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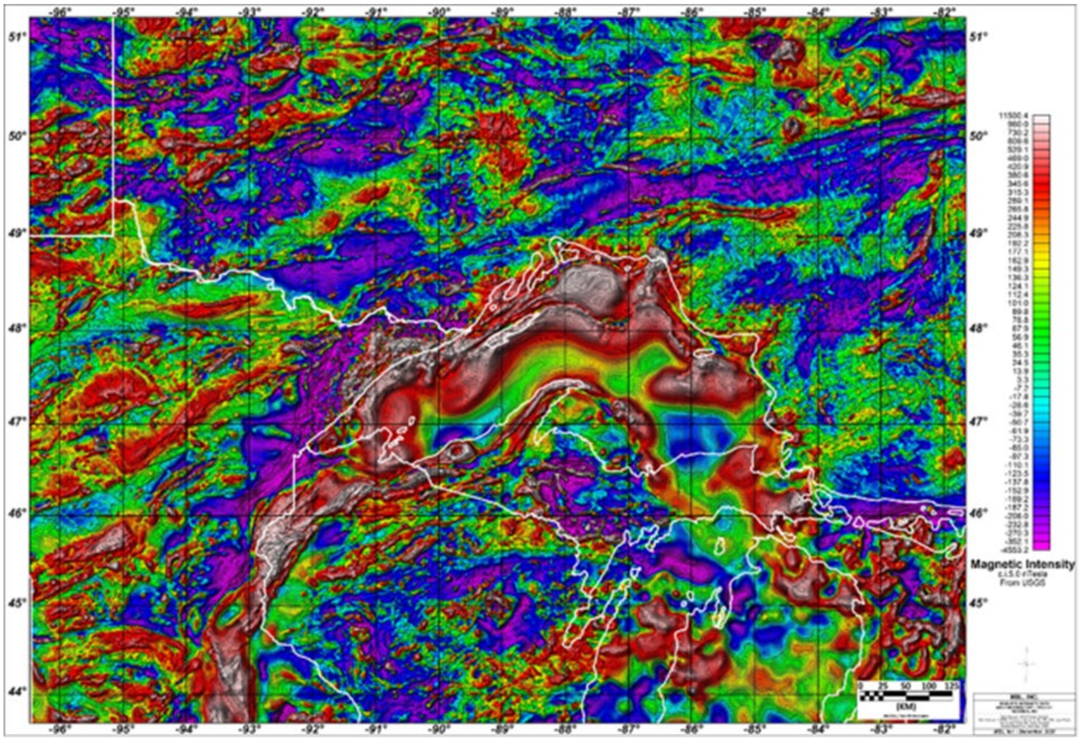
From Compass to Drone: The Evolving Role of Magnetics In Mapping the Geology and Ore Deposits Of the Lake Superior Region:

1830-2022



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Cover Illustration: Total intensity magnetic anomaly map of the Lake Superior region at ~150 m above the surface. Red to white color intervals define anomaly maxima and blue to purple intervals define anomaly minima. Green to blue is approximately zero total magnetic intensity anomaly. Color saturation is reached at approximately −1000 nT and + 1000 nT. (U.S. Geological Survey magnetic anomaly data base mapped courtesy of Mark Longacre)

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Dedication

This treatise is dedicated to Dr. Val W. Chandler on his retirement from the Minnesota Geological Survey where he served as Geophysicist and Adjunct Professor of Geophysics in the School of Earth Science at the University of Minnesota-Saint Paul. Dr. Chandler over his 40 years with the Minnesota Geological Survey has used the magnetic method to significantly contribute to the knowledge of the geology and geological processes of the Lake Superior region.

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Preface

Some of geoscience's most vexing problems relate to the terrestrial magnetic field – What is its origin? What controls its intensity? What is the source of the spatial and temporal secular variations in the field? What is the cause of reversals in the direction of the field? – these are only a few of the questions about the Earth's magnetic field that have been and are being intensely investigated. Despite these questions, the Earth's field has many uses, for example for navigation by birds for millennia and humans for centuries. More recently the directional and intensity components of the field have been used for detecting and mapping ore deposits and geologic formations and structures. This application of the Earth's field has found significant use in the Lake Superior region since the mid-nineteenth century. Since then technical advances have improved the measurement and analysis of the magnetic field leading to continuing enhancement of our knowledge of the geology and Earth resources of the Lake Superior region. It is this evolution of the magnetic method, its role and impact on mapping geology and ore deposits of the Lake Superior region, that is the subject of this treatise, a topic that is treated sparingly in historical reviews of mining and geology in the region.

I have been privileged over the last 70 years to be involved in this evolution, bridging the period from the mid-twentieth century to the early twenty first century as a student, a geophysicist for a steel company, a geophysical consultant, and a professor of geophysics at Michigan State University from 1958 to 1971 and Purdue University from 1971 to my retirement in 1997. During this period I have been fortunate to know early geoscientists such as Barrett, Dutton, Bean, Longacre, and Kronquist who measured the magnetic field with mechanical instruments to present-day investigators such as Chandler, Cannon, Ikola, Teskey, Hood, Mudrey, Drenth, and Grauch who use the newest of electronic instruments, computers, and navigational equipment. Over my career I have moved from mechanical to electronic magnetometers and from slide rule calculations to the current computers and peripherals. As a result I have a strong respect for the technical advances and their impact on our knowledge of Lake Superior geology. I trust that you, the reader, will enjoy the history of the evolution of magnetics and be impressed as I am with its role in advancing geosciences.

Preparation of this treatise was prompted by my long-standing interest in the geology of the Lake Superior region and the magnetic method of geophysical exploration and my desire to learn more about their nexus. I was particularly intrigued by geologists' use of mechanical instruments and their evolution for mapping the anomalous magnetic field associated with local geology and ore deposits during the nineteenth and early twentieth century. Also, the implementation and evolution of electronic magnetometers over the past 75 years for mapping Lake Superior region geology and ore deposits have been a strong interest of mine. This treatise is based on my personal knowledge as well as information obtained from knowledgeable colleagues and numerous journal articles and books that are referenced in the text and listed in the cited references.

One of the primary objectives of this treatise is to provide a comprehensive reference list for subsequent research. I am especially grateful for the availability of electronic and print copies of reports of state and federal surveys and publications of the Lake Superior Mining Institute, Institute on Lake Superior Geology, American Institute Mining and Metallurgical Engineers, and geology and mining engineering journals that have been made available by the library of Purdue University, the Marquette (Michigan) Regional History Center, and the archives of Michigan Technical University.

Notable advances have been made since World War II in the study of the history of the magnetic field of the Mesoproterozoic Era (1600-1000 million years ago) in the Lake Superior region from rocks that acquired their magnetization during that time, especially rocks associated with the Midcontinent Rift

System. These paleomagnetic results have been useful in deciphering the tectonic history of the region and dating rock units. The technical advances dealing with the measurement and analysis of the remanent magnetization of these rocks and their applications are beyond the scope of the herein description of the evolution and mapping role of the magnetic method and as a result are omitted from this treatise.

The sections in this treatise dealing with the dial compass and dip needle in **The Discovery Years** segment of the Evolution of Magnetic Mapping are more comprehensive than the discussions presented of other magnetic sensor instrumentation because for nearly a century these were important to the discovery and exploitation of ore deposits in the Lake Superior region especially the iron ore deposits. Additionally, there is no comprehensive description of these instruments, their use, and interpretation of their data available in the current literature. Descriptions of these instruments are limited in their scope and are largely published in what are now rather obscure publications. Thus, the descriptions in this treatise should be useful to those interested in the history of the magnetic method of mapping geology and ore deposits of the Lake Superior region.

Abstract

The Lake Superior region, the "Birthplace of North American Precambrian Geology," is noted for its world-class mineral resources, especially its native copper and iron ore deposits, and its classic bedrock of Archean and Proterozoic orogenic belts and the exposures of rocks of the Midcontinent Rift System. The magnetic method of mapping the region's ore deposits and bedrock geology has been used for nearly two centuries because of limitations in the exposure of the Precambrian bedrock in the region. For the first century magnetic mapping was directed primarily at the identification of regions favorable for iron and copper ore deposits using simple magnetic needle instrumentation. Initially instrumentation was limited to the use of the dial (sun) compass and used mainly for exploration of hard, magnetite-rich iron ore deposits. With the introduction of the dip needle, a counterbalanced magnetic needle oscillating vertically in the magnetic meridian, to the Lake Superior region likely in 1865 by T.B. Brooks, magnetic mapping was no longer restricted to the difficult to interpret magnetic field angular variations. Rather this instrument included measurement of the intensity of the Earth's magnetic field that is more readily interpreted. The dip needle was developed and first used in iron ore exploration in Sweden around 1770 and independently designed and constructed in the early 1830s by H. Lloyd, an Irish professor of physics. Geologists and prospectors using these simple magnetic needle instruments successfully identified and mapped most iron formations and potential copper-bearing volcanic rocks of the Lake Superior region by the early twentieth century. The magnetic method was limited in directly isolating iron ore deposits and unsuccessful in identifying native copper deposits because of the negligible magnetic properties of the ores, but the method did prove useful in mapping structural and stratigraphic aspects of the host rocks that are favorable for ore deposits. Airborne magnetic mapping was introduced into the Lake Superior region shortly after World War II when magnetic instrumentation was developed with the sensitivity and precision required for geologic mapping. Airborne magnetic surveying has advanced from fundamentally an iron formation detector to the detailed mapper of geology today. This has been accomplished with improved magnetic sensors, increasingly accurate mapping instrumentation especially using GPS, and computers and software for processing, interpreting, and presentation of the magnetic data. Improved airborne instrumentation and navigation have changed the magnetic method from a reconnaissance surveying tool to a high-resolution mapper. The current status and that of the past few decades of magnetic mapping of the geology of the Lake Superior region has significantly expanded knowledge of the geologic history of the region and suggested favorable areas for ore deposits. Improved airborne and ground magnetic surveying also have been useful in mapping potential magmatic sulfide deposits associated with the magmatism and tectonics of the Midcontinent Rift System, the massive sulfide deposits of the largely volcanic terrane of the Wisconsin Magmatic Terrane, and the kimberlite pipes in the Northern Peninsula of Michigan, Wisconsin, and Ontario.

1.0 Introduction

The Lake Superior region unlike the near-horizontal, layer-cake sedimentary bedrock geology of much of the North American midcontinent has complex bedrock geology of the Precambrian Canadian Shield due to several billion years of mountain building, intrusions, volcanism, metamorphism, rifting, plate collision, and erosion/sedimentation. Geological mapping in this region is a challenge because of the superimposed geologic events, the widespread cover of unconsolidated glacial sediments deposited from Pleistocene glaciation, the abundant lakes, and the cover of Phanerozoic sedimentary rocks in the eastern Northern Peninsula of Michigan and adjacent areas of Wisconsin and Minnesota. Limitations to surface geological mapping is evidenced by the few outcrops of iron formation in the iron ranges outside of the Marquette, eastern Menominee, and Vermilion Iron Ranges and iron ore outcrops which originally existed only on the Marquette and Vermilion Ranges and even they were scarce in these ranges (Royce, 1938). Furthermore, geological mapping of the region, which was initiated approximately ~200 years ago, is made difficult because of local distortion of the terrestrial magnetic field which causes problems in using the magnetic compass for surveying. However, this latter problem, the distorting effects of the Earth's magnetic field originating in the bedrock, that is magnetic anomalies, was soon turned into an extremely useful tool for geologic mapping that continues today.

Pioneer geology mappers in the Lake Superior region from Douglass Houghton (1809–1845) onward realized that magnetic anomalies from nearby intensely magnetic formations provided useful supporting information to surface geologic mapping. In Europe magnetic measurements, especially in Sweden, were used as early as the seventeenth century for detecting iron ore deposits (Viberg et al., 2011), but it was not until 1874 that Tobias Robert Thalén (1827–1905) (Figure 1), professor at the University of Uppsala in Sweden established its foundation in his book "*Examination of Iron Ore Deposits by Magnetic Measurements"*[1] (Thalén R., 1879a, b). The publication of this book may be considered the beginning of the magnetic ed of geophysical surveying. The text described magnetic instruments, methods of interpreting magnetic anomaly data, and the formulation of the magnetic anomalies from idealized magnetic sources. In the eastern United States the compass was used to locate magnetite bodies from the seventeenth century (Smock, 1876) and in the Lake Superior region from the mid-nineteenth century. Maj. Thomas Benton Brooks (1836–1900) of the Michigan Geological Survey first described the practical use of magnetic measurements for both ore deposit and geology mapping in the region in 1872 and essential mathematical theory for this application was formulated by Henry Lloyd Smyth in 1897 and his subsequent publications. It is worthy to note that the interpretation of magnetic anomaly data described by Brooks was described in Thalén's book. This is validation of the utility and importance of the Brook's interpretation methods and the effectiveness of trans-Atlantic information regarding the method.

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[1] Prof. Thalén was recognized for his work on the use of the magnetic science in geological mapping with the First Class Medal from the International Geographical Society at their Congress in Paris in 1875.

Figure 1. Tobias Robert Thalén (1827–1905) the Swedish professor whose book of 1874, "Examination of Iron Ore Deposits by Magnetic Measurements," established the foundation of the magnetic method. (Courtesy of Google Images)

The objective of this retrospective treatise is to document the magnetic method and its technical evolution for geologic mapping and mineral exploration over the past ~200 years in the Lake Superior region. The historical development of the magnetic method in the region is important to understanding the role geology and geophysics have had in understanding the geological evolution of the region and in identifying and developing natural resources critical to the growth and progress of our society. At the core of the explanation of the evolution of the magnetic method is the progress that has been made in magnetic mapping based on improvements in instrumentation and surveying technology, but additional important elements of the evolution are the analysis and interpretation procedures and our increasing knowledge of the nature of the magnetic properties of the rocks in the Lake Superior region. Since the early mapping efforts of the mid to late-1800s in the Lake Superior region there has been a continuum of technical improvements in the magnetic method (e.g., Haanel, 1904; Hotchkiss, 1923a, b; Heiland, 1926; Balsley, 1952; Monture, 1955; Slichter, 1955; Leney, 1964; Chandler, 1985; and Hood, 2007).

In the following discussion the basis, application, and problems of magnetic mapping in the Lake Superior region are described followed by an explanation of the evolution of the magnetic method that has been divided into segments of time when the application of the magnetic method to Lake Superior region geology and exploration has been relatively consistent. The description of the time segments includes a discussion of the primary published magnetic mapping during each period which is divided, where appropriate, into states and provinces of the Lake Superior region.

The treatment of the magnetic method and its history that is discussed herein is aimed at the Lake Superior geologist with a basic knowledge of geophysics and geophysicists that are interested in the history of the use of the magnetic method in the Lake Superior region and have limited experience in using the magnetic method in Precambrian shield regions. The treatise will also be of interest to historians of the region especially those interested in the developmental history of the natural resources of the region.

2.0 The Magnetic Method and Its Use in the Lake Superior Region[2]

2.1 Introduction

The magnetic method of exploring the Earth's crust is the oldest and among the most widely used geophysical techniques. It was applied to early mapping in the Lake Superior region because geologists understood that the magnetic method is simple, rapid, inexpensive, and readily applied to the mapping of buried geologic units with different magnetic properties in the complex Precambrian bedrock of the region. An ultimate objective of the magnetic method since its first application was to locate mineral resources which in the Lake Superior region were originally primarily iron and copper ores and today includes minerals critical to national security and development of advanced technologies. In recent years the method also has taken on a significant role in mapping geology important to deciphering the Precambrian history of the region.

Magnetism that is used in mapping is a phenomenon that is derived from the spin and orbital motion of electrons surrounding the nucleus of an atom and coupling of spins between particular adjacent atoms that produce dipoles with both attractive and repulsive forces and poles. A body with aligned dipoles is referred to as magnetized with the magnetization concentrated near the extremities of the body which are referred to as poles. It is the summation of the dipoles, the magnetization, that is the source of the magnetic field from the dipole oriented body which exerts a force on other magnetic bodies and is measured in magnetic mapping. Earth materials are subject to magnetization by virtue of the interaction of their atoms and the ambient terrestrial magnetic field. However, magnetization for most Earth materials is generally negligible for geologic mapping purposes except for the mineral magnetite which has a special coupling of the spin of adjacent atoms leading to intense magnetization. When magnetite occurs in rocks a local induced magnetic field is caused by the terrestrial magnetic field. Additional local magnetic fields can originate from strong dipole coupling frozen in during the formation of the rock. Both induced and the latter magnetization (remanent magnetization) cause anomalies in the terrestrial magnetic field, the character of which is dependent on the sources, their proximity, and magnetization. Mapped magnetic anomalies of both types, induced and remanent, have been extensively used in the Lake Superior region to identify and evaluate ore deposits and map geology.

Like other potential-field methods, the magnetic method is based on spatial observations to investigate horizontal variations in a physical property. The physical property of interest is magnetization produced by the combined effects of induction by the Earth's magnetic field and preservation of past fields by remanence in Earth materials. The induced field intensity largely depends on magnetic susceptibility, which varies greatly among minerals that make up the crystalline rocks of the region. The magnetic susceptibility of magnetite (Fe_3O_4) exceeds most minerals by several orders of magnitude and thus is the primary control on induced magnetization of rocks. Induced and remanent (quasi-permanent) magnetization is commonly variable among the Precambrian rocks of the Lake Superior region which makes the magnetic method particularly useful in geological mapping. Most of these rocks have been highly deformed by orogenic and

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[2] Readers experienced in the application of the magnetic method to geological studies in the Lake Superior region may wish to skip this section and go directly to the section dealing with the evolution of the magnetic method in the Lake Superior region.

other tectonic processes. As a result, contacts between rock units of contrasting magnetic properties are commonly steeply dipping causing obvious magnetic anomalies as compared to the more subtle anomalies of near-flat-lying geologic units.

Interest in magnetic mapping in the Lake Superior region has continued from the mid-nineteenth century to the present with periods of greater or lesser activity dependent largely on economic factors as well as knowledge of the magnetic response to various geological sources. Originally iron ore was discovered in proximity to positive magnetic anomalies suggesting these anomalies could be used for ore detection, but the application of the magnetic method fell out of favor for exploration in the Lake Superior region in the latter part of the nineteenth century because drilling of intense magnetic anomalies showed that they were largely associated with relatively low-grade magnetite iron formations, rather than the desirable direct shipping ores of hematite and goethite. However, as Charles Kenneth Leith (1875–1956) (1912) has pointed out, based on his experience with magnetic anomalies of iron formations and ores, not all strongly magnetic portions of Lake Superior iron formations should be eliminated from prospecting for direct shipping iron ores.

The magnetic method came back into favor as an exploration tool in the Lake Superior region at the beginning of the twentieth century because of improved understanding of the magnetic properties of iron-bearing minerals and increasing knowledge of the origin and distribution of magnetite in various lithologies. Also, discovery of iron ore associated with the magnetic anomalies of the Cuyuna Range in Minnesota, which had no outcrops of iron formation, showed the importance and role of the magnetic method in iron ore exploration. For roughly a century since iron ore was found in the Cuyuna Range, and especially since the end of World War II, the efficiency and quality of magnetic surveying has increased dramatically. These improvements have supported geologic mapping of broad areas which has been important to placing ore deposits of the region into their proper geological context (Woodruff et al., 2020).

2.2 Magnetic Mapping of Ores

Magnetic mapping of ores has been applied at a variety of scales and both directly and indirectly in the Lake Superior region depending on the magnetic properties of the ores and the surrounding rock units and the size of the ore bodies. Direct detection of ore deposit anomalies is preferred in magnetic exploration, but this requires magnetically distinctive ore minerals. Unfortunately the magnetization of native copper and copper sulfide ores of the Lake Superior region is insufficient to be identified directly by the magnetic method. The situation is different for most iron ores. In the first few decades of iron ore exploration in the Lake Superior region the principal ores of interest were hard iron ores consisting largely of magnetite which could be directly located by intense magnetic anomalies. However, this changed as the limited number of magnetite ore bodies were exhausted by mining. As a result direct shipping, soft iron ores or so-called natural iron ores which can be used directly in the iron ore smelting process became of dominant interest to the iron ore industry. The exploitation of soft ores occurred first in the Marquette Iron Range in the 1860s, but rapidly expanded to the other iron ranges of the Lake Superior region and these natural ores continued to be the primary subject of exploration activity for numerous decades. These ores consisting of 50 to 75% iron are made up primarily of non-magnetic hematite and goethite resulting from supergene enrichment of iron formations by the removal of silica and oxidation of original magnetite to non-magnetic iron minerals. Thus, these ores are associated with magnetic minima anomalies within the positive magnetic anomalies of the unaltered iron formation (e.g., Hotchkiss, 1915; Aldrich, 1929; Jones, 1946). In contrast the low-grade, siliceous, taconite deposits (banded iron formations) containing 20 to 30% iron that can be concentrated for use in smelters are commonly associated with intense magnetic anomalies. These taconite deposits began to be the subject of magnetic exploration in the 1940s in the Lake Superior region when natural ores were largely exhausted by mining during World War II and have been the primary target of more recent exploration for iron ore.

The magnetic method has also found a role in indirectly detecting and mapping of ores in the Lake Superior region that cannot be mapped directly due to their lack of a definitive magnetization. For example, the host rock for massive sulfide deposits such as peridotite are often sufficiently magnetic that their magnetic anomalies can be identified as favorable locations for intense mineral exploration. Thus, mapping of magnetic anomalies is an early step in the exploration for massive sulfide deposits (e.g., Klasner et al., 1979b). Furthermore, even though the magnetic anomalies of massive sulfide deposits are not definitive, the deposits commonly contain sufficient magnetite that a minor magnetic anomaly is associated with them. These anomalies can be used with other geophysical anomalies to delineate the deposit.

In contrast, native copper is non-magnetic and magnetite is not a trace mineral in these ores, thus magnetic methods cannot be used directly in native copper ore deposit exploration. However, they have been used for mapping structures that have served as pathways for copper mineralizing hydrothermal fluids leading to native copper ore deposits and also for tracing buried stratigraphic units important to the occurrence of copper deposits (e.g., Broderick and Hohl, 1928a, b, 1929; Broderick, 1933; Lamey, 1938; Pollock and Weege, 1966). Sulfide and oxide ores within Mesoproterozoic intrusive rocks such as the Duluth Complex may be somewhat magnetic from included magnetite, but commonly are not sufficiently magnetic to produce distinctive anomaly patterns.

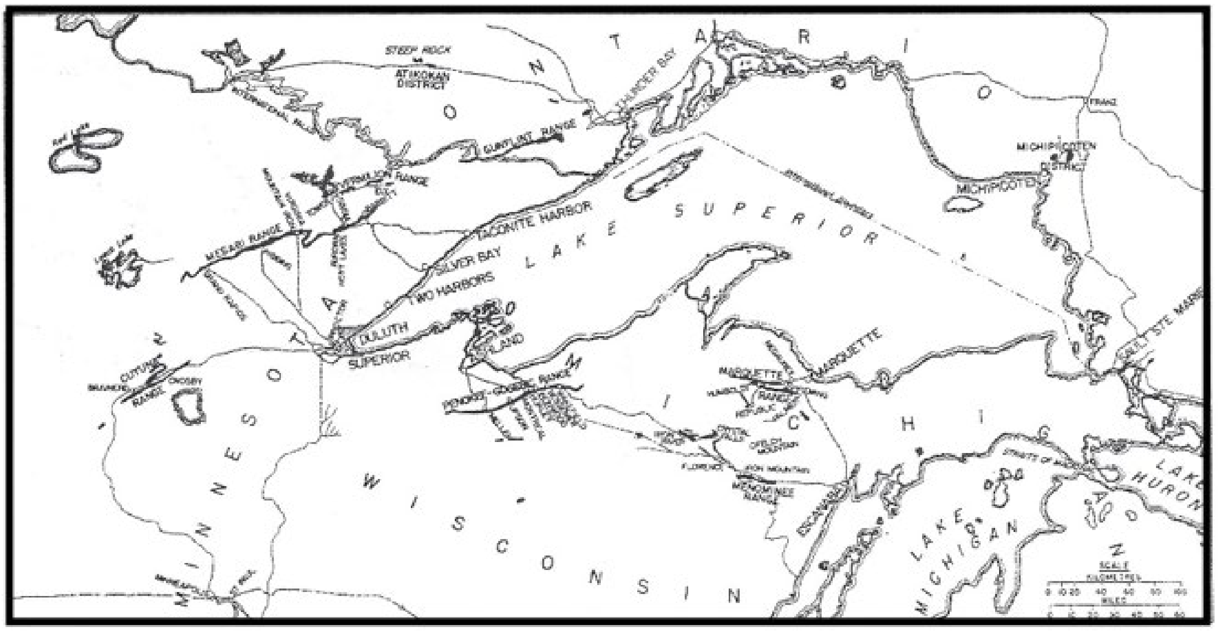

Figure 2. Map of the location of the Lake Superior iron ranges including those in Michigan, Wisconsin, Minnesota, and Ontario. (After Langford et al., 1985)

Finally, the magnetic method is also useful for basic geologic mapping that is important in exploration for ore deposits. This mapping takes advantage of the prominent contrasting magnetization characteristics of the Precambrian rocks of the region. Volcanic flows and intrusive rocks, iron formations, magnetic zones within slate units, and numerous other formations are notable mappable magnetic units that define the distribution and structure of major geologic units that are useful in defining favorable exploration areas (e.g., James et al., 1961; Leney, 1964).

The mapping of iron ore deposits, or in a broader sense iron ranges (Figure 2) that may contain ore, was the primary goal of the earliest magnetic surveying in the Lake Superior region. The magnetic method is especially useful in locating and outlining magnetic iron formations, but it has numerous limitations because of the paucity of magnetite in some iron formations such as those in the Michipocoten and Steep Rock (Atikokan) Districts of Ontario and portions of the Crystal Falls District of the Menominee Iron Range in Michigan. However, most iron formations are to varying degrees more highly magnetized than the surrounding rock units resulting in positive magnetic anomalies (Grant, 1984a, b). These variations are caused by-differences in the original iron content, the geochemistry of waters in which the sediments were deposited, type and degree of metamorphism, and the effects of supergene alteration due to oxidizing waters moving within permeable zones.

2.3 Rock Magnetization and Magnetic Anomalies

The magnetic nature of minerals and their effect on magnetic measurements has been known by geologists and prospectors for several centuries most notable in Sweden where numerous highly magnetic iron ore deposits were mapped magnetically. One of the earliest description of the magnetic nature of minerals is the article by Hans Tasche in Jahrbuch der Kaiserlich-Koniglichen Geologischen Reichsanstalt, VIII, Jahrgang, 1857 (Soske, 1935). Bruckshaw (1954) reviewed the early studies of rock magnetism which led to the understanding of the nature and cause of remanent magnetism in rocks. In the Lake Superior region. Maj. Thomas Benton Brooks (1872a, b; 1873a, b) was among the first to recognize the potential of the magnetic method to mapping geology. His insight was based on his experience in geological mapping of Precambrian crystalline rocks with magnetic needle instrumentation in northeastern United States and his knowledge of the extensive distribution of magnetite in the Precambrian rocks of the Lake Superior region. Since then recognition of the potential of the magnetic method for geological mapping has continued to grow among geologists working in the region. More recently in an attempt to improve the identification of sources of magnetic anomalies in the Lake Superior region several workers have measured and compiled magnetic susceptibility and remanent magnetization (intensity and direction) of rock formations from Wisconsin (Dutch et al., 1995), Minnesota (Mooney and Bleifuss, 1953; Sims, 1972; Chandler and Lively, 2021), Michigan (Meshref and Hinze, 1970) and in numerous journal and state/province and federal survey articles and reports (e.g., Beck, 1970; Books, 1972; Hinze et al., 1982; Halls and Pesonen, 1982; Teskey and Thomas, 1994; Thomas and Teskey, 1994; Enkin, 2018; Anderson et al., 2020).

Magnetic susceptibility generally is not diagnostic of rock type because the primary source of magnetization, magnetite, occurs as a trace mineral in nearly all rocks. Exceptions to this generalization include Archean and Proterozoic sedimentary banded iron formations of the Lake Superior region which are noted for their high magnetic susceptibilities. The high magnetic susceptibility is due to abundant magnetite in the iron-rich bands that probably formed during low-grade regional metamorphism by the oxidation of primary iron-bearing minerals such as siderite and greenalite (LaBerge, 1964). However, notably some iron formations of the region have negligible magnetization because their iron-bearing minerals are low magnetic susceptibility carbonates, silicates, or ferric oxides (hematite and goethite) rather than magnetite. Another mineral with significant magnetic susceptibility is pyrrhotite, a form of pyrite (iron sulfide), which generally has a magnetic susceptibility an order of magnitude less than magnetite. It occurs in mafic and ultramafic igneous intrusions of the Midcontinent Rift System and massive sulfide ore deposits in the Lake Superior region (e.g., May, 1977; Tyson and Chang, 1984). Ilmenite has been recognized by some investigators as having sufficient magnetic susceptibility to be of interest in magnetic surveying, but this iron/titanium oxide is only mildly magnetic. Its magnetism is commonly a result of solid solutions with hematite and intergrown magnetite.

Complicating the relationship between a rock's magnetic susceptibility and its magnetic response is the directional (anisotropic) nature of susceptibility. A rock's susceptibility anisotropy, that is the ratio of its maximum to minimum susceptibility as measured in three mutually perpendicular directions, is generally less than 1.2. However, higher anisotropy values are noted in banded iron formations. For example, the Biwabik iron formation of the Mesabi Iron Range has a value of around 4 (Jahren, 1963) with its maximum susceptibility parallel to its layering. As a result, considering the steep (~73°) dip of the Earth's field the low south-dipping, east-northeasterly-striking Biwabik iron formation is less magnetized due to anisotropy of the magnetic susceptibility of the iron-rich bands than if the iron formation was magnetized by the ambient magnetic field along its layering rather than roughly perpendicular to its layering.

The magnetic susceptibility of the basement rocks surrounding Lake Superior is further complicated by the effects of their geologic and magnetic history. The causes and effects of these complications are described in a general manner by Bath (1962), Jahren (1963), Reynolds et al. (1990), Clark and Emerson (1991), and Hinze et al. (2013). The complications described by these authors commonly makes interpretation of magnetic anomalies and identification of their source rocks difficult without additional geophysical or geologic data. For example, Bath (1962) finds no consistent relationship between magnetic anomalies of the Mesabi Iron Range and magnetite content of the Biwabik iron formation. The optimum interpretational procedure is first to identify the magnetic source rock from outcrops or by drilling and then to extrapolate this identity along the extension of a magnetic anomaly. For example, the source of a major positive magnetic anomaly of Lake Superior was identified by an experienced interpreter as a granite intrusive or a granite gneiss massif. However, additional magnetic mapping and comparison of the magnetic field over the Lake with onshore geology revised the anomaly source as being a continuation of a volcanic rock sequence, which was later confirmed by direct sampling of the source rocks.

Remanent magnetization may also complicate the magnetic response of rock formations in a profound way. The ratio of remanent magnetization to magnetization induced in magnetite by the terrestrial magnetic field, the Konigsberger ratio (Q), is less than 1 in most crystalline rocks, but it is commonly greater in volcanic rocks. Compilations of measurements of Keweenawan volcanic rocks (Hinze et al., 1966; Halls, 1972) indicate that Q ranges between 1 and 3 and induced magnetization is generally in the range of 1 to 3 A/m. As a result, dependent on the direction of the remanence and the orientation of the volcanic formations, these volcanic rocks can be strongly magnetic leading to high amplitude magnetic anomalies.

The presence and importance of remanent magnetization in Keweenawan rocks were not recognized until the pioneering work of Dubois (1955, 1962). In general, normally polarized Keweenawan volcanic rocks have remanence with an inclination of 40° and a declination of 290°, whereas remanence of reversely polarized rocks has an inclination of -60° and a declination of

110° (Mariano and Hinze, 1994b). Because the ambient magnetic field of the region is inclined 75° downward with 3° of declination, the magnetization vector used to model magnetic anomalies of the Mesoproterozoic Keweenawan volcanic rocks needs to consider the combined effect of the induced magnetization with the structurally rotated remanent magnetization. The latter vector can be determined from laboratory measurements of oriented in-situ samples or can be inferred by rotating the remanence vector for the volcanic rocks of the region by an amount equal to their tilt from an original near horizontal orientation when the remanent magnetization was acquired by these rocks.

In addition to source rock magnetization, magnetic anomalies are also related to size, configuration, proximity, depth, and orientation of the source body with respect to the ambient magnetic field. All of these parameters have to be considered in interpreting magnetic anomalies. Within and around Lake Superior, positive magnetic anomalies attain amplitudes of up to 10,000 nT primarily where source rocks are iron formations or near-surface Mesoproterozoic Era mafic rocks. Moderate magnetic highs, measured in tens to several hundreds of nanoteslas, are related to oxidized iron formations, tuffs, and lithologically diverse intrusive rocks and metamorphic massifs. Negative anomalies usually measured in a few hundred nanoteslas occur over sedimentary basins and mildly metamorphosed mafic volcanic rocks commonly called greenstones.

Although relating amplitude of magnetic anomalies to specific sources is difficult, it is less difficult and more likely to be correct when consideration is limited to an area with a known range of geologic units that have been subject to a limited number of geologic processes. Such is the case in central Dickinson County, Michigan within the Menominee Iron Range, where James et al. (1961) identified rock units with magnetic anomalies ranging from “strong” (greater than 2500 nT) through “moderate” (1000 nT or more) to “small” (less than 1000 nT) based on isolated outcrops and drill core samples. Similarly, Meshref and Hinze (1970) have subdivided on the basis of intensity the aeromagnetic anomalies of the western Northern Peninsula of Michigan into three units, each with characteristic geologic sources. This type of characterization can be useful in interpreting sources of magnetic anomalies, but only when it is limited to a region of consistent geologic history.

Unfortunately, identification and interpretation of magnetic anomalies is obscured by the dipolar nature of magnetism. As a result of this universal attribute, positive magnetization rock units produce a magnetic anomaly maximum, but also an equivalent magnetic minimum area within a profile of an infinitely long source due to the opposing pole of the dipole (Bhattacharyya, 1967; Hinze et al., 2013). The opposing magnetic pole(s) is located near the base of the unit, thus the amplitude of its effect is decreased but spread over a large area surrounding the magnetic unit compared to the positive anomaly due to the inverse distance effect. As a result, it may be difficult to identify the minimum associated with the base of a positive anomaly source that lies several kilometers below the top of the source, especially in the presence of interference from adjacent anomalies. Where the minimum can be identified, it may be misinterpreted as being related to the presence of a rock unit with little magnetization or even reversed magnetization. Rock units with reversed magnetization, such as some of the Mesoproterozoic Era volcanic units of the Lake Superior region, will cause the opposite effect of the positive magnetization. Positive and negative magnetic anomalies are identified by the variation of the measurements from normal background level of the magnetic field. The background level is commonly difficult to identify but is generally assumed to be the relatively constant value of measurements observed over adjacent anomaly-free regions such as deep basins of essentially non-magnetic sedimentary rocks.

In the Lake Superior region the peak of a magnetic maximum due to a positive magnetization source is shifted slightly to the south of center of the source and an associated minimum anomaly lies to the north of the source. An obvious example of this is the negative anomaly north of the positive anomaly associated with the Biwabik iron formation in the central and western Mesabi Iron Range (Bath, 1962). These anomaly characteristics are due to the inclination of the terrestrial magnetic field that produces the induced magnetization. This is not necessarily the case for magnetic anomalies caused by remanent magnetizations that differ significantly in direction and inclination from the ambient terrestrial field and the opposite is the case for a reversely magnetic rock unit. This description of the dipolar effect of magnetism shows that identification and interpretation of the source of magnetic anomalies can be problematic (Hinze, 1960).

2.4 Joint Interpretation of Magnetic and Gravity Anomalies

Challenges in the interpretation of magnetic anomalies in the Lake Superior region has led investigators to joint interpretation of magnetic and gravity anomalies based on their spatial correlation. This process is effective because both anomaly types are based on spatial horizontal variations in the physical properties of the subsurface. Gravity anomalies depend on horizontal variations in density and magnetic anomalies are caused by magnetic polarization contrasts. Commonly these physical property contrasts are shared by geologic formations resulting in coincident but quite different anomalies. For example, alteration of magnetite to non-magnetic iron minerals in an iron formation together with removal of silica will lead to negatively correlated anomalies with gravity maxima of the iron formation and ore contrasting with magnetic minima derived from the non-magnetic ore within the iron formation (Miller and Dransfield, 2011). Even where neither one of the anomalies is present, this result can provide important information about the anomaly source.

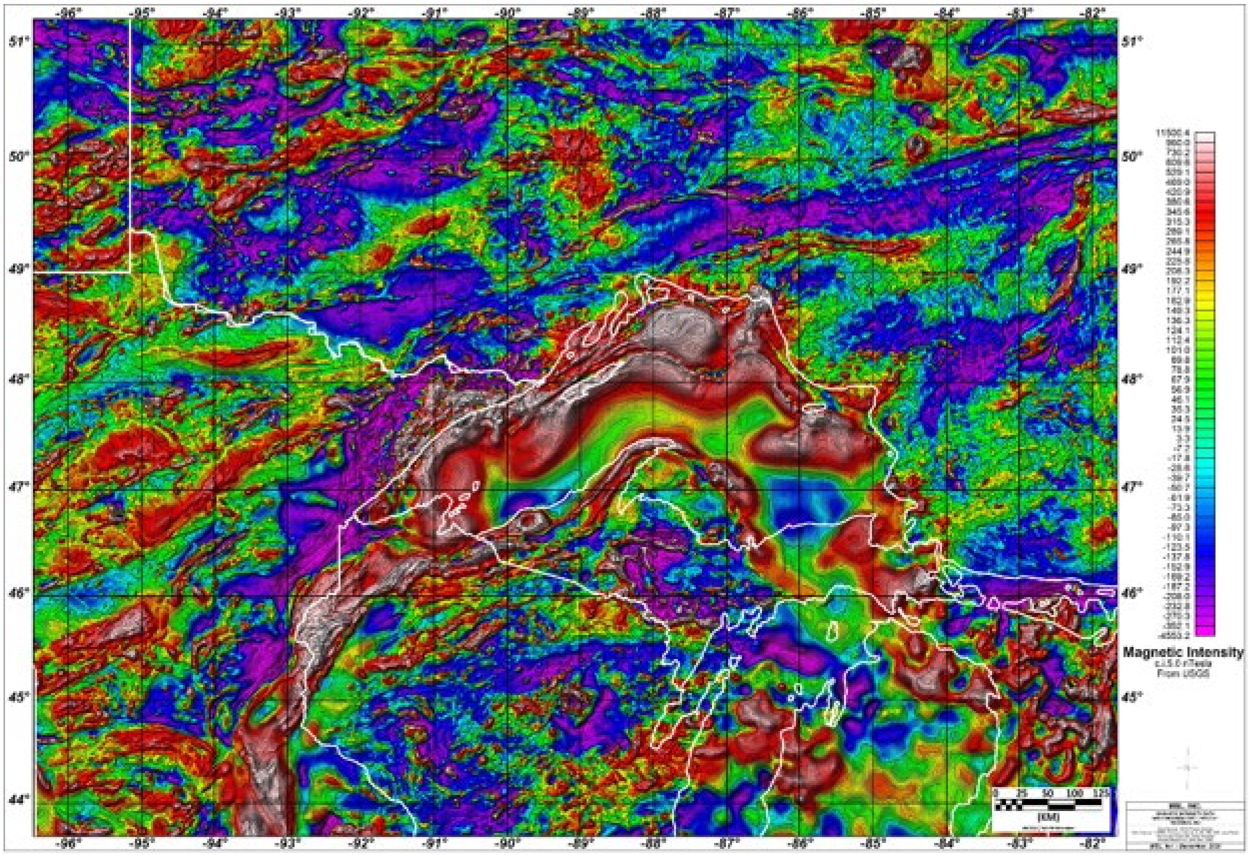

Figure 3. Total intensity magnetic anomaly map of the Lake Superior region at ~150 m above the surface. Red to white color intervals define anomaly maxima and blue to purple intervals define anomaly minima. Green to blue is approximately zero total magnetic intensity anomaly. Color saturation is reached at approximately −1000 nT and + 1000 nT. (U.S. Geological Survey magnetic anomaly data base mapped courtesy of Mark Longacre)

Magnetic anomalies unlike gravity anomalies are modified by the direction of the magnetic polarization and the properties of the ambient Earth's magnetic field and gravity anomalies can be affected by the commonly irregular distribution of observations in contrast to the generally high-density, regular magnetic observation sites of aeromagnetic surveys that lead to more precise magnetic anomaly definition. Accordingly the configuration of gravity and magnetic anomalies derived from a common source with consistent physical property contrasts will be similar but not the same, complicating the joint interpretation process. As a result various mathematical schemes such as reduction of the observed magnetic data to the magnetic pole (vertical magnetization) and pseudo-gravity modifications are used to enhance the correlation of the anomalies. A more fundamental difference in the anomalies is given by the theoretical relationship (Poisson's theorem) between the gravity and magnetic potential due to an anomaly source (Chandler et al., 1981; Chandler and Malek, 1991). This relationship shows that a magnetic anomaly is equivalent to the first derivative of the gravity anomaly in the direction of magnetization and that coincident anomalies are linearly related by the ratio of the physical property contrasts. As such, this ratio can be helpful in the inverse problem of determining the contrasting lithologies that produce coincident gravity and magnetic anomalies.

The upper surface configuration and geometrical attributes of an anomalous source can be assessed more directly and precisely from the magnetic anomaly because this method has a higher horizontal resolution than the gravity anomaly and is more sensitive to source depth. In contrast, the gravity anomaly is more useful in studying geologic sources at greater depths than the magnetic method. Additionally, the gravity method is generally more effective than the magnetic method in the quantitative analysis of geologic formations. Notably, magnetic observations can readily be taken to a high degree of detail and precision from simple mobile platforms making them cost effective and useful in local as well as regional investigations. Considering these attributes, the magnetic method is the optimum method of geophysical mapping geology and ore deposits of the Lake Superior region. However, the gravity method does have a prominent role in investigating the entire crust of the region, in quantitative modeling, and is useful in identifying anomaly sources and their lithology when integrated into the interpretation of magnetic data.

2.5 Regional Magnetic Anomalies of the Lake Superior Region

The nature of regional magnetic anomalies of the Lake Superior region is illustrated in Figure 3 which shows total magnetic intensity regional anomalies that are a few kilometers or more in minimum size. Anomalies in the figure are derived from largely buried crystalline, Archean and Proterozoic, basement rocks. The prevailing anomaly pattern has an east-northeast trend with alternating magnetic minima and maxima. In general, moderate amplitude maxima of a few to several hundred nanoteslas are associated with granite gneiss and highly metamorphosed rocks, while minima with amplitudes up to several hundred nanoteslas are commonly associated with greenstone and sedimentary terranes. Characteristically long, narrow, high-intensity anomalies within these regional negative anomalies are caused by steeply dipping, magnetic iron formation, slate, tuff, and mafic dikes. Bands of high intensity anomalies with maximum values often over a few thousand nanotesla (poorly mapped by the limited resolution of Figure 3) were the focus of most early magnetic surveys to locate iron ranges and their ore bodies. Such Paleoproterozoic Era iron formations mapped magnetically in Michigan, Minnesota, and Wisconsin (Figure 3) have been the prolific sources of iron ores of the Lake Superior region. Archean (>2500 Ma) iron formations also were identified by magnetic surveying in the Canadian Shield in Ontario. Additional information about the relationships between magnetic anomalies and Proterozoic rocks of Minnesota, Michigan, and Wisconsin is available in numerous published studies such as Broderick (1917), Grout (1929), James and Wier (1948), Good and Pettijohn (1949), James et al. (1961), Sims (1970, 1984), Meshref and Hinze (1970), Halls (1972), Sims et al. (1978), Chandler et al. (1982), Chandler (1983, 1985), Klasner et al. (1985), Cannon et al. (2001), Schneider et al. (2002), Schulz and Cannon (2007), Grauch et al. (2015, 2016, 2017, 2018a, b, 2019a, b, and 2020), and Drenth et al. (2020, 2021).

High intensity, regional magnetic anomalies of Figure 3 crudely follow the shoreline of Lake Superior and continue southwest from the west end of the lake and southeast from the east end. These anomalies commonly reach amplitudes of several thousand nanotesla and transect the prevailing east-northeast magnetic pattern associated with geologic structures of the Archean and Proterozoic rocks of the region (King and Zietz, 1971; Oray et al., 1973; Chandler et al., 1989; Hinze and Chandler, 2020). Unlike the overall anomaly pattern of the region that is derived from multiple sources, these high intensity anomalies are derived from voluminous Mesoproterozoic, mafic-dominated, volcanic flows and limited intrusive rocks associated with Midcontinent Rift System (MRS) (Hinze et al., 1997). Their intense magnetic anomalies are due largely to their strong thermal remanent magnetization which was not appreciated by magnetic mappers until well into the twentieth century (DuBois, 1955, 1962; Bath, 1960; Jahren, 1960; Halls and Pesonen, 1982).

