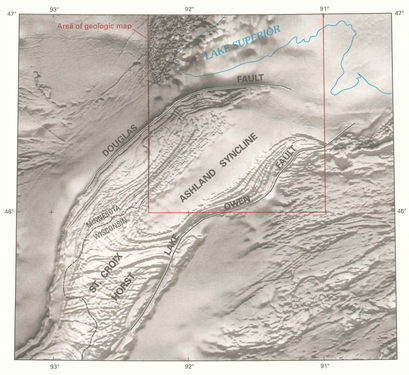

SHADED AEROMAGNETIC MAP SHOWING THE LOCATION OF THE ASHLAND SYNCLINE AND ST. CROIX HORST IN NORTHWESTERN WISCONSIN AND EAST-CENTRAL MINNESOTA.

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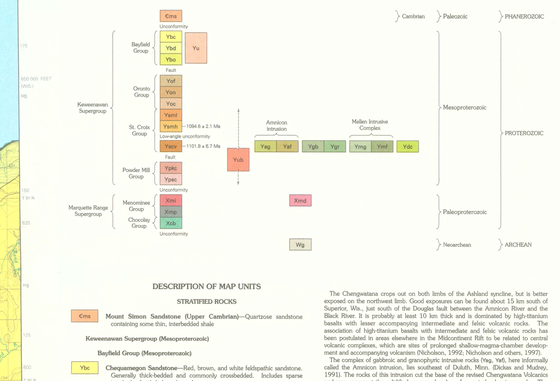
CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

STRATIFIED ROCKS

Crss **Mount Simon Sandstone (Upper Cambrian)**—Quartzose sandstone containing some thin, interbedded shale

Keweenawan Supergroup (Mesoproterozoic)

Bayfield Group (Mesoproterozoic)

Ybc **Chequamegon Sandstone**—Red, brown, and white feldspathic sandstone. Generally thick-bedded and commonly crossbedded. Includes sparse interbeds of red shale and conglomerate

Ybd **Devils Island Sandstone**—White to tan quartz arenite. Generally thin-bedded; crossbedding and ripple marks are common

Ybs **Orienta Sandstone**—Red, brown, and white feldspathic sandstone, cross-bedded in part. Includes sparse interbeds of red shale and conglomerate

Yu **Unnamed sandstone (Mesoproterozoic)**—East of Lake Owen fault, inferred from geophysical data

Oronto Group (Mesoproterozoic)

Yof **Freda Sandstone**—Red, brown, and tan sandstone containing minor shale and conglomerate interbeds. Mostly fine- to medium-grained feldspathic and lithic arenite, commonly micaceous. Well-bedded and commonly crossbedded

Yon **Nonesuch Formation**—Siltstone, shale, sandstone, mostly gray to black, some red units. No outcrops in map area, but extent and lithology of formation in Ashland syncline is well defined by numerous drill holes

Yoc **Copper Harbor Conglomerate**—Red to brown conglomerate, sandstone, and siltstone. Conglomerates are generally massive to crudely bedded and contain rounded clasts of mostly felsic volcanic rocks as much as 50 cm in diameter. Sandstones are mostly lithic arenites containing abundantly volcanic grains, commonly trough crossbedded. Conglomerates are mostly near the base and finer grained rocks are higher in section

St. Croix Group (Mesoproterozoic)

Minong Volcanics

Ynml Low-titanium flood basalt—Locally ophitic. Near top of section, contains basalt flows with composition similar to normal mid-ocean-ridge basalt (N-MORB); contains a few conglomerate interbeds that are more common on the southeast limb of the Ashland syncline than on the northwest limb of the syncline

Ynmh High-titanium basalt flow—Interlayered with andesite and rhyolite flows. Quartz-phyric rhyolite at Nelson Lake dated at 1,094.6±2.1 Ma (Zartman and others, 1997)

