometers of turbulent river up to the Cascade Falls , probably by following animal trails . The French called this trail the Great Portage because it was so long .

The first @-@ known non @-@ native visitors were French @-@ speaking people from France and eastern Canada who started to explore the area in about 1655 . They were looking for the Northwest Passage and to trade for furs , particularly beaver pelts . Beaver pelts were in demand for European fashion during the 17th and 18th centuries . The Grand Portage was on the major fur trade route of the 18th century and was the first of more than 40 portages along the fur trade route . The French @-@ Canadian voyageurs would carry two 40 kg (88 lb) packs from the main storage depot at Grand Portage Bay along the trail to their smaller storage depot at Fort Charlotte ; it took a few hours . In 1784 Grand Portage Bay became the headquarters for the North West Company . The post was abandoned in 1803 when the North West Company moved north .

= = Present @-@ day topography = =

In Ontario , the shales and greywackes from the Rove Formation of the Animikie Group are overlain by a 60 m (200 ft) cap of diabase . This diabase cap is a sill remnant , and most of the diabase is covered by a considerable thickness of mineral soil . The mesa at Russell Point (about 16 km (10 mi) south of Thunder Bay) is a Logan sill of diabase over the softer Rove Formation metasediments . It is one of the many flat @-@ topped , steep @-@ sided mesas along Lake Superior 's northwestern shore south of Thunder Bay that are collectively known as the Nor 'Wester Mountains .

In Minnesota , the Rove Formation area shows a relationship of bedrock to topography , with its valley @-@ and @-@ ridge landscape . There are several series of steep , east @-@ west oriented valleys which were created by the erosion of the exposed shale . The diabase @-@ capped ridges between the valleys slope gently to the south (4 ° to 15 ° from the horizontal) ; the northern faces are precipitous ; they rise 60 to 140 m (200 to 460 ft) above deep , cold lakes , creating an asymmetrical cross @-@ section profile . The asymmetrical cross section of the ridges is the result of bands of massive , poorly jointed rock alternating with highly jointed rock units . The valleys contain glacially quarried bedrock lakes ; they are also asymmetrical in cross section because of the same structural elements which control the ridge shapes . Most of the lakes show an asymmetrical bottom configuration , showing a steep subaqueous slope on the south shore . The northern @-@ facing cliffs provide the habitat for a few species of endangered flora . The Rove Formation has landscape features that are not found elsewhere in Minnesota .

Most of the valleys are occupied by chains of elongate lakes , many of which are bordered by solid rock on all sides . Many of the east @-@ west valleys terminate abruptly at either one or both ends when the bordering sills merge . The elevation of the lakes ranges from Rose Lake 's 465 m (1 @,@ 526 ft) to Loon Lake 's 532 m (1 @,@ 745 ft) above sea level . Lakes on the opposite sides of a single ridge may differ in surface elevation by as much as 60 m (200 ft) . Many of the rock @-@ bound lakes have a depth of about 30 m (100 ft) ; a few are deeper than 61 m (200 ft) .

A topographic map shows that the majority of the interconnected complex of tightly packed lakes with their valley @-@ and @-@ ridge landscape is primarily in Minnesota ; the border of the landscape is the Minnesota @-@ Canadian border . This border is composed of the Pigeon River , and these Rove Formation lakes (going east to west) : South Fowl , North Fowl , Moose , Mountain , Watap , Rose , South , Little North and Gunflint . The border runs approximately through the center of the lengths of these lakes . The only Rove @-@ typical east @-@ west oriented lakes lying in Ontario are Arrow and North lakes .

The preglacial drainage pattern was controlled by the rock structure . Ver Steeg reconstructed a preglacial drainage pattern that shows major streams flowing east in the slate belts . Short tributaries and short north @-@ south segments of the major streams cut across ridges which formed small gaps that are still present .

The Laurentian Continental Divide is within the formation . Between North Lake , Ontario , and South Lake , Minnesota , is a low saddle of land right on the border ; this is the divide . North Lake drains into the Rainy River and then to Hudson Bay . South Lake drains into the Pigeon River and then to Lake Superior .

Topsoils are thin and poor because the glaciers had abraded down to the bedrock . The soils are clayey silt .

= = Endangered flora = =

Topographically this is the Rove Slate Bedrock Complex Landtype Association . The sedimentary and diabase rocks are calcareous ; they produce a more basic , nutrient @-@ rich soil compared to the poorer soils typical of the Canadian shield . The Royal River drains Royal Lake [which is about 1 @.@ 2 km (3 @,@ 900 ft) east of South Fowl Lake] into John Lake , both in Minnesota . The relatively rich soils , particularly in the Royal River drainage area , along with steep , moist , north @-@ facing cliffs provide the habitat for these rare plants . For over a century this landtype association has been recognized as being ecologically and botanically unique ; it harbors a rare assemblage of plants , including the rarest plants in Minnesota . Virtually all of the known sensitive plant species in this landscape association occur on the north side of the cliffs or in the Royal River drainage .

Six vascular plants are unique in that they are at the extreme edge of their range or are disjunct from the main range of their species . They are the Maidenhair spleenwort (Asplenium trichomanes L.) , in Minnesota six small populations of 20 to 40 plants have been found in the Rove area ; Ross 's (or Short) sedge (Carex rossii) , only three populations are known to exist in the Rove area ; Large @-@ leaved sandwort (Moehringia macrophylla or Arenaria macrophylla) , evidence indicates that this is a very rare species with limited distribution and restrictive environmental needs ; Sticky locoweed (Oxytropis borealis var. viscida) , is restricted to a single cliff in Cook County ; Encrusted saxifrage (Saxifraga paniculata ssp. neogaea) , 11 populations are known to exist in the Rove formation ; and Smooth Woodsia (Woodsia glabella) , there are small , isolated populations in the Rove Formation .

During two sensitive plant surveys conducted in June and July 2003 , and July 2004 , a Superior National Forest sensitive plant , Canada Yew (Taxus canadensis) , was found ; and a state @-@ listed species of concern , Blunt @-@ fruited sweet cicely (Osmorhiza depauperata) , has only four populations within 30 km (19 mi) of each other . Minnesota 's Department of Natural Resources lists these vascular plants as being threatened : Rocky Mountain woodsia (Woodsia scopulina ssp. laurentiana) , there are few isolated populations in the formation ; and Holboell 's rock @-@ cress (Boechera retrofracta or Arabis holboellii var. retrofracta) , rare in Ontario and Minnesota .

Minnesota 's Department of Natural Resources lists the Nodding saxifrage (Saxifraga cernua) as endangered , one source refers it to being " very rare " and that Cook County has Minnesota 's single colony with about a dozen plants ? the entire population occupies less than a 1 m2 (1 sq yd) ? so it is vulnerable to singular events which would alter its habitat .