2.6 Magnetic Surveying

Magnetic observations were limited to the ground until methods to acquire airborne measurements with sufficient sensitivity and precision were developed by U.S. Geological Survey and private contractors near the end of World War II. In the decades prior to these developments, instrumentation to measure magnetic field strength from airborne platforms lacked the required attributes for geologic mapping due to errors resulting from difficulties in leveling and orientation of the magnetic sensor. Most magnetic surveys since the mid-1940s have been made from the air but both ground and airborne surveys have their advantages especially on a local scale. The principal advantage of ground measurements is their proximity to magnetic sources, which yields the highest intensity and maximum resolution of anomalies, and thus the greatest detectability of and information about the source. Ground surface measurements are still made where the highest resolution and detectability are required and the survey is limited to a local area, although even those are being replaced by surveys using drones flying at near ground levels. The speed and economy of airborne surveying makes studying extensive regions more efficient, and the greater distance from source rocks minimizes the effects of cultural features, temporal variations, and near-surface, non-lithologic geologic sources.

Airborne measurements are obtained along flight paths perpendicular to the predominate strike of geologic formations at the lowest constant elevation above ground that can be safely flown, commonly 150 meters but lower in special situations. Spatial positioning is determined within a few tens of meters using GPS and magnetic intensity measurements generally have a precision of a few tenths of a nanotesla. Ground magnetic measurements can be made with handheld or tripod-mounted instruments that must be maintained level or in a specific magnetic direction. They can also be made with scalar instruments, which require no orientation, but are placed on a staff to increase the distance between the sensor and sources of extraneous magnetism in surface material. Ground observations are typically made along traverses perpendicular to the overall strike of geologic units at intervals that permit several observations directly over the unit being investigated. Traverses are separated by distances suitable to the strike length of the target being mapped so that significant along strike changes in the magnetic field are identified, with in-fill traverses providing additional detail. Station intervals along traverses are chosen to permit accurate mapping of the marginal gradients of anomalies, generally a station distance of 0.2 of the expected depth of the source of the anomaly beneath the observation surface.

As in the case of magnetic mapping, interpretation of the results of magnetic surveying have undergone a significant change since magnetic observations were first used to map geology and ore deposits of the Lake Superior region. Until the 1940s all magnetic measurements were made on the ground with mechanical instruments using a magnetic needle. These measurements were primarily equilibrium angles that the needles took after being released from a normal, non-anomaly position either in the horizontal or vertical plane rather than the magnetic intensity that was largely measured in post-1940 time by the new instrumentation. The measurement of angles did not lend itself to quantitative interpretation. Rather interpretation was largely based on empirical results, that is observed angular deflections compared to known geologic features or results obtained from simple physical or theoretical models. Interpreters during this time were generally cognizant of the inverse square law for the change in the intensity of the magnetic field from a single magnetic pole, but not modifications in this relationship with the geometric configuration of the anomaly source and did not fully realize the significance in the spatial overlap of anomalies from multiple sources. Since the roughly 1940 time period, methods of compiling magnetic data have improved significantly (e.g., Luyendyk, 1997; Reeves, 2005; Isles and Rankin, 2013). In particular three-dimensional location of observations have taking advantage of more precise navigation with electronic navigational instrumentation and more recently with satellite based geographical positioning systems. Additionally, errors due to both short and long term variations in the terrestrial magnetic field have been minimized by improved magnetic observation leveling schemes and internationally adopted predictive and definitive terrestrial magnetic field models. Furthermore, greatly aided by the speed, storage capacity, and computational power of computers there has been a continual improvement in the methodology for interpreting and presenting magnetic intensity anomalies (e.g., Peters, 1949; Vacquier et al., 1951; Nabighian et al., 2005; Hinze et al., 2013; Fairhead, 2015) that yield ever improving quantitative interpretation. Significant technical advances in the magnetic method and resultant magnetic mapping in the Lake Superior region are identified in the 'time-line' table of Appendix A.

3.0 Evolution of Magnetic Mapping in the Lake Superior Region

3.1 Introduction

Horace Benedict de Saussure, a Genevan alpinist and physical scientist, recognized in 1780 the effect of iron-rich rocks on perturbations in compass readings, but the initial use of the magnetic method in the Lake Superior region for exploration of mineral resources did not begin until the mid-1840s. It took a century from then for technology to improve to a level that permitted the magnetic method to move from ore exploration reconnaissance to mapping of geology. Historical accounts of prospecting for mineral resources in the Lake Superior region show the sporadic nature of the process with periods of intense exploration interspersed with periods of limited activity. The first of the intense periods and the first mineral exploration rush in the United States took place in the Keweenaw Peninsula and adjacent areas in the search for copper deposits after 1843 when Douglass Houghton, State Geologist of Michigan, publicized the mineral-rich deposits of the region. The magnetic method was used during this period to trace out volcanic units in the Keweenawan rocks and structures controlling the occurrence of ore deposits. Subsequently, in the mid-1840s reports of iron-rich rocks near Marquette, Michigan led to numerous groups searching for and discovering several iron ore deposits associated with intense magnetic anomalies mapped by abnormal declination of the Earth's magnetic field. Exploration for iron ore continued throughout the Lake Superior region at a decreasing level for the next 50 years. Exploration was enhanced by development of the dial (sun) compass and the use of the dip needle from the mid-1860s, but the level of magnetic exploration declined with the realization that only a few percent of the areas of intense magnetic anomalies were actually associated with iron ore.

A second period of increased iron ore exploration started in the early 1900s with the discovery by magnetic surveying of the Cuyuna Iron Range which was completely buried by glacial deposits. In an effort to find similar buried ranges, exploration for the next few decades emphasised magnetic surveying of the glacial deposit-covered areas of the Lake Superior region in Michigan, Wisconsin, and Minnesota. These surveys discovered additional iron formations, but no iron ore.

A third period of enhanced exploration was initiated on recognition of the dwindling supplies of iron ore after their intense exploitation during World War II and the predicted needs for new ore deposits in the post-war economic recovery and for national security. This boom in exploration was focused on identifying both new direct shipping iron ore deposits in the known Lake Superior iron ranges and also on economically viable taconite deposits in both existing and undeveloped ranges that could be beneficiated for use in steel production. Magnetic methods were a prominent part of this exploration activity and similar exploration programs directed during the 1960s to finding massive sulfide, nickel and platinum group, and diamond ore deposits in the Lake Superior region.

In each of these major ore exploration booms in the Lake Superior region, magnetic methods were taking advantage of the evolution of technology that led to improved instrumentation, surveying, analysis, and interpretation of magnetic observations. With these improvements there has been an increasing use of the magnetic method to map the Precambrian geology of the region. To describe the role and evolution of the magnetic method in mapping the basement geology and ore deposits in the Lake Superior region it is useful to identify periods of time over the nearly 200 years of geologic mapping during which the magnetic method has been used in a generally consistent manner. These periods were driven largely by technical advances rather than by ore exploration programs as in the boom exploration years.

The earliest period of magnetic exploration extending from ~1830 to 1900 marks **The Discovery Years**. During this period simple magnetic needle instrumentation was used to search for and outline all of the iron ranges of the Lake Superior region and to assist in the location of direct shipping iron ore bodies and locating favorable regions for copper ore exploration. Subsequently in the period from 1901 to 1940 **The Ground Survey Years** refers to the period when standard procedures were used for ground measurement of magnetic anomalies with improved instrumentation. It was also during this period that the magnetic method was extended into new regions and was used for more detailed, precise studies that led to increased quantitative analysis of the magnetic data.

In the third period, **The Airborne Survey Years** from 1941 to 1980, airborne instrumentation and survey procedures were developed and gradually largely replaced ground magnetic surveying. Airborne surveys were used for magnetic mapping of extensive areas in a consistent manner opening the way for the method to be used not only for identification of mineral exploration but for geological mapping. The method was applied to not only the direct and indirect search for traditional iron and copper ores, but for isolated occurrences of massive sulfide deposits and other mineral resources. Finally, since ~1980 because of broadening interest in the geological history of the region and new ore deposits such as those of critical national interest, the precision and resolution of the airborne magnetic surveying was dramatically increased with improved magnetic, navigational, and computational instrumentation and analysis, as well as interpretational and data presentation procedures. This period, **The High Resolution Survey Years**, continues into the present. It is understood that the evolution and use of the magnetic method during these periods although defined with specific dates are subject to minor overlap between adjacent periods.

In the following description of these time periods consideration is given to the technical changes that paved the way for the period including magnetic instrumentation and changes in mapping, analysis, and interpretation of magnetic data that were implemented during the time span of the period. Evidence of the importance of these modifications is presented by description of the breadth of application of the method in the Northern Peninsula of Michigan, northern Wisconsin and Minnesota, and adjacent Ontario. These descriptions are based on available literature, journal articles, books, and reports of state/provincial and federal agencies. No attempt has been made to obtain pertinent information from private industry, but private sources have been engaged in magnetic studies of the region since the earliest of exploration of the region. For the most part, their data remain restricted or has been lost as mines and companies are shut down.

3.2 The Discovery Years: 1830-1900

3.2.1 Overview

The initial period of use of the magnetic method to map the geology and ore deposits of the Lake Superior region is aptly termed **The Discovery Years** because during this period of time from the ~1830s to the turn of the century the magnetic method was important to mapping the significant iron ranges of the region and investigation of the volcanic rocks of the Keweenaw Peninsula containing copper ore deposits. During this period there was a convergence of progress on several topics that led to the success and importance of the magnetic method in Lake Superior region geological studies. First, there was the western expansion of the United States during the 1800s that required a land division system which was largely established by magnetic compass surveying. Anomalous magnetic fields observed in the land boundary surveying were used to map hidden iron ranges and Keweenawan volcanic rocks. Second, there was an increasing demand for iron by the industrial revolution that was taking place in the United States and for copper for the electrification of the country in the latter part of the 1800s. Third, during the 1800s there was a strong interest in the scientific community to describe and map the global terrestrial magnetic field. This led to notable improvements in instrumentation for observing the magnetic field and theoretical developments for the analysis and interpretation of the anomalous terrestrial magnetic field. These advances significantly enhanced the use of the magnetic method in exploration. The convergence of these three developments sparked mapping of the magnetic field resulting in identifying the location of iron ranges and favorable rocks for the occurrence of copper ores.

3.2.2 Technical Developments

3.2.2.1 Magnetic Instrumentation

During **The Discovery Years** period magnetic instrumentation in the Lake Superior region was limited to relatively simple magnetic needle instruments some of which had been used for centuries in Scandinavian countries of Europe which have intense local sources of magnetization as does the Lake Superior region. All of the instruments for measuring the elements of the magnetic field in this period used a simple magnetic needle, required leveling and a stationary setting, and, for some instruments, orientation in a specific direction of the terrestrial field to obtain a precise measurement. It is also noteworthy that the measurements of the magnetic intensity were all relative which required ties to absolute base stations for adjustment of the measurements to absolute values. The simplest of these instruments were the magnetic compass and its derivatives and the dipping needle or dip circle[3]. The compass was used to determine the direction of the magnetic meridian which mapped the declination and the dipping needle measured the inclination of the terrestrial magnetic field. In the latter part of this period the dip needle was brought to the Lake Superior region. It soon became the most prominent magnetic instrumentation in the region because its observations were related to the intensity of the magnetic field and thus could be more directly linked to subsurface magnetic sources.

3.2.2.1.1 Magnetic/Solar(Sun)/Dial Compass[4]

The oldest and simplest of magnetic instruments is the magnetic compass (Hine, 1968) in which a horizontal needle that is magnetized along its long axis is free to attain a rest position while rotating on a vertical axis positioned at the center of the needle (Figure 4). The vertical axis is free to rotate on an axis within jeweled cups above and below the needle. A clockwise 360^o graduated circle marked in degrees bounds the end of the needle. The compass needle when it is released to search out an equilibrium position will oscillate around and eventually orient in the local magnetic meridian (magnetic north/south). The angle between the local magnetic meridian and the geographic meridian, referred to as the magnetic declination, is normally only a few degrees in the Lake Superior region depending on the location of the measurement and the ambient magnetic field. If geographic north and the normal declination are known, an observed deviation of the declination from the normal indicates a nearby source rich in magnetic minerals or remanent magnetization producing an abnormal magnetic field, thus a magnetic anomaly. The sun (solar) compass or its simplified derivative, the dial compass, is used to measure the declination and isolate nearby subsurface magnetic sources causing anomalies in the declination.

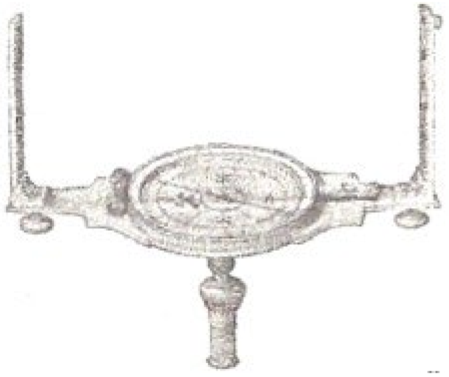

Figure 4. Plain surveying magnetic compass. (After W. & L.E., Gurley Instrument Co, 1869)

The 1785 Land Ordinance of the United States required surveying of the lands of the midcontinent including the Lake Superior region with the Public Land Survey System. Much of the area was mapped using compass and chain by surveying crews such as the one led by William Austin Burt (1792–1858) in the Northern Peninsula of Michigan. Errors were incorporated into

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[3] Note that the dipping needle or dip circle is not the dip needle.

[4] Note the description of the dial compass presentation in the Preface which explains why this section is more comprehensive than that of other instruments in this treatise.

compass surveys where local magnetic sources disturbed the normal field modifying the declination of the field and thus the direction of north. These errors cause irregularities in the rectangular land division system which show up in land survey boundaries on maps. Identification of these irregularities on published maps have been used by prospectors to isolate regions for more detailed studies where intense local magnetic anomalies are present. Similar abnormalities that occur in the Canadian land survey system were used as a first-order magnetic mapping tool of local magnetic sources.

To avoid errors in defining the direction of true (geographic) north with a compass adjusted for local declination of the Earth's magnetic field, the magnetic compass and a portable sun dial for determining local time from the position of the Sun are combined into a single instrument, the sun or solar compass. With this instrument a shadow cast by the Sun as in a sun dial is used to determine true north using a calibration based on the general location of the station at the local time. This direction is compared with magnetic north established by the direction of a magnetic compass needle inside a graduated circle to determine the declination of the magnetic field. It is necessary to calibrate the sun compass for use at a specific latitude over a range of Sun time and requires knowledge of true north. Methods for establishing true north when it is not known are described in Gurley (1869) and Hotchkiss and Bean (1929).

Figure 5. William Austin Burt (1792–1858) who devised the solar compass for land surveying where local magnetic anomalies were present that invalidated the use of the magnetic compass. This instrument indicated the presence of the first iron ore found in the Lake Superior region near Negaunee, Michigan in the Marquette Iron Range in 1844. (Courtesy of Google Images)

The principle of the solar compass was described by the British naval officer William Borough (1536–1599) in 1581, but the earliest recorded evidence of the use of declination to detect buried iron-rich deposits is in 1640 in Sweden. This methodology was brought to the United States from Europe as early as the seventeenth century and was used to locate iron ore deposits in New York and New Jersey. To assist surveyors in accurately conducting the linear (horizontal length) surveys as part of the Public Land Survey System of the United States in regions where the local geology causes intense magnetic, and thus declination anomalies, William Austin Burt (Figure 5), a Deputy Public Land Surveyor, designed a special instrument in 1835 to determine the geographic meridian. He first noted the need for the sun compass due to a declination variation he encountered while surveying in southern Wisconsin. He obtained a patent on his design in 1836 and additional patents in 1840 and 1851 on improvements to the original design. This instrument, the sun or solar compass (Figure 6) as designed by Burt and constructed by the W. & L. E. Gurley Instrument Co. of Troy, New York, was used by Burt and other surveyors involved in the 4th Meridian Survey centered on the State of Wisconsin and continued to be the standard instrument for linear surveys until the Global Positioning Satellite (GPS) system became operational in the year 2000. Estimates suggest that 75% of the public lands of the United States were surveyed with this instrument.

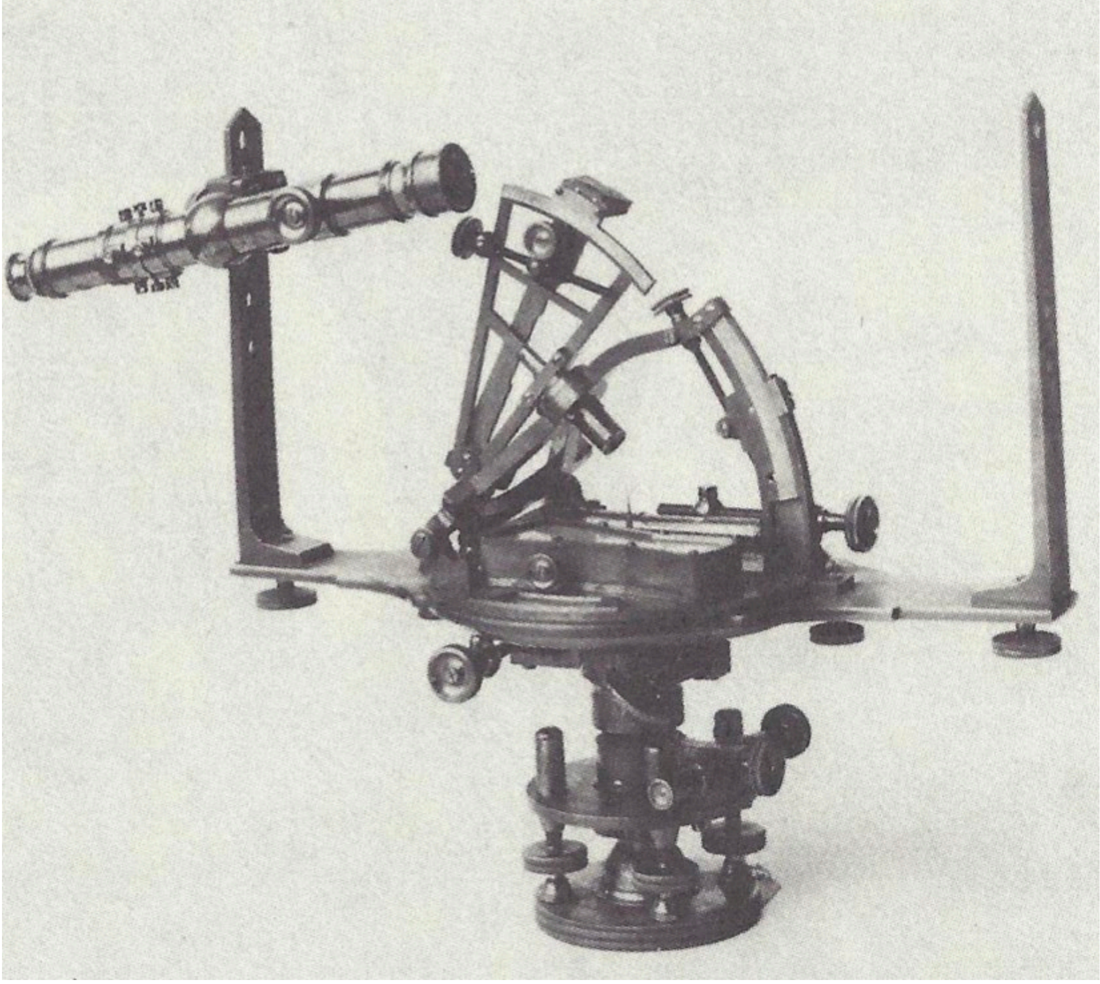

Figure 6. Solar or sun Compass designed by W.A. Burt and constructed by W. & L.E. Gurley Instrument Company. (After Rydholm, 1989)

Unfortunately, the instrument designed by Burt and constructed to his design by numerous instrument manufacturers (Smart, 1962) was too heavy, cumbersome, and complex to be used expeditiously by prospectors and geology mappers.[5] As a result, a simplified sun compass, which

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[5] John S. Hougham, the first professor appointed at Purdue University (Chairman of the Agricultural Chemistry Department) and later an acting president of the University, was an advertised manufacturer of mathematical instruments including the solar compass which he made in 1860 while Professor of Mathematics and Natural Philosophy at Franklin College in Franklin, Indiana.

is generally called the dial compass, was designed by Maj. Thomas Benton Brooks (Figure 7) (Brooks, 1873a; Wright, 1880) assisted by Raphael Pumpelly (1837–1923) and Roland Duer Irvine (1847–1888) for mapping iron formations in the Menominee and Gogebic Iron Ranges. In simple terms the dial compass (Figure 8) is a combination of a portable sun dial and a magnetic compass, hence the name dial compass. The instrument requires leveling for measurements, and although it can be hand-held for observations, it is commonly placed upon a staff thrust into the ground, a so-called Jacob's staff, to facilitate the observation which generally can be made to the nearest half degree. This instrument was used for mapping nearby geologic magnetic sources for many decades.

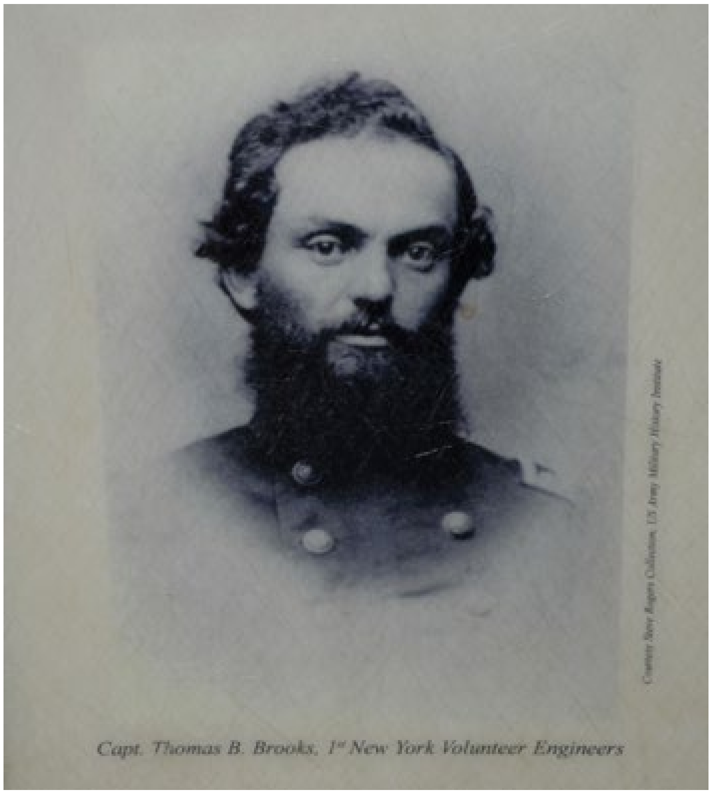

Figure 7. Civil War era photograph of Thomas Benton Brooks. Major Brooks arrived in the Marquette Iron Range in 1865 as vice president and general manager of the mines held by the Iron Cliffs Company and subsequently joined the Michigan Geological Survey in 1868. For many years he was the principal authority on the geology of the Lake Superior mining district, its ores, and mines. He developed the dial compass from the sun compass and likely introduced the dip needle to the district when he arrived from the New Jersey Geological Survey in 1865. These two mechanical magnetic instruments, the dial compass and dip needle, were the principal methods for magnetic mapping the hidden geology and ore deposits of the Lake Superior region for nearly a century. (Courtesy of Google Images)

The declination direction shown by the dial compass is the vectorial resultant of the intensity of the horizontal component and the direction of the local magnetic field from the local magnetic source and the horizontal component and direction of the normal terrestrial magnetic field at the station location. It varies from small to large angles depending on the direction relative to the true meridian and the amplitude and direction of the local horizontal component. As a result, there is an inherent ambiguity in the interpretation of the declination variations. However, the declination can be useful in investigating certain aspects of the source of the local magnetic variation.

For interpretational purposes the direction of the declination is shown by an arrow on a map with the base of arrow positioned on the location of the station as illustrated in Figure 9. In this figure the declination variation is shown at a series of locations that traverse over a vertical, linear magnetic source that is oriented in three different directions from the traverse direction. The declination is useful in detecting the source and determining its orientation. A line drawn through the maximum declination of a sequence of parallel traverses (not shown in Figure 9) parallels the strike direction of the magnetic source. Also, the declination is zero directly over the center of the magnetic formation because the magnetic effect of the formation on either side of the observation cancels out their horizontal effects providing that the source is symmetrical. If the magnetic formation is oriented in the magnetic meridian, the magnetic declination along a traverse overlying the center of the magnetic formation will not have an abnormal declination. However, magnetic declination measurements on either side of the center will increase with distance to a maximum and then with increasing distance from the magnetic formation it will decrease to normal declination. The measurements to the west of the magnetic formation will be directed to the east and those to the east will have westerly declinations. Clearly the interpretation of these measurements can be complicated and confused by the overlapping anomalies from additional magnetic sources within the range of the declination perturbances. The distance from a magnetic source that the effect can be observed with a dial compass is highly variable depending on the magnetic intensity of the local source and its location relative to the observation site. Smyth (1897) cites what appears to be an extreme case where the effect was observed 3.5 miles from the source in the Republic Trough.

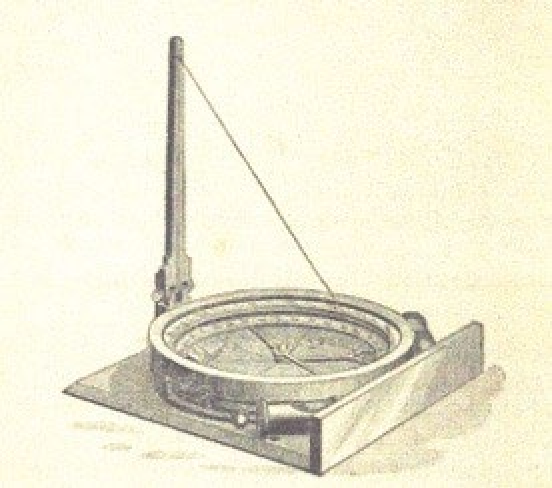

Figure 8. Dial compass as designed by Maj. T.B. Brooks and others and constructed by W. & L.E. Gurley Instrument Company. (From Gurley Instrument Catalog, 1869)

The magnetic compass was also used for measuring the horizontal intensity of the terrestrial magnetic field by determining the period of oscillating of the needle around its rest position. Beginning in the seventeenth century there was considerable interest in the physical science community in the nature of the terrestrial magnetic field including its angular relationships, intensity, and the location of its poles. This interest included measurements in the Lake Superior region beginning in the 1840s before the magnetic method became important to geological and ore deposit mapping in the region. The measurement of the intensity of the terrestrial magnetic field using the oscillation period of a magnetic needle as it settles upon its rest position was suggested by Jacques Mallet (1724–1815) in 1769 and initiated after 1778 by the French engineer and mariner Jean-Charles de Borda (1733–1799) (Multhauf and Good, 1987). The needle either in a horizontal or vertical plane oscillates around its rest position faster as the Earth's magnetic intensity increases because the period of oscillation is inversely proportional to the square root of the magnetic intensity in the plane of the oscillating needle.

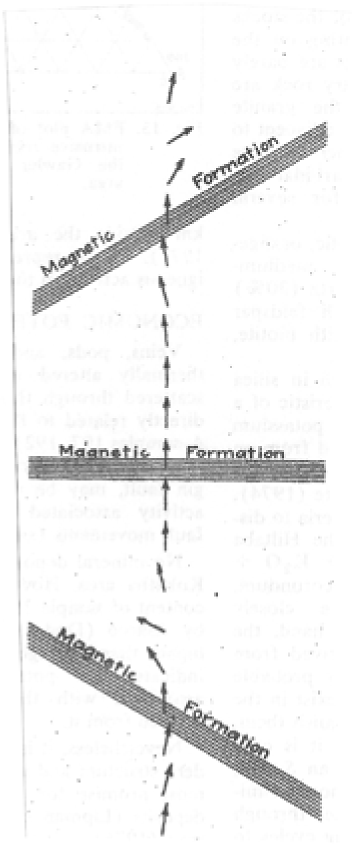

Figure 9. Variation in declination (arrows) as measured along a traverse crossing a vertical, linear magnetic source with different strike directions. Note that the declination is zero at locations over the center of the magnetic formation and that a line drawn connecting the maximum declination observed on a series of parallel traverses is parallel to the strike of the magnetic formation. (After Hotchkiss, 1915)

Measurements of the period of oscillation of the magnetic needle were first used to measure relative intensity in 1792 by Elisabeth Paul Edouard de Rossel (1765–1829) during a French exploration voyage to the South Pacific (Lilley and Day, 1993). Unfortunately, this method is limited to relative measurements of magnetic intensity because the oscillations are dependent on the magnetic strength of the needle which generally is unknown and varies among needles and decreases with time as needles lose their magnetism. However, the oscillation period of the magnetic needle was used in a qualitative way as a guide to interpretation as discussed in the next section. The total relative magnetic intensity could be calculated from the trigonometric relationship between the relative horizontal intensity and the angle of inclination measured with the dipping needle.

3.2.2.1.3 Dipping Needle/Dip Circle

Numerous instruments have been developed for determining one or more components of the terrestrial magnetic field with a magnetized needle operating in a vertical plane. The simplest of these is the dipping needle or dip circle which is essentially a compass oriented to oscillate vertically in the magnetic meridian around the inclination of the Earth's magnetic field which varies from zero at the magnetic equator to 90° at the magnetic poles. The magnetic needle of this instrument oscillates within a graduated circle divided into four quadrants of 90° with the level position set at zero degrees. Unfortunately, the name dip needle has been used in some descriptions for this instrument which confuses it with the "dip needle," which is a similar instrument but has a counterbalanced magnetic needle. Until they were replaced with electronic instruments for measuring inclination of the terrestrial field, dipping needles were constructed very carefully to avoid problems in determining the oscillation and rest position of the needle free from friction effects on the axis of rotation. This instrument has been used rarely for exploration because of its limited sensitivity and problems in maintaining the free oscillation of the needle to its rest position.

3.2.2.1.3 Dip Needle(Dip/Miners Compass)[6]

3.2.2.1.3.1 Introduction

In contrast to the dial compass, the dip needle determines the presence of an anomalous local magnetic field by its effect on a vertically positioned rather than a horizontal magnetic needle and unlike the dipping needle it is counterbalanced by an axial-symmetric weight on the south-seeking end of the magnetic needle in the northern geomagnetic hemisphere. Virgil S. Hillyer (1872–1950) presented a paper at the 10th Annual Meeting of the Lake Superior Mining Institute in 1904 that was published in the Proceedings of the Meeting (Hillyer, 1904) in which he described the construction, observations, and interpretation of the dip needle and the dial compass as employed at that time on the Marquette Iron Range. He notes in his description of the instruments that:

> …*"The dial compass is a more valuable instrument than the dip needle, for in addition to taking magnetic observations with it, an accurate closed survey may be made regardless of local attractions. The dip needle is principally used now* [1904] *as a check and also to emphasize the results obtained by the dial compass."*

This evaluation of the relative merits of the dial compass versus the dip needle gradually changed with the dip needle and its results being more commonly used in geologic mapping. The

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[6] Note the description of the dip needle presentation in the Preface which explains why this section is more comprehensive than that of other instruments in this treatise.

dip needle has greater sensitivity than the dipping needle and its observations are related directly to the intensity of the anomalous field, an advantage in quantitatively interpreting the measurements.

3.2.2.1.3.2 Origin and Development of the Dip Needle

There are two prominent questions related to the dip needle as it pertains to the Lake Superior region: How, when, and who invented the dip needle for geological mapping? and When and who brought the dip needle to the Lake Superior region for geological mapping? The answers to these questions are not directly available in the literature, but are paramount to understanding the evolution of the magnetic method for geological purposes in the Lake Superior region. Vibert et al. (2011) comment that the inventor of a form of the dip needle, the Swedish mining compass, is unknown, or at least is debated, as cited by Soske (1935) and Carlborg (1963). To investigate these and related questions requires review of both the geomagnetic and magnetic exploration literature. Fortunately because of the interest of European physical scientists in the geomagnetic field beginning in the seventeenth century major advances were made in instrumentation for measuring various components of the geomagnetic field at the same time as there was an increasing interest in mapping hidden ore deposits and mapping geology. These advances were made by scientists and engineers who were interested in communicating their progress with publications and reviewed speeches before scientific communities that are now generally available for study. In contrast, publication and other forms of communication of progress in magnetic mapping instrumentation and procedures by the exploration industry and individuals involved in mining are limited. Publication of their progress is largely restricted to descriptions many years after their related activities and limited in their detail. Additionally, progress in exploration magnetics gave the originator an advantage over their competitors and thus it was advantageous to not publicize progress in instrumentation and analysis. As a result, the dominant source of information on early magnetic instrumentation and its use are from the scientific community rather than from prospectors. The available evidence suggests that the origin of the dip needle may have been independently achieved by both mineral explorationists and scientists involved in mapping the terrestrial magnetic field.

Early geomagnetic investigations were largely concerned with mapping the Earth's magnetic field, its declination, inclination, and intensity. Nations were urged by the scientific community to establish magnetic observatories to study the magnetic field and its temporal variations and to make national surveys. Measurements of declination and inclination were made relatively easily and accurately with compasses and dipping needles as long as the instruments were well made. However, the intensity of the magnetic field was more difficult to measure. Early measurements were made based on the relationship between intensity of the magnetic field and the period of natural oscillation of a horizontal magnetic needle around its equilibrium position (Multhauf and Good, 1987). However, the oscillation method of measuring magnetic intensity has serious disadvantages. It can only measure the relative intensity difference among observation sites and errors resulted from the change in the magnetic moment of the needle with time. Carl Friedrich Gauss (1777–1855) and Wilhelm Eduard Weber (1804–1891) in

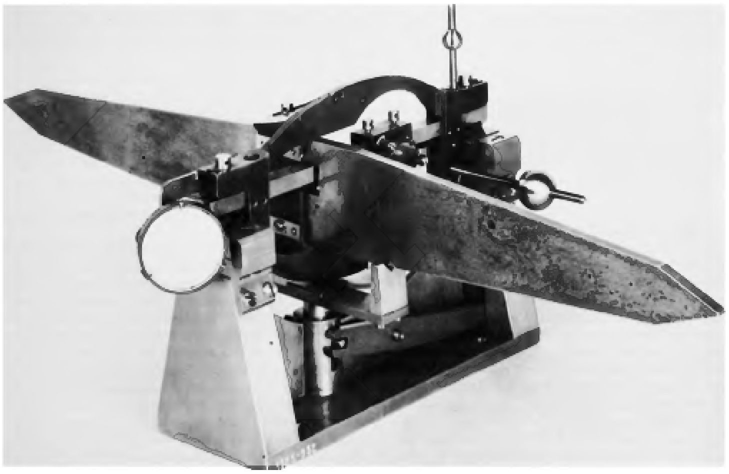


Figure 10. Prof. Humphrey Lloyd's vertical force magnetometer or balance magnetometer introduced about 1842 as an improvement of earlier versions of the counterbalanced needle. This instrument closely resembles the sensor element of the Schmidt-type balance which was developed for magnetic prospecting approximately a century later. (After Multhauf and Good, 1987)

1832 eliminated the problems of measuring the intensity of the terrestrial magnetic field with an oscillating needle using two different experiments with two magnetic bars. This procedure eliminated the effect of the magnetism, shape, and weight of the magnetic bars used in the experiments. This was a major step forward in mapping the nature of the terrestrial magnetic field, but the method was not applicable to field measurements for geological mapping because of the length of time required for the measurement and the necessary cumbersome laboratory facilities.

A useful suggestion for making magnetic intensity measurements was made by Tobias Mayer (1723–1762), a renowned German mathematician and astronomer, who near the end of his life in 1762 became interested in geomagnetic problems (Forbes, 1972). He proposed, as reported by his son Johann Tobias Mayer (1752–1830) in 1814 (Multhauf and Good, 1987), moving the center of gravity of a vertical oscillating magnetic needle from the axis of rotation, which is key to the dip needle's use to measure magnetic intensity. In addition, the elder Mayer realized that by observing the magnetic needle perpendicular to the magnetic meridian, the vertical intensity of the magnetic field was measured. This approach to measuring magnetic intensity was discussed by Samuel Hunter Christie (1784–1865) in 1833 in the Philosophical Transaction of the Royal Society of London (Christie, 1833). His article also suggested the use of the dual magnetic needles as in the Hotchkiss superdip and replacing the agate cup pivot of the needle with a knife edge similar to the one used in the Schmidt-type magnetometer.

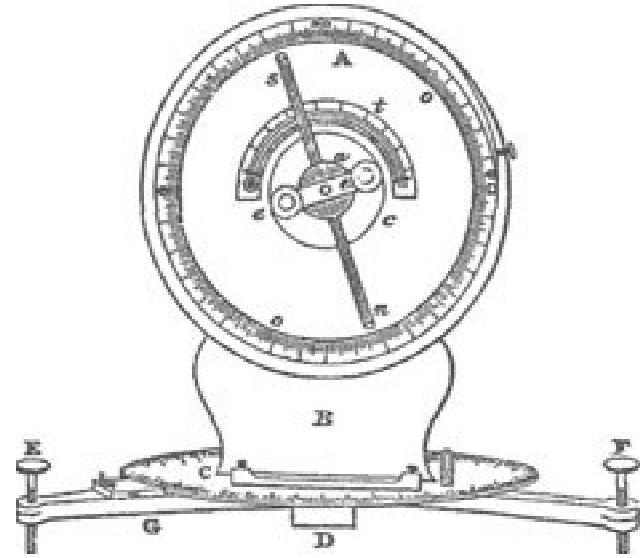
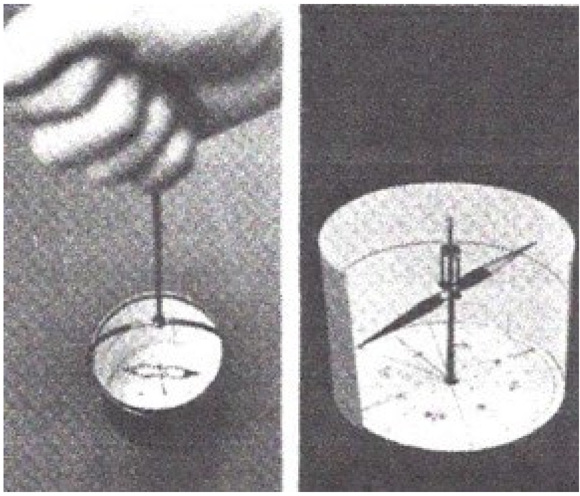
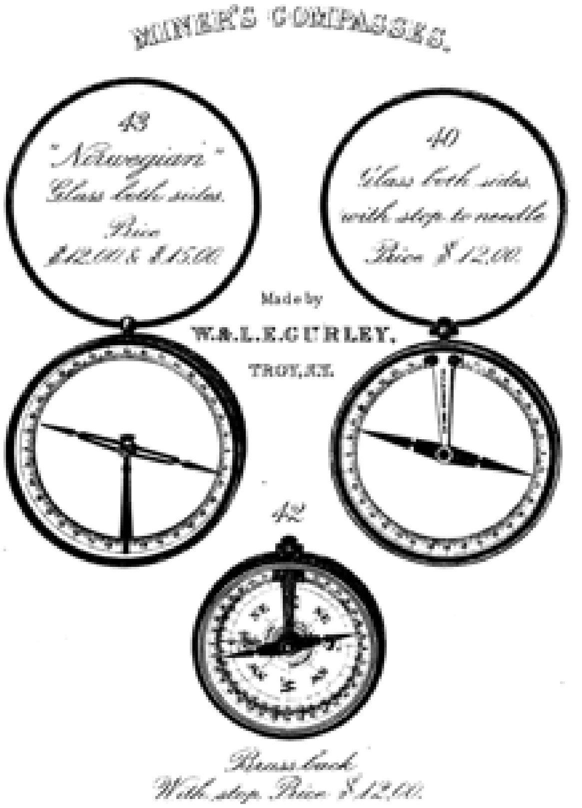


Figure 11. R.W. Fox's "dipping needle deflector"(circa 1835) that was a predecessor of the dip needle used for magnetic exploration. This instrument was used to determine the declination, dip, and intensity of the terrestrial magnetic field. The intensity was determined with counterbalancing weights suspended from the circular wheels near the axis of the needle (ns) by a silk fiber. (After Jordan, 1839)

One of the first to put the counterbalanced magnetic needle into use was Humphrey Lloyd (1800-1881), Professor of Physics at Trinity College in Dublin, Ireland. He conceived this instrument during the autumn of 1833 for a magnetic survey of Ireland in 1834-35. He continued to make improvements to the counterbalanced needle instrument through the years including the redesigned magnetic element shown in Figure 10. Robert Were Fox (1789–1877), a Cornish inventor and geologist, designed a similar instrument (Figure 11) circa 1835 which was widely used for several decades to measure magnetic intensity and had a prominent role in geophysical prospecting (Jones, 1929). It is unclear what



a.



b.

Figure 12. a. Swedish or Norwegian mining compass or dip needle that was used extensively in iron ore prospecting in Scandinavia, but not in the Lake Superior region. This instrument had freedom of movement in both the horizontal and vertical planes. (After Espersen, 1970) b. Miner's compasses (dip needles) in Gurley Instrument Company Manual (1874). The '40' instrument is a Lake Superior-type dip needle with glass covers on both sides, '42' is the same instrument with a brass cover on one side, and '43' is Norwegian dip needle with glass on both sides.

Information obtained from previous studies suggesting the use of a counterbalanced needle were useful to Fox and Lloyd, but according to O'Hara (1983):

" *To Lloyd alone is due the credit for the invention of an instrument which first made possible the observation of the changes in the third element viz., of the vertical component of the force."*

The original Lloyd instrument built by the English instrument maker Thomas Charles Robinson was too complicated for geological field operations although simpler than the instrument proposed by Christie. Later his design was simplified for use in prospecting (O'Hara, 1983). Lloyd's role in devising the dip needle is acknowledged in some descriptions of the instrument where it is identified as Lloyd's dip needle. Thus, it is appropriate to recognize Lloyd as having a or perhaps the major role in designing and constructing the dip needle, although Tobias Mayer previously had suggested the principle on which the instrument is constructed. However, a counterbalanced vertically-oscillating needle instrument, the miner's compass which oscillated in both the horizontal and vertical direction, was developed in Sweden in the latter part of the eighteenth century (~1770) (Lundberg,1929b). The inventor of this instrument is open to question, but it commonly is credited to the famous Swedish geologist Daniel Tilas (1712–1772) (e.g., Haanel, 1904). If he did not invent the miner's compass (dip needle) he was at least instrumental in championing its use in exploration. We do not know what role the studies of Tobias Mayer had in developing the miner's compass, but they may not have had any impact because his work was not published until the early nineteenth century by his son. In summary, the development of the counterbalanced dip needle by Lloyd and by Fox probably was initiated by the analysis of Tobias Mayer, but possibly an independent development of the instrument apparently took place in Sweden perhaps by Daniel Tilas[7].

The second principal question identified at the beginning of this section is: When and who brought the dip needle to the Lake Superior region for geological mapping? The first recorded use of the dip needle in North America was shortly after 1854 (Smock, 1876) by the New Jersey Geological Survey who used the instrument along with the sun compass to explore for and map magnetic iron-rich formations in northwest New Jersey and adjacent New York. This dip needle was of the Swedish or Norwegian compass type which was used extensively in mineral exploration in Scandinavia. It consisted of a needle that oriented itself in the magnetic field both in a horizontal plane (360º) and over a limited vertical range of 30º (Figure 12a). As a result, the needle oriented in the magnetic meridian and with a universal or double joint the needle adjusted to a vertical equilibrium position related to the intensity of the magnetic field. It was not very accurate and measurements were time consuming as a result of the universal joint that supported the magnetic needle. An improved version of this instrument was developed around 1870 by George Hammell Cook (1818–1889) of the New Jersey Geological Survey and constructed by the Gurley Instrument Company for marketing to the mining industry (Smock, 1876) from the mid-1870s to roughly 1920 (Figure 12b). This instrument also used a universal joint for supporting the magnetic needle. The joint limited the horizontal movement for orientation in the local magnetic meridian, but was unlimited in the vertical plane for intensity measurements.

Finally, another instrument, sometimes referred to as the "Lake Superior dip needle," was developed that eventually became the dip needle of choice for magnetic mapping in the Lake Superior region. It used only a single axis needle counterweighted on the southern arm of the needle. Although it required orientation relative to the magnetic meridian, it was more rapid to use than the Norwegian or Swedish dip needle (mining compass) and avoided the complication of the universal joint. This instrument was constructed by the Gurley Instrument Company from the mid-1850s (Figure 12b). It was still available in the early 1920s, but no longer sold by the company after 1940. Equivalent instruments were sold by the E.J. Sharpe Instruments of Canada Ltd. (later Scintrex Ltd.) of Toronto, Ontario into the 1960s. Henceforth in this text, this is the instrument that is referred to as the dip needle.

