Bibliography of Papers on the Iron Deposits of the Penokee Range, Wisconsin

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Contents

Introduction

The geology of the Penokee Range of northern Wisconsin has long been of interest because of the mineral resources and great diversity of rocks present. Specifically, the iron resources of the Ironwood Formation have been of interest since the 1850s. Recent (2011 and 2012) interest in iron mining in the Penokees has prompted this study in an effort to compile a bibliography of published information on the geology of the Ironwood Iron Formation and adjacent rocks. This compilation of published papers focuses on the bedrock geology of the range but includes some relevant papers on the origin of iron formations, surficial and environmental geology.

The bedrock is well exposed at the surface and reveals a stratigraphic section of rock approximately 25 Km thick that spans at least 1.7 billion years. This stratigraphic section contains a wide variety of rocks and records important geologic events of the Neoarchean through Mesoproterozoic. Because of this diversity of rocks, the geology of the Penokee Range has been study in some detail. Much of the foundational work has been published by the Wisconsin Geological Survey and the U.S. Geological Survey, as well as academic researchers deciphering the geologic history of the region.

The first section of this bibliography is an alphabetical listing of all papers and the second section is an annotated bibliography with papers organized by topic. Only papers that have been published in peer-reviewed or widely published journals have been included. Hyperlinks are included for papers that are available on the Internet, and hyperlinks to pdf files are included for other papers.

Special attention is given to the stratigraphy, mineralogy, and petrology of the rocks in and adjacent to the Ironwood Formation.

Part I: Alphabetical list of papers

Addison, W.D., Brumpton, G.R., Vallini, D.A., McNaughton, N.J., Davis, D., Kissin, S.A., Fralick, P.W., Hammond, A.L., 2005, Discovery of distil ejecta from the 1850 Ma Sudbury impact event: Geology, v. 33, no. 3, p. 193-196. http://geology.gsapubs.org/content/33/3/193.full.pdf+html?sid=ab16a091-d4f8-4927-a0dc-7c5c288922e0

Aldrich, 1929, Geology of the Gogebic Iron Range of Wisconsin: Wisconsin Geological and Natural History Survey, Bulletin No. 71, Economic Series No. 24. http://digicoll.library.wisc.edu/cgi-bin/EcoNatRes/EcoNatRes-idx?id=EcoNatRes.WGB71Econ24 (Also pdf files in three sections: pdf1 pdf2 pdf3)

Alwin, B.W., 1976, Sedimentation of the middle Precambrian geology of northcentral Wisconsin and northwestern Michigan: Duluth, M.N., University of Minnesota, unpublished Masters thesis, 200 p. Three sections: pdf1 pdf2 pdf3

Atwater, G.I., 1938, Correlation of the Tyler and Copps formations of the Gogebic iron district: Geological Society of America Bulletin, v. 49, p. 151-194. pdf

Bekker, A., Slack, J.F., Planavsky, N., Krapez, B., Hofmann, A., Konhauser, K.O., and Rouxel, O., 2010, Iron Formation: The Sedimentary Product of a Complex Interplay among mantle, tectonic, oceanic, and biospheric processes: Economic Geology, v. 105 no. 3 p. 467-508. pdf

Bekker, A., Holland, H.D., Wang, P.L., Rumble, D. III, Stein, H.J., Hannah, J.L., Coetzee, L.L., and Beukes, N.J., 2004, Dating the rise of atmospheric oxygen: Nature, v. 427, p. 117-120. pdf

Bekker, A., Krapez, B., Slack, J.F., Planavsky, N., Hofmanm, A., Konhauser, K.O., Rouxel, O.J., Iron Formation: The Sedimentary Product of a Complex Interplay among mantle, tectonic, oceanic, and biospheric processes – a reply: Economic Geology, v. 107, p. 377-380. pdf

Cannon, W.F. and Gair, J.E., 1970, A revision of the stratigraphic nomenclature for middle Precambrian rocks in northern Michigan: Geological Society of America Bulletin, v. 81, no. 9, p. 2843-2846. http://gsabulletin.gsapubs.org/content/81/9/2843.full.pdf+html?sid=269cd827-daa2-4e44-b95f-6ebb85190e52

Cannon, W.F., 2011, Geology of the Montreal River Monocline: Institute on Lake Superior Geology, Institute on Lake Superior Geology, 57th Annual Meeting, Ashland, WI, v. 57, part 2, p.111-126. http://mgmudrey.brinkster.net/ILSG/ILSG_57_2011_pt2_Ashland.pdf

Cannon, W.F., and Fralick, P., 2010, Western Gogebic Iron Range in Wisconsin, *in* Miller, J.D., ed., Field Guide to the Geology of Precambrian Iron Formations in the Western Lake Superior Region, Minnesota and Michigan: Precambrian Research Center Professional Workshop Series guidebook, p. 1-14. http://www.d.umn.edu/prc/workshops/Guidebooks/BIF%20Guidebook.1.pdf

Cannon, W.F., LaBerge, G.L., Klasner, J.S., and Schulz, K.J. 2008, The Gogebic Iron Range -- A sample of the northern margin of the Penokean Fold and Thrust Belt: U.S.G.S. Professional Paper 1730. http://pubs.usgs.gov/pp/pp1730/

Cannon, W.F., LaBerge, G.L., Klasner, J.S., and Schulz, K.J. 2008, The Gogebic Iron Range -- A sample of the northern margin of the Penokean Fold and Thrust Belt: U.S.G.S. Professional Paper 1730. http://pubs.usgs.gov/pp/pp1730/

