Field Guide to the Geology of Precambrian Iron Formations in the Western Lake Superior Region, Minnesota and Michigan

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Iron ranges of the western Lake Superior region. Areas to be visited during the four field trip days are shown in bold type.
FIELD TRIP 1
WESTERN GOGEBIC IRON RANGE
IN WISCONSIN

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MT. WHITTLESEY AREA

The north-dipping monocline of the Gogebic Iron Range extends for 120 km across northern Wisconsin and Michigan (Figure 1). This fieldtrip will focus on the Mt. Whittlesey area in the western part of the Gogebic Iron Range in Wisconsin. Mt. Whittlesey is a prominent ridge, about 3 km southeast of the village of Mellen, Wisconsin, that is held up by the Ironwood Iron-formation. Four stops in this area will visit some of the best exposures in the range to see important aspects of structure, stratigraphy, and depositional setting of the iron-formation and related strata. At stop 1 the contact of the Paleoproterozoic section and Archean volcanic rocks is exposed and illustrates a basal detachment fault across which the Paleoproterozoic rocks have been thrust over the Archean basement. Stop 2 displays a cross section of the Palms Formation, the basal Paleoproterozoic unit that immediately underlies the Ironwood Iron-formation. as well as an outcrop of the lower part of the Ironwood. Stop 3 shows a basal chert breccia overlain by the Palms Formation. Stop 4 is a spectacular exposure of the Ironwood Iron-formation that was created in the 1920’s by stripping of overburden from a large area in advanced of planned mining. Only a small area was mined and the remaining stripped area is a glacially polished surface on which many details of the Ironwood can be observed. The descriptions for Stops 1 and 3 are taken from a previous guidebook (Cannon, 1996) with only minor modifications.

An unusually great thickness of iron-formation is present on Mt. Whittlesey owing to structural repetition by thrust faults and folds produced during the Penokean orogeny. Figure 2 shows a recent interpretation of the geology of the Mt. Whittlesey area (Cannon et al., 2008). The area was mapped, drilled and sampled in great detail in the 1950’s by United States Steel Corporation, including mapping at a scale of 1 inch:100 feet. The map shown in Figure 2 is generalization of that detailed mapping. Mt. Whittlesey lies at the easternmost extent of the Penokean (Early Proterozoic) foreland fold and thrust belt. At Mt. Whittlesey, a series of thrusts repeats the Early Proterozoic section, having detached it from Archean rocks along a basal decollement. The thrusts all rise in the section to the east along a series of lateral ramps. Northward tilting of the region in Middle Proterozoic time resulted in the current map pattern that provides an unusual cross-sectional view of the thrust complex. To understand the Penokean structural geometry the map pattern should be viewed as a longitudinal cross section along the original trend of the thrust belt, so that the upper plates of originally nearly flat-lying faults would have moved northward away from a north-facing viewer. Because of later tilting to the north by about 70°, these original thrusts now mimic the geometry of normal faults—that is, the upper plates appear to have moved down to the north. The ramps that rise to the east are lateral ramps along which the plates have undergone transcurrent movement rather than overthrust movement. Displacement along the basal decollement diminishes eastward as splays from the decollement successively rise in the section. East of Mt. Whittlesey the Early Proterozoic section lies unconformably on Archean rocks.
Figure 1. Generalized geologic map of the Gogebic Iron Range (Cannon and others, 2008) showing the location of Mt. Whittlesey and Atkins Lake areas.
Figure 2. Geologic map of the Mt. Whittlesey area showing the location of fieldtrip stops. Geologic map from Cannon et al. (2008).
Figure 3. Cross section along line AB of Figure 2 showing the present structure (top) and those structures restored to their orientation prior to tilting at 1060 Ma (bottom). The lower section approximates the structures at the end of the Penokean orogeny. Sections from Cannon et al. (2008).

STOP 1. Contact of Early Proterozoic strata and Archean metavolcanic rocks on the southeast flank of Mt. Whittlesey.

