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GEOLOGIC AND STRATIGRAPHIC CONTROLS OF THE BIWABIK IRON FORMATION AND THE AGGREGATE POTENTIAL OF THE MESABI IRON RANGE, MINNESOTA

By

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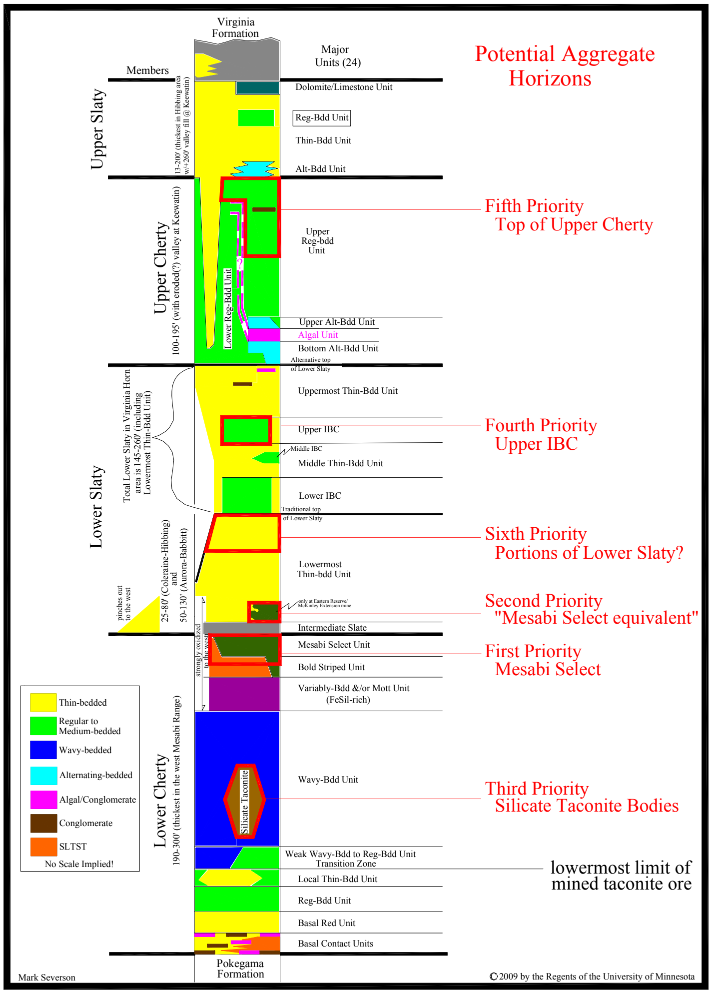

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Cover Photo Caption
Potential aggregate horizons, listed according to relative priorities, in the Biwabik Iron Formation that were defined in this investigation.

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EXECUTIVE SUMMARY

The taconite mines on the Mesabi Iron Range of northeastern Minnesota generate millions of tons of mined waste rock annually that could potentially be used as aggregate material in road building projects. Paramount to defining potential aggregate horizons within the mined iron-formation is an understanding of the stratigraphy as it relates to mined ore units and waste units at each of the respective taconite mines. However, each mine uses a different submember terminology to designate the various ore and waste horizons. The major emphasis of this investigation was to produce a stratigraphic "Rosetta Stone" of the Biwabik Iron Formation that ties the stratigraphy and differing submember terminology of one mine to all of the other mines on the Mesabi Iron Range. Toward that end, the Natural Resources Research Institute (NRRI) looked at core from over 380 drill holes, and some mine exposures, in the central and western Mesabi Iron Range (Biwabik to Coleraine, MN area) to develop a stratigraphic system that links all of the mined ore and waste submembers.

The methodology used in this investigation was to log multitudinous deep drill holes from a single mine, hang all of the drill holes on a common datum (bottom of the Lower Slaty member), and then correlate all of the submembers, as used by that particular mine, making note of bedding features and other unique features that define a particular submember. This same system of "logging, hanging, and correlating" was done at each of the taconite mines (seven different mines/areas along the Mesabi Iron Range) to better understand each mine's submember terminology. The hung stratigraphic-sections from each mine were then used to collectively make generalized stratigraphic columns for each of the mines. These stratigraphic columns were then added to the "Rosetta Stone" (Plate II of this report) that is used to illustrate how the submembers at one mine correlate with similar submembers at all of the other mines.