Cannon, W.F., Schulz, K.L., Horton, J.W., and Kring, D.A., 2010, the Sudbury impact layer in the Paloeproterozoic iron ranges of northern Michigan, USA, Geological Society of America Bulletin, v. 122, no. 1/2, p. 50-75. http://gsabulletin.gsapubs.org/content/122/1-2/50.full.pdf+html?sid=a5d2f18c-0407-4b47-bc1e-5dc22b5c6ab7

Cannon, W.F., Woodruff, L.G., Nicholson, S.W., Hedgeman, C.A., 1996, Bedrock geologic map of the Ashland and northern part of the Ironwood 30'x60' quadrangles, Wisconsin and Michigan, scale: 1:100,000, one sheet. http://tin.er.usgs.gov/catalog/cite-view.php?cite=398 Print versions of this publication available at the USGS Store: 28735

Clayton, L., 1984, Pleistocene geology of the Superior Region, Wisconsin: Wisconsin Geological and Natural History Survey, Information Circular Number 46, 40 p. Includes one plate, map at scale of 1:250,000. http://wisconsingeologicalsurvey.org/pdfs/IC46.pdf

Crowell and Murray, 1920, The Iron Ores of Lake Superior, The Penton Press, Ohio, 277 p.
http://books.google.com/books/about/The_iron_ore_deposits_of_the_Lake_Superi.html?id=TmrhAAAAMAAJ

Evans, T.J., An overview of metallic mineral regulation in Wisconsin; third edition: Wisconsin Geological and Natural History, Survey, Special Report 13. http://wisconsingeologicalsurvey.org/pdfs/miscpdf/sr13.pdf

Fisher, W.W., and Knoll, A.H., 2009, An iron shuttle for deepwater silica in Late Archean and early Paleoproterozoic iron formation: Geological Society of America Bulletin, v. 121, no. 1-2, p. 222-245. pdf

Fitz, T., 2012, The Ironwood Iron Formation of the Penokee Range: Wisconsin People and Ideas Magazine, Spring 2012, p. 32-39. pdf

Gole, M. J. and Klein, C., 1981, Banded iron-formations through much of Precambrian time: Geological Society of America Bulletin, v. 89, no. 2, p. 169-183. pdf

Hotchkiss, W.O., 1919, Geology of the Gogebic range and its relation to recent mining developments: Engineering and Mining Journal, v. 108, p. 443-582. pdf

Huber, N.K., 1959, Some aspects of the Ironwood Iron-Formation of Michigan and Wisconsin: Economic Geology, v. 54, p. 82-118. pdf

Irving, R.D. and Van Hise, C.R., 1892, The Penokee iron-bearing series of Michigan and Wisconsin: U.S. Geological Survey Monograph 19, 534 p. http://www.biodiversitylibrary.org/item/95067#page/17/mode/1up

James, H.L., 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geological Society of America Bulletin, v. 66, no. 12, p. 1455-1487. pdf

James, H.L., 1958, Stratigraphy of pre-Keweenawan rocks in parts of northern Michigan, in shorter contributions to general geology, 1957: U.S. Geological Survey Professional Paper 314-C, p. 27-44. http://pubs.usgs.gov/pp/0314c/report.pdf

Klasner, J.S., 1978, Penokean deformation and associated metamorphism in the western Marquette range, northern Michigan: Geological Society of America Bulletin, v. 89, no. 5, p. 711-722. pdf

Klasner, J.S., 1996, Lake Namekagon and Penokee Gap Areas, West Gogebic Range, Wisconsin: Institute on Lake Superior Geology, 42nd annual meeting, Cable, Wisconsin. http://mgmudrey.brinkster.net/ILSG/ILSG_42_1996_pt3_Cable.cv.pdf

Klein, C., 2005, Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origins; American Mineralogist, v. 90, no. 10, p. 1473-1499. pdf

Knoll, A.H., and Barghorn, E.S., 1974, Ambient pyrite in Precambrian chert: New evidence and a theory: Proceedings of the National Academy of Sciences, v. 71, no. 6, p. 2329-2331. Pdf http://www.ncbi.nlm.nih.gov/pmc/articles/PMC388446/pdf/pnas00059-0179.pdf

Konhauser, 2000, Hydrothermal bacterial biomineralization: potential modern-day analogues for banded iron-formations, *in*, Glen, C.R., Provot, L., Lucas, J., eds, Authigenesis: from global to microbial: SEPM Special Publication, v. 66, p. 133-145. pdf

LaBerge, G. L., 1967, Microfossils and Precambrian iron-formations: Geological Society of America Bulletin, v. 78, no. 3, p. 341-342. pdf

LaBerge, G. L., 1996, Volcanogenic massive sulfide deposits of northern Wisconsin: A commemorative volume: Institute on Lake Superior Geology Proceedings, 42nd Annual Meeting, Cable, WI, v. 42, part 2, 179 p. http://mgmudrey.brinkster.net/ILSG/ILSG_42_1996_pt2_Cable.cv.pdf

LaBerge, G. L., and Mudrey Jr., M.G., 1979, Middle Precambrian geology of northern Wisconsin *in* Proceedings, Institute on Lake Superior Geology, 25th annual meeting, Duluth, MN, May 8-13, 1979: Wisconsin Geological and Natural History Survey Field Trip Guidebook 4, 48 p. pdf

Larue, D.K., and Sloss, L.L., 1980, Early Proterzoic sedimentary basins of the Lake Superior region: Geological Society of America Bulletin, v. 91, pt. 1, no. 8, p. 450-452. pdf

Liesch, M., 2008, A Region of Hope, A Region of Despair: Print Media, geographical imagination, and the Gogebic Iron Range mining boom: Historical Geography, v. 36. http://www.historical-geography.net/volume_36_2008/liesch.pdf