Maj. T.B. Brooks[8] who had recently been discharged from the U.S. Army during the Civil War joined the New Jersey Geological Survey in 1864 and began using a dip needle for geologic mapping of deposits of magnetite-rich rocks in the New Jersey highlands and similar rocks in adjacent New York

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[7] Note that J.M. Bruckshaw (1954) wrote that Daniel Tilas devised the Swedish mining compass in 1672. However, this is impossible because he was not born until 1712. If the date in his journal article (Bruckshaw, J. M.,, 1954., Rock magnetism–some recent developments. *Science Progress,* Volume 42 (167), 406-418.) should have been 1772, that was the year of Tilas's death.

[8] See Appendix B for a biography of Maj. Brooks and his contributions to the use of the magnetic method in the Lake Superior region.

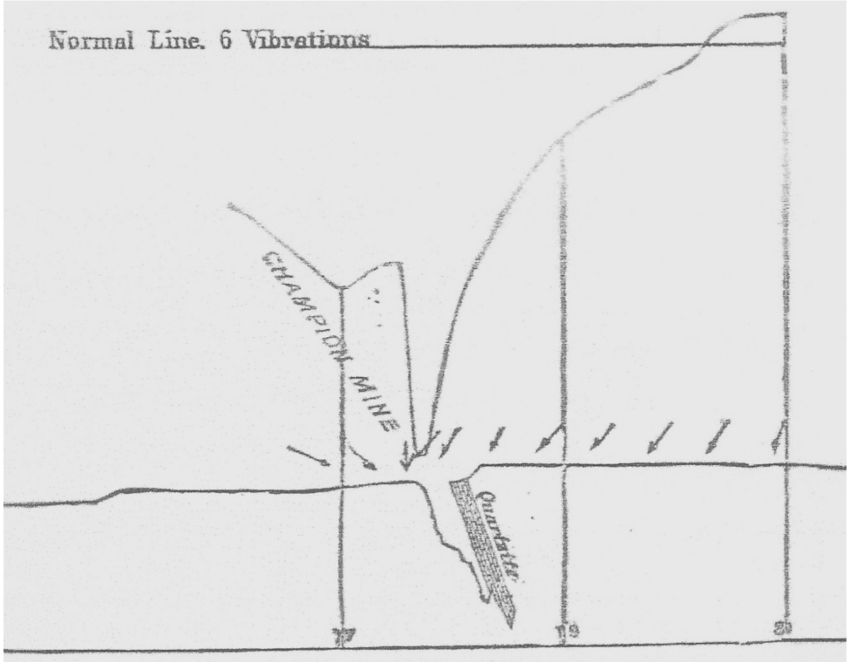

Figure 13. North (left)/South (right) topographic profile across the Champion Mine (western Marquette Iron Range, Michigan) showing the observed direction of the dip needle's magnetic needle (arrows) and oscillations (curve of vibrations) per unit time. (After Brooks, 1872a)

(Cook, 1865). Brooks left the New Jersey Geological Survey in 1865 to become vice-president and general manager of the Iron Cliffs Company iron mines near Negaunee, Michigan, the predecessor of the Cleveland-Cliffs Iron Company[9]. He likely brought the concept of the simple dip needle with him from New Jersey because he began magnetic surveying with a dip needle shortly after arriving in Michigan. Initially he referred to this instrument as a dip compass, but later used the term dip needle as well. His first instrument, which he used in the Marquette Iron Range in 1866, was a "crude home-made portable dial" (Brooks, 1880) which was counterbalanced so a horizontal rest position (0°) was taken by the needle in a normal magnetic field. An improved version was constructed by Franz Krœdel (1834-1907), a New York instrument maker, which he exhibited and explained at the American Institute of Mining Engineers meeting in 1874. An example of his dip needle mapping in the Marquette Iron Range is illustrated in Figure 13. We note the change in the magnetic needle rest position and the period of oscillation of the needle on a N/S profile across the Champion mine in the western portion of the Marquette Iron Range. Brooks joined the Michigan Geological Survey as head of the economic division of the survey in the Northern Peninsula in 1868 under the direction of Alexander Winchell, the Michigan State Geologist. Brooks in this position essentially served as state geologist of the Northern Peninsula of Michigan and continued his studies of the iron ranges of Michigan and Wisconsin and the copper ore district of the Keweenaw Peninsula with the aid of the dip needle. He did extensive magnetic mapping with the dip needle and dial compass in the Menominee Iron Range. An example of his mapping in this range is shown in Figure 14 with a key to its symbols identified in Figure 15. In a

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[9] Iron Cliffs Company was purchased by the Cleveland Iron Mining Company in 1891 to form the Cleveland-Cliffs Iron Company which maintains a dominant position today in the mining of iron ore.

talk before the American Philosophical Society in Philadelphia in 1872 he remarked that the dip needle was now being used in all of the iron ore regions of North America.

3.2.2.1.3.3 Operational Use of the Dip Needle

The single axis dip needle instrument was generally used by orienting it in the magnetic meridian by using the instrument as a compass at waist level and then placing it vertically in the meridian at eye level with the operator facing west. The needle was then released allowing it to oscillate around its rest position. The equilibrium or rest position of the needle was read at the point of the needle on a graduated circle divided into degrees measured from 0° at the horizontal. Generally the rest position was not used as the equilibrium position because it was affected by imperfections of the axis of the needle rotating in the jewel cups that hold the axis in place. Furthermore, waiting for a needle to reach its rest point can be time consuming. As a result, the equilibrium position was commonly calculated from the average of several reversal points of the oscillating needle. A satisfactory procedure was to determine the arithmetic mean of the second, twice the third, and the fourth reversals of the oscillating magnetic needle (Hinze, 1962). Brooks (1872a) noted that some users oriented the dip needle perpendicular to the magnetic meridian for their observations, but there is no indication that this orientation of the instrument was considered advantageous despite the observation of many previous workers that this position provided the measure of only the vertical magnetic intensity without any inclination effect.

The meridian orientation of the dip needle for observations was likely chosen as the standard because the axis of the needle was free to move in the jewel cups. In a position perpendicular to the meridian the axis was not free to oscillate because of binding of the axis in the cups by the magnetic force directed toward magnetic north. As a result, these measurements were subject to inconsistent errors.

Alternatively, some observers took three dip needle measurements at each observation site: one in the magnetic meridian and two others perpendicular to the magnetic meridian, one facing south and the other facing north (Waters, 1893). Figure 16 shows a model of this instrument constructed by the Sharpe Instrument Company which was held in the magnetic meridian with a ring connected to the top of the circular instrument. There are numerous potential errors in making dip needle observations.

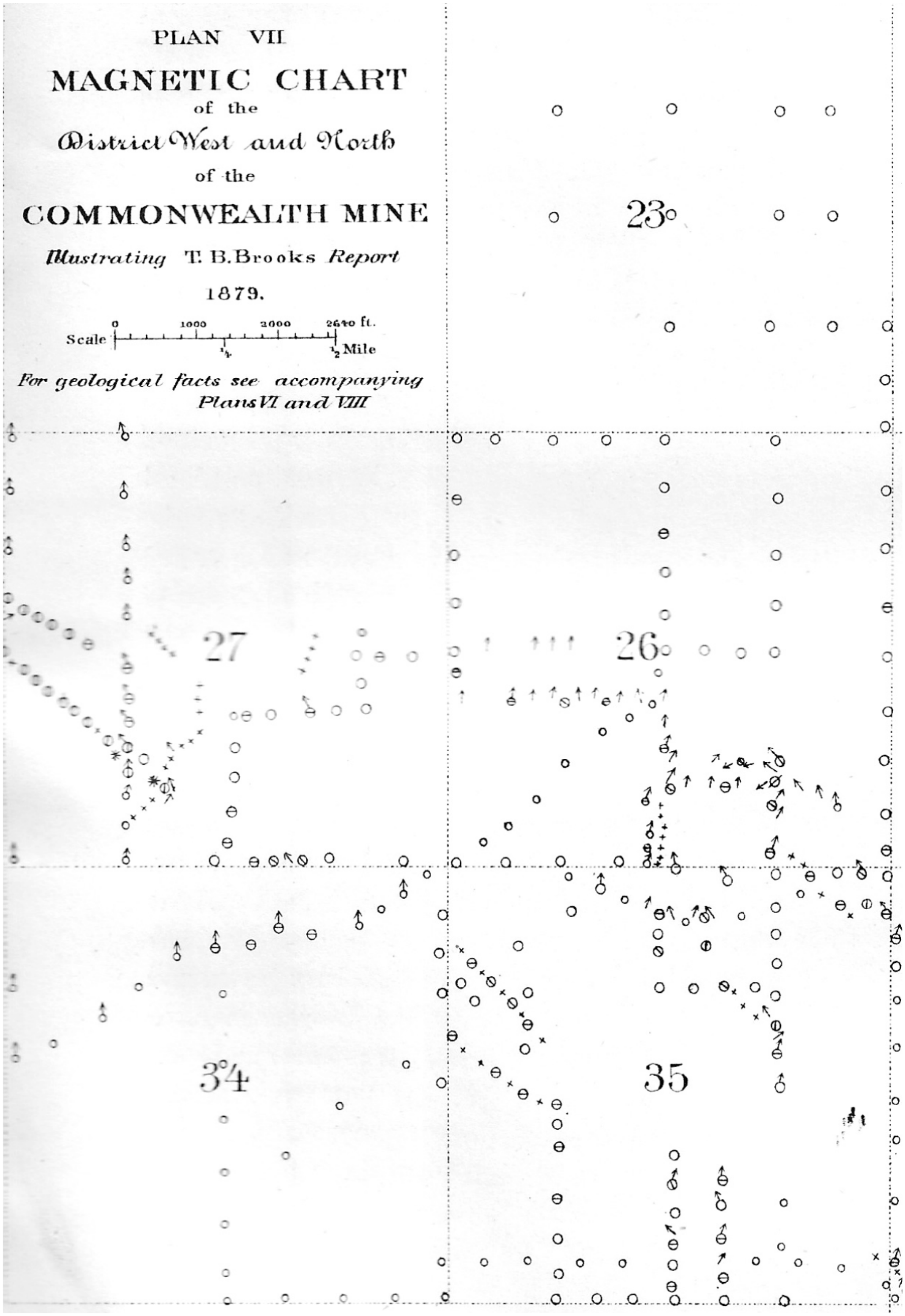
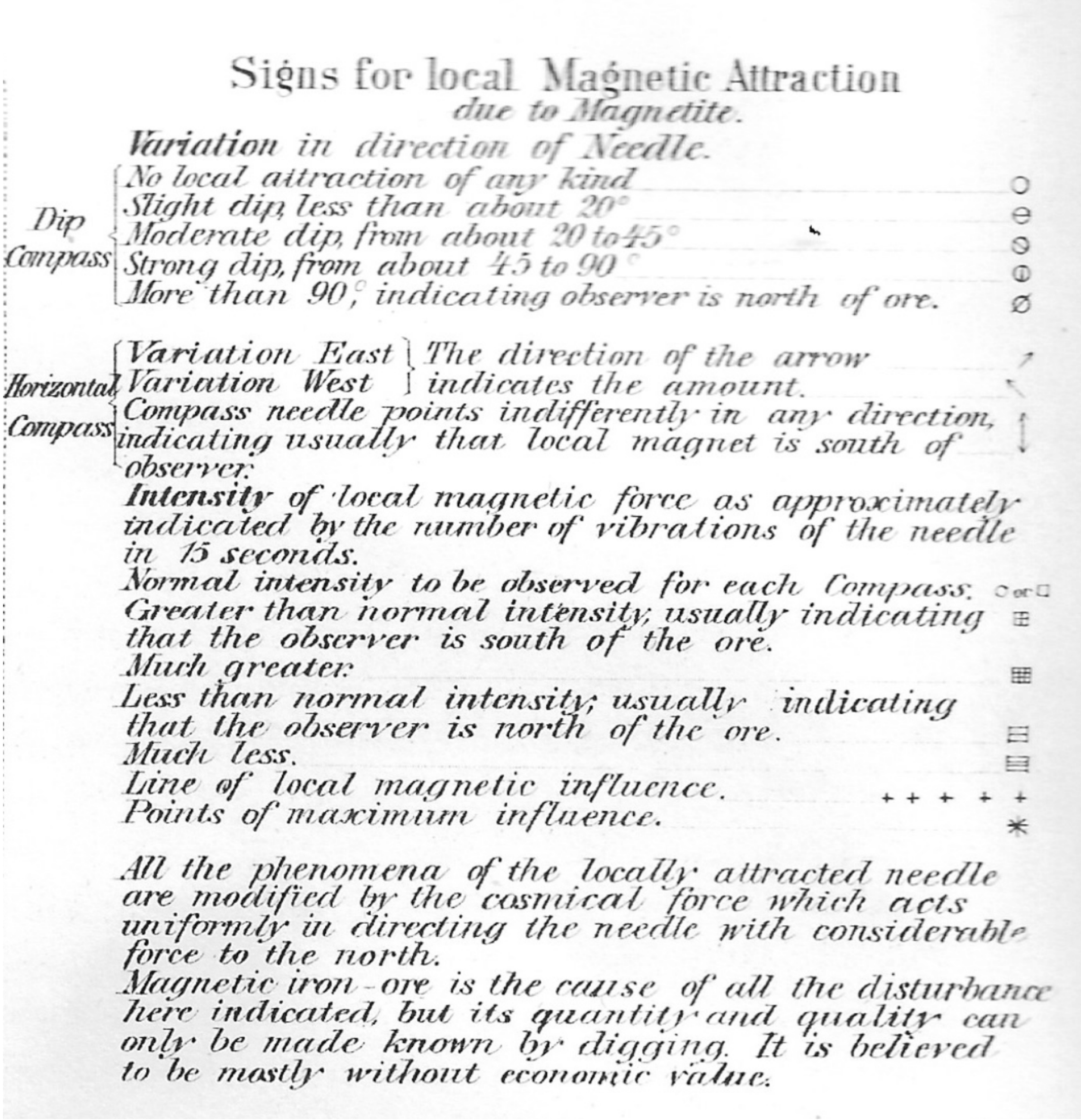

PLAN VII
MAGNETIC CHART
of the
District West and North
of the
COMMONWEALTH MINE
Illustrating T. B. Brooks Report
1879.
Scale
0
1000
2000
2640 ft.
¼
½ Mile
For geological facts see accompanying Plans VI and VIII
23
27
26
34
35

Figure 14. A portion of T.40N., R.17E. in Wisconsin showing the dip needle (dip compass) and dial compass (horizontal compass) observations in Sections 23, 26, 27, 34, and 35. (After Brooks, 1880)



Signs for local Magnetic Attraction
due to Magnetite.

Variation in direction of Needle.

Dip Compass
- No local attraction of any kind ○
- Slight dip, less than about 20° ⊖
- Moderate dip, from about 20 to 45° ⊘
- Strong dip, from about 45 to 90° ⦶
- More than 90°, indicating observer is north of ore. ∅

Horizontal Compass
- Variation East } The direction of the arrow ↗
- Variation West } indicates the amount. ↖
- Compass needle points indifferently in any direction, indicating usually that local magnet is south of observer. ↕

Intensity of local magnetic force as approximately indicated by the number of vibrations of the needle in 15 seconds.

Normal intensity to be observed for each Compass: ○ or □

Greater than normal intensity, usually indicating that the observer is south of the ore. ⊞

Much greater. ▦

Less than normal intensity; usually indicating that the observer is north of the ore. ⊟

Much less. ▤

Line of local magnetic influence. + + + + +

Points of maximum influence. ✳

All the phenomena of the locally attracted needle are modified by the cosmical force which acts uniformly in directing the needle with considerable force to the north.

Magnetic iron-ore is the cause of all the disturbance here indicated, but its quantity and quality can only be made known by digging. It is believed to be mostly without economic value.

Figure 15. Key to the symbols used in Figure 14 for the observations of the dip needle (in this figure identified as a dip compass) and dial compass. (After Brooks, 1880)

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Clarence Otto Swanson (1900–1976) (1936) has evaluated several of these and methods for correcting them, but in general usage these corrections are negligible and therefore seldom applied to the observations.

3.2.2.1.3.4 Use and Interpretation of Dip Needle Readings

Unfortunately, the equilibrium or rest position of a counterweighted magnetic needle vertically oscillating in the local magnetic meridian is dependent on both the intensity and inclination of the field (Figure 17). Generally, the effect of the inclination is limited because the inclination of most magnetic anomalies does not vary significantly. This is not the case for the high-intensity, shallow magnetic sources of many magnetic anomalies of the Lake Superior region especially those of iron formations and volcanic flows. This is illustrated in Figure 18 a SW/NE intensity, inclination, and dip needle profile across a magnetic formation west of the city of Florence, Wisconsin in the Menominee Iron Range

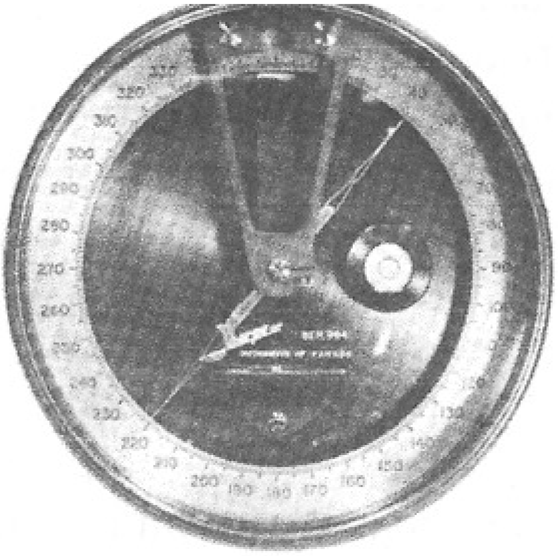

Figure 16. Sharpe Instrument Company Lake Superior-type dip needle. (After Hood, 1970)

where the inclination has a range of ~20°. We note that the crest of the dip needle anomaly is shifted to the north by the inclination effect. To the south of the anomaly, the inclination is decreased by the attractive force of the anomaly causing a decrease in the dip needle rest position and to the north, the inclination is increased causing an increase in the dip needle reading. An indication of the profound change in the inclination is given by the period of the oscillation of the needle. On the south of the anomaly, the decrease in inclination will be accompanied by an increase in the oscillation period, and on the north the period will decrease, the oscillations will be faster. Dip needle observers typically recorded changes in the "activity" or oscillation period in their notes with either a **F** for a fast oscillation or a **S** for abnormally slow oscillations. Hillyer (1904) related sluggish (slow) oscillations to a weak local force and rapid (fast) oscillations to a comparatively strong local magnetic force. He also suggested that the probable depth to the local magnetic source could be estimated from the period of the oscillations with deeper depths associated with weaker forces and thus more sluggish oscillations. Fortunately, these overly simplified procedures were seldom used as an aid in interpretation of the measurements, but the oscillation velocity provided a rough estimate of the intensity and inclination of the magnetic field because the swing of the needle is slowest where the inclination is highest (the north side of the anomaly) and fastest where the intensity is greatest (Swanson, 1934).

The dip needle because of its large measurement range is especially useful in mapping near-surface iron formations that commonly have intensities measured in thousands or tens of thousands of nanoteslas[10]. However, care must be taken in interpreting dip needle measurements because of their marked non-linearity as illustrated in Figure 17. In this figure the dip needle reading (horizontal axis with readings below the horizontal labelled +) is shown to be a function of both the total magnetic intensity (vertical axis) and the inclination of the magnetic field (65° to 85° by 5° increments). The dip needle is

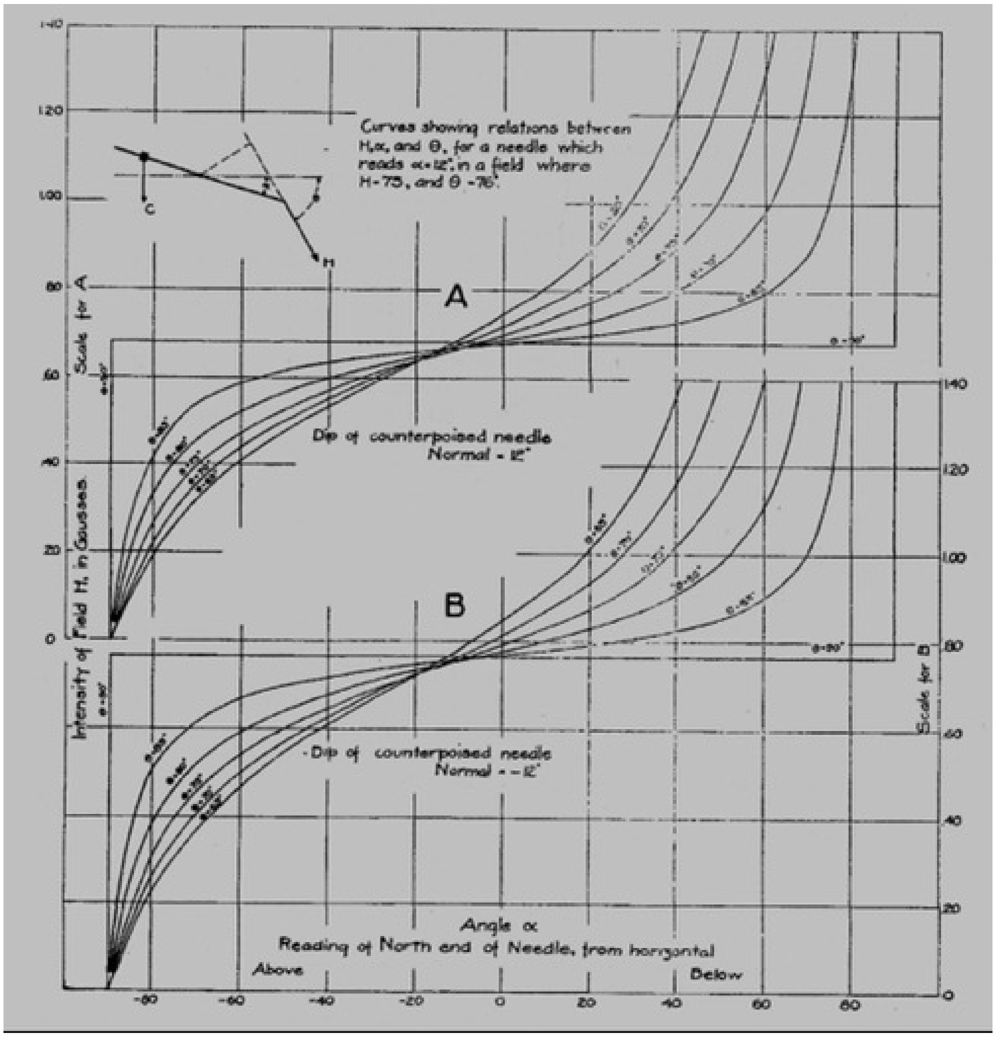

Figure 17. Dip needle calibration curves for two normal readings, +12° below the horizontal (A) and -12° above the horizontal (B). Note that negative dip needle readings are above the horizontal. (After Hotchkiss and Bean, 1929)

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[10] Magnetic anomalies reaching amplitudes of 250,000 nT – essentially five times the Earth's normal magnetic field - have been recorded in the region.

more sensitive, as indicated by flattening of the curves, at near normal intensities of the magnetic field. The sensitivity of the dipping needle is also dependent on the normal position of the magnetic needle. Fisher and Service (1936) found that the optimum normal position in degrees above the horizontal for maximum sensitivity at small magnetic fields is – (90 – I)/2 where "I" is the normal inclination of the terrestrial magnetic field in the region. The approximate normal inclination in the Lake Superior region is 75°, thus the optimum release point for the region is -7.5°. For this situation the sensitivity of the dip needle to magnetic fields is roughly 300 nT/degree where magnetic fields are of the order of a few thousand nanoteslas, but the sensitivity rapidly decreases to about 600 nT/degree at 20,000 nT, and above 50,000 nT is roughly 4000 nT/degree

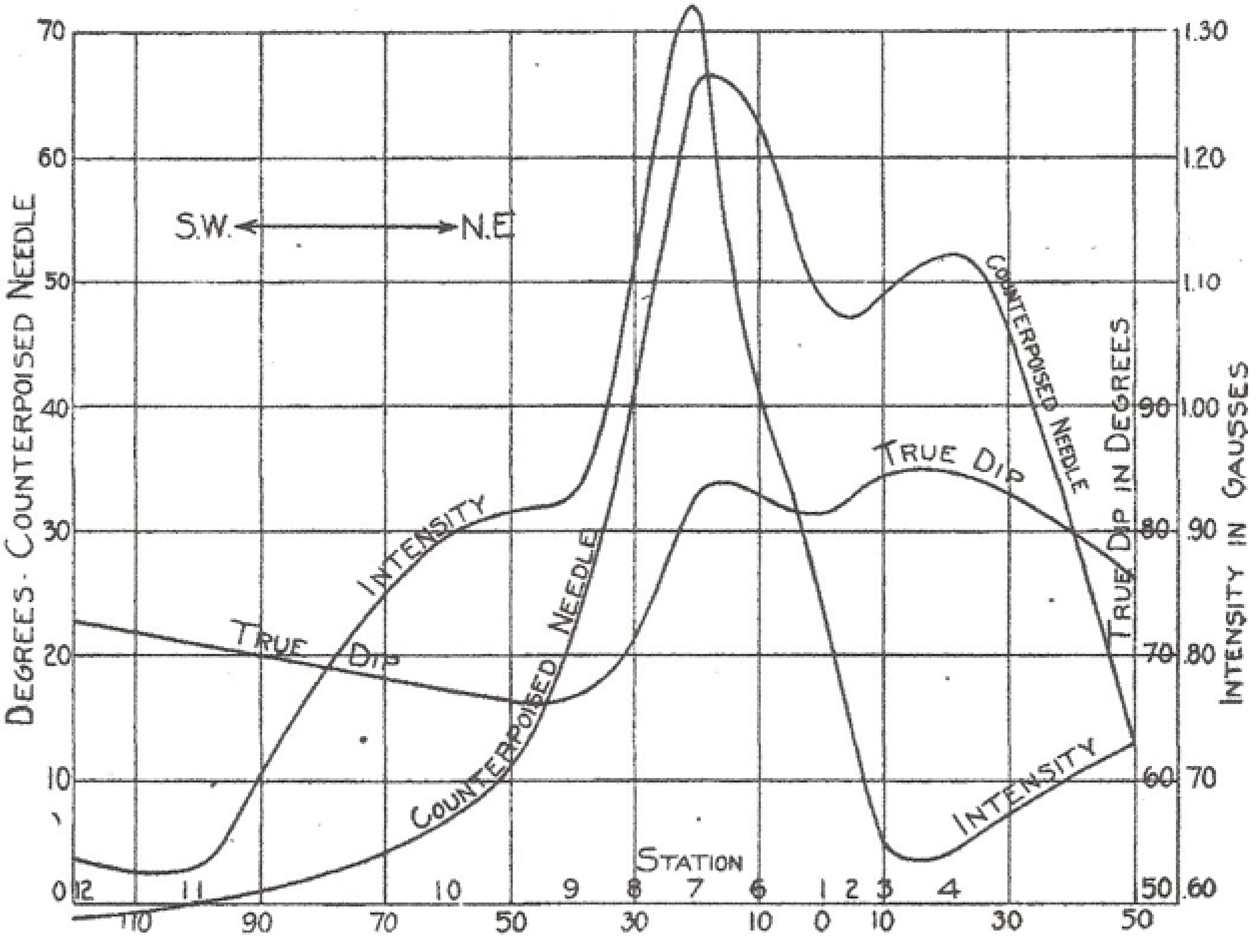

Figure 18. A SW/NE profile of the intensity, inclination, and dip needle rest position across a shallow, intense magnetic source west of Florence, Wisconsin. Note the shift of the anomaly to the northeast and the failure of the dip needle readings to track the intensity of the magnetic field. (After Hotchkiss, 1915)

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Clearly, the anomaly profiles of Figure 18 show the need for care in interpreting dip needle readings too literally. Helpful theoretical and model studies have been used to determine the response of the dip needle to idealized geometric bodies (Smyth, 1897, 1899 and 1908; Hotchkiss, 1915; Hotchkiss and Bean, 1929; Brandt, 1938) as an aid to interpretation**.** One of the more thorough descriptions of the dip needle and its use was written by Brooks (1872a). In it he describes various experiments he conducted to better understand the measurements of the dip needle including the effect of increasing elevation of the dip needle above the source of the magnetism. He correctly speculates that magnetic measurements can be used to determine the depth to the crystalline basement rocks and even to determine the depth of Lake Superior from magnetic anomalies from the basement beneath the sediments in the Lake. Smyth in his 1897 discussion of the dial compass and dip needle gives a mathematical derivation for the depth to a source of a magnetic field based on numerous assumptions. This is likely the first methodology described for using the magnetic method for determining depth to magnetic sources. Shortly thereafter Haanel (1904) described depth determination methods from the anomalies of simply geometric shape. These too needed several simplifying assumptions.

3.2.2.1.4 Thalén-Tiberg Magnetometer

In 1874 Prof. Tobias Robert Thalén (1827-1905) of Sweden developed a compass-based instrument capable of measuring the horizontal magnetic field by using deflector magnets on a graduated arm (Thalén, R., 1879a,b; note that the author of these publications is identified as Robert Thalén which is the same as Tobias Robert Thalén). Measurements made with and without the deflector magnets identified anomalies in the magnetic field. This instrument was improved in 1880 by E. Tiberg by modifying the compass to make measurements of the vertical intensity when the compass is rotated along

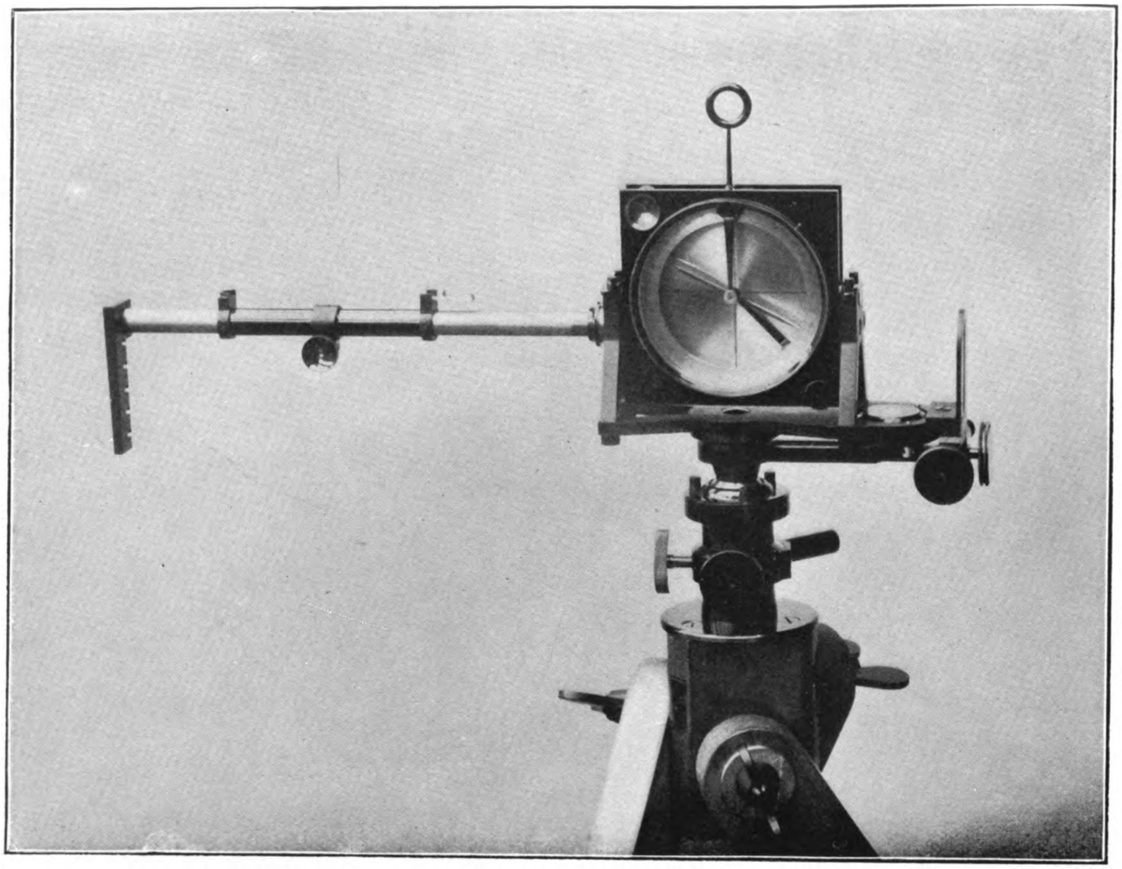

Figure 19. Thalén-Tiberg magnetometer set up to measure the vertical magnetic intensity. (After Haanel, 1904)

a horizontal axis (Lupton, 1902). The sensitivity of the vertical-measuring instrument, which was called either an inclinator or magnetometer, was modified by means of a brass screw beneath the axis of rotation which was used to alter the center of gravity of the balanced system (Nordenstrom, 1898; Haanel, 1904; Weeks, 1922; Jakosky, 1940; McConnell, 1980) that was located below the axis. The Thalén-Tiberg (Swedish) magnetometer (Figure 19) because of it greater sensitivity and accuracy largely replaced the dip needle for prospecting in northern Europe despite the need to level the instrument and place it on a tripod. Generally it was most useful in mapping anomalies exceeding 20 nT. It was also used in portions of Canada but was not widely used in the United States Lake Superior region. Smyth (1908) compared the Thalén-Tiberg magnetometer with the dial compass concluding that the dial compass is equivalent or superior to the magnetometer except that the dial compass requires sunlight, its working day is shorter, and is not totally effective in mapping east/west linear anomalies. A further modification of the Thalén-Tiberg magnetometer, called the Thompson-Thalén magnetometer only measured the vertical intensity as in the inclinator.

3.2.2.2 Other Technical Developments

The principal technical developments that pertain to magnetic mapping in the Lake Superior region during the 1830-1900 period were related to instrumentation for measuring various parameters of the Earth's magnetic field. The most important of these and those that were most widely used in the Lake Superior region were the dial compass and the dip needle. Unfortunately, methods for the interpretation of the readings of these instruments were not very reliable and based on personal experience rather than quantitative analyses. This was recognized by Smyth (1897, 1899) leading to his formulation of the theoretical basis for the interpretation of anomalies derived from simplified geometric sources. His work was the primary additional technical advance during this period.

3.2.3 Magnetic Mapping

3.2.3.1 Pre-geologic Mapping Magnetic Surveys

Prior to the use of magnetic instrumentation for the sole purpose of mapping geology and ores of the Lake Superior region, magnetic measurements were made with the compass during early land surveys that provided information on local geology. The earliest use of the magnetic method likely occurred during the federal expeditions of 1831 and 1832 to the Lake Superior region and the Mississippi River valley. These measurements were based on observations of abnormal magnetic declinations such as had been previously encountered in land boundary surveying. Douglass Houghton, who served as naturalist on these expeditions under the direction of Henry Rowe Schoolcraft (1793–1864), investigated the copper deposits on the Keweenaw Peninsula and noted that variations in the declination of the compass needle indicated that "trap" rock (dark, fine grained extrusive or intrusive igneous rocks) was nearby. These experiences led Houghton to recommend that linear surveying of new lands by the U.S. government be accompanied with thorough geological, mineralogical, topographic, and magnetic surveys. Thus, it is likely that additional significant declination anomalies were noted in northern midcontinent linear surveys and in expeditions in Wisconsin and Minnesota that were mapping the physiography, geology, and flora and fauna of the region and seeking the origin of the Mississippi River.

Local variations in the observed direction of the magnetic meridian from the regional declination direction measured in degrees east or west of true north had been used for centuries to map magnetic iron-rich formations in the Precambrian rocks of the Baltic Shield and more recently noted in laying out land boundaries in portions of New York and New Jersey that had near-surface intensely magnetized geologic units. The source of the abnormal magnetism on the Keweenaw Peninsula is the remanent magnetism of the Portage Lake lava flows that form the backbone of the Peninsula. Subsequent to the Schoolcraft expeditions, Houghton during his tenure as Michigan State Geologist traveled to the Keweenaw Peninsula in 1840 to study the geology of the region and especially the copper deposits during which he recognized the magnetic nature of the volcanic lava flows. His Fourth Annual Report as State Geologist published in 1841 regarding his 1840 expedition initiated interest in the native copper deposits which blossomed into the first mining boom in the United States beginning in 1843. The boom was made possible by the availability of land in the Northern Peninsula because the Chippewa Indians ceded 30,000 mi^2 (~77,700 km^2) of potential ore-bearing lands to the United States government. In these early surveys Jackson (1849a), a geologist of the U.S. Geological Survey, attempted to determine if copper ore bodies could be identified with magnetic measurements, but his work did not reach a conclusion. However, he did recognize the magnetic polarity of the trap rock of the Keweenaw Peninsula.

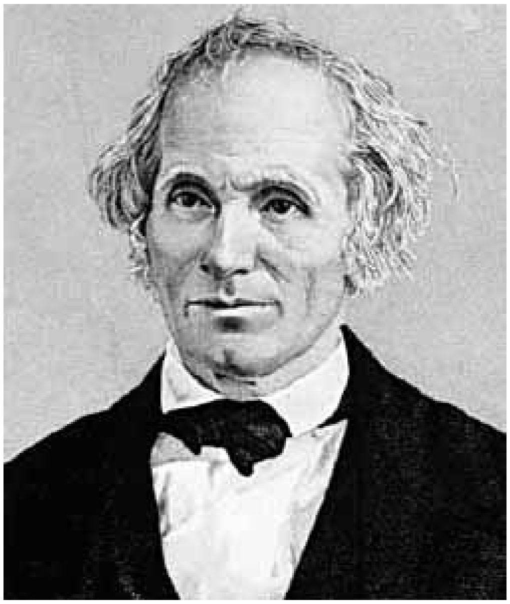

Figure 20. John Locke (1792–1856), Professor of Chemistry and Pharmacy at the Medical College of Ohio in Cincinnati, Ohio, who made observations of the components of the Earth's magnetic field in the Lake Superior region in the 1840s and observed that anomalous values were associated with certain types of nearby bedrock. (Courtesy of Googles Images)

In addition to the magnetic anomalies in declination observed during land surveys magnetic measurements were made in both the United States and Canada as part of the global scientific study of the terrestrial magnetic field, a study of broad interest at the time by the expanding scientific community. One of the early U.S. investigators of the terrestrial magnetic field was John Locke (1792–1856) (Figure 20), Professor of Chemistry and Pharmacy at the Medical College of Ohio in Cincinnati, Ohio, who beginning in 1838 made magnetic observations over the area from the east coast to Iowa and from middle Kentucky to Lake Superior and prepared contour maps of these measurements (Locke, 1846). Locke was involved in an expedition to make observations along the south shore of Lake Superior extending north into the Keweenaw Peninsula in 1844 measuring the declination, inclination and relative horizontal magnetic intensity of the Earth's magnetic field based on the period of the oscillating needle around its rest position.

Locke was charged with relating these observations to the geology of the observation sites. He noted that the magnetic iso-contours constructed from these measurements were irregular in areas where certain classes of rocks were present. In an address to the American Association of Geologists and Naturalists[11] in 1844 (Locke, 1844) when he was president, he stated that:

> *"…found, so far as I had examined, some general indications by which classes of rocks might be distinguished, although concealed at considerable depths, the magnetical[12] instruments in this respect answering the general purpose of a mineral or divining rod."*

This was likely one of the first formal recognitions in the United States that magnetic observations could be used to map geology, although widely known in the mining industry in Sweden for over a century. Locke also understood that the magnetic pole was not coincident with the geographic pole and found that some rocks were reversely magnetized from the direction anticipated from induction in the current Earth's magnetic field. His 1844 measurements of the magnetic field along the south shore of Lake Superior showed significant anomalous values where:

> *"…The subjacent rocks are various; but they consist mostly of trap rocks, and exhibit abundant signs of igneous action."*

Locke joined another expedition to the Lake Superior region in 1847. His task was to make magnetic measurements along the south shore of Lake Superior, the Marquette Range, the Keweenaw Peninsula and elsewhere in the Northern Peninsula of Michigan. His measurements during this survey in the Marquette Iron Range south of the present-day Negaunee, Michigan (T.47N., R.26W., S.18) showed large deviations of the declination that he related to nearby iron formation with intense magnetization. During this expedition he noted somewhat less but highly variable effects along the length of the Keweenaw Peninsula associated with trap rock. Prof. Locke's 1847 measurements are presented in v. 3, Article I, of the 1852 edition of the Smithsonian Contributions to Knowledge (Locke, 1852).

Similar measurements were made in Ontario, Canada. Captain John Henry Lefroy (1817–1890) (Hooker, 1891), who was the director of the Toronto (Ontario) Meteorological and Magnetic Observatory from 1842 to 1853, conducted an extensive traverse of 8800 km through central Canada in 1843-44 making measurements of the components of the terrestrial magnetic field including observations along the north shore of Lake Superior (Lafroy, 1883) in part to locate the north magnetic pole. Capt. Lefroy realized that these measurements were affected by the nearby geologic formations and noted the local geology near his observations in his notebooks.

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[11] Later this association became the American Association for the Advancement of Science (AAAS).

[12] Magnetical was a common spelling of magnetic in the 1800s.

3.2.4.2 Magnetic Mapping of Lake Superior Iron Ranges:

The initial discovery of iron formation in the Lake Superior region occurred in 1844, however, it should be acknowledged that this was the time of discovery by federal surveyors. Native Americans who used the ores primarily for jewelry and ornamentation knew of them much earlier. The time of discovery of the iron ranges in the Lake Superior region and the earliest production of iron ore from them are shown in Table 1. We note that the major ore producing districts were discovered before the end of the nineteenth century, commonly a half century before the definitive magnetic surveys of the districts specified in Figure 21. The date of discovery of the various iron districts commonly varies slightly from document to discovery may be based on the date of publication of the information rather than the actual date of discovery.

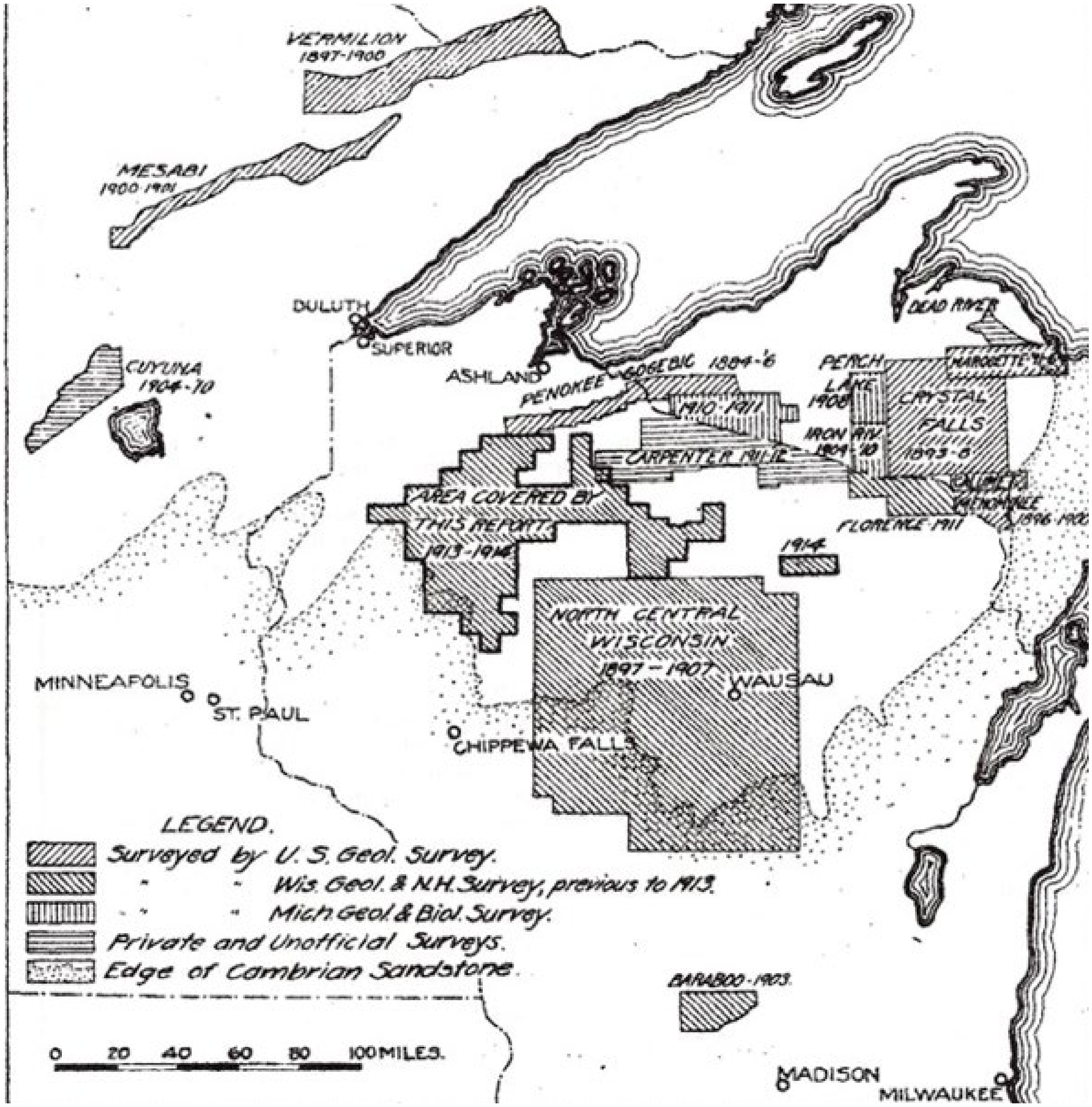

Figure 21. Map showing the source and date of magnetic surveys that mapped the iron ranges in the Lake Superior region prior to 1915. (After Hotchkiss, 1915)

In 1844 while extending an east/west line associated with the Public Land survey between townships 47N and 48N approximately one mile south of Teal Lake which lies on the northern edge of Negaunee, Michigan, William Austin Burt and his colleagues noted marked variations in their compass needle from the geographic meridian determined from Burt's sun compass. They recognized that the anomaly in the declination was due to the nearby iron-bearing rocks that occur in the now-called Marquette Iron Range. These early observations of the local geology on magnetic observations were mandated by land survey procedures suggesting that the discovery of the iron-rich rocks was not as accidental as sometimes suggested. Burt and his crew found a similar situation near Crystal Falls, Michigan in 1845 (Burt, 1849) in the Menominee Iron Range.