In the end, this investigation identified 25 major "Rosetta" units that define the stratigraphy of the Biwabik Iron Formation that can be used to link together all of the differing submember nomenclatures from the various taconite mines. This division of the iron-formation into 25 major units, based primarily on their overall bedding characteristics, is applicable to only the central and western Mesabi Iron Range and does not include the more highly metamorphosed iron-formation of the eastern Mesabi Iron Range, e.g., to the east of Aurora, MN. A listing of these 25 major "Rosetta" units is presented below (starting from the base of the iron-formation and progressing upwards):

- **Lower Cherty member:**
    - <u>Basal Contact Unit</u> – includes five interbedded rocks types: Algal Chert unit, Conglomerate unit, hematite-stained siltstone (SLTST unit) with detrital quartz grains, Ooidal Jasper unit, and Thin-Bedded unit;
    - <u>Basal Red Unit</u> – thin-bedded iron-formation (often with primary hematite);
    - <u>Regular-Bedded Unit</u> – magnetic, granular iron-formation with regular-spaced, planar, bedding planes;
    - <u>Local Thin-Bedded Unit</u> – thin-bedded iron-formation that is present in a restricted area of the Mesabi Iron Range;
    - <u>Weak Wavy-Bedded to Regular-Bedded Unit</u> – transition zone between the Regular-bedded Unit and the overlying Wavy-Bedded Unit;

  - Wavy-Bedded Unit – magnetic, granular iron-formation with magnetite concentrated in bands that pinch, swell, terminate, and bifurcate in a semi-random pattern. This unit is often further broken down into the following types at many of the taconite mines:
    - Wavy-Bedded;
    - Wavy-Bedded with salt-and-pepper texture (S&P texture);
    - Wispy Wavy-Bedded with S&P texture;
    - Wavy-Bedded with scattered, but common, wavy-bands up to three inches thick; and
    - Silicate Taconite bodies characterized by magnetite-poor, thicker-bedded zones of iron silicate-rich, granular chert;
  - Variably-Bedded and/or Mottled Unit – magnetic, granular, silicate-rich iron-formation exhibiting a multitude of bedding types that contain variable amounts of superimposed late diagenetic iron-carbonate mottles (most often pink ankerite);
  - Bold Striped Unit – uniquely banded iron-formation consisting of alternating greenish, granular, cherty bands and brown, fine-grained, iron carbonate-rich, thin-bedded sets (magnetite content decreases to nil with height);
  - Mesabi Select Unit – non-magnetic, greenish, medium-bedded, granular chert that makes excellent aggregate material.

- **Lower Slaty member:**
  - Intermediate Slate – thin-bedded, black, carbonaceous argillite that is most often at the very base of the Lower Slaty member;
  - Lowermost Thin-Bedded Unit – weakly- to non-magnetic, thin-bedded, fine-grained iron-formation;
  - Lower IBC Unit (IBC = "interbedded chert") – magnetic, granular iron-formation that is present as lensoidal, channel-like bodies in the middle portion of the Lower Slaty member in the Virginia Horn area;
  - Middle Thin-Bedded Unit – variably-magnetic, thin-bedded iron-formation that contains a localized Middle IBC Unit in the southern Virginia Horn area;
  - Upper IBC Unit – variably-magnetic, granular iron-formation that is locally present as lensoidal, channel-like bodies in the upper portion of the Lower Slaty member in the Virginia Horn area; and
  - Uppermost Thin-Bedded Unit – variably-magnetic, thin-bedded iron-formation at the top of the Lower Slaty member in the Virginia Horn area;

- **Upper Cherty member:**
  - Bottom Alternating-Bedded Unit – consists of alternating thick- and thin-bedded sets indicating deposition in progressively shallowing water at the base of the Upper Cherty member (not present everywhere along the Mesabi Iron Range, but very common in the Virginia Horn area);
  - Lower Regular-Bedded Unit – magnetic, granular iron-formation with regular-spaced, planar, bedding planes (more common in the western Mesabi Iron Range, e.g., west of Minntac);
  - Algal Unit – stromatolite-rich and conglomeratic unit (often referred to as either the "I horizon" or "Mary Ellen Jasper") that is only present to the east of Hibbing, MN;
  - Upper Alternating-Bedded Unit – similar to the Bottom Alternating-Bedded Unit, but positioned above the Algal Unit (only present at Minntac); and

  - Upper Regular-Bedded Unit – magnetic, granular iron-formation with regular-spaced, planar, bedding planes.