Marsden, R.W., 1978, Iron ore reserves of Wisconsin-A minerals availability system report, *in* Proceedings, American Institute of Mining Engineers, 51st annual meeting, Minnesota Section, Duluth, M.N. Jan. 11-13, 1978: Duluth, M.N., University of Minnesota, American Institute of Mining Engineers, no. 39, p. 24-1 to 24-28. pdf

MDEQ and Cliffs Natural Resources, January, 2010; Update on Selenium Projects at Tilden and Empire Mines, MI. http://www.michigan.gov/documents/deq/wrd-npdes-EmpireTilden-Vol1_364698_7.pdf

MI Department of Community Health, March, 2010, Letter of Health Consultation; Interim Consumption Screening Values for Total Selenium, Goose Lake, Selenium, MI. http://www.michigan.gov/documents/mdch/Goose_Lake_Selenium_LHC-_FINAL-3-10-2011_369145_7.pdf

MIDEQ, Selenium Monitoring Work Group, June, 2009, An assessment of Environmental Selenium Levels Around Empire and Tilden Mines, Marquette County, MI: MI/DEQ/WB-09/038. http://www.michigan.gov/documents/deq/wb-swas-selenium-report_287994_7.pdf

Miller, J.D., 2010, Field Guide to the Geology of Precambrian Iron Formations in the Western Lake Superior Region, Minnesota and Michigan: Precambrian Research Center Professional Workshop Series guidebook. http://www.d.umn.edu/prc/workshops/Guidebooks/BIF%20Guidebook.1.pdf

Morey, G.B., 1999, High-grade iron ore deposits of the Mesabi Range, Minnesota; product of a continent-scale ground-water flow system: Economic Geology, v. 94, no. 1, p. 30-44. pdf

Mudrey Jr., M. G., 1979, Geologic summary of the Ashland 2-degree quadrangle: Wisconsin Geological and Natural History Survey Open-File report 79-1 46 p. pdf

Nanz Jr., R. H., 1953, Chemical composition of Pre-Cambrian slates with notes on the geochemical evolution of lutites: The Journal of Geology, v. 61, no. 1, p. 51-64. pdf

Ojakangas, R.W., 1983, Tidal deposits in the early Proterozoic basin of the Lake Superior region; the Palms and Pokegama Formations; evidence of subtidal-deposition of the superior-type banded iron-formation, in Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 49-56. pdf

Ojakangas, R.W., Morey, G.B., and Southwick, D.L. 2001, Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America: Sedimentary Geology, v. 141-142, p. 319-341. pdf

Planavsky, 2011, Widespread iron-rich conditions in the mid-Proterozoic ocean: Nature, v. 477, p. 448-451. pdf

Pufahl, P.K., Hiatt, E.E., Stanley, C.R., Morrow, J.R., Nelson, G.J., Edwards, C.T., 2007, Physical and chemical evidence of the 1850 Ma Sudbury impact event in the Baraga Group, Michigan: Geology, v. 35, no. 9, p. 827-830. http://geology.gsapubs.org/content/35/9/827.full.pdf+html?sid=5b45cb10-1043-4feb-a2c1-dfe7cb341e00

Rasmussen, B., Fletcher, I.R., Bekker, A., Muhling, J.R., Gregory, C.J., and Thorne, A.M., 2012, Deposition of 1.88-billion-year-old iron formations as a consequence of rapd crustal growth: Nature, v. 484, p. 498-501. pdf

Schmidt, R.G., 1976, Geology of the Precambrian W (lower Precambrian) rocks in western Gogebic County, Michigan: U.S. Geological Survey Bulletin 1407, 40 p. pdf

Schmidt, R.G., 1980, The Marquette Range Supergroup in the Gogebic iron district, Michigan and Wisconsin: Geological Survey Bulletin 1460, 32 p. pdf

Schmidt, R.G., and Hubbard, H.A., 1972, Penokean orogeny in the central and western Gogebic region, Michigan and Wisconsin, field trip A in, Field Trip Guidebook, Institute on Lake Superior Geology, 18th annual meeting, 1972, v. 18, p. A1-A27. http://mgmudrey.brinkster.net/ILSG/ILSG_18_1972_abs_Houghton.CV.pdf

Schneider, D.A., Bickford, M.E., Cannon, W.F., Schulz, K.J., and Hamilton, M.A., 2002, Age of volcanic rocks and syndepositional iron formation, Marquette Range Supergroup; implications for the tectonic setting of Paleoprozoic iron formations of the Lake Superior region: Canadian Journal of Earth Sciences, v. 39, no. 6, p. 999-1012. pdf

Simonson, B. M., 1985, Sedimentological constraints on the origins of Precambrian iron-formations: Geological Society of America Bulletin,v. 96, no. 2, p. 244-252. pdf

Simonson, B. M. and Hassler, S. W., 1996, Was the deposition of large Precambrian iron formations linked to major marine transgressions?: The Journal of Geology, v. 104, no. 6, p. 665-676. pdf

Sims, P. 1976, Precambrian tectonics and mineral deposits, Lake Superior Region: Economic Geology, v. 71, p. 1092-1127. pdf

Sims, P.,K., and Peterman, Z.C., 1983, Evolution of Penokean foldbelt, Lake Superior region, and its tectonic environment, *in*, Geological Society of America, Memoir 160, p. 3-14. pdf

Sims, P.K., Peterman, Z.E., and Prinz, W.C., 1977, Geology of Rb-Sr age of Precambrian W Puritan Quartz Monzonite, northern Michigan: U.S. Geological Survey Journal of Research, v. 5, p. 185-192. pdf