Ynsv **Chengwatana Volcanics**—Basalt, andesite, and minor rhyolite flows. Basalt flows range from 3 to 100 m thick. At least six conglomerate beds occur between flows. Rhyolite stratigraphically overlying Amnicon intrusion is dated at 1,101.8±5.7 Ma (Clark E. Isachsen, University of Arizona, unpub. data, 2003)

Powder Mill Group (Mesoproterozoic)

Ypbc **Kallander Creek Volcanics**—Basalt, andesite, and lesser rhyolite flows. Basalt flows near base of formation contain plagioclase phenocrysts, some in radiating clusters

Ypsc **Siemens Creek Volcanics**—Basalt and lesser andesite, olive-gray to dark-greenish-gray. Basal flows are locally picritic

Yub **Unnamed basalt (Mesoproterozoic)**—Basalt flows inferred from seismic-reflection, gravity, and magnetic data. Magnetic models indicate reversed magnetic polarity (Allen, 1994); therefore, the basalt most likely predates Powder Mill Group rocks. Shown in cross section only

Marquette Range Supergroup (Paleoproterozoic)

Menominee Group (Paleoproterozoic)

Xmd **Ironwood Iron-Formation**—Banded cherty iron-formation in which iron is contained in magnetite and iron amphiboles. Magnetite content highly variable but decreases to the west; western exposures nearly magnetite-free. Contains some pyritic black shale and graywacke interbeds and minor basalt flows

Xmg **Palms Formation**—Gray, grayish-green, and reddish-brown argillite, siltstone, quartzite, and conglomerate. Locally contains thin basal conglomerate containing clasts of Archean and older Paleoproterozoic strata. Remainder of unit is generally a coarsening-upward sequence of thin-bedded siltstone to fine-grained sandstone near base, and white to pink, massive to crossbedded quartzite near top

Chocolay Group (Paleoproterozoic)

Xck **Bad River Dolomite**—Dolomite and dolomitic marble. Not exposed in map area but inferred based on exposures 1 km to the east of the map area where it is tan to white, generally thick-bedded, and commonly contains lenses or thin beds of chert. Most primary textures obliterated by metamorphism, but domal structures preserved in cherty layers are probably algal stromatolite mounds. Coarse rosettes of tremolite are common along cherty beds

INTRUSIVE ROCKS

Yaf **Granophyre of Amnicon intrusion (Mesoproterozoic)**—Pink, fine-grained granophyre containing poikilitic quartz and small plagioclase phenocrysts in a sericitized, calcitized groundmass

Yag **Gabbro of Amnicon intrusion (Mesoproterozoic)**—Gabbro generally consisting of about 70 percent plagioclase (An_{50}) and lesser olivine and clinopyroxene. Weak compositional layering

Ygb **Gabbro (Mesoproterozoic)**—Several unexposed gabbroic and anorthositic bodies occurring within Neoarchean granite and gneiss (Wg). Presence inferred based on aeromagnetic signature. One body (Round Lake intrusion) has been drilled, yielding gabbro core

Ygr **Granite (Mesoproterozoic)**—Small granitic plug near Atkins Lake

Mellen Intrusive Complex (Mesoproterozoic)

Ynmf Granophyre—Brick-red to pink, fine- to medium-grained granophyre and felsophyre. Small phenocrysts of plagioclase in graphic-textured matrix of potassium-feldspar and quartz

Ynmg Gabbro—Coarse-grained gabbro and anorthositic gabbro generally consisting of 80 to 90 percent plagioclase (An_{50} to An_{60}), lesser clinopyroxene, orthopyroxene, and sparse olivine. Plagioclase crystals commonly have a preferred orientation

Yub **Gabbro and anorthosite of the Duluth Complex (Mesoproterozoic)**—Inferred from geophysical data. Shown only in cross section

Xmd **Metadiabase (Paleoproterozoic)**—Medium- to coarse-grained, metamorphosed diabase and gabbro. Shown with a scratch boundary where outcrop is lacking