- **Upper Slaty member**:
  - Thin-Bedded Unit – dominant rock type of the Upper Slaty member characterized by variably-magnetic, fine-grained, thin-bedded iron-formation;
  - Alternating-Bedded Unit – consists of alternating thick- and thin-bedded sets indicating deposition in progressively deepening water at the base of the Upper Slaty member (only locally present at Minntac – especially in the East Pit);
  - Regular-Bedded Unit – magnetic, granular iron-formation with regular-spaced bedding planes that occur as channel-like bodies (?) in the Upper Slaty; and
  - Dolomite/Limestone Unit – iron-poor carbonate rocks (often referred to as the "A horizon") with interbedded chert and minor argillite beds at the very top of the Upper Slaty member that locally contains ejecta material from the 1,850 Ma Sudbury impact event.

Throughout this report, possible depositional environments have been suggested for many of these 25 units. However, it must be stressed that these inferred environments have been based largely on the relationships displayed in drill holes, and a detailed sedimentalogical study was not the primary goal of this investigation. Thus, the suggested depositional environments are crude comparisons to recent sedimentary systems and should only be used as starting points for future discussions. Highlights of specific and/or unique depositional environments associated with the members of the iron-formation are listed below:

- The major units of the Lower Cherty member could be likened to reworking of materials (intraclasts) in a siliciclastic environment on the edge of a continental shelf during a major regressive event;
- The depositional environment of the Lower Slaty member correlates with a transgressive deep water/offshore shelf environment below storm wave-base. The change from shallow water sediments of the Lower Cherty member to the deep water sediments of the Lower Slaty member was abrupt and could have been related to rapid tectonic subsidence of the Animikie Basin;
- The upper contact of the Upper Slaty member is highly gradational and less well defined in the Virginia Horn area where several channel-like bodies of cherty iron-formation (IBC units) are present within a dominantly thin-bedded rock package. Apparently, these channels were repeatedly eroded in the thin-bedded sediments and filled with "clastic" cherty materials by ebb-flow tidal currents and/or storm-generated currents to form channel-like IBCs;
- Near McKinley, MN, the Lower Slaty member consists of complexly interbedded rock types that often exhibit soft-sediment deformation features. This chaos of rock types indicates rapidly changing water depth conditions that were probably related to episodic additions of material that slumped downward from the nearby shallow water shelf during periods of earthquake-induced seismicity;
- The Upper Cherty member, also deposited during a regressive event, is vastly different from the Lower Cherty member, and thus, a comparison to reworking of materials in a siliciclastic environment is not totally valid. In addition, the Upper Cherty member exhibits a drastic

change in the dominant bedding types in the eastern versus the central and western Mesabi Iron Range. Unfortunately, very few holes from the eastern Mesabi Iron Range were logged in this investigation, and it is impossible to fully document the nature of this change;

- The abundance of stromatolites in the Upper Cherty member, occurring as both aerially-large fields and as scattered localized occurrences throughout the member, indicates that cyanobacteria activity increased and reached a peak during this period. There are spatial variations in the forms of the stromatolites (domes, columns, mats, and oncolites) that are related to depositional conditions such as water depth and current strength that are ultimately related to the geometry of the ancient shoreline;
- Near Keewatin, MN, the Upper Cherty thins drastically and exhibits an overall geometry suggestive of an eroded submarine valley that was filled with thin-bedded iron-formation that is correlative with the Upper Slaty member; and
- The Upper Slaty member marks a final transgressive event in that it is dominated by thin-bedded iron-formation that was deposited in deep water. At some locales, the basal contact of the Upper Slaty consists of thick packages of alternating-bedded units indicating a gradual deepening of the Animikie ocean; whereas, in other locales the change took place rapidly and regular-bedded rocks of the Upper Cherty are directly overlain by thin-bedded rocks of the Upper Slaty. These differences reflect changes in water depth along an irregular shoreline with deposition taking place in two distinct basins (see appendices). Further still, submarine valleys extending outward from the shoreline could be invoked to explain the anomalously thick Upper Slaty member and anomalously thin Upper Cherty member in the Keewatin, MN, area.