Slack, J.F., and Cannon, W.F., 2009, Extraterrestrial demise of banded iron formations 1.85 billion years ago: Geology, v. 37, p. 1011-1014. http://geology.gsapubs.org/content/37/11/1011.full.pdf+html?sid=61106771-1cb3-42c5-96cb-338c1097846a

Taylor, K.G., and Konhouser, K.O., 2011, Iron in Earth surface systems: A major player in chemical and biological processes: ELEMENTS, v. 7, no. 2, p. 83-88. pdf

Trendall, A.F., 1968, Three great basins of Precambrian banded iron formation deposition: A systematic comparison: Geological Society of America Bulletin, v. 79, no. 9, p. 1527-1544. pdf

Trendall, A.F., 2012, Iron formation: the sedimentary product of a complex interplay among mantle, tectonic, oceanic, and biospheric processes – a discussion: Economic Geology, v. 107, p. 377-380. pdf

Tyler, S.A., and Barghoorn, E.S., 1963, Ambient pyrite grains in Precambrian cherts: American Journal of Science, v. 261, p. 424-432. pdf

Van Hise, C.R., 1901, The iron ore deposits of the Lake Superior region: US Geological Survey Annual Report: U.S. Geological Survey Annual Report, v. 21, pt. 3, p. 305-434. http://books.google.com/books?id=TmrhAAAAMAAJ&printsec=frontcover&dq=The+iron+ore+deposits+of+the+Lake+Superior+region&hl=en&sa=X&ei=m6QJUbyCLObW2gW-y4GICQ&ved=0CDYQ6AEwAA#v=onepage&q=The%20iron%20ore%20deposits%20of%20the%20Lake%20Superior%20region&f=false

Van Hise, C.R., and Leith, C.K., 1911, The geology of the Lake Superior region; US Geological Survey Monograph 52: 641 p. http://www.archive.org/details/geologyoflakesup00vanh

Williams, S.C.P., 2012, Traces of Inaugural Life: Science News, v. 181, no. 10.

http://www.sciencenews.org/view/feature/id/340401/description/Traces_of_Inaugural_Life

Part II. Annotated Bibliography -- Papers Listed by Topic

Penokee Range Geology

Aldrich, 1929, Geology of the Gogebic Iron Range of Wisconsin: Wisconsin Geological and Natural History Survey, Bulletin No. 71, Economic Series No. 24.

http://digicoll.library.wisc.edu/cgi-bin/EcoNatRes/EcoNatRes-idx?id=EcoNatRes.WGB71Econ24 (Also pdf files in three sections: pdf1 pdf2 pdf3)

This book has excellent descriptions of the geology of the range – it contains some of the detailed stratigraphic, mineralogical, and petrologic information. It goes into more detail than earlier publications on the bedrock geology of the range, and is sited extensively more recent papers. The stratigraphic units are described individually on pages 82 through 110, including the stratigraphy, structure, metamorphism, contacts and ore bodies of the Ironwood, and the petrology and contacts of the Tyler. The geology of Township 44 and 45 N, Range 1 W, which is of primary interest, is covered on pages 204 to 216.

Alwin, B.W., 1976, Sedimentation of the middle Precambrian geology of northcentral Wisconsin and northwestern Michigan: Duluth, M.N., University of Minnesota, unpublished Masters thesis, 200 p. Three sections: pdf1 pdf2 pdf3

Alwin's thesis has good descriptions of the Tyler Formation where it is exposed near Ironwood, Michigan. It contains information on stratigraphic thickness of measured sections (pdf 1 and pdf 2), and petrological information and photomicrographs of slates of the Tyler (pdf 3).

Atwater, G.I., 1938, Correlation of the Tyler and Copps formations of the Gogebic iron district: Geological Society of America Bulletin, v. 49, p. 151-194. pdf

This paper discusses bounding unconformities and correlations within the Paleoproterzoic stratigraphy.

Cannon, W.F., LaBerge, G.L., Klasner, J.S., and Schulz, K.J. 2008, The Gogebic Iron Range -- A sample of the northern margin of the Penokean Fold and Thrust Belt: U.S.G.S. Professional Paper 1730. http://pubs.usgs.gov/pp/pp1730/

This is the most detailed recent publication on the Penokee/Gogebic range. It includes an excellent compilation and summary of previous work, including descriptions of the stratigraphy, a summary of the economic geology, and the latest description and interpretation of the structural geology and tectonic history. The map that accompanies the book is the most detailed published bedrock geologic map of the area. It covers the area from the western end of the Gogebic Range where the Ironwood Formation ends, eastward into Iron County, Wisconsin.

Clayton, L., 1984, Pleistocene geology of the Superior Region, Wisconsin: Wisconsin Geological and Natural History Survey, Information Circular Number 46, 40 p. http://wisconsingeologicalsurvey.org/pdfs/IC46.pdf

This is an important summary of the surficial geology of northwestern Wisconsin. The Pleistocene and Holocene deposits are described in detail and their distribution is shown on the accompanying map. The bedrock backbone of the Penokee Range does not have thick surficial units so is mapped simply as "bedrock", whereas the surficial deposits to the north and south are thicker and are shown in detail on the map.

Hotchkiss, W.O., 1919, Geology of the Gogebic range and its relation to recent mining developments: Engineering and Mining Journal, v. 108, p. 443-582. pdf

This paper describes the alteration of iron formation and the development of soft ores.

