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Supporting Information for

A New Depositional Framework for Massive Iron Formations after the Great Oxidation Event

Athena Eyster[1], Latisha Brengman[2], Claire I. O. Nichols[1], Zoe Levitt[1], and Kristin Bergmann[1]

[1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA, [2]Department of Earth and Environmental Sciences, University of Minnesota Duluth, 1114 Kirby Drive, Duluth, MN 55812, USA

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Introduction

This supporting information contains expanded and extended discussions of facies descriptions, Ironwood Iron formation member descriptions and structural interpretations (Text S1 and S2). Also included is a supplemental figure highlighting stratigraphic observations made in the central portion of the range (Figure S1). Finally, Table S1. provides the location information and existing publications regarding stratigraphy in the indicated mine locations.

Text S1. Extended facies descriptions and descriptions of general Iron formation stratigraphy in the west-central Gogebic range

Facies IF2 is the dominate Iron-Chert Arenite. This has been variously called “wavy cherty granular iron formation” (Hotchkiss, 1919) or "Upper cherty" (Pufahl and Fralick, 2004). The facies is moderately well sorted with medium-coarse iron-mineral and coated chert grains. Some outcrops display stacked medium- and large-scale trough cross-stratified grainstone lenses that are separated by chemical mudstone drapes and display intraclasts along their bases (Pufahl and Fralick, 2004). Facies IF3B and IF3A are similar to IF2 but include various proportions of interbeds dominated by angular fragments of green-grey chert and angular laminated chert and iron lutite clasts.

The facies IF4, IF5, are iron lutites. At the extreme end, IF4 is a thin bedded Fe-lutite, also described as "parallel slaty iron formation" or ”parallel laminated IF”(Hotchkiss, 1919; Pufahl and Fralick, 2004). Facies IF4A is also an iron lutite but it is distinguished from IF4 by its color, green-greenish grey- tan brown. Across the Gogebic range, IF4A is similar to descriptions of the "footwall slate" by Hotchkiss (1919) and Schmidt (1980). Facies IF5 is similar to IF4, but it contains lenses and lag deposits of medium to very fine chert- iron arenite and a few pebble lenses. It is also described as "parallel-wavy laminated lower slaty with minor ripple cherty units". Certain exposures contain asymmetric and form-concordant ripples (Pufahl and Fralick, 2004).

There are also several facies that do not fit into the iron lutite-arenite spectrum of facies. These are IF1,7, 8,9,10. Facies IF7 is an iron rudite, sometimes referred to as the Pabst conglomerate, that is highly variable and poorly sorted, dominantly composed of angular-rounded cobbles of laminated chert, iron lutite, and chert arenite. It also is described as containing interbeds of iron-lutite and immature sandstone interbeds (some reaching 40 feet) (Hotchkiss, 1919). It is distinguished by the rounded nature of some clasts and the close association with immature sandstone interbeds. Also very coarse grained, facies IF10 is an algal rudite, variously described as "jasper conglomerate," "Gnarled chert, “Algal Chert bed” (Schmidt, 1980; Hotchkiss, 1919). This facies is marked by small and rather irregular stromatolites comprised of very fine laminae in a chert matrix. Numerous oncoliths can be present, as well as scattered quartz grains and subrounded fine-medium chert/iron-mineral grains.

Moving on, facies IF1 is a ferruginous chert sandstone, that has also been described as a “quartz arenite with chert matrix”. This facies displays fine-medium quartz grains with some chert and lithic grains in a chert matrix. There are iron-oxide coatings on grains and some fine chert lenses. In addition, there are two dominantly chert facies that are not always easy to distinguish from literature descriptions. These are sometimes referred to "flinty chert" or "bedded chert" rather than granular chert or chert grains within the chert-iron arenites. Facies IF6A is a thin-bedded grey-greenish grey -yellow microcrystalline chert with dispersed interbeds of iron lutite. This facies is distinct from IF6B which is a thin bedded chert interbedded with chert arenite lenses.