Low outcrops near the base of a prominent ridge supported by the Palms Formation reveal the basal contact of Early Proterozoic strata with underlying dacite breccia of Late Archean age. The breccia has a penetrative structural fabric, best expressed by the prominent elongation of clasts. Long axes plunge moderately southward, but must have plunged moderately to steeply northward prior to tilting of the rocks into the monoclinal structure. The basal Early Proterozoic unit is chert breccia of the Bad River Dolomite, the same unit seen at stop 3. Along the contact, the upper meter or two of the dacite breccia is strongly sheared parallel to the contact, and the Archean fabric typically is completely overprinted by this secondary fabric. Shearing is weak to absent in the chert breccia. To our knowledge these outcrops are the only ones in the western part of the Gogebic Range where a basal detachment between the Early Proterozoic strata and Archean basement rocks can be directly observed. We believe the Early Proterozoic strata were thrust northward along a nearly flat-lying basal contact during the Penokean orogeny. Because of later tilting of the Montreal River monocline, the present apparent displacement reflects a down-to-the-north normal fault. Figure 3 shows a current cross section of this structure and a cross section restored to the pre-tilting orientation. This fault can be traced westward, and about 1 km to the west of these exposures it passes up-section so that the Bad River-Palms-Ironwood sequence of the
upper plate is juxtaposed over Ironwood Iron-formation in the lower plate, producing the unusually wide outcrop belt of Ironwood along higher parts of Mt. Whittlesey. Just east of this stop the basal thrust appears to pass upward into the Early Proterozoic strata. Exposures east of Ballou Creek show that the base of the Early Proterozoic rocks lies unconformably on Archean volcanic rocks without an intervening shear zone.

STOP 2. Palms Formation and Ironwood Iron-formation along Ballou Creek, east end of Mt. Whittlesey.

Recent road improvement along Lake Road has produced a set of roadcuts along the west side the valley of Ballou Creek that provide a cross section of most of the Palms Formation and part of the lower Ironwood Iron-formation. Starting at the south, at the lower part of the section, a nearly continuous exposure, about 75 m long, of laminated argillite and sandstone illustrates the lower part of the Palms Formation. About 150 feet farther south a very small roadside exposure of Archean andesite breccia indicates that the covered interval is probably underlain by the chert breccias seen at Stop 1 and the basal part of the Palms. Proceeding north, up section, along the outcrop many typical sedimentary structures of the Palms are well exposed. Farther north, a covered interval about 75 m wide is probably underlain by the upper part of the laminated lower Palms Formation and quartzite of the upper Palms Formation. Next to the north is a 30 m exposure of the upper part of the Palms Formation quartzite and the Ironwood Iron-formation. The uppermost quartzite is coarse-grained and cross-bedded. The transition to the Ironwood Iron-formation takes place in a 0.5 m interval containing reworked fragments of the Palms surrounded by magnetite. The overlying Ironwood Iron-formation varies from even-bedded magnetite-rich material to irregularly bedded jasper at a scale of a meter or less.

STOP 3. Palms Formation and Bad River Dolomite at Eagles Peak

At the southwest end of Mt. Whittlesey a prominent bluff, Eagles Peak, is held up by laminated argillite typical of the lower part of the Palms Formation. At the westernmost tip of the bluff the unconformable contact between the Palms and underlying Bad River Dolomite is well exposed. The Palms can be seen to be draped into shallow depressions along the top of the Bad River, which also has a weathered and rusty zone for about half a meter below the contact. The rusty color appears to be caused by recent oxidation of small amounts of pyrite along the contact. The Bad River Dolomite at this locality is a chert breccia composed of angular to subrounded fragments of gray chert cemented mostly by a second generation of chert. Locally, well-rounded quartz grains partly fill interstices between breccia fragments, and magnetite is locally abundant as euhedral grains in the matrix. At other localities nearby, magnetite was sufficiently abundant to have promoted the sinking of prospect shafts in the early days of iron exploration. These are present generally immediately below the contact with the Palms Formation. This distinctive chert breccia has been traced as a mappable unit for about 12 km along strike. Locally it is underlain by marble and tremolitic marble more typical of the Bad River Dolomite in this region. We believe that the breccia is a residual deposit, formed by solution of an originally thick section of cherty dolomite during the weathering interval prior to Palms deposition.