Huber, N.K., 1959, Some aspects of the Ironwood Iron-Formation of Michigan and Wisconsin: Economic Geology, v. 54, p. 82-118. pdf

This contains important descriptions of stratigraphy, lateral continuity of members, and mineral and rock types within the Ironwood Formation. It includes a brief description of pyrite-rich layers in carbonaceous slates (p. 100).

Irving, R.D. and Van Hise, C.R., 1892, The Penokee iron-bearing series of Michigan and Wisconsin: U.S. Geological Survey Monograph 19, 534 p. http://www.biodiversitylibrary.org/item/95067#page/17/mode/1up

This is earliest published work on the Penokee Range.

James, H.L., 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geological Society of America Bulletin, v. 66, no. 12, p. 1455-1487. pdf

This paper describes the metamorphic zones, their mineralogy, and the relationship between metamorphic grade and the development of soft ores. The occurrence of amphibole, including grunerite, in metamorphosed iron formation is described in areas where the metamorphic grade was high. Although the paper is of regional scope and is mostly focused on Michigan, some mention is made of the presence of amphibole in Iron County, Wisconsin (p. 1477).

James, H.L., 1958, Stratigraphy of pre-Keweenawan rocks in parts of northern Michigan, in shorter contributions to general geology, 1957: U.S. Geological Survey Professional Paper 314-C, p. 27-44. http://pubs.usgs.gov/pp/0314c/report.pdf

Marsden, R.W., 1978, Iron ore reserves of Wisconsin--A minerals availability system report, *in* Proceedings, American Institute of Mining Engineers, 51st annual meeting, Minnesota Section, Duluth, M.N. Jan. 11-13, 1978: Duluth, M.N., University of Minnesota, American Institute of Mining Engineers, no. 39, p. 24-1 to 24-28. pdf

This is a very important paper, especially the sections on pages 24-7 through 24-20 on the Gogebic Range. Marsden's figure of 3.711 billion tons of iron ore reserves and the geologic cross section of a possible open-pit mine (p. 24-11) are widely cited. The paper describes Ironwood Formation in detail including the upper and lower ore zones, waste rock, mineralogy, structure, metamorphism (including presence of grunerite), and reserves of iron. The Ironwood is described as being about 600 to 800 feet thick (p. 24-

9). There is also discussion of the possible geometry of a mine pit given the dip of the bedding (p. 24-24).

Schmidt, R.G., 1980, The Marquette Range Supergroup in the Gogebic iron district, Michigan and Wisconsin: Geological Survey Bulletin 1460, 32 p. pdf

This is a very important paper on the stratigraphy of the Penokee/Gogebic Range. It is an excellent compilation of earlier work and also contains important new information gathered by Schmidt from cores, mines, and test pits in the Hurley area which are no longer available for study.

Schmidt, R.G., 1976, Geology of the Precambrian W (lower Precambrian) rocks in western Gogebic County, Michigan: U.S. Geological Survey Bulletin 1407, 40 p. pdf

This is the best description of the Neoarchean rocks underlying the Paleoproterozoic rocks of the Range. The metavolcanic rocks of the Ramsey formation and the Puritan quartz monzonite are especially of interest since they underlying the Paleoproterozoic rocks in Wisconsin.

Van Hise, C.R., 1901, The iron ore deposits of the Lake Superior region: US Geological Survey Annual Report: U.S. Geological Survey Annual Report, v. 21, pt. 3, p. 305-434. http://books.google.com/books?id=TmrhAAAAMAAJ&printsec=frontcover&dq=The+iron+ore+deposits+of+the+Lake+Superior+region&hl=en&sa=X&ei=m6QJUbyCLObW2gW-y4GICQ&ved=0CDYQ6AEwAA#v=onepage&q=The%20iron%20ore%20deposits%20of%20the%20Lake%20Superior%20region&f=false

Field Guides

Field guidebooks from trips run at meetings of the Institute on Lake Superior Geology and the Precambrian Research Center of the University of Minnesota-Duluth give descriptions of and directions to the best outcrops in Penokee Range. They are excellent overviews of the geology.

Cannon, W.F., 2011, Geology of the Montreal River Monocline: Institute on Lake Superior Geology, Institute on Lake Superior Geology, 57th Annual Meeting, Ashland, WI, v. 57, part 2, p.111-126. http://mgmudrey.brinkster.net/ILSG/ILSG_57_2011_pt2_Ashland.pdf

This guidebook provides an excellent overview of the bedrock of the Range and describes outcrops in the Ironwood Formation on Mt. Whittlesey near Mellen, Wisconsin.

Cannon, W.F., and Fralick, P., 2010, Western Gogebic Iron Range in Wisconsin, *in* Miller, J.D., ed., Field Guide to the Geology of Precambrian Iron Formations in the Western Lake Superior Region, Minnesota and Michigan: Precambrian Research Center Professional Workshop Series guidebook, p. 1-14. http://www.d.umn.edu/prc/workshops/Guidebooks/BIF%20Guidebook.1.pdf

This field guide includes stops on Mt. Whittlesey and in the enigmatic rocks near Atkins Lake.

Klasner, J.S., 1996, Lake Namekagon and Penokee Gap Areas, West Gogebic Range, Wisconsin: Institute on Lake Superior Geology, 42nd annual meeting, Cable, Wisconsin. http://mgmudrey.brinkster.net/ILSG/ILSG_42_1996_pt3_Cable.cv.pdf

This chapter includes a stop in the Tyler Formation at Penokee Gap west of Mellen, Wisconsin where there are outcrops of pyritic carbonaceous slates in the lower part of the Tyler Formation. Outcrops in the lower part of the Tyler are rare. The guidebook includes descriptions of mineralogy and structural geology.