The second goal of this project was to delineate potential aggregate horizons within the Biwabik Iron Formation. The previous identification of "Mesabi Select" as good aggregate material from a specific layer in the iron-formation was a major catalyzing driver in the search for other aggregate horizons. Several potential horizons were found in this investigation, and they are listed below according to decreasing priority:

- Mesabi Select Unit at the top of the Lower Cherty member;
- "Mesabi Select equivalent" bodies in the Lower Slaty member near McKinley, MN;
- Channel-like silicate taconite bodies in the Lower Cherty member at Minntac and Hibtac;
- Upper IBC Unit at Minntac;
- Upper portions of the Upper Cherty member at many of the mines as their pit limits advance downdip; and
- Upper portions of the Lower Slaty member **if** tabular aggregate particles are not generated during blasting and removal of this waste material.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF PLATES
(on CD in back pocket of this report)

INTRODUCTION

Introduction

The taconite mines (magnetic iron ore) on the Mesabi Iron Range of northeastern Minnesota (Figs. 1 and 2) generate 125 million tons of mined waste rock and processing byproducts annually that could potentially be used as aggregate material in road building projects throughout the state and in other nearby states. Paramount to defining potential aggregate horizons within the iron-formation is an understanding of the stratigraphy as it relates to mined units and waste units in each of the respective taconite mines. Unfortunately, the seven operating mines, and three inactive mines, each use a different classification system to subdivide the Biwabik Iron Formation into various submembers based on bedding types, ore grades, and mineralogical characteristics. Until recently, there has been no "Rosetta Stone" that ties the submember terminology of one mine to the other mines. Toward that end, the NRRI has looked at drill core and mine exposures in the central Mesabi Iron Range (Biwabik to Coleraine, MN area) to develop a detailed stratigraphy of the iron-formation that will eventually link all of the mined and waste submembers into a coherent system.

Stratigraphic studies of this extent have not been conducted along the entire length of the range since the milestone work of Gruner (1924) and White (1954). This lack of work is mainly because out of the thousands of holes drilled by the mining companies during the last 100 years, only a few hundred are still available for examination. Companies typically consume their drill core for grade testing purposes (magnetic Fe, Si, P, Al, etc.) rather than splitting and storing the core. Any core that is split is retained by the mining companies and, therefore, is not available to the public for examination. Furthermore, due to safety-related issues, geologic descriptions of each of the iron-formation submembers in newly exposed mine walls cannot be conducted. This project was able to be completed at this point in time for the following two reasons. First, the taconite mines have recently undergone an explosion of expansions due to increased markets for steel. This explosion has resulted in a significant amount of drilling by several of the mining companies as they began to define more ore reserves both downdip and along strike of their present pit limits. Permission was granted to NRRI geologists to log many of these holes before they were consumed for grade testing. Second, permission was granted for NRRI geologists to log many of the preserved historic cores that are stored at: United Taconite (Utac) in Eveleth; Minntac in Mt. Iron; and Jones and Laughlin (J&L) core at Lerch Brothers, Hibbing.

Aggregate materials derived from the magnetite-poor mine rock (heretofore referred to as waste rock) of the iron-formation, as well as a fine-aggregate equivalent processing byproduct of Minnesota's taconite industry (coarse tailings), have been used throughout the state of Minnesota for decades. These two major types of aggregate materials have been used and documented in over 400 projects (Oreskovich et al., 2007) from 1960 to 2006 as follows:

1. Crushed mine rock has been used as coarse aggregate, primarily in bituminous pavement applications. It makes excellent Superpave mixes due to its hardness, durability, 100% fractured faces, and good friction qualities; and
2. Coarse taconite tailings, a fine (i.e., -3/8") aggregate material, are used most frequently as construction fill, given their consistent gradation (size distribution) and free-draining characteristics. Coarse tailings are also used in asphalt pavement mix designs.