Scattered outcrops in the vicinity of Mt. Whittlesey define three upward-coarsening, asymmetric cycles composed of a basal unit of slaty iron formation that is gradational into an upper unit of trough cross-stratified cherty iron formation. The middle cycle provides an unparalleled opportunity to investigate cycle sedimentology as it is completely stripped of overburden to appraise the Fe resources of this area. Like the cycles above and below, it consists of ~14 m of slaty iron formation gradationally overlain by
~16 m of cherty iron formation which is capped by a ~1m thick unit of convolute-bedded, slaty iron formation.

Pufahl and Fralick (2004) conducted a detailed description of a 40x44 m glacially polished exposure through 1.5 cycles (Fig. 4) combined with a reconnaissance study of poorly exposed strata above and below the logged section. This area provides an excellent opportunity to investigate the depositional controls governing the accumulation of iron formation facies. Their research was augmented with geochemical analysis of iron formation facies in order to elucidate the chemical controls on iron formation precipitation. This approach has yielded important insights into the relative roles tectonics, fluctuating hydraulic regime, and changing water chemistry played in governing the distribution of iron formation facies.

Figure 4. Schematic map of vertically dipping asymmetric cycles developed in Superior-type iron formation of the study area. The slaty unit forming the lower portion of cycle 1 overlies a slumped unit of convolutedly-bedded chemical mudstones and is gradational into a succession of cherty grainstone lenses. These coarse-grained beds are sharply overlain by another slumped chemical mudstone unit. The base of a second coarsening upward cycle (cycle 2) forms the upper portion of the outcrop.
Grainstone lenses become progressively thicker upwards in cycles with the largest at cycle tops, where they are sharply overlain by a unit of slumped chemical mudstone. Cycles formed through progradation when offshore-directed storm currents transported progressively greater quantities of chert sand intraclasts that were formed in nearshore settings, outboard into middle and distal shelf environments (Fig. 5). Abrupt subsidence events, probably resulting from normal faulting associated with extensional tectonism, repeatedly terminated shallow-water chert grainstone accumulation and may have also generated the slumped units at cycle boundaries. The episodic storm currents are also interpreted to have transported biologically oxygenated waters over the shallow-water, inner shelf outboard along the seafloor into otherwise anoxic bottom waters of the strongly stratified distal shelf (Fig. 6). The consequence of such transport and mixing was rapid deposition of chemical mud, mainly as precipitated Fe-oxide. In many cases the resultant decrease of Fe$^{2+}$ in the water column, together with pelagic inorganic precipitation of SiO$_2$ and rainout of terrigenous clays, resulted in sub-millimeter- to millimeter-thick, chemically graded laminae. The concomitant decreasing Fe$^{2+}$/Mn$^{2+}$ ratio also led to increasing Mn-compound precipitation and enrichment in the upper portions of some chemically graded laminae (Fig. 7).

The outcrop is mostly two-dimensional and glacially polished so that sedimentary features are well displayed. It is sub-parallel to the trend of the palaeoshoreline but oblique enough so that palaeocurrent trends can be ascertained.