LaBerge, G. L., and Mudrey Jr., M.G., 1979, Middle Precambrian geology of northern Wisconsin *in* Proceedings, Institute on Lake Superior Geology, 25th annual meeting, Duluth, MN, and Wisconsin Geological and Natural History Survey Field Trip Guidebook 4, 48 p. pdf

This guidebook contains descriptions of and directions to excellent outcrops in many parts of the stratigraphy from Grand View Wisconsin east to Hurley. There is an excellent description of the rocks on Mt. Whittlesey and a discussion of the economic geology (p. 15-20).

Miller, J.D., 2010, Field Guide to the Geology of Precambrian Iron Formations in the Western Lake Superior Region, Minnesota and Michigan: Precambrian Research Center Professional Workshop Series guidebook. http://www.d.umn.edu/prc/workshops/Guidebooks/BIF%20Guidebook.1.pdf

Schmidt, R.G., and Hubbard, H.A., 1972, Penokean orogeny in the central and western Gogebic region, Michigan and Wisconsin, field trip A in, Field Trip Guidebook, Institute on Lake Superior Geology, 18th annual meeting, 1972, v. 18, p. A1-A27. http://mgmudrey.brinkster.net/ILSG/ILSG_18_1972_abs_Houghton.CV.pdf

Maps

Cannon, W.F., Woodruff, L.G., Nicholson, S.W., Hedgeman, C.A., 1996, Bedrock geologic map of the Ashland and northern part of the Ironwood 30’x60’ quadrangles, Wisconsin and Michigan, scale: 1:100,000, one sheet. http://tin.er.usgs.gov/catalog/cite-view.php?cite=398 Print versions of this publication available at the USGS Store: 28735

This is the most detailed published map of the region. It is an excellent compilation of the data and interpretations of the geology of Penokee region in Wisconsin. It does not extend to the western extent of the Ironwood Formation (that is shown on Cannon et al., 2008). The legend contains an excellent summary of the geologic history.

Cannon, W.F., LaBerge, G.L., Klasner, J.S., and Schulz, K.J. 2008, The Gogebic Iron Range -- A sample of the northern margin of the Penokean Fold and Thrust Belt: U.S.G.S. Professional Paper 1730. http://pubs.usgs.gov/pp/pp1730/

This paper is described in the section above on Penokee Range Geology, but is included here because the map is the most detailed published map of the Ironwood and adjacent rocks in the western part of the Penokee/Gogebic Range.

Clayton, L., 1984, Pleistocene geology of the Superior Region, Wisconsin: Wisconsin Geological and Natural History Survey, Information Circular Number 46, plate 1, scale 1:250,000. http://wisconsingeologicalsurvey.org/pdfs/IC46.pdf The map is not available on the Internet, but is for sale through the WGNHS.

See description above, in the Penokee Range Geology section.

Regional Geology

Papers included in this section provide the general geologic framework and economic geology of the region.

Cannon, W.F. and Gair, J.E., 1970, A revision of the stratigraphic nomenclature for middle Precambrian rocks in northern Michigan: Geological Society of America Bulletin, v. 81, no. 9, p. 2843-2846. http://gsabulletin.gsapubs.org/content/81/9/2843.full.pdf+html?sid=269cd827-daa2-4e44-b95f-6ebb85190e52

Crowell and Murray, 1920, The Iron Ores of Lake Superior, The Penton Press, Ohio, 277 p. http://books.google.com/books/about/The_iron_ore_deposits_of_the_Lake_Superi.html?id=TmrhAAAAMAAJ

Klasner, J.S., 1978, Penokean deformation and associated metamorphism in the western Marquette range, northern Michigan: Geological Society of America Bulletin, v. 89, no. 5, p. 711-722. pdf

Knoll, A.H., and Barghorn, E.S., 1974, Ambient pyrite in Precambrian chert: New evidence and a theory: Proceedings of the National Academy of Sciences, v. 71, no. 6, p. 2329-2331. Pdf http://www.ncbi.nlm.nih.gov/pmc/articles/PMC388446/pdf/pnas00059-0179.pdf

This paper describes the “starburst” texture of pyrite in the carbonaceous shales associated with iron formations in the Hammersly Basin of Western Australia and the Biwabik Formation of Minnesota. The texture is interpreted to have formed by pressure solution caused by gas evolution from the organic material.

LaBerge, G. L., 1996, Volcanogenic massive sulfide deposits of northern Wisconsin: A commemorative volume: Institute on Lake Superior Geology Proceedings, 42nd Annual Meeting, Cable, WI, v. 42, part 2, 179 p. http://mgmudrey.brinkster.net/ILSG/ILSG_42_1996_pt2_Cable.cv.pdf

Larue, D.K., and Sloss, L.L., 1980, Early Proterzoic sedimentary basins of the Lake Superior region: Geological Society of America Bulletin, v. 91, pt. 1, no. 8, p. 450-452. pdf

Mudrey Jr., M. G., 1979, Geologic summary of the Ashland 2-degree quadrangle: Wisconsin Geological and Natural History Survey Open-File report 79-1 46 p. pdf

Ojakangas, R.W., 1983, Tidal deposits in the early Proterozoic basin of the Lake Superior region; the Palms and Pokegama Formations; evidence of subtidal-deposition of the superior-type banded iron-formation, in Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 49-56. pdf

Ojakangas, R.W., Morey, G.B., and Southwick, D.L. 2001, Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America: Sedimentary Geology, v. 141-142, p. 319-341. pdf

Schneider, D.A., Bickford, M.E., Cannon, W.F., Schulz, K.J., and Hamilton, M.A., 2002, Age of volcanic rocks and syndepositional iron formation, Marquette Range Supergroup; implications for the tectonic setting of Paleoprozoic iron formations of the Lake Superior region: Canadian Journal of Earth Sciences, v. 39, no. 6, p. 999-1012. pdf

This paper discusses the timing, environment of deposition, and the tectonics of the Paleoproterozoic rocks of the Penokee/Gogebic Range. Rhyolite correlated with the Negaunee Iron Formation dates at 1874 and 1878 Ma, post-tecontic plutons that cross cut these rocks are dated at 1833 Ma.