District	Discovered	First Production
Marquette Range	1844	1846
Eastern Menominee	1845	1877
Gogebic, Michigan (and Wisconsin)	1848	1884
Western Menominee (Iron River)	1851	1882
Gwinn District	1869	1871
Florence, Wisconsin	1873	1879
Vermilion, Minnesota	1875	1878
Atikokan, Ontario	1889	1898
Mesabi, Minnesota	1890	1891
Michipicoten, Ontario	1897	1900
Baraboo, Wisconsin	1903	1903
Cuyuna, Minnesota	1903	1904

Table 1. Year of discovery and first production from the iron ranges (Districts) of the Lake Superior Regio. (After Schaetzl, 2004).

These observations along with iron ore specimens that Dr. C.T. Jackson, the U.S. Geologist for the Lake Superior Land District obtained from the Menominee River area in 1844 (Jackson, 1849b), were among the earliest evidence of iron ore in the Lake Superior region. Unfortunately, Burt and the surveying crew attached no economic significance to this discovery. However, their recognition of the iron-rich rocks supported the early 1840s discovery by Douglass Houghton of iron-rich rock fragments near the shore of Lake Superior. Houghton failed to identify the origin location of these rocks because his mapping did not extend far enough inland from the Lake Superior shoreline to encounter the iron formations and he placed no economic importance to the presence of iron-rich rocks. Further prospecting in 1845 discovered iron ore near Negaunee which led to the first production of iron ore in the Lake Superior region in 1846.

Previously similar declination errors mapped during the Public Land linear survey were ascribed to nearby iron-rich rocks (Whittlesey, 1851), but were not used to map the local geology. Subsequently, as noted by Hotchkiss (1915) in Figure 21, defining magnetic surveys of the iron ranges were conducted by the state geological surveys, the U.S. Geological Survey, and private companies largely prior to ~1915. The Michigan Geological Survey early recognized the importance of magnetic observations in geological mapping. This is evidenced in the planned comprehensive report of the Survey by the State Geologist, Alexander Winchell, in 1871 which included a section on what was described as "Magnetography" including chapters on the nature and phenomena of magnetic force and the use and properties of the magnetic needle (Allen and Martin, 1922). Unfortunately, funds were not provided to the Survey for this publication, but Maj. T.B. Brooks (Brooks, 1873b) did publish this information in Volume 1 of the Michigan Geological Survey in 1873.

Brooks' success in magnetic mapping of the geology and ore deposits of the Marquette Iron Range (Brooks, 1872a, 1873b) led to the widespread use of the magnetic method to search for and study the iron ranges occurring in the Lake Superior region. These studies included identification of potential iron formation magnetic anomalies in the Northern Peninsula of Michigan west of the Crystal Falls District to the Wisconsin border, the extension of these anomalies from Michigan into northern Wisconsin, and anomalies in Minnesota that later were recognized as the Mesabi, Vermillion, and Cuyuna Iron Ranges. The earliest magnetic survey in Wisconsin was conducted in 1876 on the Gogebic Iron Range (Wright, 1880) and in Michigan in the mid to late 1860s in the Marquette Range as mining moved from open pit to underground (Boyum and Reed, 1988) and from magnetite and specularite (metallic luster hematite) to soft hematite ores[13]. By the late 1870s the entire Marquette Iron Range was mapped (Royce, 1938). Magnetic mapping also occurred as early as 1873 in Dickinson County, Michigan (Brooks, 1873a).

Magnetic mapping by the Michigan and Wisconsin Geological Surveys in the 1860s and 1870s (Brooks, 1873c, 1880; Pumpelly et al., 1876) was taken over after 1880 when the U.S. Geological Survey became involved in a region-wide study which led to additional magnetic surveying and the highly valuable integration of results from the various ranges of the three states in the Lake Superior region (e.g., Van Hise and Bayley, 1897; Van Hise and Leith, 1911). Charles Richard Van Hise (1857–1918) and Charles Kenneth Leith (1875–1956) remarked that by 1911 all major iron ranges of the United States had been mapped by the magnetic method. The U.S. Geological Survey has continued to be involved in magnetic mapping in this region since then to varying degrees dependent largely on the concern about critical minerals for the nation's industry.

Magnetics was limited in importance in mapping the Canadian Lake Superior iron ranges because their iron-rich rocks contain only minor amounts of magnetite in specific horizons. Both the Atikokan (Steep Rock) and Michipicoten Iron Ranges were discovered in the late nineteenth century not by magnetic surveys (Wahl, 1957), but by geological mapping of outcrops and the presence of iron-rich boulders and the extent of the iron-rich rocks were defined largely by drilling.

Further details on the mapping of the Lake Superior iron ranges by magnetic methods in the nineteenth century are provided in Chamberlin (1880), Van Hise and Bayley (1897), and Van Hise and Leith (1911) and references therein.

3.2.3.3 Magnetic Mapping of the Keweenaw Peninsula

Prior to the U.S. Geological Survey's involvement in magnetic mapping in the Lake Superior region after 1880, the study of the Keweenaw Peninsula copper-bearing rocks was largely in the domain of the state geological survey and private interests. These were initiated by Douglass

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[13] In the early 1860s S.R. Gay of the Forest Iron Company of the Marquette Iron Range was the first to recognize the value of soft ore.

Houghton in the 1840s using the sun compass to detect declination anomalies and were expanded to include the dip needle by Brooks in the late 1860s and 1870s for mapping the native-copper-bearing, intensely magnetized volcanic flows and associated conglomerate formations. There was no evidence that magnetic mapping could be used to identify and map the native copper deposits. As a result magnetic mapping was limited to studying stratigraphic and structural evidence that possibly was related to the deposits. An important example of this is the discovery in 1864 by Edwin J. Hulbert (1829–1910) of the richest lode of native copper in the Lake Superior region. He traced the largely glacial deposit-covered Calumet conglomerate lode that followed the structural trend of the magnetic volcanic flows with declination deviations determined with a solar compass (Farmer, 1884), thus discovering the lode that led to the ore-rich mines of the Calumet & Hecla Copper Company near the present city of Calumet, Michigan. Raphael Pumpelly (1837–1923) and others conducted additional magnetic mapping on Keweenawan rocks before 1875 and Arthur Edmund Seaman (1858–1937) did magnetic surveying of these rocks in the early 1890s (Seaman, 1929).

3.3 The Ground Survey Years: 1901-1940

3.3.1 Overview

During the period from 1901 to 1940 the magnetic method matured in its application to mapping the geology of the Lake Superior region. The method was recognized as an important part of the regional exploration program for iron formations as well as for identifying ore bodies and structural features that are significant to the development of direct shipping ores from iron-rich sedimentary formations. As noted by Broderick and Hohl (1928b):

"Every geologist in the iron Districts regards the magnetic dip needle as an essential part of his equipment, and a 'magnetic survey' is usually one of the first steps in exploration."

The discovery and outlining of the Cuyuna Iron Range in Minnesota by the magnetic method early in this period encouraged states to support regional magnetic exploration for undiscovered iron formations. Furthermore, the vast amount of iron ore mined during this period and especially during the accelerated iron production associated with World War I and the run-up to World War II, led to concerns that the nation needed to find new iron ore reserves. As a result, state geological surveys initiated exploration programs and the U.S. Geological Survey increased its efforts to understand the geologic processes that led to ore development and to improve exploration methods. The magnetic method also was used by private industry and government surveys to investigate the volcanic flows and conglomerate strata hosting lodes of native copper. Magnetic methods during this period generally used the same methods as in the '**The Discovery Years,**' that is the dial compass and especially the dip needle. However, the need to quantitatively interpret the parameters of the magnetic sources using enhanced theoretical developments led to improved instrumentation and procedures which more accurately measured the intensity of the magnetic fields and allowed improved interpretation of the observations.

3.3.2 Technical Developments

3.3.2.1 Magnetic Instrumentation

3.3.2.1.1 Dip Needle and Dial Compass

The construction of the dip needle remained basically the same during this period as it was in the latter stages of the nineteenth century. However, there was increasing interest in improving the instrument and understanding the significance of the measurements. Additionally, there was advancement in standardizing the measurements and instrumentation so that results could be satisfactorily compared between measurements on the various ranges using different dip needles and in constructing regional maps of dip needle readings. Examples of investigations into our knowledge of dip needle measurements and their applications include Swanson (1929, 1930, 1934), Fisher and Service (1936), Hotchkiss (1915), Hotchkiss and Bean (1929a), Hotchkiss et al. (1929b), Seaman (1929), Slichter (1929), Stearn (1929a, b), Brandt (1938), and Fisher (1939). Clarence Otto Swanson (1900–1976) (1936) devised a method for using the dip needle to measure both vertical and horizontal magnetic fields by using two sets of dip needle readings, but there is no evidence that this methodology was used to any significant degree in the

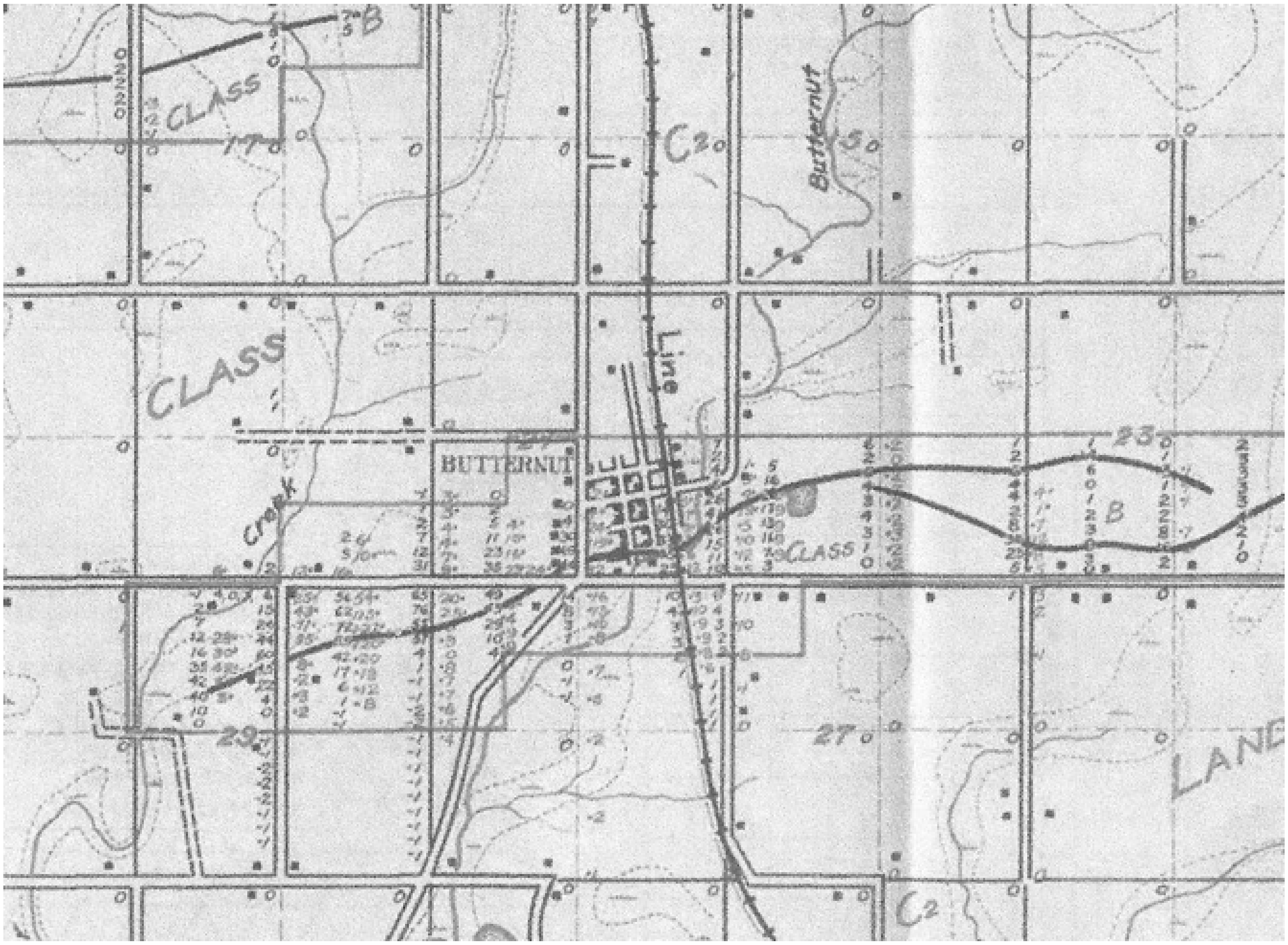

Figure 22. Magnetic observations in the Butternut (Ashland County), Wisconsin region (T.41N., R.1W.) associated with iron formation of the Turtle River Range that extends from this area ENE

into Michigan. Dial compass readings are to the right (east) of the traverses. Eastward declinations are shown with a dot to the west of the number. Dip needle readings are plotted to the west of the traverses. All are positive except for those preceded by a negative sign. All normal readings of the dial compass and the dip needle are not shown. Dip needle readings were taken every ~125 feet and dial compass readings every 250 feet. Heavy curvilinear lines follow the maximum values of the dip needle readings. (After Hotchkiss and Bean, 1929)

Lake Superior region. Nonetheless, the dip needle and the dial compass remained an important instrument for measuring magnetic fields in the Lake Superior region until about 1925 when the Hotchkiss superdip and a variety of greater sensitivity magnetometers became the instruments of choice (Royce, 1938). The dial compass which continued to be widely used for surveying was used less for magnetic investigations (Swanson, 1934) after that time, although some explorationists considered it to be more useful than the dip needle.

An example of maps prepared from dial compass and dip needle readings is illustrated in Figure 22 which shows the observations made on traverses along section and some quarter-lines in a portion of T.41N., R.1W. near Butternut (Ashland County), Wisconsin (Hotchkiss and Bean, 1929). The mapped

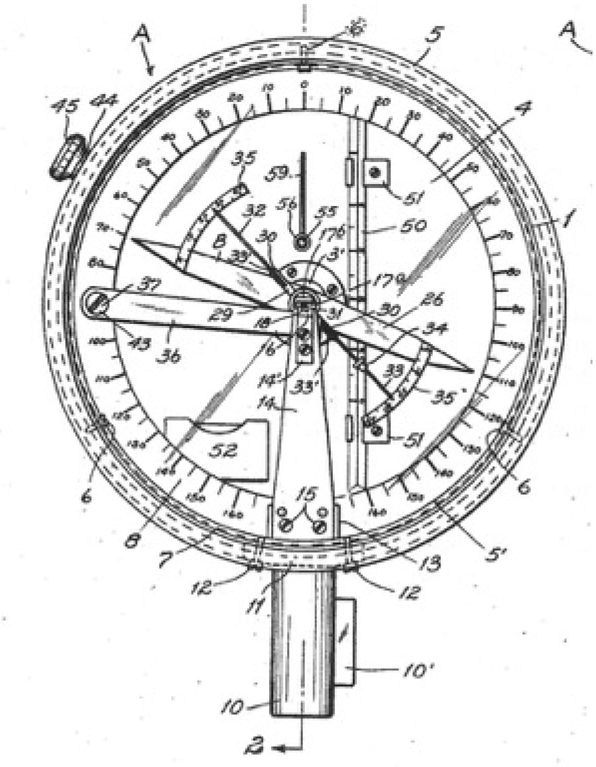

Figure 23. Hotchkiss superdip as shown in the application for a patent by Hotchkiss et al. (1929).

magnetic anomalies are associated with chlorite-grade, cherty iron formations (Mudrey, 1979b) that occur along the discontinuous Turtle River or Turtle Range which extends from the Butternut area east-northeast into Michigan to T.46N., R.39W. where it intersects Keweenawan volcanic and sandstone formations (Allen and Barratt, 1915). The Turtle River Range is one of a series of similar linear, discontinuous magnetic anomalies north of 46° N in Wisconsin and adjacent Michigan that are associated with iron formations like those found elsewhere in the Lake Superior region. These iron formations do not crop out, but they have been intersected by numerous drill holes during exploration programs that continued sporadically in these ranges. The iron formation which dips steeply to the south in the Butternut region contains fine-grained magnetite and specular hematite with associated gray chert or jasper and included schist and granite of unknown origin (Dutton, 1983). The Butternut anomaly is believed to have 48 million long tons of magnetic ore associated with it (Mudrey, 1979b).

3.3.2.1.2 Superdip

The dip needle found its most significant use in reconnaissance surveys to locate the presence of intense magnetic anomalies. Its sensitivity depending on its equilibrium position for normal fields is in the range of several hundred nanoteslas, thus it has limited use for detailed magnetic mapping and identification of iron-rich rocks that are not intensely magnetized. As exploration of the iron ranges of the Lake Superior Region matured and magnetics were used to map geology of the Precambrian bedrock, the need for greater sensitivity in magnetic mapping became important. James (1948) concludes from his studies in the Crystal Falls-Iron River District of Michigan that critical magnetic anomalies to geological mapping have a range of maximum amplitude of from 25 to 6000 nT. Obviously, anomalies at the lower end of this range will not be mapped accurately with a dip needle. The Wisconsin Geological Survey, a leader in magnetic mapping of geology of the Lake Superior region, identified this problem and solved it by

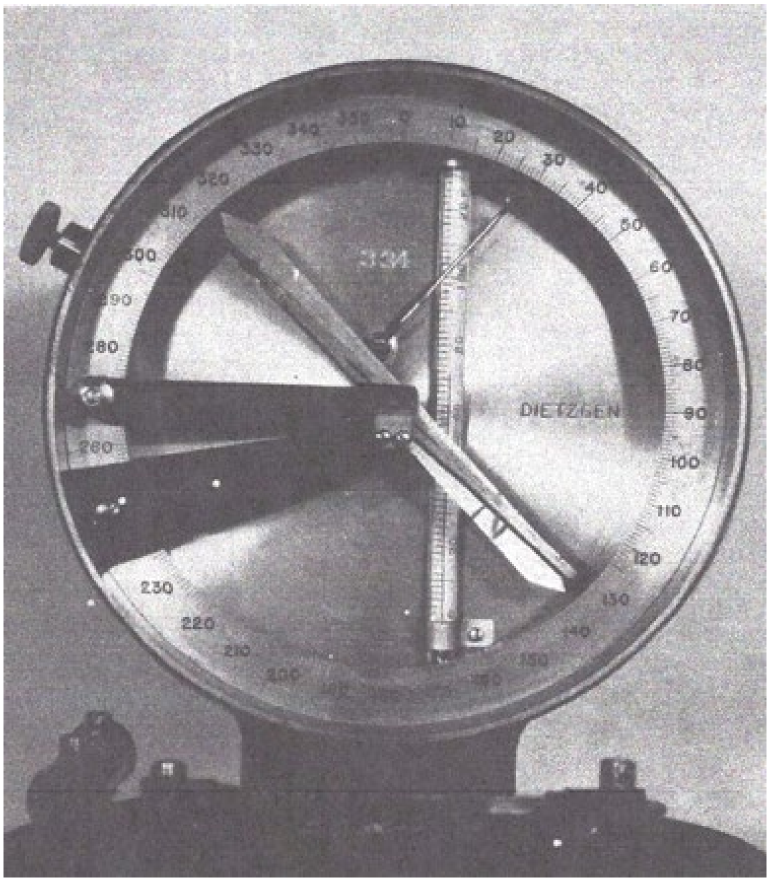

Figure 24. Hotchkiss superdip. Note the angular relationship between the needles (∑) which controls the sensitivity of the instrument and the thermometer to measure the temperature which was used to estimate the correction for the effect of temperature variations. (After Longacre, 1951)

modifying the dip needle by placing the counteracting weight on a secondary non-magnetic arm as shown in Figures 23 and 24. The improved dip needle became known as the Hotchkiss superdip after William Otis Hotchkiss (1878–1954) (Figure 25), the Wisconsin State Geologist who conceived the modification. The sensitivity of this instrument could be altered by changing the angular relationship between the magnetic and counterweight arms (Hotchkiss, 1923a; Stearn, 1932). In 1927 Hotchkiss and three of his colleagues applied for a patent on this instrumental design which was granted in 1929 (Hotchkiss et al., 1929). The resulting instrument was constructed by W. and L.E. Gurley Instrument and Dietzgen Companies (1910) and others and was used widely in the Lake Superior region and other areas for mineral exploration and geological mapping from the early 1920s to the 1940s after which the instrument was no longer manufactured (Schwartz, 1943).

The superdip was used much like the dip needle with the plane of oscillation of the arms in the magnetic meridian. However, the accuracy requirements required leveling of the instrument on a tripod, slowing the observations. Measurements made with the instrument positioned in the magnetic meridian like the dip needle were a function of both the intensity and inclination of the ambient magnetic field. Inclination of the field was especially a factor where it varied significantly because of proximity of the source of the disturbing magnetic field. Further investigation of the mechanics of the Hotchkiss superdip led to the conclusion that by orienting the instrument perpendicular to the magnetic meridian limited the measurement to the vertical component of the magnetic field (James, 1948;

Figure 25. William Otis Hotchkiss (1878–1954) Wisconsin State Geologist and later President of Michigan Mining School (now Michigan Technological University) and Rensselaer Polytechnic Institute who fostered magnetic surveying in the Lake Superior region and patented the Hotchkiss superdip, a refinement of the dip needle. (Courtesy of Google Images)

Longacre, 1951). In effect by eliminating the horizontal component of the ambient field, the inclination of the field was established as 90°. Elimination of the effect of inclination of the magnetic field was a significant advancement in magnetic mapping in the Lake Superior region where the sources of the disturbing magnetic field are relatively close to the surface, and thus have large effects on dip needle readings. The Hotchkiss superdip also had the advantage of a large range which was an important consideration in post-World War II taconite exploration. However, although it was faster to use than the Schmidt-type magnetometer, its duration as a magnetic instrument of choice in the Lake Superior region was limited because of the need to use the instrument on a tripod and orient it perpendicular to the magnetic meridian which seriously slowed its use. Furthermore, the sensitivity of the superdip was determined not only by $\sum$, the angular relationship between the magnetic and weight-bearing needles, but by the equilibrium position of the magnetic needle referenced to the vertical, 0°. The change in sensitivity of a superdip with a $\sum$ of 4° as function of θ, the measurement or reading angle with reference to vertical, is shown in Figure 26. We note that maximum sensitivity is near the horizontal and decreases toward zero as the needle approaches verticality.

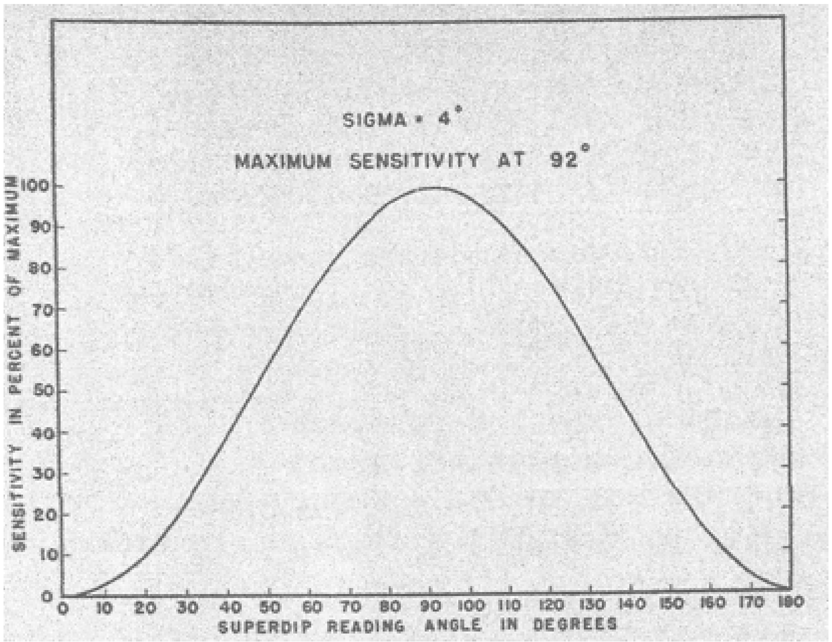

Figure 26. Sensitivity in percent of maximum of a Hotchkiss superdip oriented perpendicular to the magnetic meridian with an angle of 4° between the needles as a function of the equilibrium (reading) position of the instrument. (After Longacre, 1951)

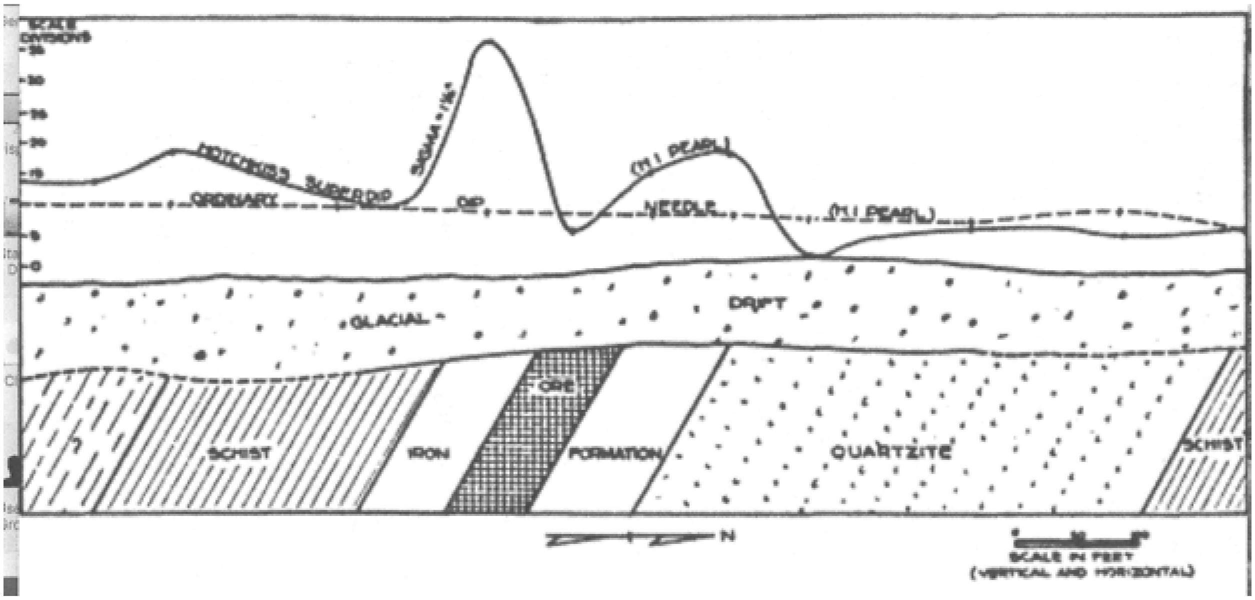

Figure 27. Comparison of dip needle and superdip readings along a N-S traverse over the Cuyuna Iron Range.). Note the increased sensitivity of the superdip and the negative anomaly associated with the direct shipping ore between the positive anomalies of the iron formation. (After Pearl, 1930)

Improvement in mapping and interpretation of magnetic anomalies with the Hotchkiss superdip is illustrated in Figure 27. which shows both Lake Superior dip needle and Hotchkiss superdip anomaly profiles across an iron ore body within an iron formation in the Cuyuna Iron Range. The dramatic improvement that is achieved with orienting the Hotchkiss superdip perpendicular to the magnetic meridian for measurements is shown in Figure 28a and b. In Figure 28a, a magnetic anomaly profile in the Crystal Falls-Iron River Iron Range of Michigan (James, 1948), the vertical intensity measured with an Askania Schmidt-type magnetometer is shown together with the results of measurements with a dip needle, a dipping circle that measures inclination of the ambient magnetic field, and a superdip with a $\sum$ of 3° oriented in the magnetic meridian. We note the shift to the north of the crest of the superdip and dip needle magnetic anomalies compared to the measured vertical magnetic intensity caused by an increase in the angle of inclination. In contrast, profiles in Figure 28b of the vertical intensity measured by Askania and Wolfson Schmidt-type magnetometers and a superdip oriented perpendicular to the magnetic meridian are similar for the same profile shown in Figure 28a.

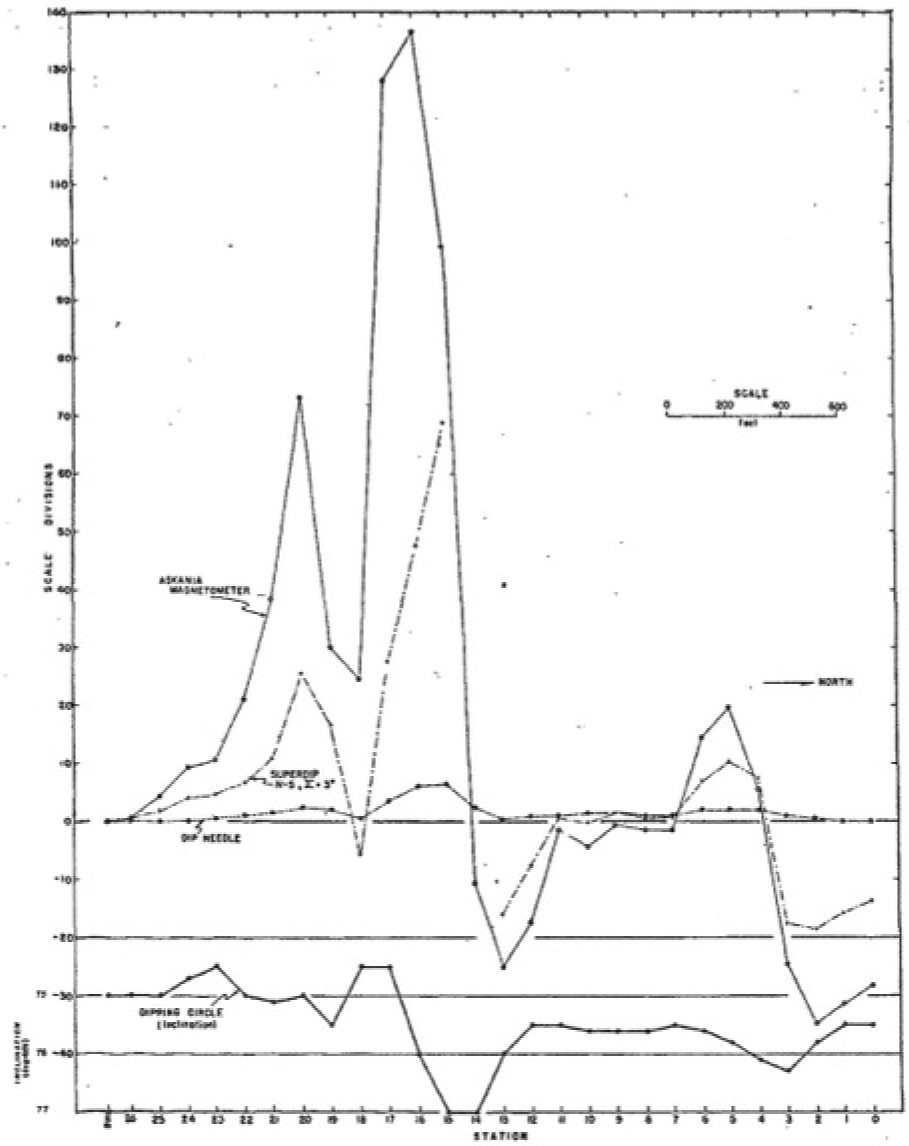

Figure 28. a. Comparison of an Askania (Schmidt-type) magnetometer (vertical magnetic intensity), superdip oriented in the magnetic meridian (N-S) (total magnetic intensity), dip needle measurements, and dipping circle (total magnetic field inclination) profiles in the Crystal Falls-Iron River Range of Michigan. Note the shift in the crest of the main magnetic anomaly to the north of the measurements made with the superdip and dip needle due to the increase in the inclination of the total magnetic field on the North side of the magnetic anomaly from 74.5°to 77°. All values in scale divisions for each instrument. (After James, 1948)

3.3.2.1.3 Schmidt-type Magnetometer

Adolf Frederick Schmidt (1860–1944) (1915) (Figure 29) designed and built a magnetic field balance (Figure 30a) similar in theory to a superdip measuring the rotation of a balanced magnet assembly with an off-axis counterweight (Figure 30b). The magnetic field causes a torque on the magnet assembly that is opposed

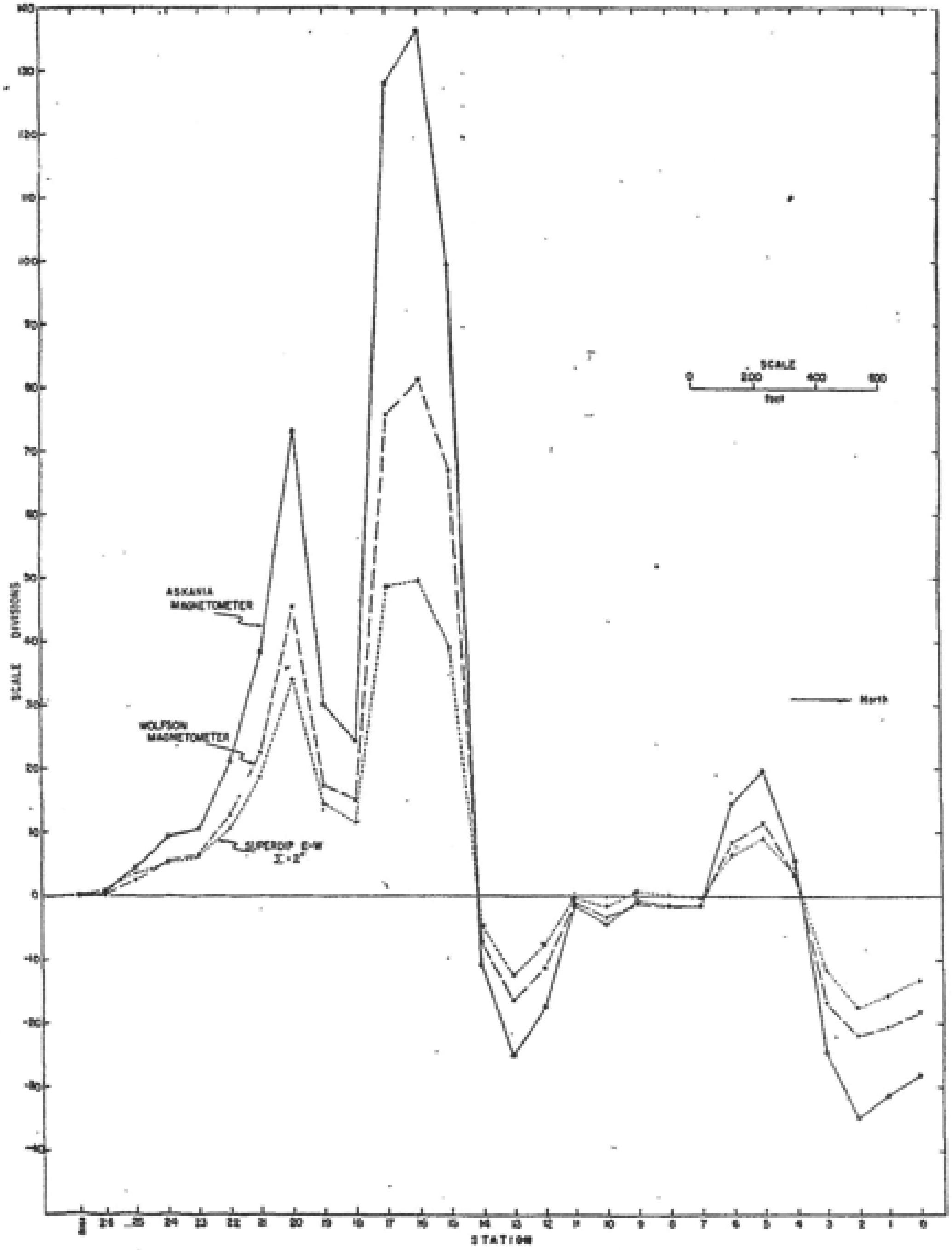

Figure 28. b. Comparison of Askania and Wolfson Schmidt-type magnetometers (vertical magnetic intensity) and superdip oriented perpendicular to the magnetic meridian (E-W) (vertical magnetic intensity) profiles over the same traverse shown in Figure 28.a. Note the similarity of the profiles in contrast to those shown in Figure 28.a. All values in scale divisions for each instrument. (After James, 1948)

by a counteracting gravitational force acting upon an off-center mass. The rest position of the assembly when oriented perpendicular to the magnetic meridian depends on the strength of the ambient vertical magnetic field (Heiland, 1926; Joyce, 1937; Eve and Keys, 1954). The rest position is amplified optically so that the instrument is capable of a sensitivity of a few nanoteslas, but the measurement range of the instrument is limited without employing a calibrated bucking exterior magnetic field derived from a magnet assembly located beneath the magnetometer which brings the instrument into viewing range. The instrument is placed in an insulated housing (Figure 30b) and is temperature compensated to minimize the effect of temperature variations on the balance of the instrument and thus, its measurement (Heiland, 1932, 1939). A similar instrument was constructed for measuring the horizontal magnetic field but had no extensive use in the Lake Superior region.

Figure 29. Adolf Frederick Schmidt (1860–1944), geomagnetist, who designed the Schmidt-type magnetometer which became the instrument of choice for magnetic mapping of the vertical and horizontal magnetic intensity from ~1915 to 1950. (Courtesy of Google Images)

The Schmidt-type variometer[14] or magnetometer, was used extensively by geologists for several decades for mapping geology, but only in a limited way in the Lake Superior region. Its use in this region was restricted to detailed surveys where the anticipated amplitude range of magnetic anomalies was low, and interpretation of the anomalies necessitated higher precision than obtainable with the dip needle or superdip. However, this precision came at a cost in the ease of making the measurements and the time to do so due to the need to level and orient the instrument on a tripod perpendicular to the magnetic meridian. The limited measurement range of the Schmidt-type balance without using exterior magnets was also a significant deterrent to its use in much of the Lake Superior region. Numerous instrument manufactures made the Schmidt-type variometer including the Askania Company in Germany, Sharpe Instruments in Canada, and the W. & L.E. Gurley Instrument Company and the Ruska Company in the United States.

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[14] The term variometer is used for magnetometers that measure only the change in the magnetic field, not its absolute value.

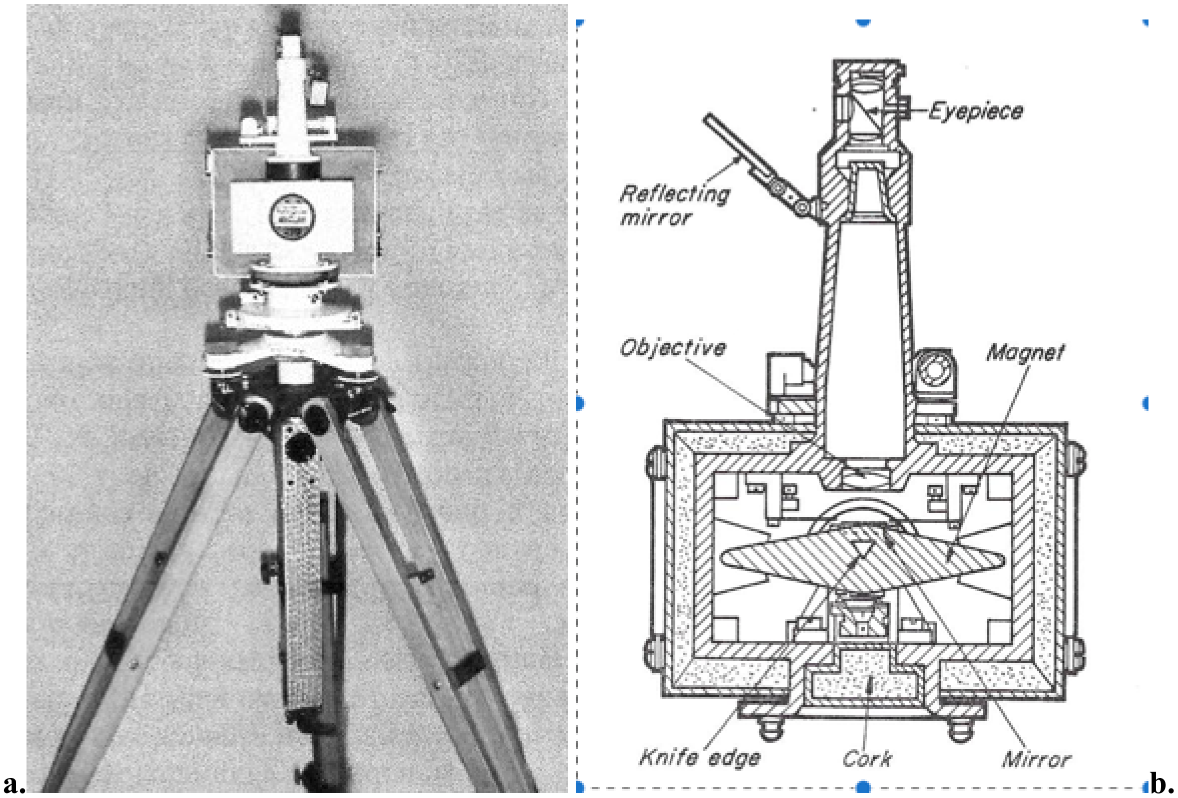

Figure 30. a. Askania Schmidt-type vertical magnetometer. b. Cross-section of the interior of a Schmidt-type vertical magnetometer. (After Joyce, 1937)

3.3.2.2 Other Technical Developments

During the period from 1901 to 1940 the primary technical developments were in the design, construction, and use of the new magnetometers, the Hotchkiss superdip and the Schmidt-type variometer. These instruments were capable of sensitives in the range of several nanotesla and were largely used perpendicular to the magnetic meridian so that they were unaffected by changes in inclination of the Earth's field but rather measured only the vertical magnetic intensity. Other technical developments were primarily in support of these instruments as well as the dial compass and dip needle which continued to have viable use in reconnaissance magnetic surveying. The dip needle in particular because of its importance in magnetic mapping was the subject of numerous studies of its mechanics and potential sources of error that have been identified in the description of this instrument for this time period. Additional technical developments were made to increase the interpretation beyond simply identifying the location of the anomaly sources including the geometric shape, depth, depth extent, and dip of the source. These include empirical observations from physical models and theoretical formulations for the magnetic anomalies of various geometric sources by Smyth (1907; 1908) and others (e.g., Soske, 1935) and that are summarized in textbooks of this period on geophysical exploration.

3.3. Magnetic Mapping

With the increasing demand for iron and copper ores, magnetic mapping with the dip needle and to a lesser degree with the dial compass continued in the **Ground Survey Years: 1901-1940**. Surveys were made on a reconnaissance basis outside of the traditional iron mining ranges and used for increasing detail of the surveys that had outlined the ranges in the previous century. A major objective of these surveys was mapping the structure and stratigraphy of the previously identified mining ranges. Detailed surveys increasingly used the Hotchkiss superdip and the Schmidt-type magnetometer where higher sensitivity and more interpretable data were deemed important. The discovery of the Cuyuna Iron Range in 1903 stimulated further magnetic surveying because identification of the Cuyuna's iron formation was based solely on magnetic declination surveys and later dip needle surveying, although in the late 1800s the presence of magnetic declination anomalies was observed in the Cuyuna area during the linear boundary survey of Minnesota. The discovery of this district solely on magnetic observations led to a renaissance in magnetic surveying by state geological surveys and private corporations for detecting iron formations in the extensive glacial deposit covered areas of the Lake Superior region that are without outcropping iron formations or topographic ranges held up by erosion-resistant iron-rich rock formations that are indicative of possible presence of iron ore.

Archibald (1925) describes the status of iron ore exploration in Wisconsin, Michigan, and Minnesota in the mid-1920s noting that exploration has been minimal in the previous several years because current production which was ramped up for the increased demand for ore during WWI exceeds or is meeting the current (1925) demand. His evaluation of the iron formations of the region and their ores suggests that new discoveries of the ores that are needed will require intensive mapping of iron formation structures and igneous intrusives into or nearby the iron formations. He suggests that magnetic mapping will have an important role in these investigations of geologic structures and intrusive rocks.

