A Story Written in Stone
The Flambeau Mine
Ladysmith, Wisconsin

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2014
Introduction

In 1968, a rich deposit of copper ore was discovered in northwestern Wisconsin, near the Flambeau River, just southwest of the town of Ladysmith in Rusk County. After more than twenty years of geological and environmental investigations, the Kennecott Copper Company began excavating an open pit mine there in 1992. Although it may seem like it took a long time to open the mine, it took nearly two billion years to produce the minerals in the ore, through geological activities like volcanoes, mountains building, weathering and erosion. This booklet recounts the long geologic history and the short human history of the Flambeau Mine operation.

Geologic History

The copper ore at the Flambeau Mine has a very long and complex geologic history, which began at a crack, or fissure, on the ocean floor nearly two billion (1.88) years ago, during the Precambrian era. Such cracks are hydrothermal vents, which are located near volcanically active spots along the boundaries of tectonic plates that make up the Earth’s crust. The hot melted rock, called magma, heats the seawater as it rises from these vents through the surrounding volcanic rocks. When it comes into contact with the cold seawater, chemicals that are dissolved in the fluid are deposited as minerals, which form cylindrical chimney-like structures. These vent chimneys can produce huge “fields” on the seafloor. In very deep parts of the ocean, these minerals form a black cloud-like feature called a “black smoker,” which rises from the vent chimneys. The black color is caused by the presence of sulfur in the heated water, which combines with metal ions like iron, copper, lead, zinc, silver and gold from the surrounding volcanic rocks. In places, instead of forming chimneys, some of the sulfur-rich water spreads out on the seafloor to create a “pancake-like” layer of sulfide minerals that may be miles across and tens of feet thick.

Diagram showing formation of vent chimneys and black smokers.
Black smokers were first discovered in the modern ocean in the 1970s. Surprisingly, the vents were found to support a high density of organisms in parts of the ocean where life is otherwise sparse. Bacteria that process sulfur compounds in the vent minerals produce organic materials that support the other organisms, such as clams, shrimp, worms and snails, living there. Scientists now think that these chemosynthetic bacteria may have been some of the first forms of life on Earth.

The sulfide mineral layer at the Flambeau Mine was deposited as one of the “pancake” layers. It is several miles long and about 50 feet thick, and probably took several thousand years to form. The original ore at the Flambeau Mine was composed mostly of the iron sulfide mineral pyrite (FeS₂) and the copper-iron sulfide mineral chalcopyrite (CuFeS₂), which are both interlayered with the silica mineral quartz (SiO₂). Because it is composed almost entirely of sulfide minerals, this kind of ore body is called a “Massive Sulfide Deposit.”

Approximately 30 million years (1.85 billion years ago) after this sulfide layer formed on the ancient ocean floor, it and the other rocks in north-central Wisconsin were compressed and folded during a collision of two tectonic plates. This activity raised a major mountain range called the Penokean Mountains, the roots of which are still traceable in an east-west direction across the state. This episode of mountain building tilted the volcanic rocks containing the sulfide layer to a nearly vertical position. Afterwards, about 1.7 billion years ago, a long (50 to 100 million year) period of erosion reduced the mountains to low rolling hills.

The rich copper ore at the Flambeau Mine probably formed during this long period of erosion. Weathering at this time produced chemical changes and caused different minerals to become layered at different depths. Near the erosion surface, the sulfide-bearing minerals became unstable. As a result, the sulfide was converted into sulfuric acid, in which groundwater carried the copper deeper into the deposit. Additionally, much of the iron combined with oxygen to form the minerals hematite (Fe₂O₃) and goethite (Fe³⁺O(OH)). These are common and highly insoluble iron oxides (called gossan), which formed a “cap” on the ore body. The ore body also contained gold. As the copper continued to be carried downward below the water table, it replaced half of the iron in the mineral pyrite, converting
it to the mineral chalcopyrite. Copper also replaced some of the iron in the older chalcopyrite, which yielded bornite (Cu₅FeS₄), a mineral still richer in copper. Finally, copper replaced all of the iron, the ore was completely converted to chalcocite (Cu₂S), and the iron was carried away in solution. Eventually, near-surface weathering dissolved enough of the original ore, especially the quartz, to open a number of cavities (commonly called “pockets”) in the enriched ore zone.