Sims, P. 1976, Precambrian tectonics and mineral deposits, Lake Superior Region Economic Geology, v. 71, p. 1092-1127. pdf

This is a wide ranging paper with broad scope about the tectonics of the region.

Sims, P.,K., and Peterman, Z.C., 1983, Evolution of Penokean foldbelt, Lake Superior region, and its tectonic environment, *in*, Geological Society of America, Memoir 160, p. 3-14. pdf

Sims, P.K., Peterman, Z.E., and Prinz, W.C., 1977, Geology of Rb-Sr age of Precambrian W Puritan Quartz Monzonite, northern Michigan: U.S. Geological Survey Journal of Research, v. 5, p. 185-192. pdf

This paper reports important radiometric age dates on the Neoarchean rocks under the Ironwood. The Puritan quartz monzonite has an age of 2710 +/- 140 Ma.

Tyler, S.A., and Barghoorn, E.S., 1963, Ambient pyrite grains in Precambrian cherts: American Journal of Science, v. 261, p. 424-432. pdf

This paper describes quartz and carbonate trails around pyrite crystals in carbonaceous slates in the Gunflint Iron Formation of the Ontario and the Biwabik Formation of Minnesota. The interpretation is that the crystallization of quartz and carbonate minerals propelled the pyrite grains through the solid rock.

Van Hise, C.R., and Leith, C.K., 1911, The geology of the Lake Superior region; US Geological Survey Monograph 52: 641 p. http://www.archive.org/details/geologyoflakesup00vanh

Origin of Banded Iron Formations

The origin of banded iron formations has been debated since they were first studied. It has long been thought that their deposition resulted from the interaction of dissolved Fe^{+2} in seawater with oxygen being liberated by photosynthetic organisms. More recent work suggests that the conditions for their deposition required a complex interplay of geochemical, petrologic, and tectonic influences. The conditions were not the same in all depositional basins

Bekker, A., Slack, J.F., Planavsky, N., Krapez, B., Hofmann, A., Konhauser, K.O., and Rouxel, O., 2010, Iron Formation: The Sedimentary Product of a Complex Interplay among mantle, tectonic, oceanic, and biospheric processes: Economic Geology, v. 105 no. 3 p. 467-508. pdf

This paper represents and important advance in understanding of the complex environmental conditions required for iron formation deposition.

Bekker, A., Holland, H.D., Wang, P.L., Rumble, D. III, Stein, H.J., Hannah, J.L., Coetzee, L.L., and Beukes, N.J., 2004, Dating the rise of atmospheric oxygen: Nature, v. 427, p. 117-120. pdf

Bekker, A., Krapez, B., Slack, J.F., Planavsky, N., Hofmanm, A., Konhauser, K.O., Rouxel, O.J., Iron Formation: The Sedimentary Product of a Complex Interplay among mantle, tectonic, oceanic, and biospheric processes – a reply: Economic Geology, v. 107, p. 377-380. pdf

Fisher, W.W., and Knoll, A.H., 2009, An iron shuttle for deepwater silica in Late Archean and early Paleoproterozoic iron formation: Geological Society of America Bulletin, v. 121, no. 1-2, p. 222-245. pdf

Gole, M. J. and Klein, C., 1981, Banded iron-formations through much of Precambrian time: Geological Society of America Bulletin, v. 89, no. 2, p. 169-183. pdf

Klein, C., 2005, Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origins; American Mineralogist, v. 90, no. 10, p. 1473-1499. pdf

Konhauser, 2000, Hydrothermal bacterial biomineralization: potential modern-day analogues for banded iron-formations, *in*, Glen, C.R., Provot, L., Lucas, J., eds, Authigenesis: from global to microbial: SEPM Special Publication, v. 66, p. 133-145. pdf

LaBerge, G. L., 1967, Microfossils and Precambrian iron-formations: Geological Society of America Bulletin, v. 78, no. 3, p. 341-342. pdf

LaBerge describes spheres and ellipsoidal features in iron formations around the world. These are interpreted as microfossils. They are significant because of their implications for early life and the environments of deposition of iron formations.

Morey, G.B., 1999, High-grade iron ore deposits of the Mesabi Range, Minnesota; product of a continent-scale ground-water flow system: Economic Geology, v. 94, no. 1, p. 30-44. pdf

The origin of the high-grade soft ores has long been debated. In this paper Morey presents evidence from mapping in mining pits on the Mesabi Range that the soft ores formed by rising hydrothermal solutions during the Penokean Orogeny, and are not the result of younger weathering by downward moving water.