Figure 5. Physical depositional model for an asymmetric iron formation cycle. Rapid transgression was followed by formation of a shoaling upwards, prograding cycle. Offshore flow during or immediately after major storm events built shelf sand sheets from chert and Fe-oxide intraclasts which progressively migrated into more distal environments as water depth decreased.
Figure 6. (1) Chemical depositional model for an asymmetric iron formation cycle. Low free oxygen levels allowed Fe and Mn to remain dissolved in a water mass with near-neutral pH. The main O$_2$ production took place near-shore where light penetration to the seabed allowed cyanobacteria to flourish. (2) Storm-generated offshore flows, which were responsible for generating hummocky cross-stratification in more shore-proximal locations, transported the oxygenated coastal waters to the mid and outer shelf where they mixed with Fe- and Mn-bearing offshore waters, with resultant chemical precipitation. Storm-wave mixing of the stratified water body may have also played a role in this process, although an O$_2$-bearing surface layer is not necessary. The succession represented by A reflects the formation of thick Fe-oxide laminae overlying grainstone lenses. The succession illustrated in Column B would have developed in a more distal shelf position resulting in thinner and finer grained sand lenses and thinner chemical layers than in A. The assemblage that developed furthest offshore is shown in Column C.
Figure 7. Progressive formation of a millimetre-scale chemical mud laminae. Chemical grading is interpreted to be the result of changes in water chemistry driven by the precipitation process. (A) Offshore currents generated during storm events delivered near-shore oxygenated water to deeper portions of the shelf, where it mixed with normal (Fe$^{2+}$-, Mn$^{2+}$- and PO$_4^{3-}$-bearing) ocean water. (B) Precipitation proceeded relatively rapidly as the abundant Fe$^{3+}$ and O combined to probably form FeOOH’s. (C) As Fe content decreased in seawater precipitation rate slowed and ambient clastic and SiO$_2$ deposition gained in importance. (D) As the Fe/Mn ratio in the aqueous phase decreases, Mn$^{2+}$ more effectively combined with oxygen. A progressively decreasing Fe$^{2+}$/PO$_4^{3-}$ ratio results in more scavenging of PO$_4^{3-}$ by the FeOOH’s. Carbon is delivered to the sediment by the rainout of phytoplankton from the surface ocean. (E) Diagenesis and low-grade metamorphism resulted in the mineral assemblage present today.
Numerous exposures of the Ironwood Iron-formation and the Palms Formation are present in a 4,000 m long northeast-trending zone from Atkins Lake to the Marengo River (Fig. 1), where the Early Proterozoic units are truncated by the Marenisco-Atkins Lake fault (Fig-1). The Palms Formation consists of an upper massive quartzite member and a lower argillaceous quartzite member, similar to exposures elsewhere on the Gogebic Range. (Note: Due to time limitations, we will not visit exposures of the Palms Formation here). The Ironwood Iron-formation consists of magnetic wavy-bedded and laminated cherty iron-formation and argillite, some of which is also magnetic. Mafic sills or flows lie in contact with iron-formation. Unusual breccia units, the focus of field stops in this area, are associated with one of the sills. Many details of the breccias described here are from Fehrer and Flood (1995). The breccia units contain angular to sub-rounded clasts, up to several meters in length, of banded siliceous sedimentary rocks in a matrix of fine-grained, massive igneous rock. The igneous rock is locally fine-grained near the margins where the breccia occurs, but coarse-grained in the interior of the igneous body, where it ranges from fine-grained diabase to medium-grained gabbro. However, the mineralogy and, to some extent, the textures have been modified by Middle Proterozoic (Keweenawan) metamorphism. Clasts within the breccia are mainly siliceous argillite: a few are magnetic. Most clasts are long, tabular bodies. Bent or folded clasts are not uncommon, suggesting that the sediments were only semi-lithified when incorporated in the breccia. The argillite consists of alternating layers of recrystallized quartz, fine-grained chlorite, biotite or actinolite, garnet, and variable amounts of magnetite. The matrix is a fine-grained mafic rock with conspicuous vesicles around some clasts. The matrix is composed of medium-grained amphiboles and plagioclase laths, probably a relict ophitic texture. Plagioclase phenocrysts are present locally. Preliminary geochemical data indicates a tholeiitic composition for the matrix. The origin of the breccia is problematic. The breccia is not a debris flow because the matrix is igneous and not fragmental: the clasts appear to have been incorporated into a magma. The presence of angular, and in places deformed, blocks of country rock within a magma argues for intrusion into semi-consolidated sediments at a shallow depth. The presence of breccia at both the upper and lower margins of the igneous body argues for a common origin for both breccia units, most likely the intrusion of a sill into wet, unconsolidated sediments, forming, perhaps, a peperite-like body. Alternatively, the breccia and mafic rocks may represent an extrusive basaltic flow that incorporated blocks of the sediments over which it flowed, with subsequent concordant intrusion of a mafic sill separating the basalt flow into two parts. Features arguing for this origin are: 1) perfectly concordant contacts with thinly laminated sediments exposed at several outcrops, and the lack of any observed cross-cutting contacts; and 2) marked lithologic contrast between the breccia and undoubted intrusive sills of coarse-grained, massive, inclusion-free metadiabase within the same outcrops. Regardless of whether the breccias are the result of an extrusive or a very shallow intrusive igneous event, they indicate that igneous activity was occurring contemporaneously with iron-formation deposition in the western part of the Gogebic Range.