Wg **Granite and gneiss, undifferentiated (Neoarchean)**

EXPLANATION OF MAP SYMBOLS

- Contact—Mostly inferred from geophysical data. Dotted where concealed by water
- Inferred fault
- Thrust fault—Teeth on upper plate. Dotted where concealed by water
- Anticline—Approximately located
- Synicline—Approximately located
- Aeromagnetic form line—Drawn from aeromagnetic data (Daniels and Snyder, 2002)
- Strike and dip of bedding
- Strike and dip of flow contacts
- Rock quarry—Intermittently active
- Abandoned copper mine
- Copper prospect
- Drill hole
- Location of sample used for U-Pb age dating; age given in Ma (millions of years)
- Bedrock outcrop or area of abundant outcrops

DISCUSSION

INTRODUCTION

This map portrays the geology of Mesoproterozoic rocks of the Keweenawan Supergroup in northwestern Wisconsin. The map area encompasses the St. Croix horst and part of the Neoarchean and Paleoproterozoic crystalline basement over which the Keweenawan rocks were deposited. To the east, rocks of the Keweenawan Supergroup are notable for their sediment-hosted copper deposits, including the White Pine deposit, as well as for their contained extensive native copper deposits in both volcanic and sedimentary rocks. In the region of the St. Croix horst, native copper ore is widely distributed, but few concentrations were of sufficient quantity to be economic. This area also encompasses the western extent of Paleoproterozoic iron-formation of the Gogebic iron range, which historically has been an important source of iron ore. The western Lake Superior basin and the western arm of the Midcontinent Rift, including the area of this map, were the target of a petroleum exploration play from the early 1980s to early 1990s. Although petroleum potential ultimately was deemed poor, the seismic data collected to evaluate that potential substantially improved the understanding of the three-dimensional aspects of the rift.

Limited geologic data exist for this area, as most studies of the Midcontinent Rift system were focused farther east or northwest. The data that do exist are largely in unpublished theses and dissertations, including Hitz (1968), Myers (1971), Suzaek (1991), and Ali (1982); and other reports of limited availability, including private company reports and township reports on file at the Wisconsin Geological and Natural History Survey. Many published reports are very old (Grant, 1901; Thwaites, 1912; Aldrich, 1929), or cover a small area (Cannon and others, 1981). Previous maps of this area are at a smaller scale and include Dutton and Bradley (1970), Mudrey and Brown (1988), and Sims (1992). This map incorporates some data from these earlier reports and includes the results of our investigations from 1991 to 2000. Our studies used recently acquired aeromagnetic data (Daniels and Snyder, 2002) to help interpret this area of limited outcrop.

STRATIGRAPHY AND TECTONIC SETTING

Three principal stratigraphic sequences, separated by significant unconformities, are present in the map area. Each sequence was deposited in a distinct tectonic setting as the region evolved from an Archean orogenic belt to a Mesoproterozoic craton.

Neoarchean

Neoarchean rocks (Wg) are inferred to form the bedrock surface in the southeastern part of the map area. In this area of extensive glacial deposits, there are about a dozen drill holes that have penetrated these rocks, yielding mostly migmatite and gneiss as well as some massive granites (Mudrey and Brown, 1988). The only modern presentations of the geology of this area are by Mudrey and Brown (1988) and Sims (1992), both of which were based largely on (1) projections of rock relations that are somewhat better exposed to the east (Cannon and others, 1996), and (2) an interpretation of magnetic and gravity data. Sims (1992) inferred that rocks of both Neoarchean and Mesoarchean age are present, with the former lying in a belt to the north and the latter to the south. There are no radiometric ages to verify this interpretation. We have shown the Neoarchean entirely as an undivided unit of granitic and gneissic rocks.