3.3.3.1 Michigan

There was widespread use of the magnetic method to locate iron formations and to map the stratigraphy and structure of iron ore ranges of the Northern Peninsula of Michigan during **The Discovery Years** Period: 1830 to 1900. However, interest in iron ore exploration in the Lake Superior region decreased in the early twentieth century and use of the magnetic method by the Michigan Geological Survey slackened off largely because of lack of legislative support. During these early decades the primary emphasis in Michigan was on compilation and mapping of existing magnetic surveys of the Michigan Geological Survey and assembling commercial magnetic data released to the Survey. However, this situation started to change in 1927 with magnetic surveying in Iron County, Michigan which was continued into Dickinson County in subsequent years and with detailed mapping of the Gogebic Iron Range in Michigan and the western part of the Marquette Iron Range (Pardee, 1929) largely to study the stratigraphy of the iron formations.

Magnetic surveying of potential copper ore-bearing Keweenawan formations also became of interest to the Michigan Geological Survey as well as commercial groups in the 1920s. Starting in 1925 the Calumet & Hecla Corporation under the direction of Thomas M. Broderick (1889-1965) (Figure 31) initiated dip needle surveys of copper ore bodies and found, as anticipated, that there were no definitive anomalies associated with the ore bodies (Broderick and Hohl, 1928a; 1928b). However, they did find that dip needle measurements were useful in mapping the stratigraphy and structure of the volcanic flows and interbedded conglomerate units. Folds, faults, fissures, and alteration zones associated with faults were successfully mapped with dip needle surveys (Broderick and Hohl, 1929). The Michigan Geological Survey in 1926, under the direction of Leslie Park Barrett (1887–1972), initiated magnetic surveying of the volcanic rocks showing that the edges of the flows could be identified if the dip needle observations were made at intervals as close as roughly 5 m (Seaman, 1929). The magnetic mapping was particularly useful in mapping cross and along-strike faults that were of interest in locating copper ores.

Figure 31. Thomas M. Broderick (1889-1965) pioneer in the use of the magnetic method to study the Mesoproterozoic geology of the Lake Superior region and its copper and iron ore deposits. (Courtesy of Google Images)

Interpretation of the magnetic observations generally assumed that the magnetization of the source rocks was due to the induced magnetization of magnetite by the Earth's magnetic field (Mooney and Bleifuss, 1953). However, study of the Keweenawan volcanic flows by Dubois (1955, 1962) and others showed that the remanent magnetization was several orders greater than the induced magnetization. This was substantiated by Bath (1962) in successfully modeling the magnetic anomalies of the Keweenawan volcanic flows at the western end of Lake Superior using remanent magnetization. The interpretation of magnetic surveying of the Keweenaw Peninsula also did not consider the presence of reversed remanent magnetization (Dubois, 1962) except for the negative anomalies associated with many Keweenawan diabase dikes. Magnetic surveying by the state in subsequent years was continued south of Houghton (Spiroff, 1941) and north of Houghton extending up the Keweenaw Peninsula (Eddy, 1933).

In establishing the significance of magnetic surveying to geologic mapping, it is interesting to note that the 1936 Centennial Geologic Map of the Northern Peninsula of Michigan prepared by the Michigan Geological Survey (Martin, 1936) included magnetic trend lines mapped by the Survey in the preceding decades. The trend of these magnetic anomalies in Gogebic County are shown in Figure 32. They include from north to south the Marenisco, Turtle River, and Manitowish Ranges within Paleoproterozoic rocks. Similar trend lines are shown in Iron County and in the extension of the Menominee Range easterly beneath the Paleozoic sedimentary rocks to Lake Michigan in Delta and Menominee Counties. The location of these trend lines was specified by

L.P. Barrett who oversaw the State of Michigan's magnetic surveying for several years. The Menominee Range and its easterly

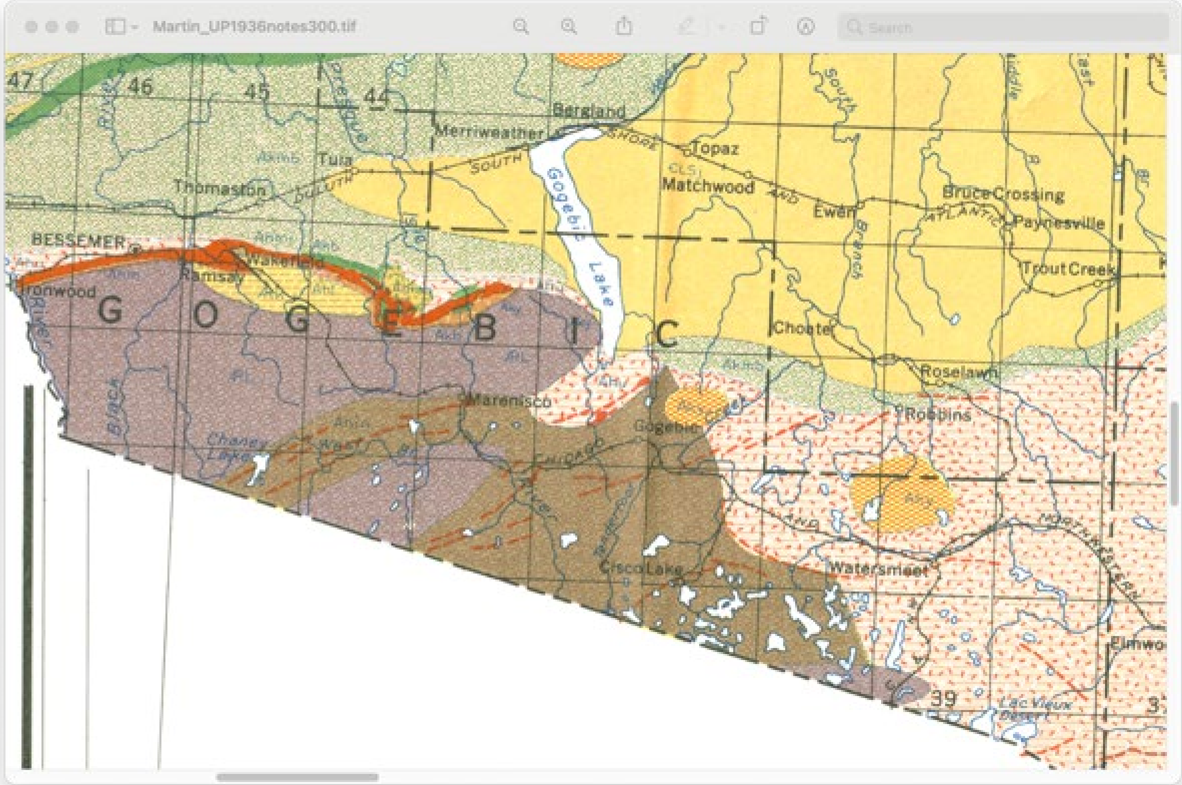

Figure 32. The southwestern portion of the 1936 Centennial Geologic Map of the Northern Peninsula of Michigan showing magnetic trend lines by red dashed lines east of Ironwood, Michigan in Gogebic County that were mapped with dip needle and dial compass. (After Martin, 1936)

extension to the Lake Michigan shoreline was mapped with the dip needle prior to a drilling program initiated in 1914 to sample the Vulcan iron formation.

3.3.3.2 Wisconsin

The magnetic method was used extensively in the State of Wisconsin by the state geological survey and to a lesser extent by private industry to search for undiscovered iron formations and iron ore in the northern half of Wisconsin where the glacial deposits are thick minimizing the outcrops of bedrock. Many of these surveys are identified in Figure 21. Prior to 1913 a large area in the north-central part of the state was surveyed, as well as surveys in the Florence area of the Menominee Iron Range along the Wisconsin/Michigan boundary, the Baraboo region, and the Carpenter Company survey area extending for several tens of kilometers west from the Wisconsin/Michigan border. In 1913 the Wisconsin legislature directed the state survey to conduct surveys in the northern part of the state to identify possible new mining ranges. This led to surveys in 1913 and 14 in an irregular area south and west of the Gogebic Iron Range shown in Figure 33. These surveys that included dip needle and dial compass measurements along north/south section and quarter section lines led to better definition of the

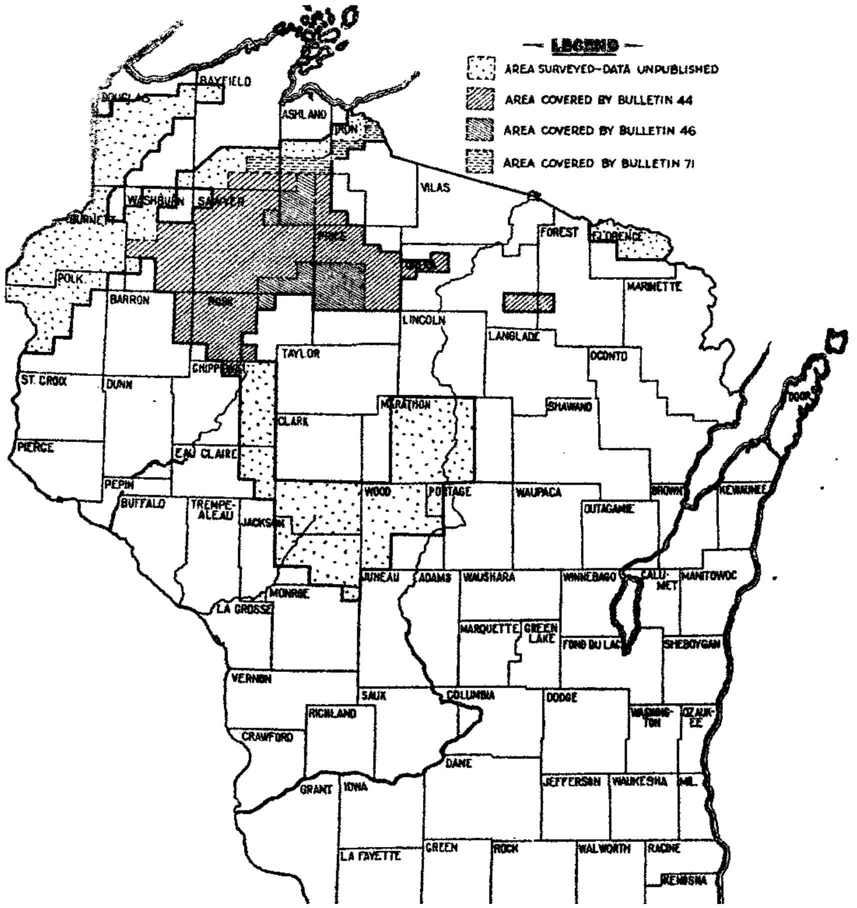

Figure 33. Map of magnetic survey regions of Wisconsin from 1910 to 1927 by the Wisconsin Geological and Natural History Survey. (After Bean and Aldrich, 1929)

Menominee Range in Wisconsin and identification of five discontinuous, linear magnetic trends associated with Early Proterozoic iron formations that strike generally east-northeast to east across northern Wisconsin north of 46° N into adjacent Michigan. The iron formations are like those found elsewhere in the Lake Superior iron mining ranges (Beutner, 1958; Mudrey and Brown, 1988), but at least locally are intensely metamorphosed (Allen and Barrett, 1915a). They are from north to south the Marenisco, Turtle River, and Manitowish Ranges and the Vieux Desert and Conover Districts (Figure 34) (Allen and Barrett, 1915a, b, c, d, e).

One of the more magnetic iron formations of these ranges that has been studied and drilled occurs in the Marenisco Range roughly 20 km directly south of Hurley, Wisconsin (T.44N., R.3E.). Allen and Barrett (1915a) recognized the intensity of the magnetic field with the statement:

> *"The range is characterized by a strong to violent magnetism which furnishes a ready means and, for the greater part of its extent, the only means of determining its position. That this*

strong magnetism attracted the early explorers is evidenced by traces of their prospects in the most violently magnetic localities."

The use of the adjective "violent" to describe the magnetic field is testament to the intensity of the field for it is not a common adjective applied to the intensity of magnetic anomalies. This intensity was recognized by early workers in the naming of the nearby, now non-existent, village of *Magnetic Center* at the north end of Pine Lake. No direct shipping iron ores were derived from these ranges, although latter drilling results suggested the possibility of segments suitable for taconite ores. Marsden (1978) estimates that there are 206 million long tons of taconite available at this site. Potential taconite ore has also been identified with the intense magnetic anomaly at the western end of the Turtle River Range near the village of Butternut, Wisconsin (T.41N., R.1W.) (Figure 22) and the garnet-grade Agenda taconite deposit 16 km to the northeast which has a reserve of the order of 160 million long tons. This range extends east-northeast for roughly 100 km into Michigan to T.46N., R.39W. where it intersects Keweenawan volcanic and sandstone formations. Mudrey

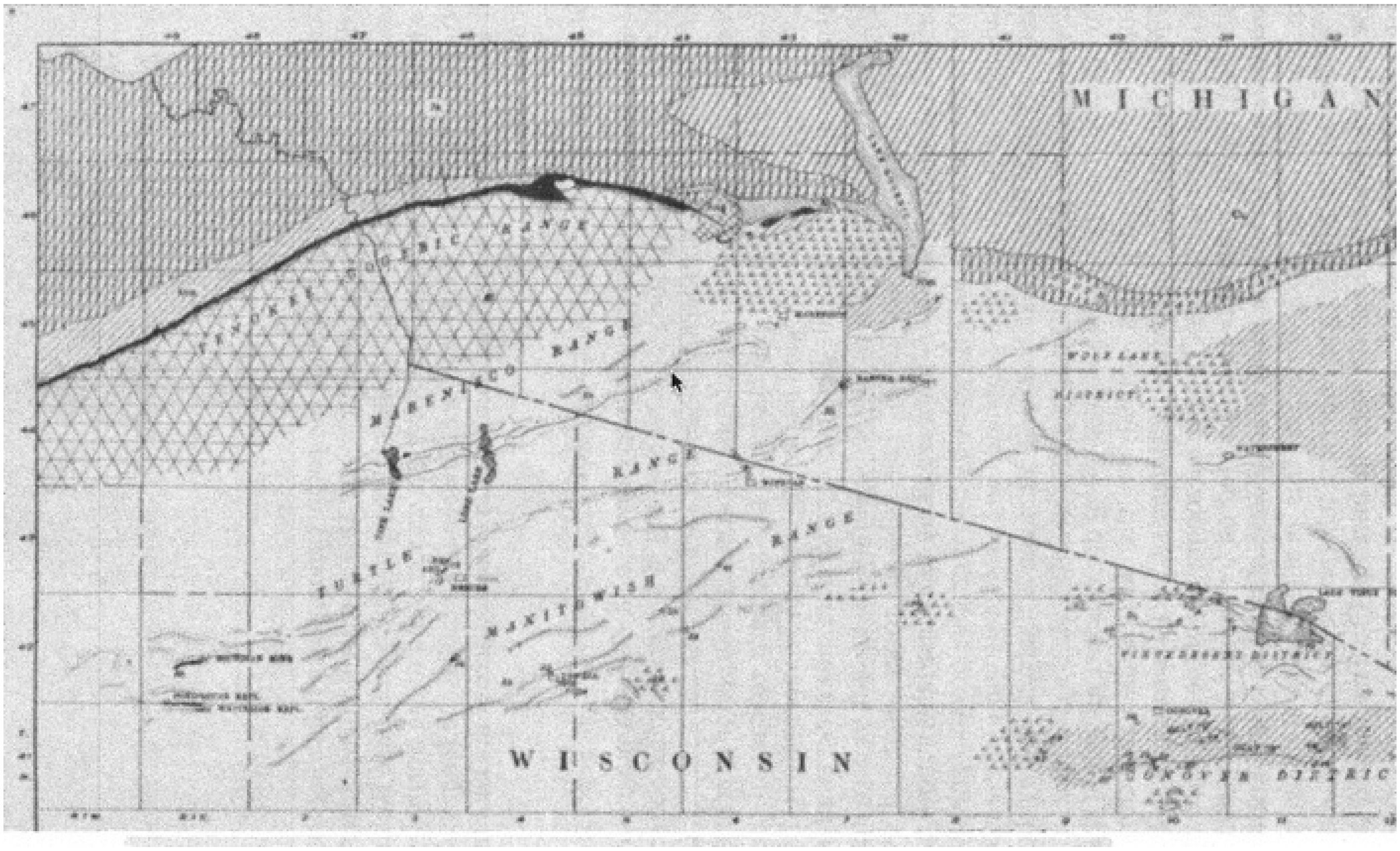

Figure 34. Map of the geology along the western limit of the boundary between Wisconsin and the Northern Peninsula of Michigan (Wisconsin – T.41-47N., R.1-13E.) showing the axes of magnetic anomalies (solid lines) which define the Marenisco, Turtle River, and Manitowish Ranges and Vieux Desert and Conover Districts. (After Allen, 1915)

(1979b) describes the source of the Butternut anomaly as a chlorite-grade, cherty iron formation from drill core. Magnetic surveying continued to be a component of exploration of the Gogebic Range in this period. Hotchkiss (1923b) was particularly active in using magnetic methods for investigating the boundaries of the iron formation, the stratigraphy, and structure of the Range and the location of ore deposits especially those related to cross-faults that could readily be mapped with careful magnetic surveying. He and his colleagues at the Wisconsin Geological and Natural History Survey were strong advocates of magnetic surveying in exploration and were instrumental in establishing procedures for the observation and interpretation of both dip needle and dial compass measurements (e.g., Hotchkiss, 1915, 1923a).

Bean and Aldrich (1929) reviewed the surveys and their accomplishments that were conducted by the Wisconsin Geological and Natural History Survey from 1910 to 1927. Figure 33 shows the areas surveyed totaling 288 townships, 18 in Huronian (Animikian) regions, 85 in Keweenawan bedrock regions, and 188 in undifferentiated Precambrian bedrock areas and where these surveys are published. These surveys included dip needle and dial compass observations. They did not lead to identification of direct shipping iron ore deposits, but subsequently potential taconite ores have been located using the information from these surveys to isolate areas for more detailed surface and drill hole studies. The surveys in the Keweenawan bedrock townships dating to 1915 (Aldrich, 1923, 1929) showed the utility of magnetic surveying to mapping the stratigraphy and structure of the Keweenawan rock formations. This information was not only important to studying the Midcontinent Rift System but led to further commercial and governmental dip needle and dial compass surveys of the potential copper-bearing Keweenawan formations in the Keweenaw Peninsula and western Northern Peninsula of Michigan.

3.3.3.3 Minnesota

The most successful magnetic mapping in the Lake Superior region was the identification of the Cuyuna Iron Range southwest of Duluth, Minnesota because this is the only iron range that produced direct shipping iron ore that had no direct surface indications of the iron-rich rocks. The presence of magnetic anomalies in the region was recognized with abnormal declinations prior to the 1870s by Northern Pacific Railway survey crews and in the 1870s by land surveyors suggesting the presence of magnetic iron ore in the region (Harder and Johnston, 1918). In the late 1890s magnetic surveys were conducted to locate possible iron formations, but their significance was not ascertained until 1903 when Cuyler Adams mapped declination anomalies with a dial compass and his drilling in 1904 confirmed the presence of iron-rich rocks under several tens of meters of glacial deposits.

Magnetic surveying of the region around the site of the discovery of the Cuyuna Range and the Mesabi and Vermillion Ranges with the dial compass and dip needle continued largely by commercial interests and locally by governmental surveys. Possible iron formations that were delineated by some of these surveys were included on the State Bedrock Map by Grout (1932). One of more intensely surveyed regions is the eastern end of the Mesabi Iron Range where the metamorphic effects from the Duluth Complex led to conversion of the predominantly hematite of the Biwabik iron formation to magnetite. Comprehensive magnetic mapping by the Minnesota Geological Survey of this segment of the Mesabi Range (Grout and Broderick, 1919) showed lower intensity anomalies than anticipated from the quantities of magnetite in the iron formation, at least in part a result of the shallow, southerly dip of the iron formation that are nearly perpendicular to the inducing Earth's magnetic field (Broderick, 1918).

In the early 1900s while investigating the Duluth Complex in northeastern Minnesota the Minnesota Geological Survey conducted dip needle magnetic surveys of the intrusive (Broderick, 1918). Their reconnaissance surveys along north/south section and quarter section lines encountered magnetic anomalies due to magnetite segregation zones and from inclusions of iron formations mapped to the west of the intrusive that were incorporated into the intrusive. In addition, they performed detailed dip needle and dial compass surveys of titaniferous magnetite segregations on a 12.5-foot grid (dip needle) and 25-foot grid (dial compass). Examples of their detailed dip needle surveys are shown in Figures 35 and 36. As shown in these figures they encountered negative magnetic anomalies that are prominent over the Duluth Complex immediately west of Lake Superior as illustrated in Figure 3.

An explanation for the negative magnetic anomalies was central to Broderick's *Economic Geology* paper in 1918. He considered the explanation that Dobie (1915) developed for the intense negative anomaly that had been mapped by the Wisconsin Geological and Natural History Survey in T.41N., R.7W. near Round Lake, Wisconsin. Dobie suggested that the Round Lake negative anomaly and the positive magnetic anomaly approximately 1.5 km to the south of the negative anomaly (Figure 37) were caused by the magnetization acquired by an iron formation when it was flat lying. According to his hypothesis this magnetization was retained during the folding of the iron formation leading to a horseshoe shaped formation with positive pole to the north causing a negative anomaly and a negative pole to the south resulting in a positive anomaly. Subsequent studies and drilling into the Round Lake anomaly have shown that the source of the anomaly is not an iron formation but is an approximately 12 km long, east-northeast-striking, funnel-shaped mafic/ultramafic intrusion that has concentrations of Fe-Ti-V (Zwickey, 1969; Stuhr, 1976; Mudrey et al., 2003; Schulz et al., 2014; Woodruff et al., 2020). It is one of several similar intrusives that are commonly reversely magnetized and likely of Mesoproterozoic age that have been identified adjacent to the Midcontinent Rift System in Wisconsin, Iowa, and southern Michigan.

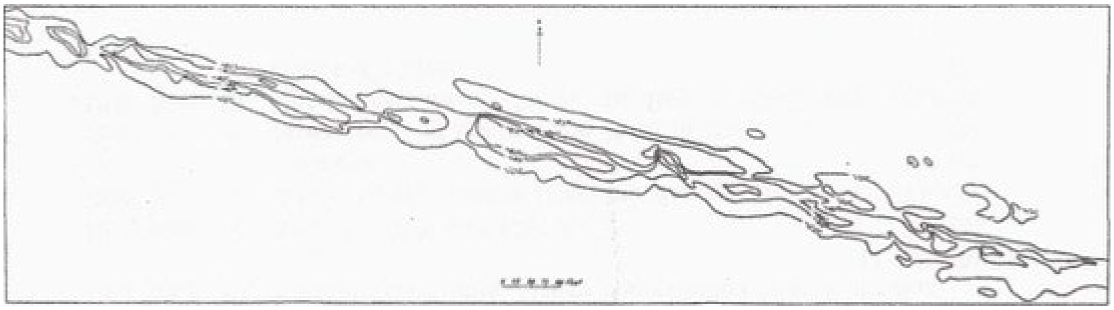

Figure 35. Dip needle map of a titaniferous magnetite segregation zone in the Duluth Complex. The contour interval is 20° and all readings are negative. (After Broderick, 1918)

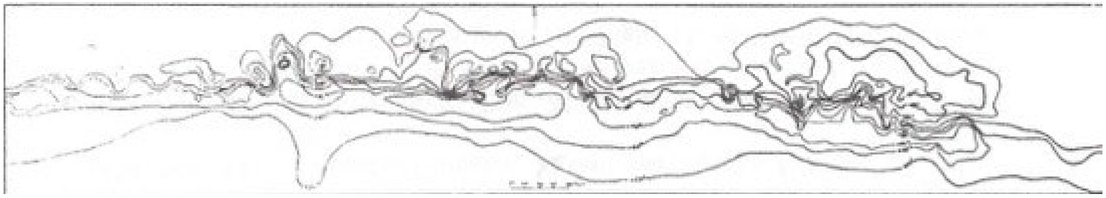

Figure 36. Dip needle map of an inclusion of iron formation in the Duluth Complex. The contour interval is 20º and are all negative. (After Broderick, 1918)

Broderick did not accept Dobie's explanation of negative anomalies for the Duluth Complex negative magnetic anomalies because he did not believe the magnetism acquired during the formation of the segregation zones would last through their subsequent structural deformation and folding of the titaniferous magnetite zones in the Duluth Complex was only minor. Rather he suggested that the negative anomalies were due to the shallow dip of the segregations which resulted in a negative magnetic anomaly on the northern edge of the source in the northern magnetic hemisphere, as observed associated with Biwabik iron formation of the Mesabi Iron Range (Bath, 1962) (Figure 38). Unfortunately, neither Dobie nor Broderick were aware of the strong thermal remanent magnetization of the Keweenawan igneous rocks that was not identified until after World War II (Dubois, 1955). Furthermore, they were unaware of the reversal of the terrestrial magnetic field which would lead to negative magnetic anomalies of rock units that acquire their remanent magnetization during the reversal, although Schwartz (1943) does speculate that magnetic anomalies may originate from variation in the polarity of the magnetized magnetic anomalies that are associated with the Keweenawan diabase dikes found on the margins of Lake Superior. Graham (1953) based on observations of self-reversal of the magnetism within certain rocks components. As a result of the lack of knowledge of reversal of the magnetic field, they assumed that any remanent magnetization in rocks would lead to positive anomalies. The exception to this is the negative and using Neel's (1955) proposed mechanisms for self-reversal within minerals, suggested the possibility that the negative magnetic anomalies were caused by self-reversal within rocks and not reversal of the Earth's magnetic field. However, by the late 1950s, early 1960s, the global synchroneity of the sign of the remanent magnetism of equivalent aged rocks led to the acceptance of reversals of the Earth's magnetic field which is now taken as the origin of the negative anomalies associated with the Duluth Complex and other Keweenawan igneous rocks of the Lake Superior region including the titaniferous magnetite in the Round Lake intrusive.

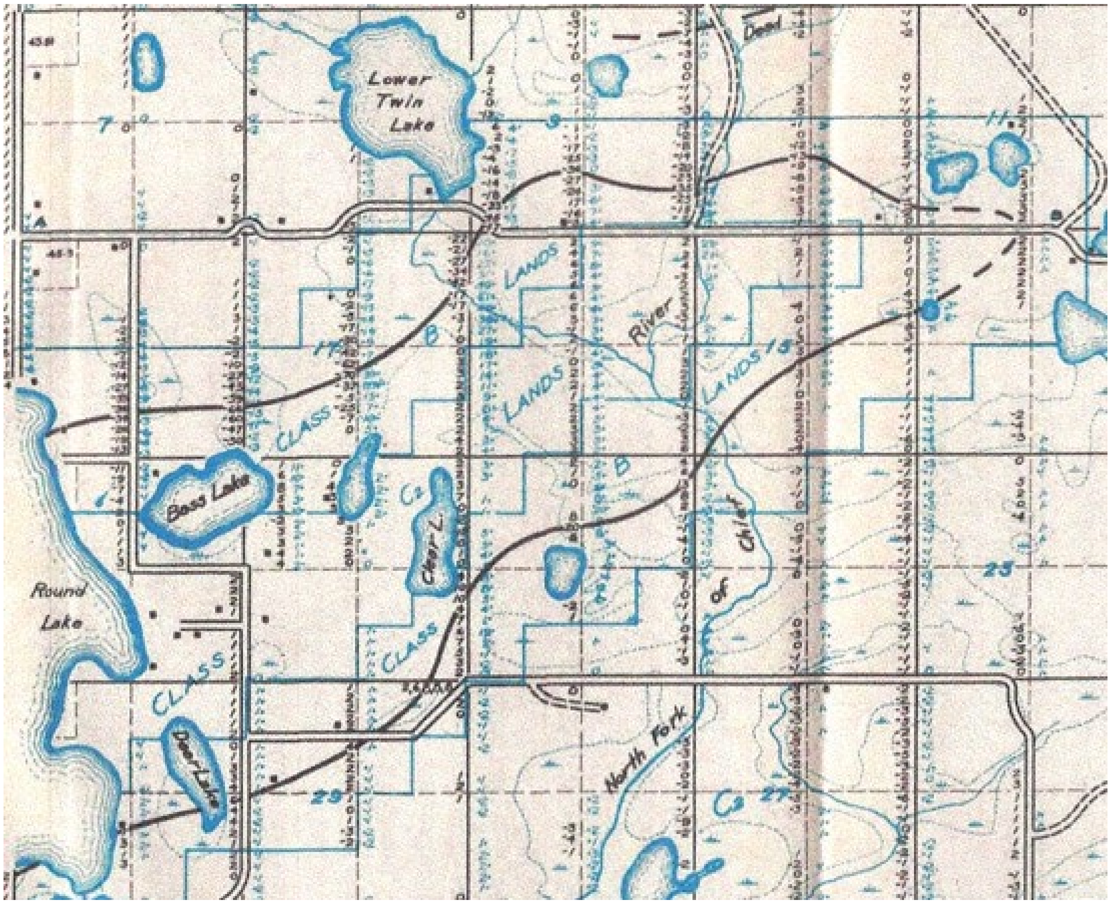

Figure 37. A portion of T.41N., R.7W. east of Round Lake, Wisconsin showing the dip needle and dial compass observations. Dial compass readings are to the right (east) of the traverses. Eastward declinations are shown with a dot to the west of the number. Dip needle readings are plotted to the west of the traverses. All are positive except for those preceded by a negative sign. All normal readings of the dial compass and the dip needle are not shown. Dip needle readings were taken every ~12.5 feet and dial compass readings every 25 feet. Heavy curvilinear lines follow the maximum values of the dip needle readings. (After Hotchkiss, 1915) The total intensity magnetic anomaly has an approximate amplitude of -40,000 nT (After Mudrey, 1979b).

3.3.3.4 Ontario

As noted previously the Lake Superior region's Steep Rock and Michipicoten Iron Ranges (Marks, 1925) of Ontario, Canada was discovered by surface prospecting and not by magnetic studies because the iron formations of these ranges are almost devoid of strongly magnetic minerals. However, some geologic units of the Steep Rock Range are sufficiently magnetic to be studied by magnetic investigations. Dip needle surveying in the early 1930s indicated the presence of magnetic anomalies in the vicinity of Steep Rock Lake which were later identified as caused by a magnetic tuff. These anomalies were mapped in greater detail with a Schmidt-type magnetometer in 1938-39 by A. Brandt (1939, 1940). The pattern of the anomalies that he mapped defined the geologic structure of the region which was useful in locating the non-magnetic hematite ore body.

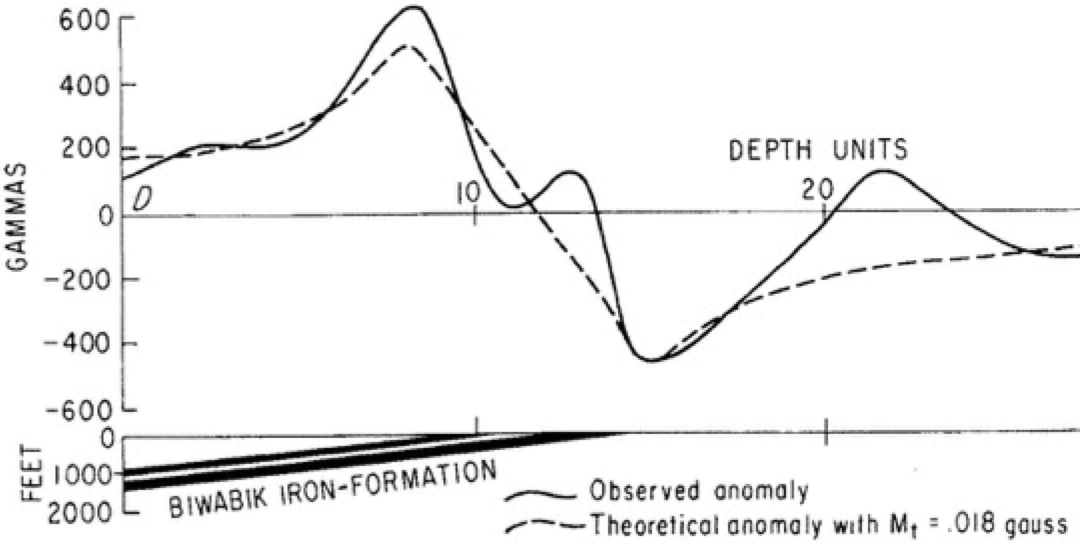

Figure 38. Simplified, averaged geologic profile perpendicular to the strike of the Mesabi Iron Range with the associated observed total intensity magnetic anomaly and theoretical anomaly profiles. North is to the right (D'). Note the intense negative magnetic anomaly on the northern margin of the Biwabik iron formation. (After Bath, 1962)

3.4 The Airborne Survey Years: 1941-1980

3.4.1 Overview

The **Airborne Survey Years** from roughly 1941 to 1980 were critical for mapping the geology of the Lake Superior region. It was during this span of time that mining in the region drastically decreased with the closure of most of the iron and copper mines due to dwindling reserves. Exploration for direct shipping iron ores largely ceased with increasing attention devoted to locating taconite ores for beneficiation prior to their use in the steel industry and greater interest in searching for copper and other metallic sulfide ores rather than native copper deposits. This was also a time for much more interest and investment in time and resources to deciphering the structure and tectonics of the Lake Superior region and describing the geologic history of the region. All these changes continued the use of magnetics for mapping and prospecting with new instruments developed based primarily on electronic rather than mechanical devices. These instruments rapidly became the principal method of mapping the magnetic field over a broad range of scales.

The most important development in the Lake Superior region during this time span from the standpoint of magnetic mapping was the invention of the airborne magnetometer – and thus the title of this period. Prior to 1940 numerous unsuccessful efforts were made to develop viable airborne magnetic instrumentation for geologic exploration objectives (Morrison, 2021), but success was not achieved until the United States government developed sensitive magnetic instrumentation for detecting submerged submarines during World War II. Subsequently, the U.S. Geological Survey became involved and developed instrumentation and procedures for conversion of the instrumentation to geologic mapping. This technology was shared with private contractors and the Geological Survey of Canada which continued to improve the instrumentation and airborne procedures for geologic purposes. This led to extensive airborne mapping of the Lake Superior region by federal and state/province geological agencies and private exploration and survey companies both in the United States and Canada over the decades that followed. Airborne surveying has been particularly useful in the Lake Superior region because of the relationship of ore bodies to magnetic anomalies, the marked magnetization contrasts among the shallow crystalline rock units of the region that can be used in geologic mapping, and the lack of ready access to many regions for ground magnetic surveying. However, flight path recovery using procedures developed by the U.S. Geological Survey (Balsley, 1952) and others (Jenson, 1945) was a problem during this period because of the lack of cultural, topographic, and surface features and quality base maps in many areas of the Lake Superior region to use as location control. The result was errors in the location of the magnetic measurements leading to erroneous magnetic anomaly location and problems in interpretation of anomalies. Hill (1986a, b) has prepared a comprehensive index of magnetic anomaly maps from the Lake Superior region that were published by the U.S. Geological Survey prior to 1986.

Despite the focus on airborne magnetic mapping, ground magnetic surveys continued during this period because of limitations in the resolving power of the early airborne surveys and the costs involved especially in surveying limited areas. To increase flight safety and facilitate aircraft navigation most surveying was conducted at a minimum of ~150 m terrain clearance which limited the resolving power of the methodology for geologic mapping purposes. The limitations in mapping geology are well illustrated by Wier (1950) in his comparison of ground and airborne magnetic surveys along several profiles in the Northern Peninsula of Michigan. These comparisons show that airborne surveying mapped the high intensity anomalies associated with iron formations and strongly magnetized volcanic flow and slate units but failed to map more subtle anomalies that could be of importance to geologic mapping. Ground magnetic surveying continued to be an important part of magnetic mapping for several decades not only because of the restrained resolution of the airborne mapping, but because of the potential error in the navigation of the airborne surveying which reached values of ~90 m (300 ft) or more, and the limited coverage of the federal and state (province) surveying. This is evidenced in the continued sale of dip needles and superdips well into the 1960s. These instruments remained useful because most of the resource magnetic surveying was directed at high-intensity anomalies associated with taconite formations and volcanic flow units. However, new electronic instruments were taking over from the mechanical instruments largely because of their high sensitivity, measurement range, and ease of operation. Many of these instruments were simplified versions of instrumentation developed for airborne measurements, and thus measured the same component determined by airborne surveys which facilitated comparison of ground and airborne surveys and their joint interpretation.

An important scientific development during this period was the construction of instruments for accurately determining the remanent magnetization of rocks. This led to the discovery that the Earth’s magnetic field reverses polarity at irregular intervals and that the Keweenawan extrusive and intrusive rocks of the Lake Superior region have intense thermal remanent magnetization of both positive and negative polarity (Dubois, 1955). This information is important to the interpretation of the magnetic anomalies associated with the Midcontinent Rift System and as discussed in the previous section in the analysis of intense magnetic minima related to Keweenawan rocks. Furthermore, concurrent development of modern geochronology leading to accurate age dating of the direction and reversals of the magnetic field of these rocks was used to date Keweenawan rocks based on their magnetization.

3.4.2 Technical Developments

3.4.2.1 Magnetic Instrumentation

During this period there were major developments in magnetic instrumentation which led to greater efficiency and effectiveness of magnetic surveying. Improvements were made in the mechanical magnetometers used in ground surveying, but the primary advancement was in the invention and development of magnetometers capable of high precision measurements in aircraft despite the variable accelerations that they are subject to which prevent precise airborne measurements with mechanical magnetometers. The new instruments were based on the rapidly developing electronics industry and knowledge of the interaction between the ambient magnetic field and atoms during and after World War II. All the instruments developed during this period for airborne magnetic observations measure the magnitude of the total field (the so-called scalar field) independent of its direction in contrast to the vertical or horizontal magnetic field that were measured hitherto by mechanical magnetometers. In the succeeding years protocols were established for eliminating extraneous magnetic fields from the magnetic observations and procedures established for accurately determining the ground positions of the airborne observations. Many of the airborne instruments also were modified for ground observations eliminating the need for leveling and orienting the magnetometer prior to making a measurement.

It was also during this period that gravity surveys using newly developed instrumentation became available for analysis with magnetic measurements leading to improved interpretations. Numerous gravity meters were developed during the 1930s with sensitivities useful for geological purposes including the zero-length spring meters (LaCoste, 1934) made by the Worden Gravity Meter Company (Houston Technical Laboratory) and the LaCoste and Romberg Gravity Meter Company. The Worden instrument is very portable without the need for external batteries to maintain a constant temperature within the instrument which made it particularly useful for exploration investigations in remote areas. In contrast the LaCoste and Romberg gravity meters which must be kept at a constant temperature are very stable with low internal variation rates. Thus they were widely used, particularly in regional gravity surveys in the Lake Superior region.

3.4.2.1.1 Fluxgate (Saturable-Core) Magnetometers

The promise and advantages of airborne magnetic surveying were well known to geophysicists prior to 1940 leading to numerous attempts to develop instrumentation and procedures for airborne magnetic measurements in airplanes and lighter-than-air aircraft. Unfortunately, these were not met with success

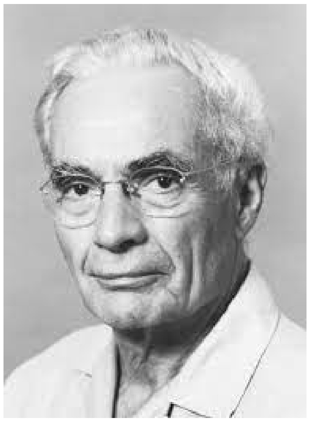

Figure 39. Victor V. Vacquier (1907-2009) who was instrumental while employed at the Gulf Research and Development Company in developing the fluxgate magnetometer for airborne measurements of the total magnetic field. (Courtesy of Google Images)

in achieving sensitivities useful for geologic mapping. However, this changed when scientists and engineers at Gulf Research and Development Company (GRDC), a subsidiary of Gulf Oil Corporation and the most notable applied geophysical research organization of the time, using a concept for measuring the magnetic field developed in Germany in the mid-1930s, initiated efforts to develop an airborne magnetometer system. The concept, which became known as the fluxgate magnetometer, became the basis of an airborne system developed by J.D.C. Hare and Victor V. Vacquier (Figure 39) in

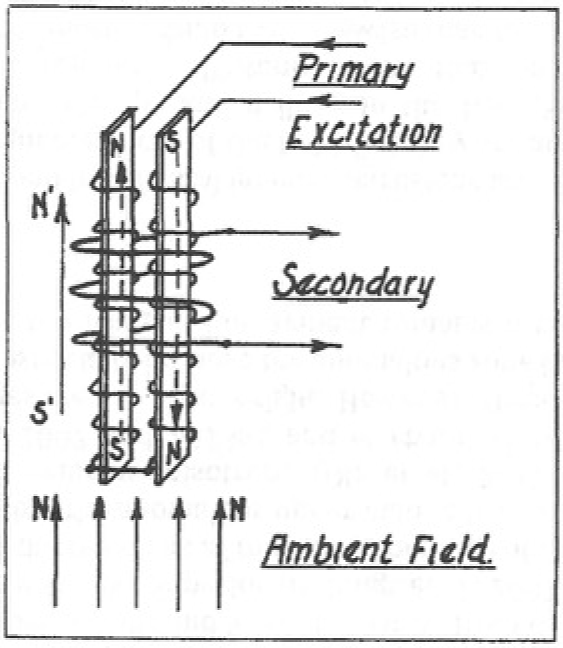

Figure 40. Schematic diagram of the Vacquier-fluxgate magnetometer sensor showing the opposed primary coils around the permeable magnetic cores and the single pickup secondary coil. (After Wycoff, 1948)

1940 at GRDC (Vacquier, 1945; Muffly, 1946; Hanna, 1990). The term fluxgate refers to the periodic switching or gating of the magnetic flux in the measurement system. It also is known as the saturable-core magnetometer because a high-permeability magnetic core that can easily be magnetically saturated is employed in the detector to amplify the magnetic signal. The instrument devised by GRDC was suitable for sensitive magnetic observations (~1 nT) in an airborne mode because it was free of mechanical parts that are subject to gravitational and vehicular accelerations (Gulf Research and Development Company, 1943). Similar instruments were developed by other nations during World War II for use in submarine detection but were not adapted to geological mapping (Morrison, 2021).

There are numerous designs of the fluxgate magnetometer (Grosz et al., 2017), but the classic Vacquier-sensor design consists of two parallel high-permeability cores with oppositely directed primary windings connected in series which are readily brought to saturation in opposite directions by alternating current passing through them (Figure 40). However, the ambient magnetic field parallel to the cores advances the saturation in the coil directed with the exterior field in contrast to the other coil. This advanced saturation is observed in a secondary pickup coil surrounding both coils as a voltage either the peak or second harmonic voltage which are measures of the intensity of the ambient magnetic field in the direction of the coils. Unfortunately, in an airborne environment it is impossible to keep the coils oriented in a sufficiently vertical direction to attain a suitable sensitivity. Thus, it was impossible to measure the commonly measured vertical intensity with sufficient precision for geological purposes. However, it is possible to keep the coils in the direction of the ambient field to achieve a sensitivity useful in magnetic mapping. Using three mutually perpendicular sensors the measuring sensor is oriented in the direction of the Earth's magnetic field, thus measuring the changes in the total magnetic field. The fluxgate magnetometer was also used for ground surveying instruments with the sensor self-orienting in a vertical direction.

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Figure 41. James R. Balsley (1916–1994) making magnetic observations in a U.S. Geological Survey aircraft. Balsley was among the first to recognize the importance of the airborne magnetometer in mapping geology, conducted some of the first aeromagnetic surveys, and

developed survey and processing procedures for implementing airborne methods. . (Courtesy of the U.S. Geological Survey Photo Archives)

The history of the airborne fluxgate instrument is complicated because its development was taken over by the military near the beginning of World War II for its use in detecting submerged submarines. As a result, several companies and military agencies became involved in completing the instrumentation. Building upon the concept of the fluxgate magnetometer devised by GRDC the second harmonic fluxgate was developed and built by the Airborne Instruments Laboratory at Columbia University where Vacquier was employed during World War II, the Naval Ordinance Laboratory, and Bell Telephone Laboratory. The GRDC continued to develop the magnetometer for geological mapping and in 1943 the U.S. Geological Survey became aware of the development of the airborne magnetometer and recognized its potential to geologic mapping. James R. Balsley (1916–1994) (Figure 41) of the U.S. Geological Survey discussed the use of the instrument for geologic purposes with the U.S. Naval Ordinance Laboratory leading to improvements that enhanced its use in geological mapping. This led to the use of the GRDC instrument with the sensor towed behind a single-engine biplane of the Aeroservice Company of Philadelphia, Pennsylvania in test flights made along three traverses near Boyertown in southeast Pennsylvania that had been previously magnetically surveyed by the U.S. Geological Survey. Comparison of the ground and airborne magnetic measurements showed the viability of the aircraft instrumentation (Balsley, 1946). With this success the aircraft was flown to Iron River, Michigan where it surveyed 3900 sq km (~1500 sq mi) of swamp and timbered area in May and June of 1944 (Balsley, 1946). This led to further successful test flights over the Benson Mines iron ore deposits and other iron deposits in the Adirondack Mountains of New York. These tests and others validated the fluxgate instrumentation, the procedures for flight path recovery, and airborne magnetic mapping of geology. The Iron River, Michigan and nearby area surveys were related to the geology by Barrett et al. (1946), Balsley et al. (1949), and Wier et al. (1953) in some of the first aeromagnetic maps published by the U.S. Geological Survey.