The situation is similar to that of the eastern part of the Gogebic Range where the Emperor Volcanic Complex is interlayered with the Ironwood Iron-formation (LaBerge and Klasner, 1994). In both areas platformal sediments, including the Bad River Dolomite, the Palms Quartzite, and the Sunday Lake Quartzite in the east, are similar to equivalent rocks in the central part of the Gogebic Range. Igneous activity, however, becomes a significant feature during the time of deposition of the Ironwood Iron-formation on both ends of the Gogebic Range. Whereas igneous activity in the central part of the range is limited to deposition of a few minor ash beds (R. G. Schmidt, personal communication, 1995). Igneous deposits on either end of the Gogebic Range indicate a far more volcanically active environment in these regions.
AITKINS LAKE STOP DESCRIPTIONS

A series of closely spaced outcrops along a ridge east of Atkins Lake shows typical metamorphosed Ironwood Iron-formation, unusual intraformational breccias within it, and metamorphosed gabbro sills (Figure 8). These outcrops give a good representation of the Ironwood in the western extremity of the Gogebic Range, and the igneous and tectonic activity that are more pronounced here than in the central part of the range.

Figure 8. Detailed map of the Atkins Lake area showing outcrops and geologic relationships among iron-formation, breccia units, diabase and gabbro. Stops A1-A8 are described below. Unpublished map prepared by Klasner and LaBerge.

STOP A1. This outcrop consists of layered magnetic, greenish, actinolitic iron-formation with metadiabase, and a breccia zone with clasts of iron-formation in a fine-grained metadiabase matrix. Bedding orientations at this outcrop are consistent with orientations of bedding elsewhere in the area indicating that the outcrop is in place and not a raft of iron-formation entrapped in the igneous rock.  

* Walk northeast about 60 m to the top of a hill.*

STOP A2. At this location, large thin slabs of argillite lie in a matrix of locally vesicular metadiabase. The slabs have various orientations: some are contorted and folded, and one is rolled into a ball with a central layered portion surrounded by a concentric zone of smaller clasts in a metadiabase matrix. Slabs from a meter or more in length down to a centimeter or less.
Walk east along the crest of the hill about 90 m to a north-northwest-trending valley. When in the valley follow the edge of the hill toward the south-southwest for about 60 m.

STOP A3. Strongly magnetic, wavy-bedded, cherty iron-formation. Lenticular chert beds are up to 15 cm thick. This bedding style is typical of wavy-bedded iron-formation farther east along the Gogebic Range.

Walk north-northeast along edge of hill about 25 m.

STOP A4. Thin-bedded, non-magnetic chert-argillite or argillaceous iron-formation. Some cherty layers appear boudinaged. The argillite unit is about 50 m thick and grades into a more argillaceous unit with less cherty layers to the north.

Walk northeast about 55 m.

STOP A5. The top of the argillaceous iron-formation layer (LIP on Fig. 8) is in sharp contact with the overlying breccia unit, in which argillite clasts are surrounded by a metabasalt matrix. Clasts in the breccia tend to become larger higher in the section (northward from the contact). Remnants of what appears to be a thin slab of iron-formation lie along the top of the breccia unit (Br on Fig. 8) at both stops A5 and A6.

Walk east-southeast about 10 m.

STOP A6. Observe the southeast continuation of the thin slab of iron-formation that lies along the contact between the breccia on the southwest and massive metagabbro on the northeast.

Walk northeast about 50 m.


Walk northwest about 35 m.

REFERENCES