Finally, there are two unique facies that only appear at specific stratigraphic levels. First, facies IF9 is a black, parallel-bedded, finely laminated iron formation with disseminated black carbon. The other facies is IF8 that is marked by dull grey massive beds that may contain black to grey angular-rounded lithic fragments.

Composite general stratigraphy The basal unit of the Ironwood Iron Formation Plymouth Member may be IF1, if present, or IF10. Facies IF10 is found near the base of the

Ironwood Iron Formation across the Gogebic range and normally 1-4ft thick from Plumer to Eureka mine. Near the Penokee gap it is 8-10 ft thick, while in the Mikado mine it is thought to reach 40 ft, where it is also associated with IF2. It is described as variously overlying the Palms Quartzite or ferruginous chert sandstone (IF1) (Hotchkiss, 1919). Facies IF4A overlies IF10 near the base of the Ironwood Iron Formation. This facies is not always present in this stratigraphic position across the range. This is followed by a coarsening upward sequence of IF2 (Hotchkiss, 1919), which then grades into thin-bedded chert (likely IF6B) (Schmidt, 1980). The chert is overlain by IF3, marking the top of the Plymouth Member. There is then an abrupt contact going into the Yale Member. The basal part of the Yale Member may be IF4, IF9 (in the middle of the range) or IF5 (in the eastern end of the range). Overlying IF5 only in the eastern portion of the Gogebic range is a lens of IF8 (east of the Puritan mine; Schmidt, 1980). Overlying IF4, IF8, and the Plymouth Member itself is stratigraphy of facies IF9. Finally, the top of the Yale Member is facies IF4 across the Gogebic range.

The transition from the Plymouth Member to the basal IF2 facies of the Norrie Member is either gradational (Hotchkiss, 1919) or marked by a thin conglomerate (Schmidt 1980). The Norrie Member displays dramatic thickness changes from 30 ft in the Windsor mine to 230-330 ft in east (Yale mine). This thickening is accompanied by increase of thick-bedded units, as well as more lutite interbeds east of the Davis mine (Hotchkiss, 1919). Finally, west of Ashland mine, the top of the Norrie Member is IF3B which grades into IF2 in the east.

From the Norrie Member, there is then an abrupt contact with facies IF4 of the Pence Member. This unit of IF4 is about 80-130 ft thick in the west, and then abruptly switches to 25ft thick at the Davis mine. Also, only in the western part of the range is 20-30 ft of IF6, marking the top of the Pence Member.

The Pence Member then is either in gradational or abrupt contact with the Anvil Member, the most variable of the Ironwood Iron Formation members. In fact, the Anvil Member is missing at certain portions in the center of the Gogebic range (Hotchkiss, 1919 and Fig 3A). The Anvil Member includes lenses of IF4 in the middle as well as near the top. At the top of the Anvil Member (or overlying the Pence Member if the Anvil is not present), is IF7. This unit is found across the range and is thought to mark the top of the Ironwood Iron Formation or the base of the overlying Tyler Formation.

Text S2. Expanded discussion of structural interpretations and comparison to previous interpretations

Mesoproterozoic Structures- Little Presque Isle thrust Across the range the Paleoproterozoic strata is overlain via an angularly unconformity by Keweenawan strata dipping steeply to the north. Based on displacement of the Keweenawan basal contact with the Tyler Formation, associated thrust faulting along the Little Presque Isle thrust was identified (see figure 3). The current orientation of the strata and this fault activity is likely due to Grenville-aged reverse faulting on the Atkins Lake Marenisco Fault to the south (cannon et al., 2008; Cannon, 1990). Restoring the Keweenawan strata rotates Paleoproterozoic units to be gently dipping south at the time of deposition and eruption, yet the there are roughly 700 million years between the Keweenawan eruptions and the original deposition of the Gogebic range Paleoproterozoic strata (Schmidt and Hubbard, 1972; Cannon et al., 2008). Thus, we argue that contrary to previous authors, this steep tilting doesn't add any crucial information in determining the much earlier original geometry and kinematics of structures developed during iron formation deposition (e.g. Cannon et al., 2008).