Minerals produced by this kind of weathering typically are very fine grained and grow as columnar (e.g., stalactites and stalagmites) or globular forms (e.g., botryoids). All of these features were present in the chalcopyrite, bornite and chalcocite in the Flambeau Mine ore body, which suggests that this rich ore was formed near the Earth’s surface.

In contrast, the vast majority of chalcocite ore was coarsely crystalline. Interestingly, large crystals, especially of sulfide minerals, do not form in the near-surface environment. Instead, these crystals form in a higher temperature environment. Despite the potential limitations for forming large crystals, cavities in the ore zone contained classic chalcocite crystals as long as four inches. Curiously, the chalcocite also crystallized in a wide variety of shapes. For example, some are curved crystals that look like “flames,” whereas others are the shape and size of pinecones.
This enigma may be explained by additional geological events, the evidence for which is preserved in the rocks of northern Wisconsin. Here, granitic rocks, which have been dated as 1.74 billion years old, indicate that another mountain-building event had taken place. Sand that was metamorphosed into the Barron Quartzite (known locally as the "Blue Hills") and the Flambeau Hills, near the junction of the Flambeau and Chippewa Rivers, are likely sediments that were deposited before this mountain-building event. Heat and pressure during this mountain building event produced metamorphic minerals, such as garnet, andalusite and actinolite, within the volcanic rocks that enclosed the ore body. The heat also recrystallized the fine-grained chalcocite into coarser-grained material. In addition, the heat generated hot, copper-rich fluids, which moved up from deep in the Earth and deposited large chalcocite and dolomite crystals in cavities within the ore body. Subsurface bacteria thriving in the warm, chemically diverse environment may have assisted this process.
The colorful copper carbonate minerals, blue azurite and green malachite, were present only locally and very sparsely in the Flambeau ore. A number of other sulfide minerals (zinc sulfide: sphalerite, lead sulfide: galena, iron, arsenic sulfide: arsenopyrite, and complex minerals such as tetrahedrite, a copper, iron, zinc, silver sulfide), which are present at the Flambeau Mine, are unstable in a weathering environment, so they must have been added after the weathering event that formed the main ore body.

Another long episode of erosion, which lasted more than 600 million years (1.74 to 1.1 billion years ago), followed the period during which the main ore body was recrystallized and the large chalcocite crystals were formed. Following this extensive period of erosion, the Ladysmith area (and probably most of Wisconsin) was buried by thousands of feet of basalt lava flows, which erupted onto the land surface over a period of 70 million years. Remnants of this event can be seen along the shore of Lake Superior in western and northern Wisconsin and northern Minnesota and Michigan.
Following this extended period of volcanic activity, yet another long episode of erosion took place, during which most of the volcanic rocks were stripped away. About 550 million years ago during the Cambrian Period, which marks the beginning of the Paleozoic Era of Earth’s history, marine waters flooded the area. Fortunately, the Flambeau ore body experienced little or no erosion at this time. Instead, a thick layer of sand covered the deposit. Luckily, a few tens of feet of this Cambrian sandstone remained to protect the rich copper ore at the Flambeau Mine site from later erosion as well.

Over the next 200 million years, the seas advanced and withdrew from the region numerous times. The seas left Wisconsin for the last time about 300 million years ago. Since then, the region has been exposed land and has undergone still more erosion. In fact, it appears that the periodic weathering and erosion at the land surface over 1.7 billion years is responsible for producing the rich diversity of secondary minerals in the Flambeau deposit. One could describe the rocks at the mine as a mineralogical “rain forest” where rare and diverse minerals can be found in a small area.

The final geologic event affecting the Flambeau ore body was glaciation during the last “Ice Age.” Beginning a little more than a million years ago, ice sheets a mile or more in thickness advanced and retreated across most of Wisconsin. The cover of Cambrian sandstone prevented erosion of the ore body at this time; however, the jumbled mixture of boulders, sand, gravel and clay called “glacial drift,” which was deposited by the ice sheets, served to obscure the ore, and prevented its discovery until modern geophysical techniques had been invented.

**History of the Mine**

The Bear Creek Mining Company, an exploration branch of Kennecott Copper Company, discovered the copper-rich ore body south of Ladysmith in 1968. This discovery resulted from an extensive airborne geophysical survey, which had been conducted across much of north-central Wisconsin, to measure variations in various characteristics of the Earth. The presence of an ore body was indicated by substantial differences in physical and chemical properties, such as density, magnetism and gravity, between the massive sulfide deposit and the rock in which it formed. In order to verify what was causing the anomalous geophysical data, a number of core holes were drilled into the ground to obtain rock samples that could be tested. These subsurface rock cores showed that an exceptionally rich deposit of copper, which consisted mainly of the mineral
chalcocite, had produced the geophysical anomaly. It is possible that the Ladysmith deposit may be one of the richest deposits of copper ore ever discovered.