The first full-scale survey was conducted by the U.S. Geological Survey with the cooperation of the U.S. Navy over Petroleum Reserve #4 in northern Alaska in 1946 (Zietz et al., 1960). The Survey continued to conduct magnetic surveys in various places in the United States in coordination with the states including states within the Lake Superior region. Gulf Oil Company using the instrumentation developed at GRDC conducted airborne magnetic surveys in both the United States and Canada as part

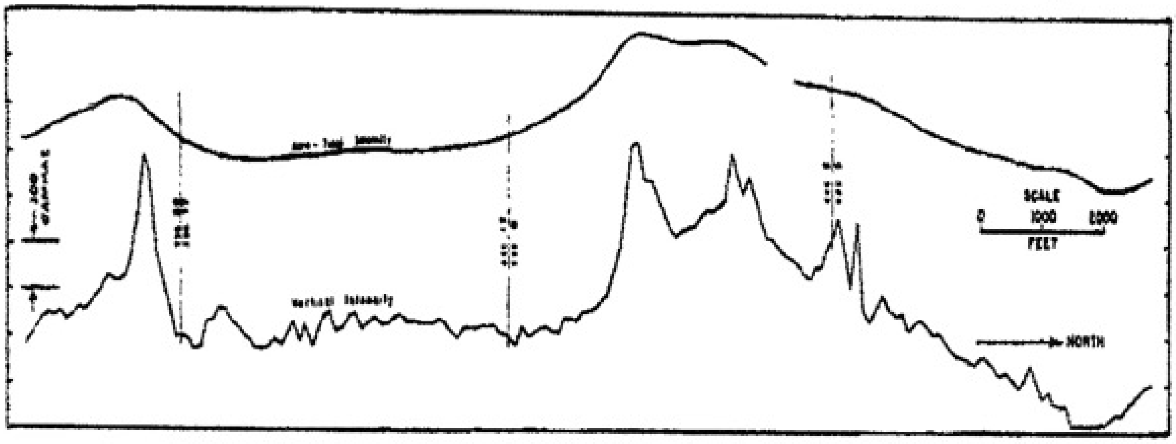


Figure 42. Comparison of ground vertical magnetic intensity profile (lower) and airborne total magnetic intensity profile observed at ~150 m (~500 ft) in the Iron River District. Note the attenuation and merging of ground surface anomalies at the altitude of the airborne measurements. Vertical and total magnetic intensity values are nearly the same at the latitude of the Lake Superior region. (After Wier, 1950)

of their reconnaissance petroleum exploration program and in areas of interest to their mineral resource exploration program. In addition, several private companies, including the Aeroservice Company that was involved in the first surveys, conducted contract surveys for petroleum and mining exploration companies and for geologic mapping required in the construction of critical engineering structures. The U.S. Geological Survey shared their airborne magnetic mapping experience with geologists of the Canadian government in 1946 leading to the Canadians purchasing three of GRDC airborne fluxgate magnetometers which in short order were put into service in magnetic mapping in Canada (Hood, 2007). The fluxgate magnetometer underwent continued improvement increasing its sensitivity to 0.01 nT, range to 100,000 nT, and its stability (Hood, 1970; Teskey et al., 1993).

The early tests by the U.S. Geological Survey of the system for making aeromagnetic surveys showed numerous advantages over ground surface magnetics. However, there are disadvantages to airborne measurements. A principal concern is the attenuation and merging of the anomalies with increasing observation distance. This is illustrated in Figure 42 which compares the vertical intensity of the ground magnetics with airborne measurements along a several kilometer profile in the Iron River District of Michigan. In the right half of this figure three individual anomalies in the ground survey that originate from magnetic slates are coalesced into a single high in the airborne measurements, thus impairing the horizontal resolution of the measurements. The single anomaly at the south (left) end of the ground profile which is caused by magnetic greenstone (Wier, 1950) is highly attenuated and broadened in the airborne profile significantly complicating the interpretation of the location and margins of the source. The peak of the anomalies is shifted to the south in the northern magnetic hemisphere with increasing distance between the measurements and the source and decreasing ambient magnetic inclination, but this shift is not a significant factor at the inclination of the Earth's magnetic field at the latitude of the Lake Superior region. However, the location of the peak of the greenstone airborne magnetic anomaly near the south end of the profile shows a shift of the order of ~ 150 m (500 ft) to the south which is excessive suggesting that there is an error in the flight path recovery. As a result of the deleterious effects of increasing elevation of airborne surveying, aeromagnetic observations are made as low as possible while flying high enough to accurately navigate and determine flight position recovery and fly safely.

As an aid to interpretation of magnetic anomalies by a process known as forward modeling, the anomalies from idealized geologic sources are calculated and compared with the observed magnetic anomaly. The sources are modified and recalculated considering constraining information derived from geologic sources, other geophysical data, and the mismatch of the observed and calculated anomalies until a satisfactory match of the observed data is achieved with the model sources. The resulting sources used in the calculation are a possible interpretation of the observed anomaly, but not a unique solution. In contrast to the measurement of the total magnetic field by the airborne fluxgate magnetometer and all subsequently developed airborne magnetometers, quantitative ground magnetic observations with the Hotchkiss superdip, Schmidt-type variometer, and ground fluxgate and torsion magnetometers are vertical-field measurements. As a result, forward modeling of ground measurements only required calculation of the vertical field. To compare ground and airborne measurements and calculate the vertical field from the total field for forward modeling, a formulation was developed by Hughes and Pondrom (1947) based on a combination of the vertical and horizontal fields of geologic sources. However, as more ground magnetic measurements were made with scalar magnetometers that became increasingly available and airborne magnetic measurements became generally available, Hughes and Pondrom's equation was modified to calculate the total magnetic field of geologic sources from the vertical and horizontal components of the assumed geologic sources. Accordingly, forward modeling is universally used today based on the observed total magnetic intensity and the summation of vertical and horizontal magnetic components using Hughes and Pondrom's equation.

3.4.2.1.2 Resonance Magnetometers

The fluxgate magnetometer and associated instrumentation developed by the GRDC and the United States government laboratories proved to be very useful for observing the total magnetic field from the air. However, resonance magnetometers developed after World War II had several advantages over the fluxgate instrument, and thus gradually displaced them for most airborne surveying organizations by the mid-1960s. The magnetometer systems also were greatly improved by recording digitally, replacing the analog systems of the early airborne instruments. Resonance magnetometers such as the proton-precession and alkali-vapor devices have sensors containing fluids or gases with atomic properties that are sensitive to changes in the magnetic field.

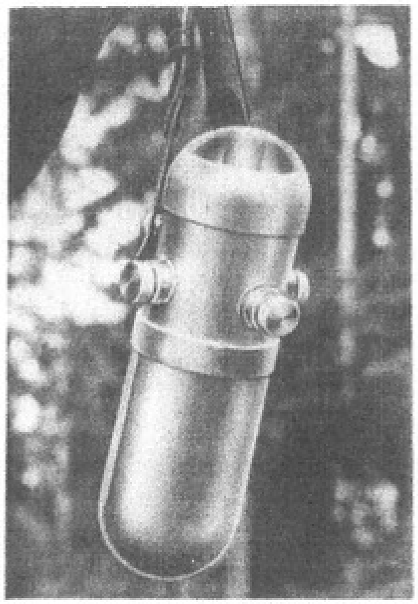
The proton-precession magnetometer which was suggested by the work of Packard and Varian (1954) is based on determining the precession frequency, which is a measure of the ambient magnetic field, of protons in a hydrogen-rich fluid container oriented at a large angle to the ambient field by a strong direct current magnetic field originating from a current passing through a wire coil around the container. Upon terminating the direct current magnetic field the protons precess around the ambient field inducing a current in a surrounding coil with a frequency dependent on the ambient magnetic field. This frequency is measured and converted to the intensity of the magnetic field by the well-known gyromagnetic ratio of protons. This instrument was widely used in airborne surveying starting in the mid-1960s because of its low cost and ease of operation and maintenance and was also adapted for ground surveying instruments. However, it has several disadvantages which fostered the use of alkali-vapor resonance magnetometers for airborne surveying and largely replaced the proton-precession as the airborne instrument of choice by the 1990s.

Alkali-vapor instruments are miniature atomic absorption instruments which measure the Larmor frequency associated with optical pumping and optical monitoring of an alkali vapor cell that are used in radio-frequency spectroscopy (Hine, 1968). The measured Larmor frequency is proportional to the total ambient magnetic field. Cesium or potassium vapor have been generally used in airborne instrumentation. These devices have an order of magnitude greater sensitivity and shorter cycling time and are tolerant of much higher magnetic gradients than proton-precession magnetometers. A commonly used airborne magnetometer is the cesium self-oscillating split beam instrument, the G-822A manufactured by Geometrics Inc. As in the case of the proton-precession instruments, these instruments have been adapted to ground surveying systems. More detailed descriptions of these instruments are available in general exploration texts such as Telford et al.

(1976) and Hinze et al. (2013). These instruments have also been used for direct measurement of the vertical gradient of the magnetic field by placing two magnetometers at a fixed vertical distance. The difference between the two measurements is the measured vertical gradient which has a higher resolving power than the measured field. Airborne gradient instrumentation has been pioneered by the Geological Survey of Canada and has been used by the Canadian Survey in special airborne mapping programs (Hood et al., 1985; Hood and Teskey, 1989). Gradiometers are also used in ground magnetic mapping programs utilizing the difference between two magnetometers placed vertically at a fixed distance.

3.4.2.1.3 Magnetic Variometers

During this period,1940 to 1980, airborne magnetic mapping was initiated and continued to have a prominent role in geologic mapping in the Lake Superior region, but ground magnetic surveying as discussed previously also had a significant role especially in detailed, high resolution mapping. In the interval between roughly 1940 to 1965 the dip needle and superdip were used in taconite exploration because these instruments were inexpensive and have a large measurement range which was needed to map the highly magnetic taconite formations. However, shortly after World War II several different



a.


b.

Figure 43. Jalander a. and Sharpe b. magnetometers based on the fluxgate principle of measuring the vertical component of the Earth's magnetic field. (After Hood, 1966)

instruments became available for ground magnetic mapping. These included simplified versions of airborne magnetometers, the fluxgate, proton precession, and alkali-vapor, all had a sensitivity of 10 to 1 nT or greater. The proton precession and cesium or potassium-vapor instruments are scalar instruments eliminating the need for precise orientation and leveling. The measurements made with these instruments could be directly related to the total intensity measurements of airborne surveying. Numerous versions of these instruments were developed by Canadian, British, and Finnish instrument makers including the widely used Jalander (Figure 43a), McPhar, and Sharpe instruments (Figure 43b). The ground fluxgate instruments which measure the vertical magnetic intensity using a saturable-core element on a gimbal suspension are self-leveling and require no orientation (Hood, 1964 and 1966). Another group of ground surveying instruments (Figure 44) was introduced based on measurement of the torque experienced by magnet on a quartz string (Haalck, 1956). These instruments are largely independent of orientation, but have to be leveled, thus requiring a tripod mount. They have a resolution of the order of 1 nT, a large measuring range, and can be adapted to measuring either the vertical or the horizontal component of the ambient field. Pocket-sized versions of this instrument were constructed with low sensitivity but large ranges (hundreds of thousands of. nanoteslas) by Arvela and Minimag that were convenient to use for reconnaissance measurements of the intense magnetic anomalies associated with magnetic taconite deposits. As such they were useful as a replacement for dip needle measurements.

3.4.2.2 Other Technical Developments

It was during this period that significant improvements in magnetic surveying and the availability of computers for analysis, interpretation, and presentation that are capable of storage of large data sets and rapid computations led to the development of new magnetic data interpretation techniques. These included a wide variety of processing procedures to emphasize particular attributes of aeromagnetic anomaly data that will enhance anomaly interpretation such as derivative, continuation, reduction to pole, etc. (e.g., Peters, 1949; Telford et al., 1976). In addition, computer programs became available for forward modeling of the total intensity magnetic field derived from sources of various geometric shapes (e.g., Vacquier et al., 1951; Talwani and Heirtzler, 1964) and for inverse modeling. The method of interpretation described by Vacquier and his associates in their 1951 Geological Society of America memoir was prominently used as a guide to interpretation for several years.

3.4.3 Magnetic Mapping

Despite the acceptance by the profession in the latter 1940s of airborne magnetic surveying as a geologic tool, ground surveying continued in the search for direct shipping and taconite iron ores and geologic mapping in limited areas to achieve maximum mapping resolution and to avoid the high survey cost where charges for airborne survey mobilization and demobilization were encumbered for a small area survey. However, airborne surveys were made over large areas previously unstudied for purposes of locating potential ore deposit regions and for geological mapping. Initially surveys were made by federal geological surveys, but gradually surveys were contracted out by governmental agencies and all industrial exploration groups to private organizations specializing in conducting magnetic airborne surveying.

Airborne magnetic mapping began in the iron range regions of Michigan shortly after the end of World War II with the publication of the U.S. Geological Survey GP-3 by L.P. Barrett et al. in 1946. Shortly thereafter numerous U.S. Geological Survey publications with the state geological surveys were published for Michigan, Wisconsin, and Minnesota. The Geological Survey of Canada in cooperation with the Province of Ontario also conducted extensive reconnaissance airborne magnetic surveys in the Lake Superior region and published the resulting maps. The anomalies shown by these maps were used by the exploration industry to localize regions with possible ore deposits for geological investigations and more detailed aeromagnetic surveys by survey contractors.

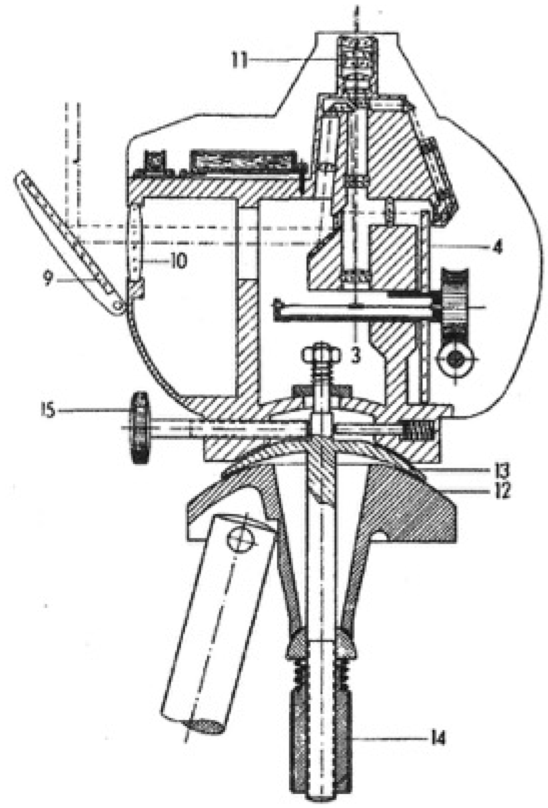


Figure 44. Schematic cross-section of the Askania torsion magnetometer mounted on a tripod. The magnet that is rotated by the ambient magnetic field is located directly above the numeral 3 on the quartz string. (After Haalck, 1956)

Systematic gravity surveys of the states/province initiated by universities and state and national agencies were tied into national networks with observations at established base stations. These led to publication of state/province anomaly maps and eventually to national maps that are useful in magnetic interpretation. Subsequentially data bases of the principal facts of the observations and data grids were prepared and made available to the geological/geophysical communities. In Ontario the Dominion Observatory of Canada (Innes, 1960) initiated a gravity survey of Ontario at a grid spacing of 10 to 15 km in 1947 which was largely completed by 1964. Subsequent surveying by the Earth Physics Branch of Energy, Mines and Resources, Canada increased the data coverage in geological interesting areas. In the Northern Peninsula of Michigan gravity anomaly data of large segments of the western part of the region were observed in the 1950s and 60s and reported on by Michigan Technical University (e.g., Bacon, 1957), Michigan State University (e.g., Oray et al., 1973, and U.S. Geological Survey (e.g., Klasner et al., 1979a). The Bouguer gravity anomaly map of Wisconsin was compiled by Ervin and Hammer (1974a) from their gravity observations and numerous surveys by the University of Wisconsin and the Wisconsin Geological Survey (Ervin and Hammer, 1974b). A systematic gravity survey of Minnesota and state-wide base station network were initiated in the mid-60s by R.J. Ikola under the auspices of the Minnesota Geological Survey which served as the foundation for incorporating prior and subsequent gravity surveys into state-wide gravity anomaly coverage (e.g., Chandler and

Schaap, 1991; Chandler and Lively, 2019). All of these data have an important continuing role in mapping the geology of Minnesota.

The results of significant gravity surveys interpreted jointly with magnetic surveys published during this period include those connecting the western arm of the MRS to western Lake Superior structures (Thiel, 1956; Craddock et al., 1963, 1970); surveys investigating the geology of the Keweenaw Peninsula, northern Wisconsin, and central Northern Peninsula of Michigan (Bacon and Wyble, 1952; Bacon, 1957, 1966; Miller, 1966; Bork, 1967); surveys of eastern Northern Peninsula of Michigan (Oray et al., 1973) and the Southern Peninsula of Michigan (Hinze et al., 1975); maps of Lake Superior gravity anomalies (Weber and Goodacre, 1966; Wold and Ostenso, 1966; Wold, 1969; Wold and Berkson, 1977; Klasner et al., 1979a); and surveys of iron formations identified by magnetics and geology (Hinze, 1960; Leney, 1964; Klasner and Cannon, 1974).

In the 1970s the United States government became concerned about the availability of uranium resources in the United States. As a result, the U.S. Atomic Energy Commission initiated a program in 1973 to identify uranium resources in the conterminous United States and Alaska. This program, the National Uranium Resource Evaluation (NURE) program (Hill et al., 2009), included an Airborne Radiometric Reconnaissance Survey project of the 625 1- by 2-degree quadrangles that cover the conterminous Unites States and Alaska. Magnetic observations were added to the flight program for general mapping purposes and for use in interpreting favorable geological formations for the occurrence of uranium deposits, but specifications of the airborne survey were established solely based on the radiometric surveying requirements. Flights were generally made at roughly ~120 m (400 ft) above mean terrain along east/west flight lines spaced at 5 or 10 km (3 to 6 mi) with local areas of special interest at closer intervals. Observations were made at an interval of 45 to 60 m. Many of the quadrangles in the Northern Peninsula of Michigan and northern Wisconsin were flown at 5 km intervals. These surveys provided only a very broad reconnaissance of the magnetic field especially in the Lake Superior region with its generally high wavenumber (frequency) magnetic pattern and east/west striking geological formations roughly parallel to the flight lines.

3.4.3.1 Michigan

The earliest and the most extensive magnetic surveying during this period (1941-1980) was conducted in the Menominee and Iron River-Crystal Falls Iron Ranges primarily by the U.S. Geological Survey with the support of the Michigan Geological Survey. Considering the extensive cover of the basement bedrock by glacial deposits in this region it was apparent that geophysical methods were needed to aid in locating ore deposits and mapping the geology of the region. As a result, a research program was performed by the U.S. Bureau of Mines and Harvard University (Stratton and Joyce, 1932) in the early 1930s to determine the relevance of the magnetic surveying to studying the iron deposits in the Menominee Iron Range. In the early 1940s an additional study was performed in the area by the U.S. Bureau of Mines in coordination with the U.S. Geological Survey to investigate the application of a variety of geophysical methods, including the magnetic method, to locate iron ore deposits and map the geology of the iron ore districts of the Northern Peninsula of Michigan (Zinner et al., 1949). This study was conducted in three different areas in the Iron River District of Michigan where the geology could be predicted by projection from mines or drill holes. The investigation showed that generally iron-oxide bearing formations could be identified with the magnetic method, but they concluded that:

"Magnetic surveys made with the Hotchkiss superdip produced anomalies that defied interpretation."

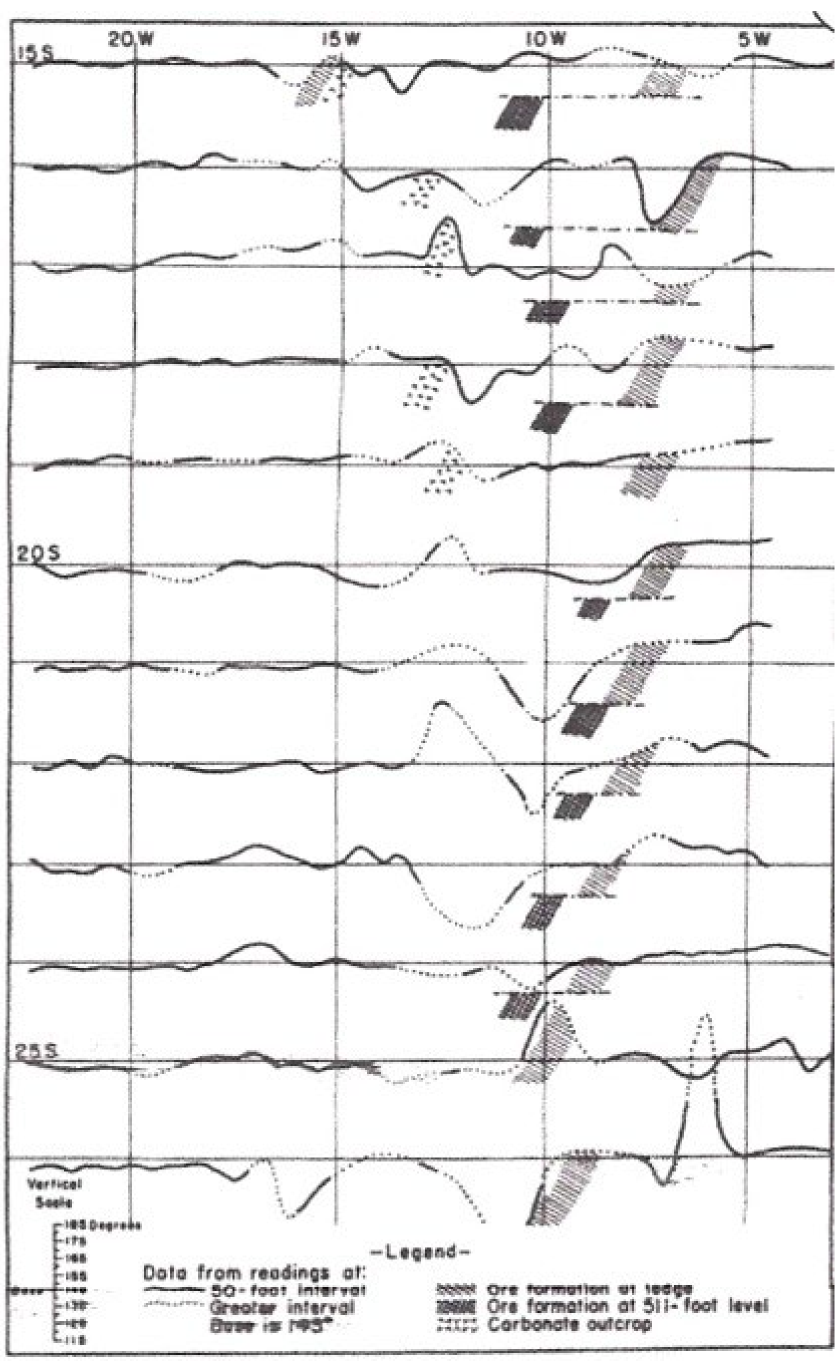


Figure 45. Magnetic profiles in degrees measured by a Hotchkiss superdip oriented in the magnetic meridian over projected near surface and deep iron ore on west/east profiles separated by ~33 m (100 ft).) Note the generally consistent measurements west of the highly variable

magnetic observations over the iron formation and the inconsistent anomalies related to the iron ore bodies. (After Zinner et al., 1949)

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Their studies in the Stambaugh area south of Iron River led them to the conclusion that:

"The employment of this [magnetic] *method alone as a means of localizing iron-bearing formations is shown in this report to be difficult or impossible in some cases."*

These conclusions are consistent with their measurements presented in Figure 45 which show magnetic profiles over an iron formation with both near-surface and deep iron ores. The lack of consistent magnetic response to the identified iron ore bodies is likely due at least in part to the effect of the variability in the ambient magnetic inclination upon the superdip readings as measured in the magnetic meridian. Furthermore, the iron in the Riverton Iron formation of the Iron River-Crystal Falls District is primarily in the form of non-magnetic siderite. Magnetite occurs only locally in the iron formation, thus intense, continuous magnetic anomalies are not observed over the iron formation (James and Wier, 1948; James et al., 1968). It is likely that the conclusions from this study were not readily accepted by others mapping geology in the area because the U.S. Bureau of Mines reports are not cited in subsequent publications on the use of the magnetic method in the Iron River-Crystal Falls Iron Range. Furthermore, the magnetic method continued to be used intensely in mapping the geology and magnetite-rich formations of this region. The primary target of these surveys was a magnetic slate unit in the Stambaugh formation which lies stratigraphically above the iron formation. Mapping of the intensely folded and highly complex structure of this district was largely achieved by the magnetic anomalies of this unit.

In the 1940s and 50s the U.S. Geological Survey under the supervision of Harold Lloyd James (1912–2000) in coordination with the Michigan Geological Survey conducted geological studies of the Menominee Iron Range, the Felch trough, and the Iron River-Crystal Falls Iron Range of Dickinson and Iron Counties, Michigan. These studies led to numerous reports including James and Wier (1948), Gair and Wier (1956), Bayley (1959), James et al. (1961, 1967), and U.S. Geological Survey (1970, 1981) which describe the associated magnetic surveying which was an integral part of their studies. Initially the magnetic surveying was conducted with the dip needle and then with the Hotchkiss superdip, and then with Schmidt-type magnetometer for detailed studies of relatively small areas. Initially the Hotchkiss superdip was used with the instrument oriented in the magnetic meridian, but James (1948) showed that if the orientation was used perpendicular to the magnetic meridian that the more interpretable vertical magnetic intensity was measured. The effect of this orientation was discussed earlier by Lundberg (1929a) and others. As a result, subsequent measurements with the Hotchkiss superdip were made with the instrument oriented perpendicular to the magnetic meridian. This avoided the vexing problem caused by large variations in the magnetic inclination from the near-surface sources prominent in the area. Similar superdip measurements were made throughout the Marquette Iron Range (Longacre, 1951) during this period.

The widespread use of ground magnetic measurements for mapping geology in the Northern Peninsula of Michigan led to interest by the U.S. Geological Survey in testing the use of aeromagnetic mapping as a replacement for or a supplement to ground mapping. It was the convergence of the Survey's investigation of the application of aeromagnetic mapping and the need for magnetic surveys in Michigan that resulted in early testing of aeromagnetics for geologic mapping in the Iron River area in 1944 (Hanna, 1990). The success of these tests as illustrated in

Figure 42 showing a comparison of ground and airborne measurements led to the first comprehensive survey in Alaska in 1946 and the U.S. Geological Survey conducting preliminary surveys in a variety of geological terranes across the nation. These surveys included mapping a portion of Dickinson County, Michigan in 1948 that was under investigation by the Survey as part of their restudy of the iron ranges of the Northern Peninsula of Michigan (Weir et al., 1953). The major source of error in this survey as in many others was flight-path recovery. Inadequate base maps, lack of readily recognizable cultural and terrain features, and the assumption that the aircraft flew at a constant speed in a straight line between navigation check positions limited the flight-path recovery accuracy. These early surveys had a potential location error of ~100 m (300 ft) which in some cases was as large as 400 m. As a result, some of the early surveys, including the 1948 survey of a part of Dickinson County, were not mapped as magnetic intensity contour maps but rather as a so-called "red-ball" map. Red-ball maps show the location of the peak of the magnetic anomalies with a red ball whose diameter is related to the measured magnetic anomaly amplitude as shown in Weir et al. (1953). These were obviously reconnaissance survey maps showing trends of magnetic anomalies and regions to be investigated with more detailed surveys.

Airborne magnetic surveying in the Northern Peninsula of Michigan west of the margin of the Paleozoic sedimentary rocks became an important effort of the U.S. Geological Survey from the 1950s with publication of more than 50 magnetic maps largely as Geophysical Investigation Maps and Open-File Reports. Most of these publications were authored anonymously or senior authored by J.R. Balsley, or K.L. Wier. These maps were used individually to assist in mapping the bedrock Precambrian geology and were composited into maps for mapping the regional geology (e.g., Meshref and Hinze, 1970; Zeitz and Kirby, 1971; King, 1975). The surveys were all flown at an elevation of ~150 m (500 ft) above the ground surface with traverses spaced at intervals of approximately 400 m (~1/4 mile). The flight path was recovered from a gryrostabilized, continuous-strip camera typical of the surveys of that era. The flight-path of the surveys in the region east of 88°30'W, west of longitude 88°07'30" W, and south of latitude 46°25'N latitude was east/west because most of the geologic units and structures strike roughly north/south in this area while the remainder of the survey region was flown in a north/south direction which is perpendicular to the general strike of the trend of the geologic structures in this area. The airborne surveying of the Iron River area reported on by King and Cannon (1979) was supplemented by a truck-borne survey to increase the resolution of the data.

Aeromagnetic surveying was also used in its early stages to map the geology of the Keweenaw Peninsula (Balsley et al., 1949) and the native-copper-bearing Portage Lake volcanic rocks that form the backbone of this topographic/geologic feature. Subsequently, aeromagnetic maps have been used to trace the multiple components of the Keweenaw fault from Wisconsin to the tip of the Peninsula into Lake Superior (Cannon and Nicholson, 2001). Additionally, aeromagnetic anomaly data from the U.S. Geological Survey as well as ground magnetic mapping have contributed significantly to the interpretation of the occurrence and structure of the Keweenawan volcanic rocks lying south and east of the Keweenaw fault beneath the Jacobsville sandstone (e.g., Bacon, 1966; DeGraff, 1976). More recently ground magnetic surveying has been used to map details of the complexity of the Keweenaw fault near the tip of the Keweenaw Peninsula (e.g., Tyrrell, 2019) and aeromagnetic data have been used to investigate the nature of the Keweenaw fault (DeGraf and Carter, 2022).

Airborne magnetic surveying of the eastern part of the Northern Peninsula of Michigan, roughly east of the western limit of the Paleozoic sedimentary rocks which make up the bedrock of the region, was conducted in 1964 along east-northeast traverses separated by ~10 km (6 mi) at an elevation of ~915 m (3000 ft) above sea level. These observations were part of a reconnaissance aerial magnetic survey of Lake Superior (Hinze et al., 1966; Wold and Ostenso, 1966) and the Great Lakes to the south which showed the continuation of the Keweenawan Midcontinent Rift System from Lake Superior across the eastern part of the Northern Peninsula southerly into the basement of the Southern Peninsula of Michigan (Hinze et al., 1966; Oray et al., 1973). Previously Patenaude (1962) conducted a reconnaissance aeromagnetic survey of the eastern Northern Peninsula. Subsequently, the U.S. Geological Survey surveyed this region with a line spacing of 1.6 to 3.2 km (~1 to 2 mi) generally in a north/south direction at an elevation above the ground of ~150 m (500 ft) and published the results in GP 947 (Cannon and Fenchel, 1981). These various surveys were combined by Zietz et al. (1974) into a magnetic anomaly map of Michigan.

3.4.3.2 Wisconsin

During the period from 1941 to 1980 magnetic surveying continued in Wisconsin to explore for iron ore as well as massive sulfide deposits and as to aid in mapping the geology of Precambrian bedrock of the Lake Superior region. Most of the iron ore exploration investigated the iron-rich formations associated with the linear, discontinuous east-northeast to easterly magnetic trends that extend across northern Wisconsin into Michigan south of the Gogebic Iron Range and north of 45^o 30'N latitude. Originally these trends were identified by surveying with dip needles and dial compasses by the Wisconsin Geological and Natural History Survey (Allen and Barrett, 1915f; Hotchkiss, 1915; Hotchkiss and Bean, 1929; Bean and Aldrich, 1929). No direct shipping ore deposits were discovered along these magnetic trends, but after World War II they were explored for taconite ore deposits. Special interest was directed to the western end of the Turtle River Range (the Agenda and Butternut deposits) and the Marenisco Range (Pine Lake deposit) with detailed ground magnetic surveying initially with dip needles and then with more sensitive ground magnetic instruments and limited aeromagnetic surveying. These surveys were conducted by industrial companies. Many surveys have been donated to the Wisconsin Geological Survey by companies including M.A. Hanna, Jones & Laughlin Steel Co., and U.S. Steel Co.

Additional magnetic surveys starting in the 1960s were conducted in the Paleoproterozoic Ladysmith to Pembine Belt of the Wisconsin Magmatic Terrane (Mudrey, 1979a; Sims, 1984) that extends across northern Wisconsin as part of the exploration for massive sulfide deposits in this largely volcanic rock terrane. Airborne electromagnetic surveying was the principal reconnaissance surveying method backed up by airborne magnetic surveys. Distinctive magnetic anomalies are not associated with the massive sulfide deposits (Mudrey, 1979a), but the anomalies were useful in localizing mineralized zones and mapping regional geology. The only volcanogenic massive sulfide deposit that has been mined is the Flambeau deposit (May, 1977) near Ladysmith, Wisconsin. The ore deposit was discovered in the late 1960s using airborne electromagnetics (Schwenk, 1977) supported by a variety of geophysical methods including ground and airborne magnetic surveys and was mined from 1993 to 1997.

The U.S. Geological survey was active in conducting and interpreting several aeromagnetic surveys in Wisconsin during the 1941 to 1980 period. Heyl and King (1966) studied the lead/zinc mining region of southwestern Wisconsin, Allingham and Bates (1961) related the geology of central Wisconsin to magnetic anomalies, King and Zietz (1971) included a portion of northwestern Wisconsin in their aeromagnetic study of the Midcontinent Rift System, and King et al. (1966) surveyed a portion of northeastern Wisconsin in the vicinity of the Menominee Iron Range. Zietz et al. (1978) published a preliminary aeromagnetic anomaly map of the Precambrian basement rock regions of northern Wisconsin and Dutton and Bradley (1970) provided an index to the aeromagnetic maps of Wisconsin to 1970.

The first public regional aeromagnetic survey in Wisconsin was conducted by Robert Patenaude (1964) primarily along north/south range lines at a mean elevation of ~915 m (3000 ft) with a proton-precession magnetometer measuring the total magnetic intensity at roughly ~300 m (1000 ft) intervals. This survey delineated major regional magnetic anomalies including those associated with the Gogebic Iron Range, the magnetic trend lines of the iron-rich formations between 45° 30'N and the Gogebic Iron Range, and the Keweenawan volcanic rocks in northwestern Wisconsin (Patenaude, 1966). A similar aeromagnetic survey was made and interpreted by Wold and Ostenso (1966) of northwestern Wisconsin to 46°N including the Bayfield Peninsula and western Lake Superior and adjacent land areas. Unfortunately, the magnetic surveys of northern Wisconsin by both Patenaude and Wold and Ostenso were not designed to map in any detail the bedrock Precambrian geology of the region. As a result, Karl (1986) conducted a detailed aeromagnetic survey of north-central Wisconsin in an area bounded by 44°30' to 46°30'N. and 92° to 88°30' W. over a five-year period in the mid-1970s. The data were collected digitally at an interval of ~40 m (65 ft) with a proton-precession magnetometer along north/south tracks spaced at ~0.8 km (0.5 mi). The cross-track navigational errors in this survey may be up to ~150 m (240 ft) and along-track errors may be as large as ~70 m (110 feet). The results of this survey were published by the Wisconsin Geological and Natural History Survey in the 1980s and were used by the U.S. Geological Survey to prepare a preliminary map of the Precambrian geology of northern Wisconsin (Sims et al., 1978; Mudrey et al., 1982).

3.4.3.3 Minnesota

During the period from 1941 to 1980 magnetic surveying was initiated with ground measurements by the Minnesota Geological Survey using Schmidt-type magnetometers to measure the vertical magnetic intensity. A reconnaissance survey was conducted early in this period to investigate the Animikie Group sedimentary rocks south of the Mesabi Iron Range in St. Louis County for possible iron formations that might have included ores (Schwartz, 1943). Unfortunately, no intense linear magnetic highs were found that would suggest the presence of iron formations in the bedrock. Schwartz notes erratic magnetic highs of up to 200 nT that distort the magnetic field in this region are caused by erratic boulders of mafic igneous rocks within the surface glacial deposits. An important part of this survey was mapping the hidden boundary of the Duluth Complex between Duluth and the Mesabi Iron Range to the north. Schwartz (1943, 1944) mapped this contact at the inflection point of a dipolar anomaly which has a minimum over the slate along the contact with the gabbro of the Complex and a maximum on the gabbro side of the contact.

Vertical magnetic intensity surveys have also been reported in the Mesabi Iron Range for the purpose of mapping direct shipping ore deposits (e.g., Jones, 1946; Leney, 1964). Within the ore deposits the primary magnetite in the Biwabik iron formation has been oxidized into non-magnetic hematite and goethite ores. As a result, the oxidized ore deposits produce negative anomalies in contrast to the highly variable and intense magnetic anomalies of the non-oxidized taconite. This is illustrated in Figure 46. which shows a vertical magnetic intensity profile over a geologic section of the Biwabik iron formation on the western Mesabi Iron Range. The oxidized taconite ores produce the illustrated magnetic anomaly minima. Figure 47 shows a contour map of observations with a superdip in degrees over a portion of the iron formation that has been oxidized into ore. The oxidized zone shown by the mined-out ore zones coincide with the mapped magnetic minima. Also, note the profile of drill holes showing the oxidized ore zone within the magnetic minima outlined by the 65° contour.

Although ground magnetic surveys continued in Minnesota for detailed studies, a cooperative agreement between the Minnesota Geological Survey and the U.S. Geological Survey was established to conduct and publish airborne magnetic surveys of much of Minnesota north of ~45°45' N. latitude. This agreement was established in 1947 shortly after the U.S. Geological Survey finalized their initial procedures for airborne magnetic mapping and resulted in the publication of 54 magnetic anomaly maps between 1949 and 1963 at a scale of 1:63,360 (Beltrame, 1978) which led to compilations of portions of northern Minnesota by Bath et al. (1964a, b; 1965a, b) and Kirby and Petty (1966). The cooperative agreement was extended to cover the entire State of Minnesota leading to publication of 10 maps between 1964 and 1970 at a scale of 1:250,000 covering most of the State. This led to final publication of a magnetic map of the entire state (U.S. Geological Survey GP Map 725) at a scale of 1:1,000,000 (Zietz and Kirby, 1970). The majority of the state was surveyed at a mean ground clearance of ~300 m (1000 ft) with the sensor ~23 m (75 ft) below the aircraft and at a traverse interval of 1.6 km (1 mi) during the period from 1947 to 1966. A minority of the state was flown along NE/SW traverses at ~150 m (500 ft).

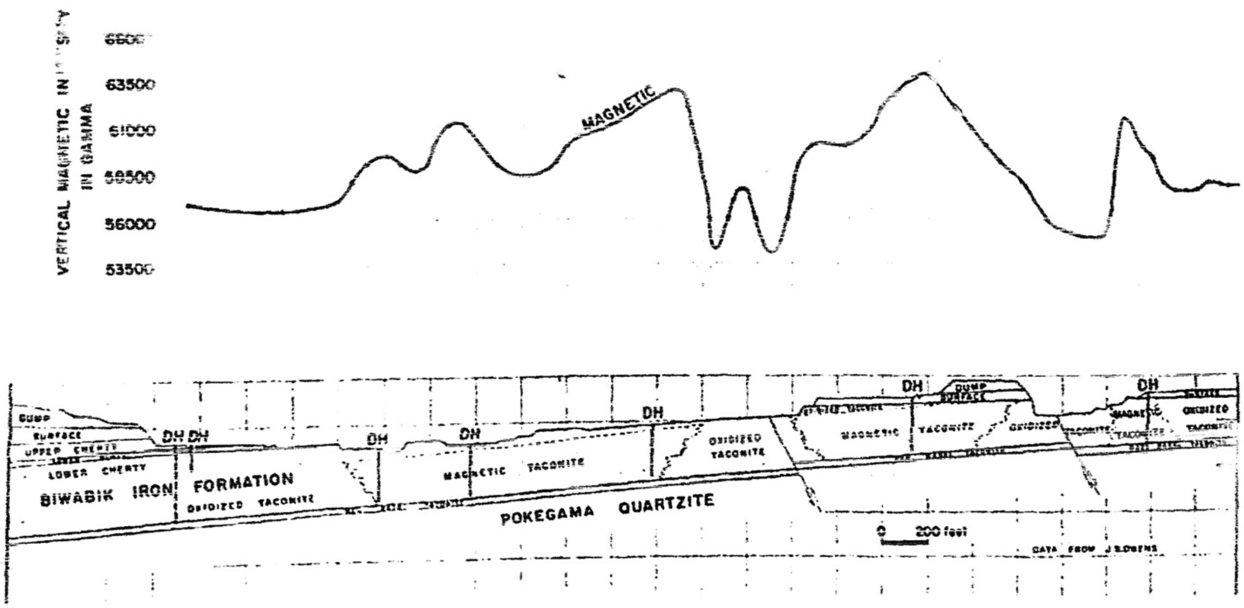

Figure 46. Vertical magnetic intensity profile over a section of the Biwabik iron formation on the western Mesabi Iron Range. Note the negative magnetic anomalies associated with the oxidized taconite zones. (After Leney, 1964)

From early in the cooperative program of the surveys, the U.S. Geological Survey aeromagnetic program has proven to be beneficial to Precambrian studies in Minnesota, and it eventually revolutionized Precambrian bedrock mapping in the state. For example, George Melvin Schwartz (1892–1980), Minnesota State Geologist, announced in 1951 that an extension of the Vermillion Iron Range was discovered by the airborne survey in northern St. Louis County southeast of the village of Soudan (Anonymous, 1951). The U.S. Geological survey's aeromagnetic map GP-563, which covered a large tract of east-central Minnesota and northwestern Wisconsin at a 1:250,000 scale, included a geologic map overlay that was largely derived from qualitative interpretation of the accompanying aeromagnetic contours, in conjunction with outcrop and drillhole data (Sims and Zietz, 1967). In a similar fashion, a series of 1:250,000-scale bedrock geology maps were subsequently produced for southwestern Minnesota (Austin et al., 1970), northeastern Minnesota (Sims et al., 1970; Southwick et al., 1979; Green, 1982), northwestern Minnesota (Ojakangas et al., 1979), and east-central Minnesota (Morey et al., 1981). A 1:1,000,000-scale state bedrock map was also compiled from these data (Sims, 1970) (Figure 48). Aeromagnetic interpretation for these maps was supplemented by magnetic susceptibility data produced by Mooney and Bleifuss (1953) and magnetic susceptibility and NRM data measured by G.D. Bath and C. E. Jahren (Bath, 1962; Jahren, 1965; and Sims, 1972).

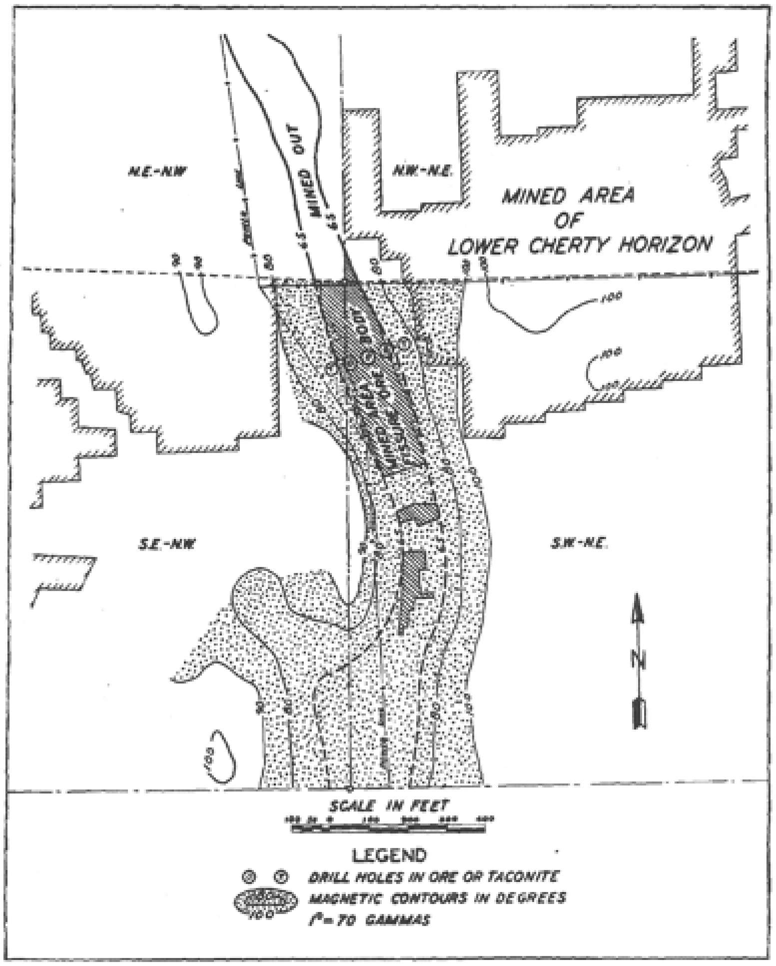

Figure 47. Magnetic anomaly contour map in degrees measured with a superdip. The oxidized taconite of the Biwabik iron formation of the Mesabi Iron Range is located within the minima marked by the heavy dashed line. The mined-out parts of this fissure ore body are shown by the diagonal parallel line zones. Note the profile of the drill holes indicating either the ore or taconite encountered in the holes. (After Jones, 1946)

The bedrock geology maps of the State of Minnesota described above were a major improvement beyond those previously available. However, as interpretation of the U.S. Geological Survey aeromagnetic data progressed it became clear that the resolution of the anomaly data was limited by the original flight specifications and by its analog presentation. High resolution and digitally based aeromagnetic surveys in Scandinavia over similar geologic terranes as in Minnesota allowed significantly improved geological mapping. As a result, support was developed for a low-altitude, high resolution (LAHR)[15] survey of the state. Chandler (1979) described the advantages and objectives of the LAHR survey of Minnesota and a plan for conducting, presenting, and interpretation of the survey. This project was initiated by the Minnesota Geological Survey in 1979 under the direction of Val W. Chandler and completed in 1991 (Chandler, 1991).