Late Paleoproterozoic Structures-Wolf Mountain Anticline and Wolf Mountain Thrust

The Wolf Mountain Anticline is one of the of the most obvious structural features in the area, first described by Trent, 1967. This is a structure that is plunging to the northeast in its present-day geometry, and impacts all the Paleoproterozoic strata, including the intrusions. Displacements in the basal Tyler formation contact highlight major thrust faulting along the Wolf Mountain Thrust. This thrust activity could be consistent with the generation of the wolf mountain anticline as well as explain the differences on the east and west.

Early Paleoproterozoic Structures- Emperor Fault, and Presque Ilse Fault Furthermore, the onset of explosive activity (member A) and thickness of iron formation prior to the onset of explosive activity reveals several possible locations of fault related activity and suggest the presence of faults. The Emperor fault is highlighted by displacements of the basal contact of member A south-east on the north side. This fault goes through near center of anticline and restores to correct synthetic normal fault. The emperor fault may have been associated with the eruptive phase of the emperor volcanics. However, basal D contact is not dramatically displaced by this fault, and thus faulting may have ceased by the time of its eruption. Finally, we followed the existing framework regarding the Paleoproterozoic strata-basement contact as a very early (syndepositional) normal faulted contact along the Presque Ilse fault (e.g. Cannon et al., 2008), which could be related or connected to additional extensional activity along the Wolf mountain fault. A more detailed examination of this contact is the focus of current and ongoing investigations.

Comparison to Previous interpretations There are some differences suggested based on this facies approach compared with previous interpretations (Cannon et al., 2008; Klasner et al., 1998 and Trent, 1979l; Prinz, 1967). The two most important differences are the decreased importance of extension along the little Presque isle fault and the lack of evidence for bedding parallel faults. It has been suggested that the eruption of the Emperor volcanics was associated with an extensional graben between the little Presque Isle thrust and Presque Isle fault. This interpretation stems from the observations that the volcanics appear to be thicker to the east of the little Presque Isle thrust. Yet, when the Keweenawan displacement and intrusions are removed from the units on either side of the little Presque Ilse thrust, thickness variations or displacements of the initial explosive volcanism (member A) do not exist. Thus, we suggest that this was not an important normal fault and there was not major syn-eruptive and sedimentation activity across this fault. Instead, the decreasing thickness of the volcanics to the west is a result of facies differences.

Finally, previous authors (Prinz, 1967), have suggested multiple faults with strike paralleling bedding, to explain the thickness of the iron formation in the map area. These features are suggested to be at the base of the volcanics and formed very early and folded by the Wolf Mountain Anticline (e.g. Cannon et al., 2008). Elsewhere along the Gogebic range, a bedding parallel fault ("Great Bedding Fault" of Hotchkiss, 1919) is interpreted near the top of the Yale member, but no kinematic indicators were ever identified. Without clear stratigraphy or evidence to support the bedding parallel faults or repetition, we suggest that there is indeed stratigraphic thickening in the area. However, this is the focus of continuing and future work.