Nanz Jr., R. H., 1953, Chemical composition of Pre-Cambrian slates with notes on the geochemical evolution of lutites: The Journal of Geology, v. 61, no. 1, p. 51-64. pdf

Planavsky, 2011, Widespread iron-rich conditions in the mid-Proterozoic ocean: Nature, v. 477, p. 448-451. pdf

Rasmussen, B., Fletcher, I.R., Bekker, A., Muhling, J.R., Gregory, C.J., and Thorne, A.M., 2012, Deposition of 1.88-billion-year-old iron formations as a consequence of rapd crustal growth: Nature, v. 484, p. 498-501. pdf

Simonson, B. M., 1985, Sedimentological constraints on the origins of Precambrian iron-formations: Geological Society of America Bulletin,v. 96, no. 2, p. 244-252. pdf

Simonson, B. M. and Hassler, S. W., 1996, Was the deposition of large Precambrian iron formations linked to major marine transgressions?: The Journal of Geology, v. 104, no. 6, p. 665-676. pdf

Taylor, K.G., and Konhouser, K.O., 2011, Iron in Earth surface systems: A major player in chemical and biological processes: ELEMENTS, v. 7, no. 2, p. 83-88. pdf

Trendall, A.F., 1968, Three great basins of Precambrian banded iron formation deposition: A systematic comparison: Geological Society of America Bulletin, v. 79, no. 9, p. 1527-1544. pdf

Trendall, A.F., 2012, Iron formation: the sedimentary product of a complex interplay among mantle, tectonic, oceanic, and biospheric processes – a discussion: Economic Geology, v. 107, p. 377-380. pdf

Williams, S.C.P., 2012, Traces of Inaugural Life: Science News, v. 181, no. 10, p.

http://www.sciencenews.org/view/feature/id/340401/description/Traces_of_Inaugural_Life

Demise of Banded Iron Formations

Addison et al. 2005 revealed evidence for a major meteor impact event that occurred 1850 Ma ago that corresponded with the formation of the impact structure at Sudbury, Ontario. This timing also corresponded with the end of iron formation deposition in the Lake Superior Region. Work since 2005 has allowed correlation of the impact layer around the Lake Superior Region (Pufahl et al., 2007; Cannon et al., 2010). The impact at Sudbury is interpreted to have caused chemical changes that ended iron formation deposition (Slack and Cannon, 2009).

Addison, W.D., Brumpton, G.R., Vallini, D.A., McNaughton, N.J., Davis, D., Kissin, S.A., Fralick, P.W., Hammond, A.L., 2005, Discovery of distil ejecta from the 1850 Ma Sudbury impact event: Geology, v. 33, no. 3, p. 193-196. http://geology.gsapubs.org/content/33/3/193.full.pdf+html?sid=ab16a091-d4f8-4927-a0dc-7c5c288922e0

Cannon, W.F., Schulz, K.L., Horton, J.W., and Kring, D.A., 2010, the Sudbury impact layer in the Paloeproterozoic iron ranges of northern Michigan, USA, Geological Society of America Bulletin, v. 122, no. 1/2, p. 50-75. http://gsabulletin.gsapubs.org/content/122/1-2/50.full.pdf+html?sid=a5d2f18c-0407-4b47-bc1e-5dc22b5c6ab7

This paper describes the impact layer at the top of the iron formations where it is known in the Gogebic Range of Michigan. The impact layer has been found in drill core from western Michigan and may be present at the top of the iron formation in the Penokee Range as well.

Pufahl, P.K., Hiatt, E.E., Stanley, C.R., Morrow, J.R., Nelson, G.J., Edwards, C.T., 2007, Physical and chemical evidence of the 1850 Ma Sudbury impact event in the Baraga Group, Michigan: Geology, v. 35, no. 9, p. 827-830. http://geology.gsapubs.org/content/35/9/827.full.pdf+html?sid=5b45cb10-1043-4feb-a2c1-dfe7cb341e00

Slack, J.F., and Cannon, W.F., 2009, Extraterrestrial demise of banded iron formations 1.85 billion years ago: Geology, v. 37, p. 1011-1014. http://geology.gsapubs.org/content/37/11/1011.full.pdf+html?sid=61106771-1cb3-42c5-96cb-338c1097846a

Selenium Associated with BIFs

Elevated levels of selenium are found in water down gradient of tailings piles at iron mines near Marquette, Michigan. This could have implications for the implications for mining in the Penokee Range of Wisconsin as well. The geologic and geochemical conditions responsible are not clear, but work is ongoing. These papers supply some information about recent work to understand the variables leading to elevated selenium.

MIDEQ, Selenium Monitoring Work Group, June, 2009, An assessment of Environmental Selenium Levels Around Empire and Tilden Mines, Marquette County, MI: MI/DEQ/WB-09/038. http://www.michigan.gov/documents/deq/wb-swas-selenium-report_287994_7.pdf

MI Department of Community Health, March, 2010, Letter of Health Consultation; Interim Consumption Screening Values for Total Selenium, Goose Lake, Selenium, MI. http://www.michigan.gov/documents/mdch/Goose_Lake_Selenium_LHC-_FINAL-3-10-2011_369145_7.pdf

MDEQ and Cliffs Natural Resrouces, January, 2010; Update on Selenium Projects at Tilden and Empire Mines, MI. http://www.michigan.gov/documents/deq/wrd-npdes-EmpireTilden-Vol1_364698_7.pdf

Wisconsin Mining Topics

This section contains papers on miscellaneous topics relevant to iron mining in Wisconsin.

Evans, T.J., An overview of metallic mineral regulation in Wisconsin; third edition: Wisconsin Geological and Natural History, Survey, Special Report 13. http://wisconsingeologicalsurvey.org/pdfs/miscpdf/sr13.pdf

Fitz, T., 2012, The Ironwood Iron Formation of the Penokee Range: Wisconsin People and Ideas Magazine, Spring 2012, p. 32-39. pdf

Liesch, M., 2008, A Region of Hope, A Region of Despair: Print Media, geographical imagination, and the Gogebic Iron Range mining boom: Historical Geography, v. 36. http://www.historical-geography.net/volume_36_2008/liesch.pdf