Figure 48. Paul K. Sims (1918-2011) Director of the Minnesota Geological Survey from 1961 to 1973 who was a pioneer in using magnetic anomaly data to map the basement Precambrian geology of the Lake Superior region. (Courtesy of Google Images)

3.4.3.4 Ontario

As previously described, ground magnetic surveying had a limited role in the exploitation of the Canadian Lake Superior iron ranges because of the non-magnetic nature of their iron formations and ores. However, with the development of airborne magnetometry, aeromagnetics took on an important role in Canada in mapping local and regional geology that has had a very important role in mineral exploration in the Lake Superior region. The Geological Survey of Canada was introduced to magnetic surveying in 1947 by the U.S. Geological Survey with test surveys that showed the viability of the method for mapping geology. The Canadian Survey obtained several fluxgate magnetometers and put them to work surveying generally at a ground clearance of ~305 m (1000 ft) along primarily ~805 m

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[15] The title “low altitude, high resolution aeromagnetic survey (LAHR)”was assigned to the Minnesota Geological Survey’s aeromagnetic program beginning in 1979, but subsequently the adjective low-altitude has not been used for the survey. As a result, the title used herein is simply, “high resolution aeromagnetic survey.”

(0.5 mi) North/South tracks (Hood et al., 1985; Hood, 2007; Dods et al., 1985). The aeromagnetic surveying was established in 1960 as a national/provincial program with publication of magnetic anomaly maps at a scale of 1:63,360 and later at 1:50,000 and a variety of smaller scales using improved instrumentation and surveying methods. Additionally, beginning with aeromagnetic surveying by Dominion Gulf, a subsidiary of the Gulf Oil Company who held the patents on the fluxgate magnetometer, numerous surveys more detailed than the national/provincial surveys were made by the private exploration industry.

The first shipborne survey in Lake Superior was conducted in 1966 by Gordan F. West and Henry P. Halls in the Isle Royale Channel between Isle Royale and the North Shore using instrumentation and procedures similar to those employed in aeromagnetic surveying (Halls, 1972). The principal advantage of shipborne surveys is that data are obtained from a towed sensor located closer to the source of the geological magnetic anomalies than in aerial surveys, thus improving the resolution of the magnetic mapping.

3.5 The High Resolution Survey Years: 1981-2022

3.5.1 Overview

During "The **High Resolution Survey Years**" from roughly 1981 to the present, magnetic surveying in the Lake Superior region for geologic mapping purposes has been largely restricted to airborne surveying with instrumentation that has continued to improve over previous airborne studies. Ground magnetic surveying, when conducted, has been restricted to surveys by mining companies to investigate ore prospects in detail with high resolution surveying. Airborne surveying commonly has repeated in greater detail, resolution, and precision previous airborne surveys. Greater precision in magnetic mapping was achieved by improved instrumentation, more precision in navigation and flight-path recovery, and use of advanced reduction and analysis procedures (Camara and Guimaraes, 2016). New instrumentation has increased the sensitivity of the measurements and decreased the time, and thus distance, between airborne observations. Additionally, surveys were flown at closer and more rigorously defined flight paths and, most important, at lower elevations. In the previous period reconnaissance surveys were commonly flown at ~150 m (500 ft) to several hundred meters altitude to permit greater flight visibility that improved navigation and allowed greater separation between flight paths.

Greater precision in navigation and flight-path recovery was accomplished with improving navigational instrumentation, specifically with the use of the Global Positioning System to locate the geographic position of observations to a precision now of at least a few meters. Furthermore, improvements have been made in minimizing the temporal variations of the magnetic field that lead to errors in the magnetic observations. Also, improved spatial geomagnetic reference fields have become available and removed from airborne observations to increase the precision of the observations. In addition, several improved methods have become available to illustrate and interpret airborne magnetic data. These improvements have served to enhance the accuracy and detail of the magnetic observations and the geologic information from them as described by Reeves (2005), Hinze et al. (2013), and Fairhead (2015). Typical detailed technical specifications of a high resolution airborne magnetic gradiometer survey are provided in Appendix A of a guide to aeromagnetic specifications and contracts by the Aeromagnetic Standards Committee of the Geological Survey of Canada (1991) that has been a useful starting place for designing high resolution surveys. Surveying during this high resolution period conducted by both the U. S. and

Canadian Geological Surveys and state and province geological surveys has been directed especially at regions likely to be the location of new ore bodies and regional surveys to study the Midcontinent Rift System in the Lake Superior region and potential ore bodies and petroleum reservoirs within it. A recent aeromagnetic-geologic compilation has been useful in reinterpreting the Paleoproterozoic accretionary boundaries of the United States north-central region including the Lake Superior region (Holm, D.K., et al., 2007).

During this period there has been increasing interest in conducting high resolution airborne surveys in areas where there is the potential for the occurrence of critical minerals. Executive Order 13817 dated December 20, 2017, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals," led to a U.S. Geological Survey project, Earth Mapping Resources Initiative (Earth MRI). This project which began in 2019 in partnership with state geological surveys is nationwide, including several areas in the Lake Superior region. The acquisition of geophysical data especially high resolution aeromagnetic data is focused on deciphering geologic framework and tectonomagmatic history of the region.-The Earth MRI for the conterminous United States is described in U.S. Geological Survey Open-File Report 2019 - 1023 (Hammarstrom et al., 2020). To date this program has conducted or contracted for high resolution aeromagnetic surveys in Michigan, Wisconsin, and Minnesota.

With the advent of microprocessors and computers beginning in the 1980s, gravimeters, such as the Scintrex meter, were developed with improved measuring characteristics leading to enhanced combined gravity/magnetic interpretation. The LaCoste and Romberg instrument was also modified for use on ships and aircraft using a gyrostabilized platform which significantly broadened the use of the gravity method. The availability of GPS to determine the location and elevation of instrument observations beginning in the 1990s has been a major step in the evolution of gravity measurements in the area. Further developments in the 1980s and 1990s of accelerometers led to improved airborne gravity measurements with minimal errors. when measuring the tensor gradients (Dransfield et al., 1994; Dransfield, 2007). Improvements continue today in the observation of gravity tensor gradients (Stolz et al., 2021a, b.). The first use of the gravity method in the region was in the detailed analysis of iron formations identified by magnetics and geology and subsequently it has become part of the arsenal of methods used in investigating other mineral resource deposits in the region.

In the 1980s and subsequently there has been increasing interest in the possibility of petroleum production from the sedimentary section within and adjacent to the Midcontinent Rift System (MRS). This interest was prompted by recognition of the potential for hydrocarbons in Proterozoic rocks, by deep drilling in the center of the Michigan Basin of sedimentary rocks in the basement rift identified by magnetic and gravity surveys (Sleep and Sloss, 1978), and identification of the presence of oil seeps in the Northern Peninsula of Michigan (Dickas, 1991). This interest together with investigations of the MRS led to a flurry of geophysical surveys in the next two decades including seismic reflection surveys by geophysical contractors, petroleum exploration companies, and the U.S. Geological Survey and the Geological Survey of Canada (GLIMPCE project) (Cannon et al., 1989; Dickas, 1999) as well as other geophysical surveys including gravity surveys (Hinze et al., 1992) that have been used to enhance the interpretation of the magnetic surveys.

The aeromagnetic database of the Lake Superior region during this period has been increased by contributions of survey data from contract surveying performed for exploration companies. Generally, these data are from high quality, high resolution surveys.

3.5.2 Technical Developments

3.5.2.1 Magnetic Instrumentation

A primary enhancement in magnetic instrumentation during this period is the availability of an improved proton-precession magnetometer, the Overhauser magnetometer (Figure 49) for both ground and airborne application. It derives its name from the Overhauser effect (Overhauser, 1953) which describes the transfer of energy from orbital electrons to the protons of hydrogen atoms. It requires less power and measures nearly continuous field variation at high sensitivities (0.1-0.01 nT) over broad operating range without heading error or dead zones where they are inoperative. Accordingly, they are a significant improvement in operation with improved signal-to-noise and reduced measurement uncertainty (Acuna, 2002). This magnetometer plus others that have been significantly improved such as the Cesium Larmor frequency instrument are used in current aeromagnetic surveys providing high quality and sensitive, dense measurements. Additionally, the precision of GPS navigation and mapping instrumentation and software have improved (National Research Council, 1995) limiting the horizontal and vertical errors to the order of approximately a meter. Furthermore, data reduction has been improved with upgraded levelling software and geomagnetic reference fields and analysis has been enhanced with revised and new presentation and interpretation software.

An additional enhancement in magnetic instrumentation over the past few decades has been the use of unmanned aerial vehicles (UAV or drone) in high resolution magnetic surveying (Figure 50) and development of magnetic sensors of low-weight and low-energy requirements to use on these aerial platforms (e.g., Morales, 2019; Mu et al., 2020; Walter et al., 2020). UAVs have the advantage of rapid, low-cost surveying and the facility to measure the magnetic field close to the ground to achieve near ground-level resolution. One of the primary problems with magnetic measurements on UAVs is the elimination of the interfering magnetic signal derived from the airborne platform. This signal can be

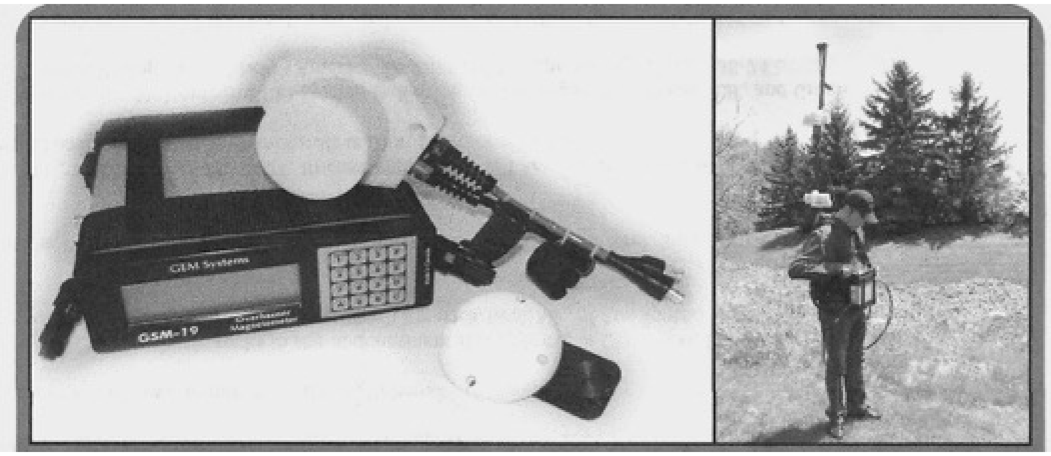


Figure 49. Ground Overhauser magnetometer (left) and instrument carried by a surveyor with the sensor mounted on a vertical shaft to eliminate local magnetic effects from the surface soil. (After GEM Systems)

minimized by locating the magnetic sensor at a distance on a tether or by a compensation scheme using airborne testing procedures and associated software (Kaub et al., 2021). Both procedures have their advantages.

3.5.2.2 Other Technical Developments

The significant success of the results of the low-altitude, high resolution magnetic survey of Minnesota conducted during the period 1979-1991 encouraged other agencies to embark on similar magnetic surveys. These surveys were enhanced by improved magnetic sensors as well as by advanced navigation utilizing the high resolution global positioning system for flight positioning recovery and more precise geomagnetic reference systems to remove the Earth's magnetic field from the observed data. The interpretation of these data has been enhanced by more comprehensive and representative magnetic property data from the Lake Superior region and upgraded computers and software for analyzing, modeling, and presentation of the data (Reeves, 2005; Hinze et al., 2013; Isles and Rankin, 2013 and Fairhead, 2015).

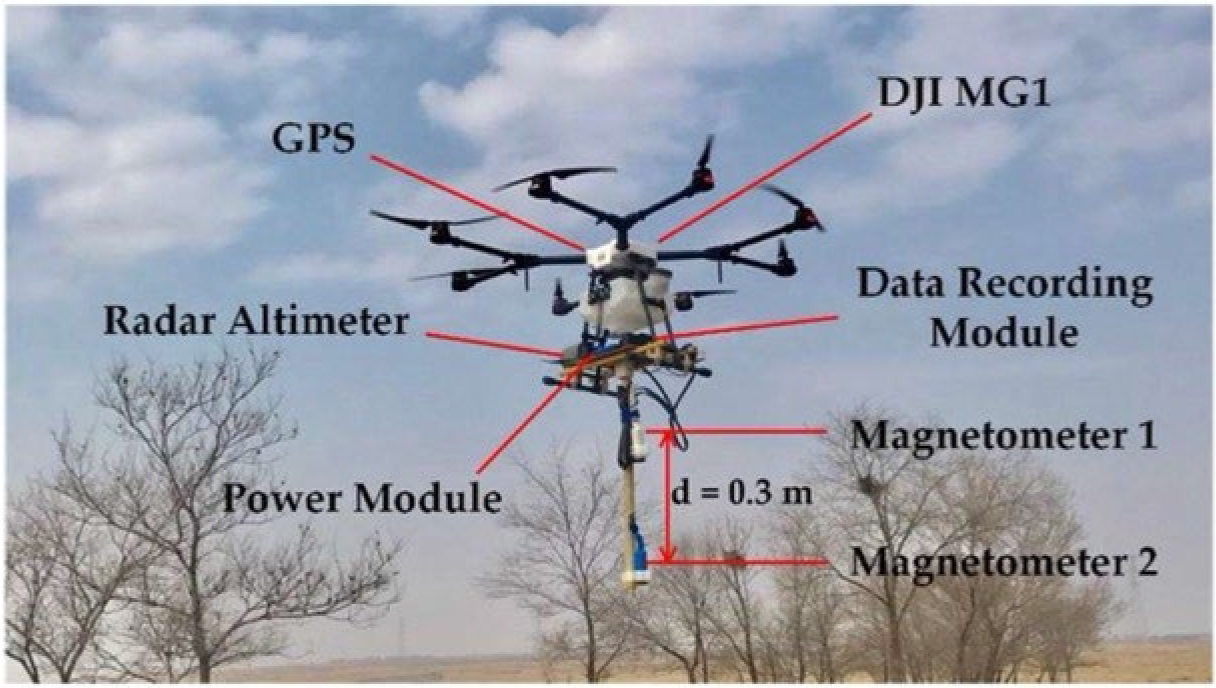


Figure 50. Example of an Unmanned Aerial Vehicle being used to measure the vertical gradient of the Earth's magnetic field using two magnetometers vertically separated by a fixed distance. Instrumentation includes radar altimeter and GPS. (After Mu et al., 2020)

3.5.3 Magnetic Mapping

3.5.3.1 Michigan

As part of the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) the Geological Survey of Canada in 1987 conducted a high resolution aeromagnetic survey of Lake Superior including portions of the Lake in Michigan, Wisconsin, and Minnesota as well as the province of Ontario (Teskey et al., 1991). This survey increased the spatial and intensity resolution of the previous 1964 reconnaissance aeromagnetic survey of Lake Superior (Hinze et al., 1966; Wold and Ostenso, 1966). The resolution of the 1987 survey was increased by decreasing the line spacing roughly five-fold and the survey altitude over the Lake by more than a half and increasing the magnetometer sensitivity by an order of magnitude. The 1964 survey was interpreted by Hinze et al. (1982). Subsequently, numerous improved interpretations have been made of the geology of Lake Superior utilizing the GLIMPCE data. These are listed in the comprehensive bibliography of Michigan Precambrian geology references (Voice, 2019).

Identification of the Lake Ellen diamond-bearing kimberlite pipe in Iron County, Michigan in 1971 (Cannon and Mudrey, 1981; McGee, 1987) led to subsequent discovery of numerous similar pipes in a northwest-striking zone across Menominee and Dickinson Counties into Iron County, Michigan. These discoveries led to increasing interest in high resolution aeromagnetic as well as ground surveying to detect additional pipes (Carlson and Floodstrand, 1994). The Lake Ellen kimberlite pipe was first identified in an outcrop in a road cut. However, it is marked by a high-gradient intense magnetic anomaly mapped by a ground vertical magnetic intensity anomaly (Gair and Wier, 1956) (Figure 51) that unfortunately was interpreted as due to an accumulation of magnetite in the glacial till overlying the bedrock. A more detailed ground magnetic survey of the region shows the complex anomaly defining

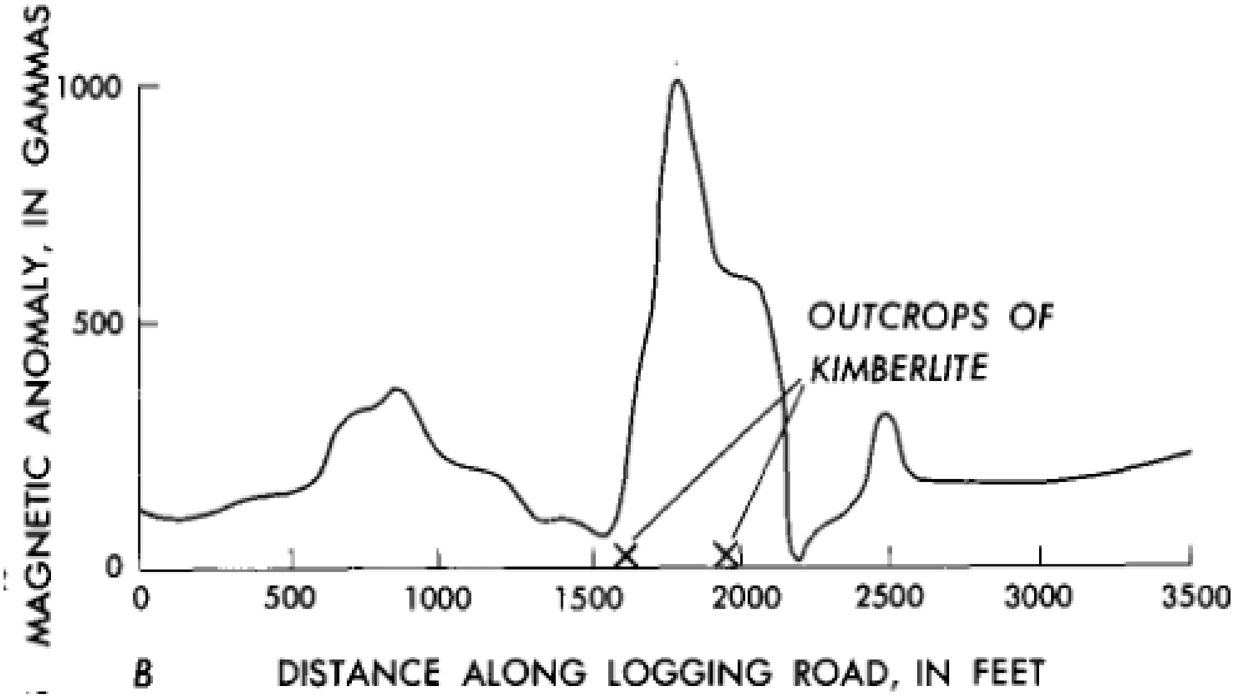


Figure 51. Ground magnetic anomaly across the Lake Ellen kimberlite, Michigan. (After Cannon and Mudrey, 1981)

the margins of the kimberlite pipe. The aeromagnetic survey of the region conducted by the U.S. Geological Survey in cooperation with the Michigan Geological Survey in 1949 (Balsley et al., 1949) which consisted of east/west survey lines separated by ~400 m and flown at an altitude of ~150 m did not observe the magnetic anomaly of the pipe because of the large line spacing illustrating the need for high resolution surveys to map kimberlite pipes.

Magnetic mapping, both airborne and ground, has been important in localizing the position of the Eagle Mine, a magmatic sulfide deposit that is being mined for Ni-Cu-PGE, that occurs in the Baraga Basin in western Marquette County, Michigan. The peridotite in which the deposit occurs was intruded into pelitic sedimentary rocks of Paleoproterozoic age in an early stage in the development of the Midcontinent Rift System. The potential for a mineral deposit was focused on an aeromagnetic anomaly with geologic mapping and ground geophysical studies including magnetics, gravity, and electromagnetics (Klasner et al., 1979b). Drilling on the ground-survey magnetic high, 'Bn', the closed contour feature north of the horizontal baseline on the right (Figure 52) led to the discovery of the ore deposit.

High resolution aeromagnetic data has become an important part of the geological mapping program of the U.S. Geological Survey's Earth Mapping Resource Initiative in Michigan. The data have been derived from improved digitization of existing data (Drenth et al., 2015, 2019, 2021; and Drenth and Ailes, 2016) and new high resolution surveying (Drenth, 2020; Drenth and Brown, 2020). The new

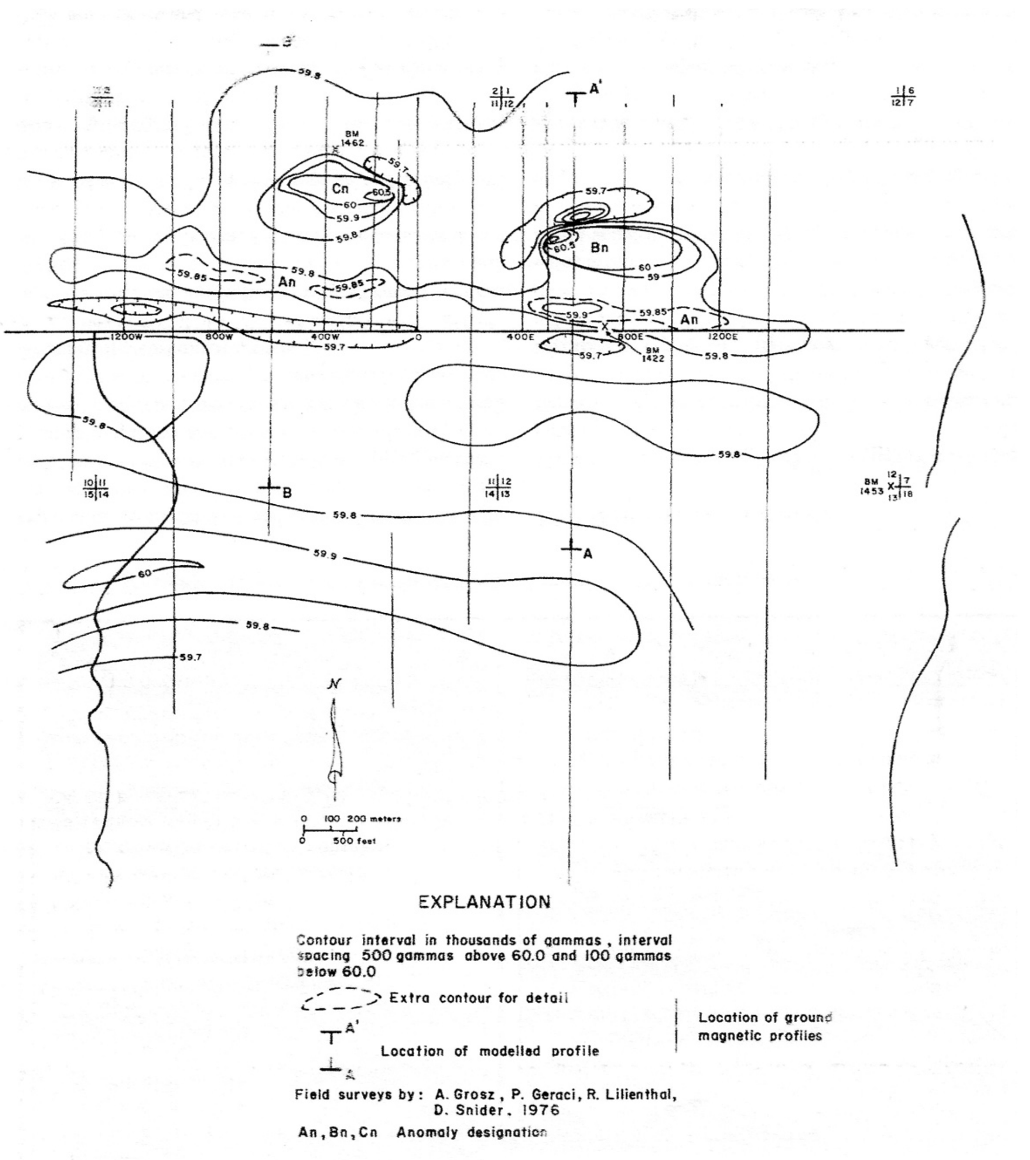
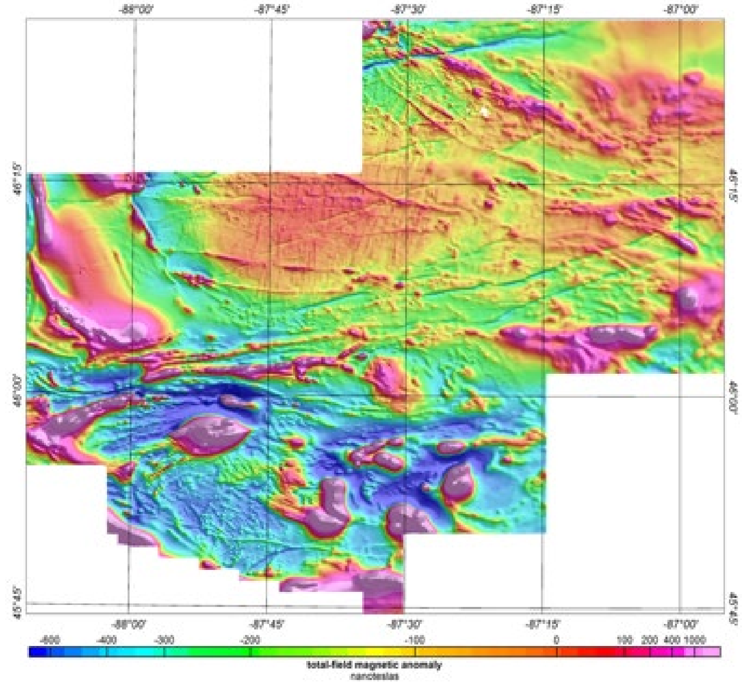
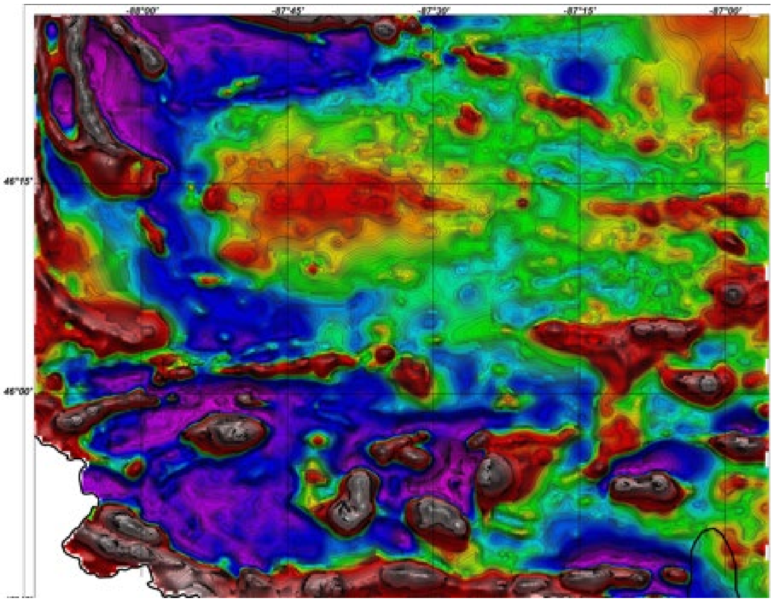


Figure 52. Ground magnetic anomaly map of the Eagle Mine area, Michigan. The intense anomaly, Bn, is located over a peridotite outcrop which is also a gravity and electromagnetic anomaly. (After Klasner et al., 1979b)

surveys were flown in 2016 and 2018 under contract along north-south lines generally separated at 150 m intervals at an altitude of 80 m with a cesium-vapor, split beam sensor. The 2016 survey was conducted in the Iron Mountain-Menominee region of Michigan and Wisconsin and the 2018 survey was completed in the Iron Mountain-Chatham region of central Northern Peninsula of Michigan. The improvement in magnetic mapping because of the parameters of the recent surveying is illustrated in Figure 53 which compares the 2018 survey results with the previous U.S. Geological Survey mapping with a line spacing of ~800 m (0.5 mi) and an altitude of ~150 m (500 ft). Note that the major anomalies are shown in both



a.



b.

Figure 53. a. 2018 high resolution aeromagnetic survey map of the central Northern Peninsula of Michigan observed at an altitude of ~80 m along north/south lines separated by ~150 . (After Drenth and Brown, 2020) b. Comparative aeromagnetic survey map of the same central Northern Peninsula of Michigan area shown in a. This map was obtained from a digitized mid-1960s vintage aeromagnetic data observed along north/south lines separated by ~800 m at an altitude of ~150 m. (After Daniels et al., 2018)

maps, but the high resolution magnetic map (Figure 53a) shows much more significant detail related especially to the structure of the Precambrian basement and the configuration of the rock units.

Ground magnetic surveying has been initiated by J.M. DeGraff to map faults associated with the Keweenaw fault near the tip of the Keweenaw Peninsula with the highest possible resolution (e.g., Tyrrell, 2019). This surveying takes advantage of the marked magnetization contrast between the Portage Lake volcanic rocks and the Jacobsville sandstone.

3.5.3.2 Wisconsin

The aeromagnetic survey of north-central Wisconsin conducted by John Karl in the mid-1970s and published in 1986 (Karl, 1986) was supplemented with additional surveying by the U.S. Geological Survey (Heyl and King, 1966; Bracken and Nicholson, 1999; Daniels et al., 1998, 1999a, b; Snyder, 2001; and U.S. Geological Survey, 1981) and exploration company surveys made available to the Wisconsin Geological Survey (Mudrey, 1996a, b, 1998) to produce the magnetic map of Wisconsin (Karl et al., 1993; Daniels et al., 2001) by Daniels and Snyder (2002). Individual segments of this map have been interpreted by numerous authors since the mid-1980s and used in preparing maps of the geology of the Lake Superior region.

As described above in the segment on Michigan as part of the Geological Survey's Earth MRI, a high resolution magnetic survey was conducted in the Michigan/Wisconsin area of Iron Mountain-Menominee Iron Range during 2016 which included the northeastern corner of Wisconsin (Drenth, 2020). This survey has been reported upon by Drenth et al. (2019).

3.5.3.3 Minnesota

In the late 1970s the Director of the Minnesota Geological Survey, Matt S. Walton, became interested in the possibility of conducting a high resolution magnetic survey of the State of Minnesota. Walton had a background in aeromagnetic surveying as a member of the initial U.S Geological Survey airborne magnetic mapping group under the direction of J.R. Balsley in the mid-1940s. He was impressed with Precambrian bedrock geological mapping that was going on in Scandinavia using high resolution aeromagnetic surveying and a similar state-wide aeromagnetic survey was recommended in 1978 by an international workshop held by the Minnesota Geological Survey. As a result, during the period from 1979 to 1991 the Minnesota Geological Survey conducted a low-altitude, high resolution (LAHR) aeromagnetic survey of Minnesota as described by Chandler (1979, 1991a). The survey was largely flown on north/south tracks separated by ~400 m (1310 ft) at a mean terrain clearance of ~150 m (500 ft) with observations at a ~50–75 m (160–240 ft) intervals. In addition to acquiring its own data contributions of comparable digital data were received for limited areas of the state from the U.S. Geological Survey, the Geological Survey of Canada, and the U.S. Steel Corporation.

The maps and digital data in the form of both flight line and gridded data were the subject of continuing interpretation by Chandler and others at the Minnesota Geological Survey (e.g., Sims, 1984; Chandler, 1985; Chandler, 1991b). To date the Minnesota Geological Survey has published over 100 bedrock geologic maps that are based to some degree on the results of the high resolution aeromagnetic data using a variety of derived maps and modeling of the data. Particular emphasis was placed on interpretation of anomalies associated with the Duluth Complex because of the strong interest in the possible mineral resources associated with this Mesoproterozoic intrusive suite (Chandler and Ferderer, 1989; Chandler, 1990, 2002). Spector and Lawler (1995) have also used both ground and airborne high resolution magnetic data to investigate the mineral potential of an area west of Duluth at the southern end of the Animikie Basin containing Paleoproterozoic rocks that were involved in the Penokean orogeny. Among other results of their study, they have identified several anomalies that may be associated with kimberlite pipes. Chandler and Jirsa (2021) have used gravity and magnetic data interpretation to map the depth to the basement beneath the Animikie Basin.

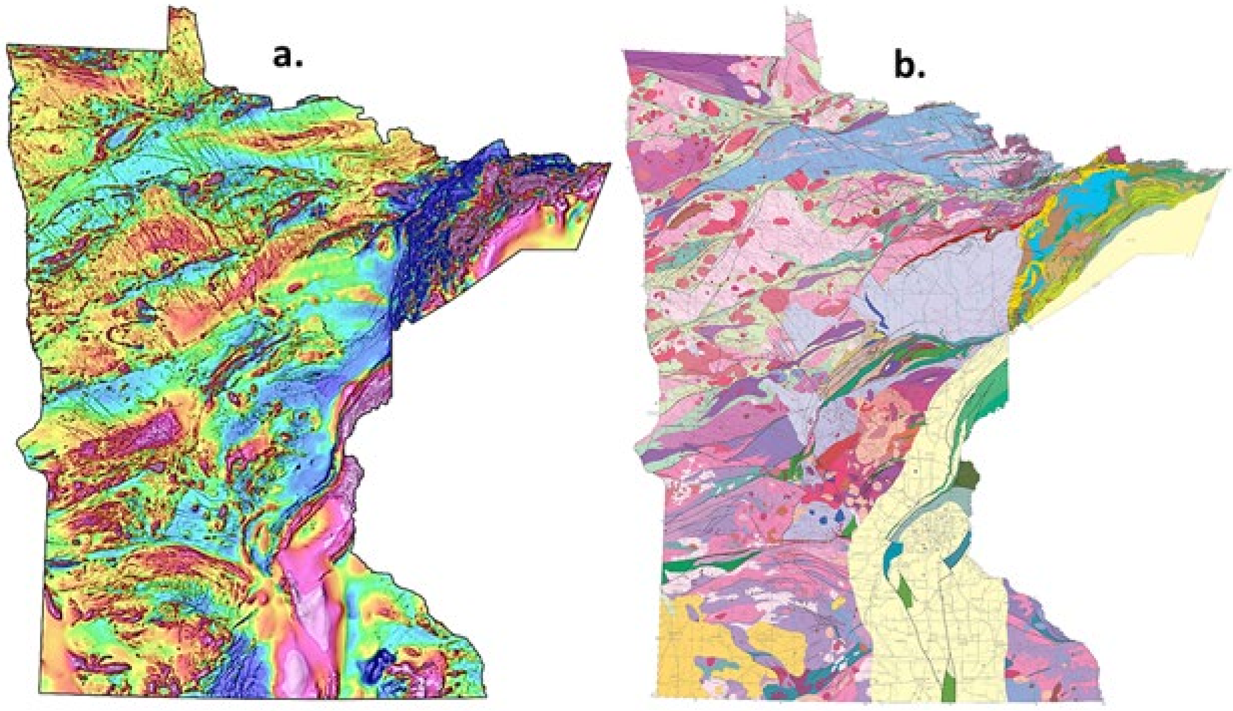


Figure 54. a. Color shaded relief total magnetic intensity anomaly map of Minnesota based largely on data acquired from 1979 to 1991 high resolution aeromagnetic survey. b. Precambrian bedrock map of Minnesota. (After Jirsa et al., 2012) based in part on the magnetic anomaly data in a.. (Courtesy of V.W. Chandler)

Upon successful completion of the LAHR aeromagnetic survey the Minnesota Geological Survey hosted a second international geophysics workshop in 1991 (Chandler, 1991a) to discuss how the data of the survey together with other geophysical data could be effectively used in mapping and investigating Minnesota geology and what new geophysical studies were needed for Minnesota. Among the recommendations of the workshop was the continuing improvement and use of the magnetic data to map the geology of Minnesota with ground-truthing of interpretations with critically located drill holes and making the geophysical data available to the public in readily usable formats. Also, the workshop strongly supported the current work of the Survey to acquire gravity and rock properties data useful in interpreting geophysical data including the high resolution aeromagnetic survey. A shaded relief map of the high resolution survey of Minnesota and a generalized Precambrian geology map of Minnesota based on the results of the high resolution survey, other geophysical data, and existing geologic information are shown in Figure

54. A comparison of these maps illustrates the usefulness of the magnetic survey in mapping the bedrock geology of the region.

The recommendations pertaining to the high resolution aeromagnetic survey were generally implemented by the Survey in the years following the workshop. In addition, a significant upgrade of the magnetic anomaly data was carried out in the 2005–2007 period (Chandler, 2007). This upgrade included filling in missing flight data, improved levelling of data and integration with adjoining data sets and regridding the data at a closer interval (100 m). Additionally, the survey continued to acquire rock physical property data (Chandler and Lively, 2021) as did the U.S. Geological Survey (Dentith et al., 2020). High resolution private magnetic surveys continue to be used over the Mesabi Iron Range to assist in selecting areas for future taconite mining of the Biwabik iron formation (Morales, 2019) using small and ultralite aircraft. Additionally, high resolution magnetic data are being acquired with airborne electromagnetic data over selected portions of the Duluth Complex as an aid to geologic mapping.

As part of the Earth MRI and in cooperation with the Minnesota Geological Survey the U.S. Geological Survey under the direction of B.J. Drenth have contracted for an aeromagnetic survey to be flown in the Spring of 2021 in northwestern Minnesota. The survey largely in Polk County will investigate the Mentor Igneous Complex and environs with flight lines at 250 m (~820 ft) at a nominal elevation of 120 m (~400 ft). The Mentor Complex is a Neoarchean anorthosite and gabbro intrusive that is potentially the source of several critical minerals.

The nature and pattern of magnetic anomalies on regional magnetic anomaly maps provide useful information for mapping the lithologic variations and structural features of the basement rocks which in turn illustrate terranes of varying age and tectonomagmatic history. Interpretation of these magnetic maps utilizing changes in the consistency of patterns of anomalies can identify the limits of specific geologic terranes. This is well illustrated in the interpretations of Holm et al. (2007) of the terranes of north-central United States which includes the U.S. Lake Superior region. Using a total magnetic anomaly map compiled from a large number of surveys modified to consistent survey specifications and reduced to a single grid of anomaly values (Figure 55) they have identified the basement Precambrian terranes formed by a series of geologic arcs extending from generally north to south over an age range from 1.9 to 1.6 Ga as determined from age dating of outcrop and drill hole rock samples. Major limits to the terranes of the region and geologic structures are shown in a general manner on the magnetic anomaly map with more detail provided in their proposed geologic terrane map of Precambrian basement rocks of the region (Figure 56) which is based on the magnetic anomaly map, the few outcrops in the region, and isotopic age dating of rock samples.

3.5.3.4 Ontario

During this period as described above the Geological Survey of Canada conducted a high resolution aeromagnetic survey of Lake Superior in 1987 covering both the Province of Ontario and the adjoining states of the United States (Teskey et al., 1991). Further, Manson and Halls (1994, 1997) report on their results of high-frequency filtering of the GLIMPCE magnetic anomaly data in southeastern Lake Superior and a shipborne magnetic survey along the southeastern shore of the Lake. The high-frequency magnetic anomaly component of the GLIMPCE magnetic data in southeastern Lake Superior supported by the shipborne data are interpreted to be derived from juxtaposing of the Freda and Jacobsville sedimentary rocks by high-angle faulting which has uplifted the rift to the north. Additional interpretation of the GLIMPCE data incorporating GLIMPCE gravity and deep seismic reflection data and commonly using new analysis methodologies are reported by Teskey and Thomas (1994), Thomas and Teskey (1994), Mariano and Hinze (1994a, b), and Manson and Halls (1994). Additional analysis of the GLIMPCE magnetic data in Lake Superior has been initiated by the U.S. Geological Survey primarily

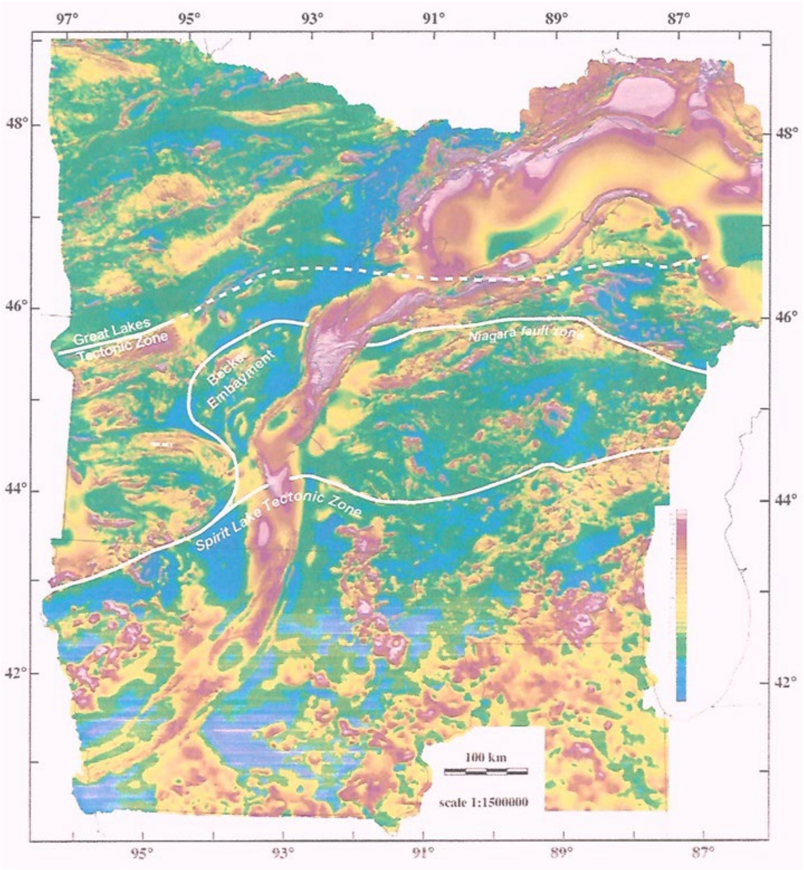


Figure 55. Total magnetic anomaly map of north-central United States compiled to consistent survey specifications. Red to pink color intervals define anomaly maxima and blue intervals define anomaly minima. Red to orange colors is approximately zero total magnetic intensity anomaly. The white lines are interpreted terrane margins. Dashed white line is approximated position of the Great Lakes Tectonic Zone. Further interpretation of these data is shown in Figure 56. (After Holm et al., 2007)

under the leadership of V.J.S. Grauch (Anderson et al., 2015; 2018; Anderson and Grauch, 2017a, b; Grauch et al., 2014; 2015; 2016; 2018; 2019a, b; 2020; 2021). Coyle et al. (2014) updated the requirements of magnetic surveying for the Geological Survey of Canada.

Increasing interest in Ontario for locating kimberlite pipes as a source of diamonds has led to the high resolution magnetic surveying by the Ontario Geological Survey during this period. The Lac des Mille, Lacs-Nayagami survey with flight lines at 200 m spacing and an altitude of 100 m is an example of this type of survey. In addition, independent exploration companies have conducted both high resolution aeromagnetic surveys as well as ground surveys such as those that led to identification of the Pagwachuan cluster of 220 Ma-old kimberlites.