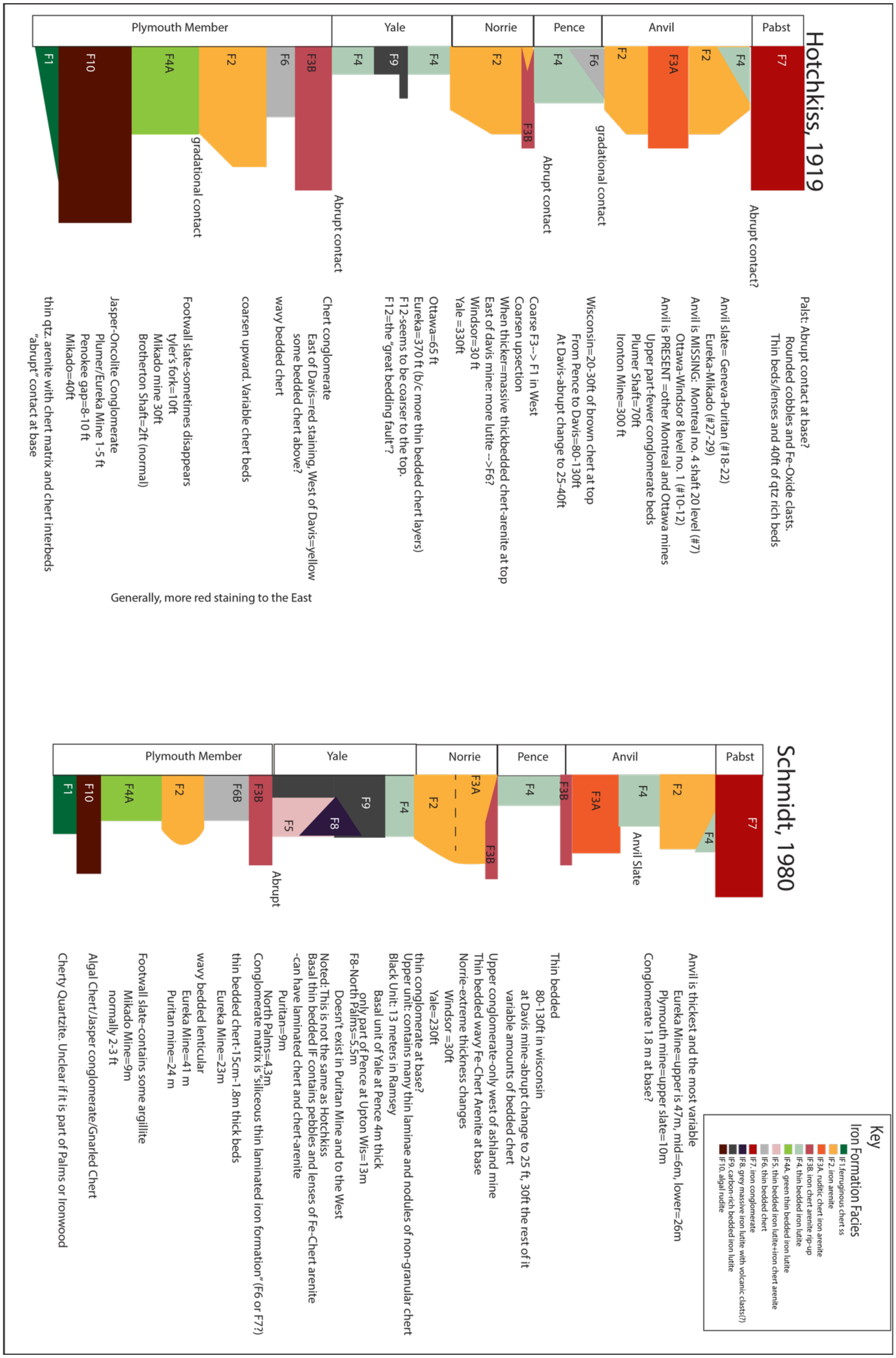

Figure S1. Composite stratigraphic data from the central Gogebic range

Supplemental Table S1-Mine information and source

Section number	Name	Location Latitude (°N), Longitude (°W)	Source
1	West side of Penokee Gap	46.2972, 90.6534	Section 1, Hotchkiss (1919)
2	Tyler's fork	46.33611, 90.49194	Section 2, Hotchkiss (1919)
3	Atlantic mine(No. 3 shaft)	46.40305, 90.30778	Section 3, Hotchkiss (1919)
4	Plumer Shaft (5 level cross cut) (aka Plummer Mine)	46.409750, 90.288742	Section 4, Hotchkiss (1919)
5	Pence No. 2 shaft and diamond drill hole	46.4166, 90.2637	Section 5, Hotchkiss (1919); Schmidt 1980
6	Montreal no 20 crosscut 23 level	46.428113, 90.233671	Section 6, Hotchkiss (1919)
7	Montreal No. 4 shaft, crosscut 20 level	46.428113, 90.233671	Section 7, Hotchkiss (1919)
8	Montreal No. 4 shaft, 8 level diamond drill hole	46.428113, 90.233671	Section 8, Hotchkiss (1919)
9	Ottawa 10 level shaft crosscut	46.428089, 90.229861	Section 9, Hotchkiss (1919)
10	Ottawa 14 level crosscut near east end of mine	46.428199, 90.229381	Section 10, Hotchkiss (1919)
11	Cary 19 level no 16 crosscut	46.43666, 90.20333	Section 11, Hotchkiss (1919)
12	Windsor 8 level No 1 crosscut (approximate)	46.442251, 90.197025	Section 12, Hotchkiss (1919); Schmidt 1980
13	Ashland Mine 13 level no 9 shaft crosscut	46.45139, 90.17178,	Section 13, Hotchkiss (1919)
14	Norrie combined 14 and 17 A shaft cross cut (approximate)	46.452507 90.161367	Section 14, Hotchkiss (1919)
15	Aurora 13 level E shaft crosscut (approximate)	*46.449987, 90.146039*	Section 15, Hotchkiss (1919)
17	Davis 4 level shaft crosscut (aka Geneva-Davis Mine)	46.461160, 90.112927	Section 17, Hotchkiss (1919); Schmidt 1980
18	Geneva 17 level crosscut 350 ft east of shaft	46.461124, 90.112892	Section 18, Hotchkiss (1919)
19	Puritan 14 level shaft crosscut	46.46944, 90.08722	Section 19, Hotchkiss (1919); Schmidt 1980
20	Ironton Crosscut 500 ft east on 17 level (aka petersen mine)	46.47194, 90.06750	Section 20, Hotchkiss (1919)