Paleoproterozoic

Paleoproterozoic strata of the Marquette Range Supergroup underlie a belt about 2 km wide near the east margin of the map area. They were intruded by gabbro sills, also of Paleoproterozoic age. These rocks represent the westernmost edge of the Gogebic iron range, which extends for more than 100 kilometers (km) east of the map area. The rocks are well exposed in the easternmost few kilometers of the belt, but exposures are sparse farther west so that the western termination of the belt is poorly known.

In the map area, the Marquette Range Supergroup is composed of the basal Chocolay Group that is overlain by strata of the Menominee Group. In this quadrangle, the only member of the Chocolay Group is the Bad River Dolomite (Xck), which unconformably overlies the Neoarchean rocks. This contact is exposed locally in sec. 15, T. 44 N., R. 5 W., where about 10 meters (m) of dolomitic arkose and arenaceous dolomite constitute the base of the Bad River Dolomite. Above the base, the Bad River consists of a few hundred meters of cherty dolomite with abundant algal stromatolites. The Menominee Mineral Lake intrusion produced a contact aureole that was subsequently metamorphosed and now contains abundant tremolite from the reaction between chert and dolomite.

Overlying the Bad River Dolomite is the Menominee Group, which, in this quadrangle, consists of the basal Palms Formation (Xmg) and overlying Ironwood Iron-Formation (Xmd). The Palms Formation, which is about 100 m thick, has a lower layered argillite member and an overlying thick-bedded quartzite member; the members are not differentiated on the map. The Ironwood Iron-Formation is a banded, cherty iron-formation in which the iron is contained in magnetite- and iron-bearing amphiboles. The magnetite content is highly variable, but decreases toward the west so that the westernmost exposures are nearly magnetite-free. A few drill holes (sec. 26, T. 44 N., R. 6 W.) indicate that clastic rocks, including pyritic black shale and graywacke, are interbedded with the iron-formation in the westernmost parts of its belt of exposure. Thin concordant units of fine-grained, mafic rock probably metamorphosed basalt flows) occur within the Ironwood east of Atkins Lake.

A narrow belt devoid of outcrops north of the exposures of Ironwood Iron-Formation may be underlain by the Paleoproterozoic Tyler Formation, which is known to overlie the Ironwood east of the map area. In this quadrangle, these rocks are assigned to the Ironwood Iron-Formation because of the lack of data. To the east, the Tyler is mostly a sequence of graywacke and shale, commonly in graded units that suggest turbidite deposition.

Mesoproterozoic

Along the eastern margin of the map, volcanic rocks of the Powder Mill Group crop out between the Mellen Intrusive Complex to the east and the Lake Owen fault to the west. The basal unit, flood basalts of the Siemens Creek Volcanics (Ypsc), has not been dated but is considered to be correlative with basalts of the Oker Group, on the north shore of Lake Superior, which were deposited at about 1,109 mega-annum (Ma) (Davis and Sutcliffe, 1985). East of the map area, the Siemens Creek Volcanics are divided into two subunits based on chemical composition (Nicholson and others, 1997). Although both subunits are present just to the west of the Mellen Intrusive Complex, they were not differentiated on this map. Likewise, to the east of the map area, the overlying Kallander Creek Volcanics (Ypbc) contains two subunits: a basal flood basalt unit dated at about 1,106 Ma, and an upper localized unit of mostly andesite and lesser rhyolite dated about at about 1,099 Ma (Cannon and others, 1995; Nicholson and others, 1997). The upper subunit appears to be, in part, a central-volcanic complex that probably erupted from vents near Mellen, Wis., and was deposited over the Siemens Creek (Cannon and others, 1993). Although the Kallander Creek subunits continue to the west of the Mellen Intrusive Complex, they were not differentiated on this map. The Mellen Intrusive Complex (Ynmf, Ynmg) appears to consist of near-surface intrusions emplaced into the central volcanic complex and was probably a magma chamber from which part of the Kallander Creek Volcanics erupted.