Over the next several years, more than 100 additional rock cores were drilled. These showed that the ore body had a tabular shape and a nearly vertical orientation. The deposit was determined to be about 50 feet wide, 2,400 feet long and extended to a depth of about 800 feet. It stretched from near Highway 27 southwestward, beneath the Flambeau River, continuing a short distance west of the river (see map).

![Side view and angled top view of the 6-inch-diameter subsurface rock core through the copper-rich mineral deposit.](image)

Continued investigation showed that the copper ore body extended to a depth of about 300 feet below the ground surface, at which point the ore changed over from chalcocite to iron-bearing minerals and pyrite. In fact, these iron- and sulfur-rich minerals composed about seventy-five percent of the mineable ore within the deposit.

The change in ore body mineralogy required a different method of processing the ore, as the pyrite would have to be removed from the copper-bearing chalcopyrite. This separation could be readily accomplished, and the company demonstrated that the iron and sulfur in the deeper part of the ore body could be disposed of safely. However, disposing of the sulfur-rich residue so near to the Flambeau River sparked major environmental concerns, and the State of Wisconsin declined to issue a permit to mine the deeper ore. After struggling with the problem for more than two decades, Kennecott eventually decided to mine only the enriched, high-grade chalcocite ore in the upper 225 feet of the deposit and leave behind the deeper (and most of the mineable) ore in the ground.

Construction at the mine project began in 1991, and ore shipments from the site began in 1993. The ore was mined from a 35-acre open pit, which was 2,600 feet long, 550 feet wide and about 220 feet deep. The pit was located only 140 feet from the Flambeau River. Bedrock was buried beneath 15 to 40 feet of glacial sediments and topsoil, which had to be removed before mining and stockpiled for site reclamation. Then, the bedrock was drilled and blasted. The ore was crushed at the mine site and shipped by rail to smelting facilities in Canada.
Mining continued for more than four years, ending in 1997. Approximately 70 people, mostly from Rusk County, were employed at the mine. Over these four years, the mine produced nearly six million tons of copper-bearing minerals from the enriched chalcocite ore body, as well as 181,000 tons of pure native copper. It also produced 3.3 million ounces of native silver and 334,000 ounces of gold. The silver was associated mainly with the copper, but the gold was recovered chiefly from a layer of reddish-brown silty clay that was separate from the rich copper ore.
With the close of operations in early 1997, the open pit mine was backfilled with material removed from the site during mining. Waste materials that contained a significant amount of sulfur-bearing pyrite were returned to and buried in the deepest part of the pit, keeping it well below the groundwater table in the area and greatly reducing the likelihood of sulfur being oxidized to sulfuric acid. The high-sulfur rock was blended with limestone, which reacted with the acid to produce gypsum (CaSO₄·2H₂O) (commonly known as plaster of Paris), which neutralized the waste. The original topsoil, which had been stockpiled at the beginning of mining, was spread back as the last layer of fill.
Reclamation activities were completed at the end of 1999. The 181-acre site was reclaimed for wildlife habitat, including wetlands and woodlands, and for recreation, including a trail system. In October 2003, the U. S. Bureau of Land Management recognized Kennecott Minerals Company for its efforts in sustainable development with their "Award for Community Outreach and Economic Security."

The story of the Flambeau copper deposit is a complex one, but it demonstrates some simple mining principles. The early chapters of the story show how society is dependent upon geologic processes, often very ancient ones, to provide the raw materials we need in our daily lives. Without the shifting tectonic plates, volcanic activity, mountain building, weathering, erosion, and chemical interactions that took place over the last two billion years, this ore deposit would not have existed, especially as rich in copper as it is. Later chapters in the Flambeau story show how a mineral deposit needs to be located where it is reachable from the ground surface, environmentally sustainable, economically feasible, near a market, and have access to infrastructure. In other words, it is not possible to dig a hole just anywhere and be able to mine whatever mineral is needed! Finally, the latest chapter in the Flambeau story shows how modern mining practices can be sensitive to the environment and responsible reclamation.