21	Ironton crosscut 1860 ft east on 17 level (aka petersen mine) Note Ironton and Petersen mine, not exact location (shifted over the years)	46.47194, 90.06750	Section 21, Hotchkiss (1919)
22	Yale no 1 shaft crosscut 11 level (aka Valley; Benjamin; West Colby; Yale Jackpot)	46.4681, 90.0673	Section 22, Hotchkiss (1919) Schmidt 1980
23	Colby 9 level no 2 shaft crosscut (Colby Mine, Peterson Mine)	46.47333, 90.05611	Section 23, Hotchkiss (1919)

24	Tilden 9 level no 6 shaft crosscut	46.47389, 90.03639	Section 24, Hotchkiss (1919)
25	Tilden 23 Level no 10 shaft crosscut 1250 ft west of shaft	46.47389, 90.03639	Section 25, Hotchkiss (1919)
26	Tilden 14 level no 10 shaft crosscut 180ft east of shaft	46.47389, 90.03639	Section 26, Hotchkiss (1919)
28	Eureka 15 level no 2 shaft crosscut (aka Eureka-Asteroid Mine (Eureka Mine))	46.47583, 89.98427	Section 28, Hotchkiss (1919); Schmidt 1980
29	Mikado mostly from diamond drill footwall	46.4755, 89.9756	Section 29, Hotchkiss (1919) Schmidt 1980

*Note sections 16 and 27 from Hotchkiss 1919 were not included in this compilation as original name or location data was not provided

*Mine locations via USGS Mineral resource database -obtained via google earth .kmz files

The following mine locations are not on the MDRS database:

The Ottawa Mine is reported to have been located in Gogebic County but the exact location has not been identified. But in old bulletins, appears to be near/associated with the Montreal Mine (WIS)

The Norrie Mine, including the North Norrie Mine, was located southeast of downtown Ironwood. It was also known as the "big" Norrie Mine. The mine was owned and operated by the Oliver Mining Company.

Aurora Mine was located in Ironwood, east of the Norrie Mine. It was owned by the Oliver Mining Company. It was located in the southwest 1/4 of Section 22, T47N-R47W and also part of Section 21.

Windsor 8 level No 1 crosscut (approximate: http://mattsonworks.com/1912/1912Ironmap.html)

http://mattsonworks.com/1912/1912Ironmap.html

http://www.michiganrailroads.com/stations-locations/645-gogebic-county-27/gogebic-county-mines

Table S1. Location and source details for mine stratigraphic data