South of the area of this map, the St. Croix horst contains the southernmost exposure of volcanic and sedimentary rocks related to the Midcontinent Rift system. The Keweenawan Supergroup rocks are 15 to 20 km thick in the map area and are confined between two pairs of major thrust faults that brought formerly deeply buried volcanic rocks over younger sedimentary units. The Ashland syncline, located in the northern part of the St. Croix horst, is a major fold structure in which younger Keweenawan sedimentary formations crop out in its center and older volcanic formations occur on both limbs.

Previous workers assigned the volcanic rocks in the St. Croix horst to the Chengwatana Volcanics. Hall (1901) described basalt flows at the type locality in eastern Minnesota as the Chengwatana series. Subsequently, the term "Chengwatana Volcanic Group" was used by Morey and Mudrey (1972) and Hassan and Mudrey (1980) to include the volcanic rocks within the entire St. Croix horst. Cannon and others (1996) revised the nomenclature to Chengwatana Volcanics to conform to the standards of the 1983 North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983).

Since then, detailed aeromagnetic imaging of the horst was used to subdivide the volcanic section initially into three units (Cannon and others, 2001; Nicholson and others, 2001). However, new age determinations and a re-evaluation of the aeromagnetic data suggest that the volcanic rocks can be better placed in two units. In this report, we formally define these two volcanic units. The upper unit is herein defined as the Minong Volcanics (Ynml, Ynmh). The lower unit is herein revised as a more narrowly defined Chengwatana Volcanics (Ynsv) (Nicholson and Cannon, 2003; Clark E. Isachsen, University of Arizona, unpub. data, 2003). Outcrops within the St. Croix horst are sparse. The volcanic rocks are dominantly subaerial basalt flows with lesser rhyolite flows. The Chengwatana and the Minong have similar chemistry, but are distinguished by structure and age.

Paleozoic

A thin veneer of Upper Cambrian Mount Simon Sandstone (Crss) unconformably overlies the Mesoproterozoic volcanic and sedimentary rocks along the southern boundary of the map area. The Paleozoic sedimentary rocks thicken to the south. The Mount Simon is a quartzose sandstone that contains some thin shale beds (Austin, 1972).

STRUCTURE

A monoclinal succession of Paleoproterozoic rocks dips moderately to the north and provides the basement on which the Mesoproterozoic rocks of the Midcontinent Rift were deposited. The St. Croix horst, which is bounded by two sets of major reverse faults and is the dominant feature of the map, formed during the Mesoproterozoic.

Penokean Orogen

The Paleoproterozoic rocks exposed in the map area are structurally simple and typical of much of the Gogebic Iron Range, which lies on the northern margin of the Penokean fold and thrust belt. The strata form a monoclinal succession that dips moderately to the north. This northward dip, however, is thought to have resulted from Mesoproterozoic tilting rather than from Penokean deformation. This concept is based both on regional relationships (Cannon and others, 1993) and the observation that Mesoproterozoic dikes exposed in the dolomite quarry in sec. 22, T. 44 N., R. 5 W. (just east of the map area, as shown by Cannon and others, 1996) are inclined to the south, in contrast to their likely near-vertical emplacement.

Few folds at outcrop scale were observed and none were of sufficient magnitude to repeat the stratigraphy at map scale. The only major Penokean structure identified in the field was a broad zone of intense shearing in argillite near the base of the Palms Formation. This shear zone is well exposed to the east of the map area in sec. 16, T. 47 N., R. 5 W. along the Marengo River. It lies parallel to bedding and consists of a zone about 50 m thick in which all the original bedding has been obliterated except for hinges of dismembered folds in the quartzose layers. The intensity of deformation diminishes upsection, but mylonitization is obvious for an additional 100 m of section. The zone appears to be a major detachment surface along which the Palms Formation, Ironwood Iron-Formation, and metagabbro sills were thrust over undeformed Bad River Dolomite.