4.0 Summary and Conclusions

The Lake Superior region is generally regarded as the cradle of Precambrian geological studies in North America. It has been the location of intense successful exploration and production of copper and iron ores, the mapping of numerous Precambrian orogenic belts, and the focal point of the Midcontinent Rift System, a unique and outstanding structure of the North American continent. Unfortunately, geologic mapping required for all three of these accomplishments is thwarted by the lack of surface exposures of rocks because of the widespread cover of deposits from Pleistocene glaciation, abundant lakes, and Paleozoic sedimentary rocks. As a result, geologists have had to resort to tools for their studies beyond surface geological mapping. Fortunately, the Precambrian rocks of the Lake Superior region have a wide range of magnetizations which make it possible to use magnetic mapping to identify

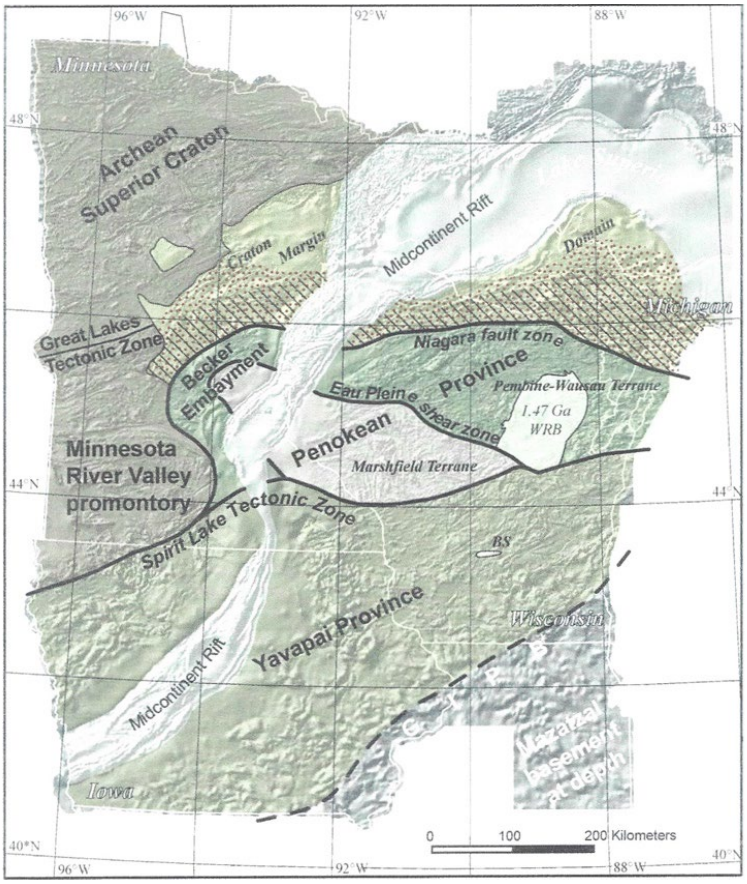


Figure 56. Proposed geologic terrane map with underlying magnetic anomaly map of Figure 55. Craton margin domain represents sedimentary and volcanic rocks deposited from 2.3 to 1.77 Ga; stippled pattern is area of Penokean deformation; cross-hatched pattern represents area affected by Yavapai interval (1.8–1.7 Ga) deformation. (After Holm et al., 2007)

horizontal variations within and between rock units. The interpretation of the geologic sources that cause disturbances, that is anomalies, in the core-derived magnetic field of the Earth are not unique, but the anomalies can be successfully interpreted with the integration of other remote sensing information derived from the Earth's gravity field, geoelectric mapping, and seismic investigations, especially seismic reflection data which largely provides information on the vertical variations among rock units and their nature. Furthermore, interpretation is especially enhanced when the magnetic variations can be tied to outcropping geology or lithologic information from surface exposures and drill holes.

During the past two centuries while the magnetic method has been used in the Lake Superior region there has been profound changes in technology. These technical developments, often driven by other uses, have been used to enhance magnetic sensors, mapping procedures, and the analysis and presentation of magnetic anomaly data that have in turn improved mapping of the geology of the region and the identification of potential ore deposits. Iron-rich rock units have been located since the 1840s by virtue of the effect of the iron oxide, magnetite, on the core-derived magnetic field and the presence of copper-bearing volcanic rocks have been identified as a result of the intense remanent magnetization of their trace quantities of magnetite. It is the variability of the quantity of magnetite within both the crystalline and sedimentary rocks and in some cases their remanent magnetization that are largely responsible for the magnetic anomalies of the Lake Superior region which are used for geological mapping.

The past 200 years when magnetic surveying has been effective in mapping the geology of the Lake Superior region is divided into four periods during which the magnetic method has been used in a generally consistent manner. The earliest period extending from ~1830 to 1900 marks **The Discovery Years**. During this period simple magnetic needle instrumentation was used to discover the iron ranges of the Lake Superior region and to assist in the location of magnetite ore bodies and largely low magnetic direct shipping ore bodies. Although the effect of geology on magnetic measurements was observed earlier, the first identification of an iron-rich formation took place in the Marquette Iron Range in Michigan in 1844, leading to iron ore mining in 1846. It was also during this period that the magnetic effect of copper-bearing volcanic rocks of the Keweenaw Peninsula of Michigan was noted by Douglass Houghton. This magnetic effect in the early times of **The Discovery Years** was observed as variations in the declination of the ambient magnetic field using a simplified version of the sun (dial) compass patented in 1836 by Burt whose survey party first identified the location of the iron formation of the Marquette Iron Range. Subsequently, dial compass measurements were supplemented by dip needle measurements that were initially made in Michigan in the mid-1860s to map iron-rich rocks. The dial compass was primarily developed by Maj. T.B. Brooks who also likely brought the dip needle from the New Jersey Geological Survey who in turn brought it from Scandinavia. The dial compass and dip needle were also used during this period on the Keweenaw Peninsula to map the volcanic and associated conglomerates as an aid to exploration for native copper deposits. One of the most famous and richest mines of the Keweenaw Peninsula is located in the Calumet conglomerate which was mapped with a dial compass in the 1860s. The use of the magnetic method was waning at the end of the nineteenth century because by then the major iron formations of the region were mapped both magnetically and geologically and because sampling of the iron formations in the more intensely magnetic zones did not find rocks of sufficient ore grade to be worthy of mining. Furthermore, the native copper deposits were found to not have a direct magnetic response.

The next period of magnetic mapping extended from approximately 1901 to 1940, **The Ground Survey Years**. At the start of the twentieth century magnetic mapping was rejuvenated with the discovery by magnetic surveying of the Cuyuna Iron Range in Minnesota which had no surface exposures. Also, mapping of iron ore deposits was improved by the realization that direct shipping ores were made up of essentially non-magnetic iron oxides. This led to the search for negative anomalies within iron formation anomalies where the original magnetite was oxidized. Additionally, the dip needle was improved leading to greater sensitive and more error-free measurements. As a result, the magnetic method was increasingly used to map geology, explore unsurveyed regions, and map iron formations and Keweenawan volcanic rocks in greater detail to investigate the stratigraphy and structure of the units that played a role in localizing ore deposits.

After 1940 magnetic needle instrumentation was gradually displaced by a series of electronic sensors that measured the total magnetic intensity from mobile platforms. This set the stage for **The Airborne Survey Years**: 1941 to 1980. Gulf Research and Development Company, the U.S Navy and its contractors, and the U.S. Geological Survey all played a role in developing the magnetic sensor used to detect submerged submarines from aircraft and converting it to aeromagnetic mapping for geologic purposes. The airborne magnetometer was extensively used in the Lake Superior region to search for taconite iron ore deposits that gradually replaced the direct shipping ore deposits which were largely exhausted in the region during World War II and to map the Precambrian geology of the region including the Midcontinent Rift System.

In 1946 J.R. Balsley, who initiated aeromagnetic studies in the U.S. Geological Survey and was a strong proponent of the method for geological mapping, reviewed the pros and cons of the airborne magnetometer and concluded:

"The airborne magnetometer will by no means replace the usual surface instruments, but will certainly serve to delineate areas that deserve intensive detailed work."

At that period in the development of the airborne system he was justified in reaching that limiting conclusion because of the numerous problems in instrumentation, flight path recovery, navigation, and aircraft. However, this conclusion is no longer valid because subsequently vast improvements have been made in all aspects of the airborne magnetic surveying system leading to high resolution surveying. As a result, airborne measurements are now capable of replacing surface surveys for geological purposes except for detailed surveys in, for example, archeological and munition investigations.

The continuing improvement in the aeromagnetic mapping system has led to the current period, **The High Resolution Survey Years**: 1981 to 2022. The Global Position Satellite system has been particularly important in improving the precise navigation and accurate flight path recovery required for high resolution studies. The current high resolution airborne magnetic mapping with its high sensitivity, improved isolation of the geological signal from the ambient magnetic field, enhanced digital analysis, and presentation methodologies and computer power, and improved navigation provides detailed maps for structural and stratigraphic analysis. Unmanned aerial vehicles (drones) flying at altitudes too low for aircraft are taking on an ever-increasing role in increasing the resolution of magnetic surveying.

In summary, evidence from the past 200 years is overwhelming that the ever evolving magnetic method of mapping has had a profound impact upon the geological studies in the Lake Superior region. Magnetic methods were first useful in the discovery and mapping of iron formations of the region and then in the search for direct shipping iron ores and after World War II in studying taconite iron ore deposits. The method was less important to native copper ore exploration but did find a role in mapping the structure and stratigraphy of the Keweenawan volcanic and associated sedimentary rocks that has been useful in studying their hosted copper deposits. In addition, during the past few decades regional scale magnetic anomaly compilations of increasing resolution have proven to be useful in mapping the regional Precambrian basement geology of the Lake Superior region that has allowed geologists to gain improved knowledge of the regions's geologic history.

The principal steps in the evolution of the magnetic method in the Lake Superior region in chronologic order are:

- Recognition in the 1830s and 1840s that anomalies in angular components of the Earth's magnetic field mapped in the Lake Superior region during land surveys and geomagnetic surveys to study the Earth's magnetic field were caused by nearby magnetic rock units, both iron-rich and trap (volcanic) rocks.
- Mapping of the major iron formations and mafic volcanic units with their associated copper ores by the end of the nineteenth century with compass deviations and implementation of dial (sun) compass and dip needle surveying after 1865. The dip needle was brought from Sweden where it was likely developed near the end of the eighteenth century, to the New Jersey Geological Survey around 1854 and was subsequently brought from there to the Marquette Iron Range by T.B. Brooks in 1865. Recognition of magnetic properties of iron ores became important in planning and interpreting magnetic surveys.
- Development and use in more detailed studies after ~1915 of the Hotchkiss superdip and Schmidt-type magnetometer both based on the dip needle principle.
- Development of airborne magnetic surveying after ~1945 by the U.S. Geological Survey and independent contractors using the fluxgate magnetometer developed during World War II for non-geologic uses and application of the airborne mapping system to mapping geology in the Northern Peninsula of Michigan to aid in iron ore exploration.
- Reconnaissance aeromagnetic mapping of the Lake Superior region with improving magnetic sensors and surveying procedures during the period 1945-1980 by federal and state (province) agencies and academic units. Development during this period of improved techniques for analyzing and interpretation of data with increasing use of computers. Adaptation of sensitive airborne sensors to ground magnetic surveying minimized leveling and orientation instrumentation requirements.
- After 1980 implementation of high resolution magnetic surveying in significant areas of the Lake Superior region including the State of Minnesota, Lake Superior, and localized mineral exploration target areas in the U.S. and Canada with improved instrumentation and electronic aids to navigation and after 1990s using the Global Positioning System for improved surveying and flight path recovery. Increasing availability of software for use on personal computers to map, analyze, and interpret data.

5.0 And what of the future?

It is difficult in these times of rapidly advancing technology to predict the advances in magnetic mapping and analysis that will lead to improved geologic mapping and ore body detection. However, we can anticipate greater use of the current high resolution techniques and an ever-increasing search for greater detail in magnetic mapping. Increased detailed measurements should prove very useful building on the “principle of infinite detail” that as the measurement detail is increased, there will be increased information obtained. Unmanned aerial vehicles (UAV) (drones) are rapidly being improved by minimizing the effect of the vehicle on the magnetic sensor and improving its measurement of the position location. We can anticipate that drones will be used in making magnetic observations at greater detail in local areas and they will be extended to more extensive areas. Additionally, we can expect improved elimination of extraneous effects from the magnetic observations by removing or minimizing the effect of topography, surface glacial deposit signals, temporal variations of the Earth’s magnetic field at a range of scales, and other sources of error.

The need for more extensive sampling of the magnetic properties of the Precambrian rocks of the Lake Superior region and understanding their origin will continue to improve analysis and interpretation of magnetic anomaly measurements and their isolation. It is likely that current and future studies of magnetic sensors in a variety of life forms will give us a new view of sensing the magnetic field. Perhaps this will give us improved ways of observing the components of magnetic fields in greater detail and precision. Artificial intelligence will increasingly be applied to the elimination of non-geologic effects from magnetic data and vastly improved magnetic modeling. We will undoubtedly see in the near future essentially immediate interpretation of observed magnetic data where schemes will be used to interrogate a wide variety of data bases dealing with the terrestrial magnetic field, topographic and geologic information from surface and subsurface data, and collateral geophysical data constrained by assumed parameters based on geological knowledge of the region that will be used to compute a range of geologic models ranked in terms of their probability.

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[16] R. Thelén in 1879 a, b is the same as Tobias Robert Thalén

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Appendix A

Time Line for Events Related to the Evolving Use of Magnetics In Mapping Geology and Ore Deposits Of the Lake Superior Region

Year	Event
1581[17]	***W. Borough describes the sun(dial) compass.***
~Late 1600s	Declination anomalies observed with a compass used in iron ore exploration in New Jersey and New York.
~1760	***Tobias Mayer suggests use of counterbalanced magnetic needle for measuring the intensity of the terrestrial magnetic field.***
~1770	**Dip needle may have been developed in Sweden by Daniel Tilas** who uses the instrument extensively in Scandinavia for mapping magnetic iron ore deposits.

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[17] Technicalevents in italics and bold.

1780	H.B. de Saussure recognizes the effect of iron-rich rocks on compass readings.
1785	U.S. Land Ordinance surveys are initiated that are used to detect magnetic anomalies associated with local geologic formations.
~Early 1800s	In Europe Baron von Humboldt conducts a magnetic survey for mapping geology.
1814	***Johann Tobias Mayer, son of Tobias Mayer, introduces counterbalanced magnetic needle suggested by his father at ~1760.***

The Discovery Years (1830-1900)

1834	***H. Lloyd in Ireland designs a counterbalanced magnetic needle that is used to measure the relative vertical magnetic intensity of the terrestrial field while oscillating perpendicular to the magnetic meridian. He modifies his instrument for geophysical prospecting. Dip needle is sometimes referred to as the Lloyd dip needle.***
1835	***R.W Fox designs a counterbalanced vertical oscillating needle instrument, "dipping needle deflector," for measuring the relative intensity of terrestrial magnetic field. Modification of this instrument was used for prospecting for iron-rich rock units.***
1843	***Freiherr von Wrede discusses the application of magnetic science to mapping magnetic ores.***
1831/32	***D. Houghton identifies effect on compass headings of mafic volcanic rocks on Keweenaw Peninsula.***
1835	***W.A. Burt develops solar (sun) compass for surveying in the northern Midwest where local geology causes irregularities in declination of the terrestrial magnetic field.***
1836	***W.A. Burt patents solar compass.***
1840-41	D. Houghton describes the presence of native copper on Keweenaw Peninsula. Houghton, W.A. Burt, and F. Hubbard mention declination anomalies on Keweenaw Peninsula associated with "trap-rock." Houghton also recognizes the presence of iron-rich rocks along the south shore of Lake Superior, but does not identify the location and does not consider the presence of these rocks as economically important.
1843	Copper exploration boom starts in Keweenaw Peninsula.
1843-44	J.H. Lefroy makes magnetic observations along the Canadian north shore of Lake Superior and recognizes effect of local geology on the magnetic observations.
1844	W.A. Burt's surveying crew identifies declination anomaly near Negaunee, Michigan as caused by iron formation, but they do not recognize the potential economic significance of their discovery.
1844	J. Locke makes magnetic observations along south shore of Lake Superior noting the effect of local geology.

1846	Eastern Menominee Iron Range is located by Public Land Survey declination anomaly.
1847	J. Locke returns to Lake Superior making additional magnetic measurements that are affected by local geology in Marquette Iron Range and Keweenaw Peninsula.
1848	A. Randall discovers Gogebic Iron Range by declination anomaly during land surveying with a solar compass.
1854	New Jersey Geological Survey uses sun compass and dip needle in iron ore exploration. ***The dip needle is modified from the Swedish dip needle.***
1864	E. J. Hulbert maps the Calumet conglomerate lode with a sun compass.
1865	***T.B. Brooks likely brings the concept of the dip needle to Michigan from New Jersey for mapping the iron formation and ores of the Marquette Iron Range. He constructs a crude home-made instrument. With colleagues Brooks simplifies Burt's solar compass to dial compass for use by geologists.***
1866	H.H. Eames describes iron ore on the Mesabi Iron Range.
1868	***T.B. Brooks joins the Michigan Geological Survey and describes magnetism and its use with magnetic needles to map iron formations.***
1872	***T.B. Brooks recognizes that magnetic anomalies observed over the non-magnetic Paleozoic (then Silurian) sedimentary rocks of the Northern Peninsula of Michigan were likely derived from the basement Precambrian rocks that crop out to the west. Accordingly, he suggests that these anomalies can be used to trace the basement rocks and their structure beneath the sedimentary rocks and that characteristics of the anomalies can be used to determine the thickness of the sedimentary rocks and even possibly the depth of Lake Superior from lake magnetic anomalies. (This is likely one of the earliest suggestions that the magnetic method can be used to study sedimentary basin basement rocks and their depth.***
1874	T.B. Brooks of the Michigan Geological Survey uses the dip needle to map the iron-bearing rocks of Oconto County, Wisconsin.
1874	***T.R. Thalén devises instrument for measuring both the horizontal and vertical magnetic field which after improvements in 1880 by E. Tiberg is used widely in Europe for mapping geology but never extensively used in the Lake Superior region.***
1875-1878	Gogebic Iron Range is mapped with dip needle and dial compass by the Wisconsin Geological Survey.
1879	***Publication of Prof. Tobias Robert Thalén's 1874 book entitled "Examination of Iron Ore Deposits by Magnetic Measurements" which lays the foundations for the use of magnetic measurements for mapping magnetic iron ores. Thalén discusses the work of T.B. Brooks in this book.***
1880-	

1910 U.S. Geological Survey is involved in mapping Lake Superior iron ranges under the direction of C.R. Van Hise. Michigan Geological Survey started studies of iron and copper ores again in mid-1930s and U.S. Geological Survey once again became involved in Michigan in early 1940s.

1880 ***T.B. Brooks describes the various ores of iron and their characteristics.***

1880 ***C.E. Wright describes three different magnetic needle instruments used in northern Wisconsin in surveys performed by the Wisconsin Geological Survey and how to use them.***

1881 J.M. Longyear conducts dip needle survey outlining the Menominee Iron Range northwest of Iron Mountain, Michigan.

1884 A.H. Chester recognizes the magnetic nature of the Mesabi Iron Range.

1890 Iron ore is discovered in Mesabi Iron Range. The Merritt family mines the first iron ore in this range.

1891 Iron-rich formations are recognized at Steep Rock, Ontario but not investigated until 1897.

1897-1908 ***H.L. Smyth gives guidance on interpretation of dial compass and dip needle measurements emphasizing that positive magnetic anomalies do not indicate ore bodies, rather the converse. He also derives formulas for the magnetic effect of idealized geometric sources of magnetic fields.***

The Ground Survey Years (1901-1940)

1903 Cuyler Adams using declination anomalies discovers the Cuyuna Iron Range and confirmed it in 1904 by drilling. However, the magnetic anomaly of the range was recognized previously in late 1800s during land surveys.

1904 ***E. Haanel authors a book describing magnetic instruments and their use in mapping geology and ore deposits.***

1904 ***V.S. Hillyear discusses importance of observing speed of oscillation of dip needle in interpretation of the measurements.***

1910 Eugene Dietzgen Company catalog lists Miner's dip needle and Norwegian compass for both horizontal and vertical intensity magnetic measurements.

1912 C.K. Leith reports that it is a common fallacy that intense magnetic anomalies are favorable sites for the occurrence of iron ore.

1913 Wisconsin legislature passes an act directing the Wisconsin Geological and Natural History Survey to examine lands of northern Wisconsin for mineral deposits. From 1913 to 1922 the Survey maps 206 ½ townships using a combination of dip needle and dial compass observations. They identify several iron formations south of the Gogebic Iron Range similar to those found elsewhere in the Lake Superior region. From north to south they are the Marenisco, Turtle River, and Manitowish Ranges and the Vieux Desert and Conover Districts.

1915 ***A. Schmidt develops the Schmidt-type (Askania) magnetometer which becomes the standard instrument for both vertical and horizontal magnetic measurements from 1915 to 1950. The principle of the instrument is the same as that of the superdip and the Lloyd instrument. Sometimes identified as the Schmidt-Lloyd variomenter.***

1915 W.O. Hotchkiss reports on Round Lake, Wisconsin magnetic anomaly which subsequently is identified with a mafic intrusive associated with the Midcontinent Rift System (MRS). Similar anomalies and intrusives are identified in proximity to the MRS along continuation of its limbs to the south.

1915 W.L. Dobie submits a BA thesis to the University of Wisconsin-Madison, “Methods and Interpretation of Magnetic Anomalies of Iron formation.” His study focuses on T.41N., R.7W., east of Round Lake, Wisconsin. Dobie concludes that the anomalies are due to a sedimentary iron formation that acquired its magnetization when it was laying horizontal and has retained that magnetization through its folding into a form similar to a horseshoe magnet with the north limb dipping steeply to the south and the south limb dipping north at approximately 30°. Dobie was unaware of remanent magnetization of the Keweenawan rocks of Lake Superior. Rather the source of the Round Lake anomaly as described by Woodruff et al. (2020) is a 12 km long funnel shaped mafic/ultramafic Ti-Fe oxide intrusion striking ENE.

1917 Dip needle surveys of Duluth Complex are conducted by F.F. Grout and T. M. Broderick.

1920+ ***Calumet & Hecla Mining Company starts magnetic investigations in 1920. They initiate research to evaluate statements in the literature that copper-bearing lodes cause magnetic disturbances. To check this view dip needle surveys were conducted over the Kearsarge, Pewabic, and Baltic amygdaloidal ore deposits. As a result of these measurements and those made at a later date for the same purpose, they decide that there are no obvious magnetic anomalies in the vicinity of the native copper deposits which can be detected by ordinary dip needle practice. However, the magnetic work of the first year of their research does demonstrate the possibility for tracing the strike of certain volcanic rock units by their magnetic characteristics.***

1922-

1930 W.O Hotchkiss starts magnetic surveys in the Keweenawan rocks of Wisconsin which are continued by H.R. Aldrich of the Wisconsin Geological and Natural History Survey. This mapping is used to study the stratigraphy and structure of the Keweenawan rocks. Surveys in 1915 had shown the feasibility of using dip needle observations for mapping Keweenawan igneous rocks in Wisconsin. Anomalies mapped margins of volcanic flows and internal boundaries within them.

1923 ***W.O. Hotchkiss describes modification of the dip needle to achieve greater sensitivity leading to the Hotchkiss superdip which is based on the same principle as the Schmidt-type magnetometer and the dip needle.***

1925-1926	***Calumet & Hecla Mining Co. conducts surveys in portions of the Keweenaw Peninsula that contain native copper ore bodies. These surveys show that it was possible with dip needle measurements to map stratigraphy and structure including folds, faults, fissures, and alteration zones including those associated with faults because of oxidation of magnetite within the volcanic rock units. They find that the thicker mafic flows appear to have stronger magnetic effects perhaps due to the slower cooling of the thicker flows which allowed more complete segregation of magnetite. The magnetization of the Keweenawan lavas was assumed to be the result of induced magnetization considering the magnetic susceptibility due to the presence of magnetite. However, studies of the remanent magnetization of Keweenaw flows by Dubois and others shows that the remanent magnetization of these rocks are several orders of magnitude greater than the induced magnetization.***
1927	***W.O. Hotchkiss and three of his colleagues apply for a patent on the superdip which was granted in 1929.***
1929	Michigan initiates dip needle magnetic surveys along section lines in the Keweenaw Peninsula to aid in mapping strata. These surveys continue into the 1930s along N/S and E/W lines with readings every 10 paces on E/W and N/S lines and 15 paces on NW/SE lines with 2 1/2 miles of traverse in each section. Kearsarge ophite was extended for 18 miles with dip needle readings that are useful for mapping structure and continuity of volcanic flows. There is no reason to believe that native copper ore bodies in amygdaloids and conglomerates can be detected by magnetic methods. There is no feature of magnetite distribution known to be in any way related to the presence of the copper. However, there may be a zone of alteration adjacent to fissures and faults in which some of the magnetite has been destroyed causing a minimum magnetic anomaly. Some of these may be mineralized, and it is conceivable that a search for fissure deposits in glacial deposit covered country might be aided by magnetic surveying.
1930s	Dip needle and Schmidt-type magnetometer surveys are conducted by A. Brandt over the Atikokan iron formation near Steep Rock Lake. The iron minerals are generally hematite and limonite and thus are not detected in magnetic surveying, but anomalies associated with a magnetic tuff are used to map iron formation structure. Mining began in 1932 and terminated in the 1980s.
1930	H.I. Pearl maps negative magnetic anomaly related to iron ore within positive anomaly of the iron formation in the Cuyuna Iron Range.
1936	***C.O. Swanson describes a method of using the dip needle to measure both the vertical and horizontal magnetic field. This procedure has limited use in the Lake Superior region.***
1936	Centennial geologic map of the Northern Peninsula of Michigan prepared by Helen Martin shows the axes of intense magnetic anomalies provided by L.P. Barrett of the Michigan Geological Survey.
1936	***Fisher and Service describe optimum normal release position for dip needle to achieve maximum sensitivity.***

The Airborne Survey Years (1941-1980)

1940	***Fluxgate magnetometer is conceived and built by J.D.C. Hare at Gulf Research and Development Company and refined by V. Vacquier. Continued development of the magnetometer by government laboratories in the early 1940s leads to a practical instrument for measuring the total magnetic field from an aircraft. It is replaced by resonance magnetometers in airborne surveys in 1960s.***
1943	G.M. Schwartz maps 50 miles of the edge of the Duluth Complex north from Duluth with a Schmidt-type magnetometer based on strong negative magnetic anomaly to the west of the contact and a positive to the east. He provides no explanation of anomaly.
1943	Reconnaissance magnetic survey made of Animikie Group sedimentary rocks south of the Mesabi Iron Range by the Minnesota Geological Survey.
1943-44	***The U.S. Geological Survey learns of the success of the fluxgate magnetometer for airborne measurements and realizes its significant potential in geological mapping. Under the direction of J.R. Balsley, Jr. of the Survey and with the cooperation of the U.S. Naval Ordnance Laboratory the potential for mapping geological anomalies from the air is confirmed by a survey in southeastern Pennsylvania and is used to map the magnetic anomaly field of a segment of the Iron River Iron Range in May and June of 1944 and magnetite deposits in Oswegatchie County, New York (Adirondack Mountains). The latter are published as USGS GP-1 and 2 and the former as GP-3 in 1946.***
1944-50	Intensive magnetic mapping of Dickinson County, Menominee Iron Range with dip needle, Hotchkiss superdip, and aeromagnetics made during this period by U.S. and Michigan Geological Surveys. ***First aeromagnetic map of the area published by USGS (GP-3) in 1946 by Barratt et al. GP-1[18] and GP-2 also published in 1946 mapped iron-rich rocks in the Adirondack Mountains. These early surveys were subject to significant location errors because of problems in precise flight path recovery. Errors of 100 meters (~300 feet) are common and some errors are as large as 450 meters (~1500 feet).***
1946	***U.S. Geological Survey and U.S. Navy conduct first airborne magnetic survey for geological purposes over the Naval Petroleum Reserve No. 4 on the northwest coast of Alaska. Procedures used were employed in subsequent surveying by the U.S. Geological Survey.***
1946	Geological Survey of Canada purchases fluxgate magnetometers and initiates comprehensive airborne magnetic survey program which in the Lake Superior region is affiliated with the Ontario Geological Survey.
1947	***Hughes and Pondrom derive formula relating total magnetic intensity to horizontal and vertical components.***
Late	

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[18] GP-1 was modified and later published with J.R. Balsley as senior author.

1940s	U.S. Geological Survey conducts reconnaissance airborne magnetic surveys of the Keweenaw Peninsula to study the copper-bearing rocks of the region.
1947-66	Minnesota Geological Survey and U.S. Geological Survey conduct airborne magnetic survey of Minnesota with flight lines generally separated by 1 mile but 2-4 miles in some areas. Aeromagnetic map of this survey is published by the U.S. Geological Survey in 1970.
1948	***H.L. James of the U.S. Geological Survey shows that the dip needle and Hotchkiss superdip measure the vertical magnetic intensity when oriented perpendicular to the magnetic meridian significantly simplifying the interpretation of magnetic anomalies. This was previously recognized by Lloyd (1856) and others.***
1948	***The first aeromagnetic survey of a region in the conterminous U.S. by the U.S. Geological Survey was a survey of Dickinson County, Michigan with a fluxgate magnetometer (AN/ASQ-3A) flown at 500 ft AMT with 1/3 mile N/S lines and flight path recovery using a gyrostabilized continuous strip film camera. Published in 1953 with preliminary geologic interpretation. (Weir et al., 1953). Aeromagnetic survey of Dickinson County, Michigan with preliminary geologic interpretation, U.S. Geological Survey, Geophysical Investigations Preliminary Report GP-115).***
1949	***L.J. Peters publishes several computational methods devised by the Gulf Research and Development Company for enhancing the attributes of magnetic anomalies as an aid to interpretation. Improvements in these procedures continue to the present.***
1949	***U.S. Bureau of Mines conducts a research program in the Iron River District to determine the application of the magnetic method to mapping the geology of the Lake Superior region iron ranges and to locating iron ore. Results suggest that it is difficult to interpret magnetic anomalies observed with the superdip. Most of the iron minerals in the iron formation of this District are non-magnetic.***
1950-60s	***Airborne fluxgate magnetometers are simplified for measuring the vertical magnetic field in ground surveying and additional ground survey instruments developed for measuring total magnetic intensity.***
1950s	U.S. Geological Survey in coordination with the Michigan Geological Survey conducts geological studies including ground and airborne magnetic surveying in the Menominee Iron Range, Iron River-Crystal Falls Iron Range, and Felch trough in Iron and Dickinson Counties, Michigan. Ground surveying initially used the dip needle which subsequently was replaced by the Hotchkiss superdip and the Schmidt-type magnetometer.
1950s	***Development of the proton precession magnetometer by R. Varian measured absolute total (scalar) magnetic intensity. This instrument gradually became the instrument of choice for airborne surveys generally replacing the flux-gate magnetometer by the mid-1960s, but largely replaced in subsequent years by alkali-vapor magnetometers because of sensitivity and high sampling rate advantages. These airborne instruments were modified for ground use because they did not require orientation or leveling and measured the total magnetic intensity for ease in relating ground measurements to airborne observations.***

1950s	***Beginning in the 1950s studies were made of the magnetization of the Keweenawan rocks which showed intense remanent magnetization and inverse magnetization in some of these rocks.***
1953	Publication of U.S. Geological Survey, GP-115 showing stacked profiles and ‘red ball’ aeromagnetic map of Dickinson County, Michigan.
1953-59	J.R. Balsley as U.S. Geological Survey, Geophysics Branch Chief (through GP-307, 1961) promoted aeromagnetic studies.
1955	***P.M.Dubois cites the intense remanent magnetization both positive and negative of Keweenawan igneous rocks.***
1956	***F. Haalck describes torsion magnetometer which leads to the development of several different ground use magnetometers largely replacing needle magnetic instruments for mapping geology and ore deposits.***
1960	***First recognition of remanent magnetization of Keweenawan mafic volcanic and intrusive rocks and use in magnetic interpretation.***
1960s	Numerous aeromagnetic surveys of Paleoproterozoic Ladysmith to Pembine Belt of the Wisconsin Magmatic Terrane by mineral exploration companies in search for massive sulfide ore deposits.
1961	Review of magnetic surveys both ground and airborne in Dickinson County, Michigan by James et al. of the USGS (Professional Paper-310) identifies types of rocks that cause anomalies of various intensity.
1963	***C.E.Jahren recognizes the highly anisotropic magnetic susceptibility of the layered Biwabik iron formation of the Mesabi Iron Range and its impact on magnetic anomalies.***
1960s	Flambeau massive sulfide deposit near Ladysmith, Wisconsin is found by airborne surveys and outlined with ground surveys including magnetic observations. Several other deposits of a similar nature discovered in northern Wisconsin that have not been mined.
1964	***G.L. LaBerge reports that magnetite in iron formations is believed to have formed during low-grade regional metamorphism by oxidation of primary iron minerals such as siderite and greenalite, not by reduction of hematite.***
1964	Publication of a reconnaissance magnetic anomaly map of Wisconsin.
1966	Airborne magnetic survey of Wisconsin with 6 mile flight lines at an elevation of 3000 ft ASL mapped Penokee Iron Range and similar ranges immediately to the south (Marenisco, Turtle River, and Manitowish Ranges and the Vieux Desert and Conover Districts).
1966	***First shipborne magnetic survey conducted in Lake Superior between Isle Royale and the North Shore by H.Halls and G.West.***
1966	Lake Superior magnetic anomaly map published including the eastern portion of the Northern Peninsula of Michigan.

1970 U.S. Geological Survey publishes a magnetic map of Minnesota, GP-725.

1973- Airborne Radiometric Reconnaissance Survey project of the National Uranium Resource Evaluation program included measurements of total magnetic intensity over the Lake Superior region of the United States.

1972 F.Pettijohn used magnetic surveying in the Crystal Falls portion of the Menominee Iron Range.

Mid-1970s J.Karl conducted a detailed aeromagnetic survey of north-central Wisconsin which was used to prepare a preliminary Precambrian geology map of northern Wisconsin.

1978 USGS published preliminary aeromagnetic anomaly map of north-central Wisconsin.

The High Resolution Survey Years (1981-2022)

1979-91 High resolution magnetic survey conducted by the Minnesota Geological Survey with data updated during 2005-2007.

1980s Initial use of GPS by civilians.

1980s Discovery of kimberlite in the Northern Peninsula of Michigan promotes magnetic surveying for other kimberlite pipes in the Lake Superior region.

1985 Geological Survey of Canada pioneered the development and use of airborne vertical gradiometers.

1987 Geological Survey of Canada as part of the GLIMPCE program conducts a high resolution magnetic survey of Lake Superior.

Late-1980s Aeromagnetic and ground magnetic surveys conducted to identify kimberlite pipes in southern Northern Peninsula of Michigan counties.

Early-1990s Most aeromagnetic surveys in the United States are conducted by contractors.

1991 Minnesota Geological Survey Workshop on “Geophysical Solutions to Geologic Problems of Continental Interiors” as reported in their Circular 35 described the uses of the high resolution magnetic survey data.

1995 Highly accurate GPS is made available to civilians with continual increase in accuracy to less than a meter. Accuracy in aircraft is ~20 m horizontally and 40 m vertical.

2000s Improved magnetic instrumentation is obtained with Overhauser and Cesium-vapor magnetometers and GPS surveying to one meter precision that support high resolution aeromagnetic surveys. Improved and readily available computer software provides more easily interpreted magnetic maps.

2002 U.S. Geological Survey publishes a magnetic anomaly map of Wisconsin.

2005-07	***Minnesota Geological Survey conducts an upgrade of the high resolution magnetic survey data base.***
2010	***Unmanned aerial vehicles (UAVs or drones) began to be employed in high resolution magnetic surveys in the Lake Superior region.***
Mid- 2010s	U.S. Geological Survey reinterpreted magnetic anomalies of Lake Superior.
2010s	Ontario Geological Survey and private exploration organizations conducted airborne and ground magnetic surveys in Lake Superior region to search for kimberlite pipes.
2016	U.S. Geological Survey Earth Mapping Resources Initiative in the Lake Superior region included high resolution aeromagnetic surveying in Michigan, Wisconsin, and Minnesota together with the state surveys to aid in deciphering the geologic framework and the tectonomagmatic history of the region.

Appendix B:

Thomas Benton Brooks

A Pioneer of Geology and Iron Ore Exploitation of the Lake Superior Region

"*During many years Major (T.B.) Brooks was the chief authority in the region on matters pertaining to geology, the ores and the mines of the iron region of Lake Superior.*"[19]

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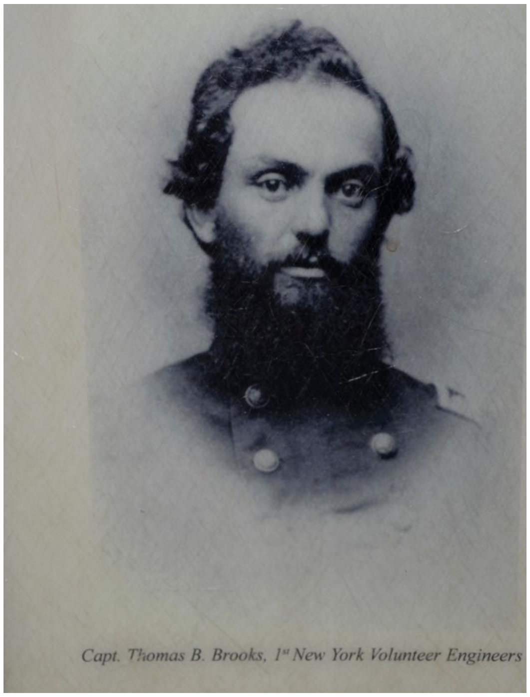
[19] Quoted from an article by Chas. A. Lawton in the Daily Mining Journal, November 29, 1900 entitled *The Late Major Thomas Benton Brooks: Biographical Sketch of a Man Whose Name is Intimately Associated With the Early Development of Michigan's Iron Mines.* The Mining Journal, the predominant daily newspaper of Marquette, Michigan and the Northern Peninsula of Michigan, was founded in 1841.



Civil War era photograph of Thomas Benton Brooks (Courtesy of Google Images)

Shortly after the U.S. Civil War Major Thomas Benton Brooks moved to the Marquette Iron Range. There over the course of less than a decade, he became the premier geologist, prospector, mining and civil engineer, and mining company executive of the region. During these formative years of the iron ore industry, when the Lake Superior region was providing about one-quarter of the iron ore used in the U.S., he was employed by the Iron Cliffs Company, the predecessor of the Cleveland-Cliffs Company, the Michigan and Wisconsin Geological Surveys, and served as a consultant to iron ore exploration and mining companies of the region. His contributions had a significant role in mapping the Precambrian geology and iron ranges of Michigan and Wisconsin and a lasting impact on the iron ore industry of the region. As stated by Prof. C.R. Van Hise, Brooks' successor as the premier geologist of the Lake Superior region[20]: "Notwithstanding the immense advantage which it has been to have Brooks' work as a foundation, it has taken many years of labor fairly to complete the structural story to which Brooks contributed important chapters. Only those who have labored in the Lake Superior region and who understand its peculiar difficulties can give Brooks credit for the remarkable work he did. His geological work is my ideal of what should be done in a new region of complex geology."

Thomas B. Brooks was born on June 15, 1836 in Monroe, NY, near the New Jersey border, and died nearby on November 22, 1900. In 1852 at the age of 16, he joined a surveying crew of the Erie Railroad and rapidly advanced from woodsman to instrument man. In 1853 he was employed with the New York Topographic and Geological Survey and then entered the Engineering Department of Union College of Schenectady, NY in 1856, graduating in 1858 in civil engineering. He remained at Union College as an instructor for a year and then took part in topographical surveys in New York, New Jersey, Pennsylvania and the U.S. Gulf Coast. In 1860 he attended a series of lectures on geology given by Prof. J.P. Lesley former state geologist of Pennsylvania and Professor of Geology at the University of Pennsylvania. This was his only formal education in geology. He volunteered for the Union Army in 1861 and organized an

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[20] As quoted by Bailey Willis of the U.S. Geological Survey in an obituary for Major Brooks in the Proceedings of the American Association for the Advancement of Science, New Series, v. 13, No. 325(March 22, 1900), 460-462.

engineering company that had a distinguished record during numerous Civil War campaigns. He retired from the Union Army in 1864 as a brevet colonel after being wounded in the battle of Denly's Bluff, but referred to himself after the war as Major Brooks.

In 1864 after leaving the Union Army he accepted a position with the Geological Survey of New Jersey where he conducted magnetic surveys with a dip needle to locate iron ores and was put in charge of mines and furnaces. Shortly thereafter, he was induced to take charge of the mines of the Iron Cliffs Company in the Marquette Iron Range as vice-president and general manager. He moved to Negaunee, Michigan, where his practical knowledge of geology and engineering, leadership skills, originality, keen powers of observation and deduction, and intense work ethic served him, the company, and the Lake Superior region well. This is where his extensive geological studies began and where he developed the instruments and methodology to exploit the iron ores of the Lake Superior region. He brought the concept of the dip needle to the Lake Superior region and was among or possibly was the very first, to use it in iron ore exploration and geologic mapping in the region. His first instrument in the Lake Superior region was home-made. He also pioneered the dial (sun) compass, which he modified for geologic use from the surveying solar compass developed by W.A. Burt.

In 1868 he resigned from the Iron Cliffs Company and was given the responsibility of mapping and reporting on the Marquette Iron Range and was placed in charge of the Economic State Geological Survey of the district by the Michigan Geological Survey, essentially becoming the State Geologist of the Northern Peninsula. He received no salary for this position, but he was allowed to receive private funds from numerous iron ore companies and mines. Unfortunately, his intense work schedule took a toll on his health that caused him to leave Marquette with his family in the winter of 1872-73 for London, England and eventually Dresden, Germany, where he hoped to regain his health, but failed to do so. During this period he prepared reports on his iron range geologic studies for publication by the Michigan and Wisconsin Geological Surveys (Brooks, 1873 and 1880), articles on the geology of the region and magnetic surveying instruments and their use published in various journals including the American Journal of Science and Arts (Brooks and Pumpelly, 1872; Brooks, 1875), and co-authored the book "Iron Ores of Missouri and Michigan" (Pumpelly, Brooks, and Schmidt, 1876).

During his years involved with the geology and ores of the Lake Superior region Major Brooks made numerous advances in the geological knowledge of the region that have served as a foundation for future studies and developed methods and instruments that proved useful for exploiting the ores of the region for many years. The following are a list of his major lasting accomplishments:

- He brings the concept of the counterbalanced dip needle from the New Jersey Geological Survey to the Marquette Iron Range in 1865. He constructs a crude dip needle which is first dip needle used for magnetic surveying in 1866 on the Marquette Iron Range until a more refined instrument can be constructed by an instrument maker (Brooks, 1880).
- He with the assistance of R. Pumpelly and R.D. Irving developed the dial (sun) compass for geologic studies based on the principal of Burt's surveying solar compass which together with the concept of the dip needle that he brought from the Geological Survey of New Jersey were used in the Lake Superior region for nearly a century to locate and outline iron-rich rocks and ores. His publications on these instruments led to their extensive worldwide use.
- He established procedures for conducting magnetic surveys for geological purposes in the Lake Superior region and methods of interpreting the observations of the surveys based on empirical studies.
- He was the first to describe the magnetic characteristics of the minerals and rocks of the Lake Superior region.
- He (Brooks, 1872a) recognized that magnetic anomalies observed in the area of non-magnetic Paleozoic (then Silurian) sedimentary rocks of the eastern part of the Northern Peninsula of Michigan were likely derived from the basement Precambrian rocks that crop out to the west. Accordingly, these anomalies could be used to trace the basement rocks and their structure

beneath the sedimentary rocks. Furthermore he realized that anomaly characteristics could be used to determine the depth to magnetic sources and thus, the thickness of the sedimentary rocks. In a similar manner he understood that perhaps the depth of Lake Superior could be determined from analysis of the lake magnetic anomalies.

- He founded the first assay facility for iron ores in the Lake Superior region in the city of Marquette which facilitated iron ore mining in the region.
- He conducted one of the first geological surveys of the Marquette, Menominee, Crystal Falls, and Gogebic Iron Ranges. He was the first to understand that the Marquette Iron Range occurs within a 75-km long syncline extending to the west from near Marquette, Michigan (Allen and Martin, 1922).
- He recognized the stratigraphic position of the copper-bearing rocks of the Northern Peninsula of Michigan and suggested the name Keweenawian (note his spelling) for the age of these rocks in American Journal of Science and Arts articles of 1872 and 1875. Subsequently, the term Keweenawan has been used for these rocks.
- His method of locating iron ore deposits using magnetic triangulation was described in the 1874 book by Tobias Robert Thalén *"Examination of Iron Ore Deposits by Magnetic Measurements*," which is considered to mark the beginning of the magnetic method of geophysical surveying. This verified Brook's importance to the magnetic method and his international reputation.
- He had an important role in developing safe, efficient methods of mining iron ores of the Lake Superior region (Brooks, 1972b).
- He was intensely interested in the education of his children and supported the studies of his son, Alfred Hulse Brooks, a famed geologist of the U.S. Geological Survey, Alaska Branch, who is honored by naming of the Brooks Range of Alaska after him.

These are all significant contributions that have had a profound role in understanding of the geology of the Lake Superior region and the exploitation of its ores. They have largely gone unrecognized for the past century and a half, but they clearly distinguish **Major Thomas Benton Brooks as a Pioneer of Lake Superior geology.**

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[21] R. Thelén in 1879 a, b is the same as Tobias Robert Thalén