Midcontinent Rift System

The interior of the prominent St. Croix horst is characterized by a sequence of basalts overlain by Oronto Group sedimentary rocks, all of which were folded into the broad Ashland syncline that plunges very gently to the northeast. The horst was originally an asymmetric graben, or possibly a half graben. The Lake Owen fault was a major growth fault on the southeast side of the graben as suggested by seismic-reflection data, which show that the volcanic fill thickens toward and terminates against the fault. The Douglas fault on the northwest side of the horst was not a growth feature and may simply be a thrust fault formed during inversion of the graben. As magmatism ceased and sedimentation became dominant, the extensional regime dominant during rifting changed into a compressional regime. In what is now northern Wisconsin, a horst was formed that now exposes some of the more deeply buried parts of the rift basin. Thrust displacement on the Douglas fault must have been 20 km or more because it has juxtaposed the base of a thick volcanic sequence (St. Croix Group) above the younger Bayfield Group (see cross section *A*–*A*').

METAMORPHISM

In the St. Croix horst, the metamorphic grade of the volcanic rocks ranges from zeolite to lower greenschist facies. In general, the metamorphic grade of the Chengwatana Volcanics is higher than that of the overlying Minong Volcanics and increases towards the south along the trend of the St. Croix horst. At the southern end of the Keweenawan exposures (south of the map area near Taylors Falls, Minn.), greenschist-facies minerals are common constituents of the basalts. Chlorite is ubiquitous and crystalline epidote commonly occurs in amygdules, and granular epidote occurs in the groundmass. Actinolite also occurs as a groundmass mineral and as a replacement after clinopyroxene. These basalts are estimated to have been buried beneath 6 to 7 km of younger sedimentary rocks and were subjected to a peak metamorphic temperature of about 350°C (Wirth and others, 1997).

In the map area, metamorphic conditions in the rocks appear to be have been somewhat cooler and transitional into the lower grade assemblages common to the east. On the south limb of the Ashland syncline, most of the basalts have mineral assemblages similar to those of the Taylors Falls area. The uppermost kilometer or two of section, however, contain prehnite and pumpellyite in widespread amygdules, which suggests that the transition into the zeolite facies occurs near the top of the Minong Volcanics. On the north limb, relationships are not as clear. The uppermost part of the volcanic section is not well exposed and flow tops, which would best display the metamorphic mineral assemblages, are not exposed. The lower part of the section has been complicated by widespread hydrothermal alteration, which resulted in epidote located in both amygdules and the groundmass of the rocks. Prehnite and pumpellyite are also present even in the stratigraphically lowest basalt flows, which suggest low-temperature mineral growth. Whether these two minerals formed under retrograde or prograde conditions has not been established. If they formed in a prograde event, then the presence of zeolite suggests maximum burial of a few kilometers and it is therefore likely that the extensive epidote in these rocks has a hydrothermal origin.

MINERAL RESOURCES

Exploration for a variety of magmatic ore deposits began in this area in the late 1800s. Although world-class sediment-hosted copper and native copper deposits occur in the same rocks east of the map area, exploration in this area for these ore types suggested only limited potential. Over time, exploration took place for magmatic copper, nickel, platinum-group-element, and titanium-vanadium ore deposits, with little success. In the 1980s, petroleum exploration was a short-lived idea. The principal mineral-resource produced today is sand and gravel.

Sediment-Hosted Copper

Basal beds of the Nonesuch Formation are the host for major copper deposits (chalcocite and native copper) in Michigan, east of the map area. The principal deposit is at the White Pine mine, about 150 km to the east; an additional important, but as yet unmined, deposit is in the Presque Isle syncline (see summary by Cannon and others, 1995). These deposits provided the impetus for exploration further west in the Ashland syncline.

Between 1955 and 1960, about 40 holes were drilled by a mineral exploration company in the Ashland syncline to evaluate the mineral potential of the Nonesuch Shale (Cannon and others, 1981). However, copper concentrations were found to be much lower than in the east and additional exploration was considered unjustified (Cannon and others, 1981).

Magmatic Copper,