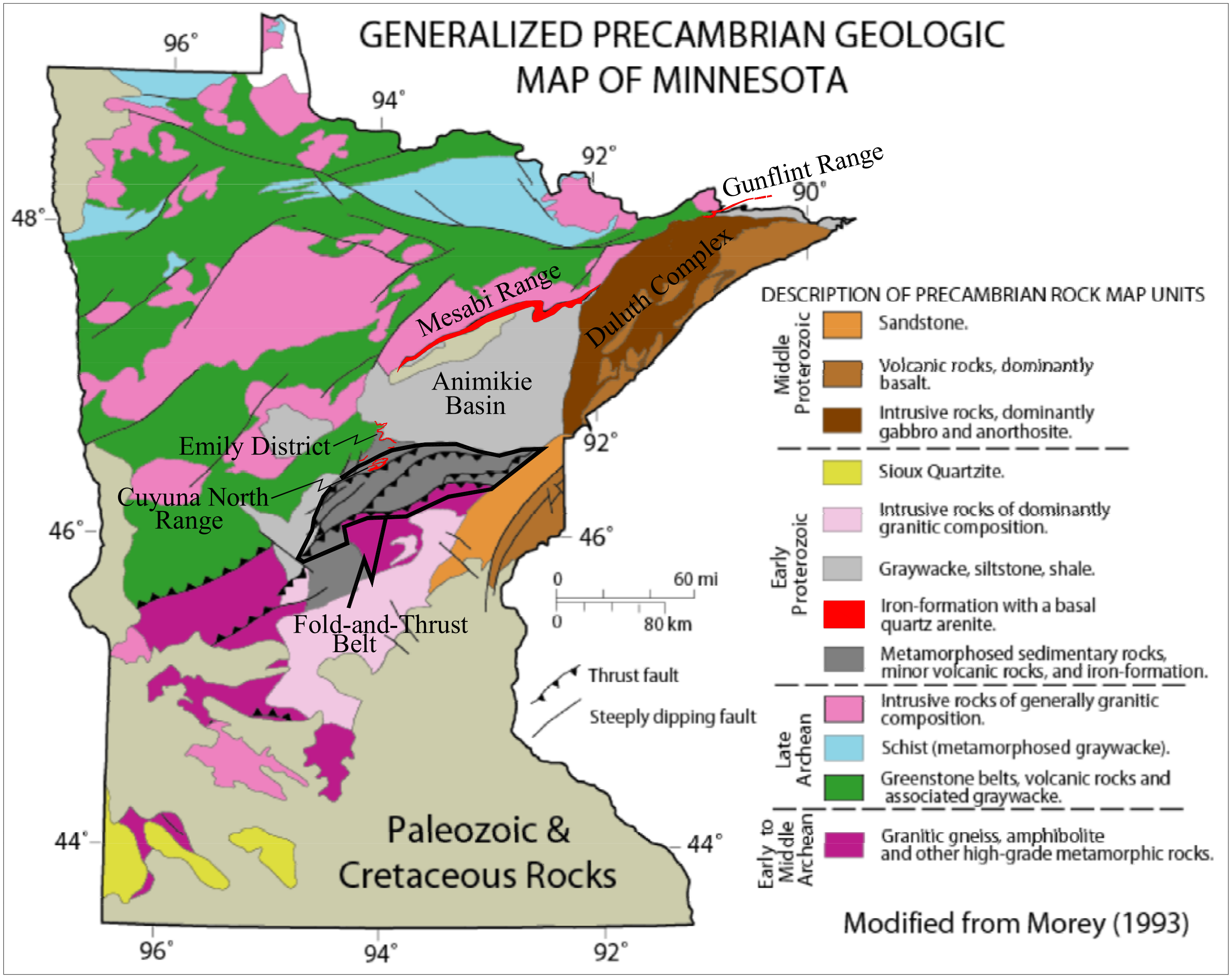


Figure 1. Generalized geologic map of Minnesota showing the locations of the Fold-and-Thrust Belt, Animikie Basin, and Paleoproterozoic iron-formation trends (in red) of the Mesabi Iron Range, Gunflint Range, Emily District, and Cuyuna North Range.

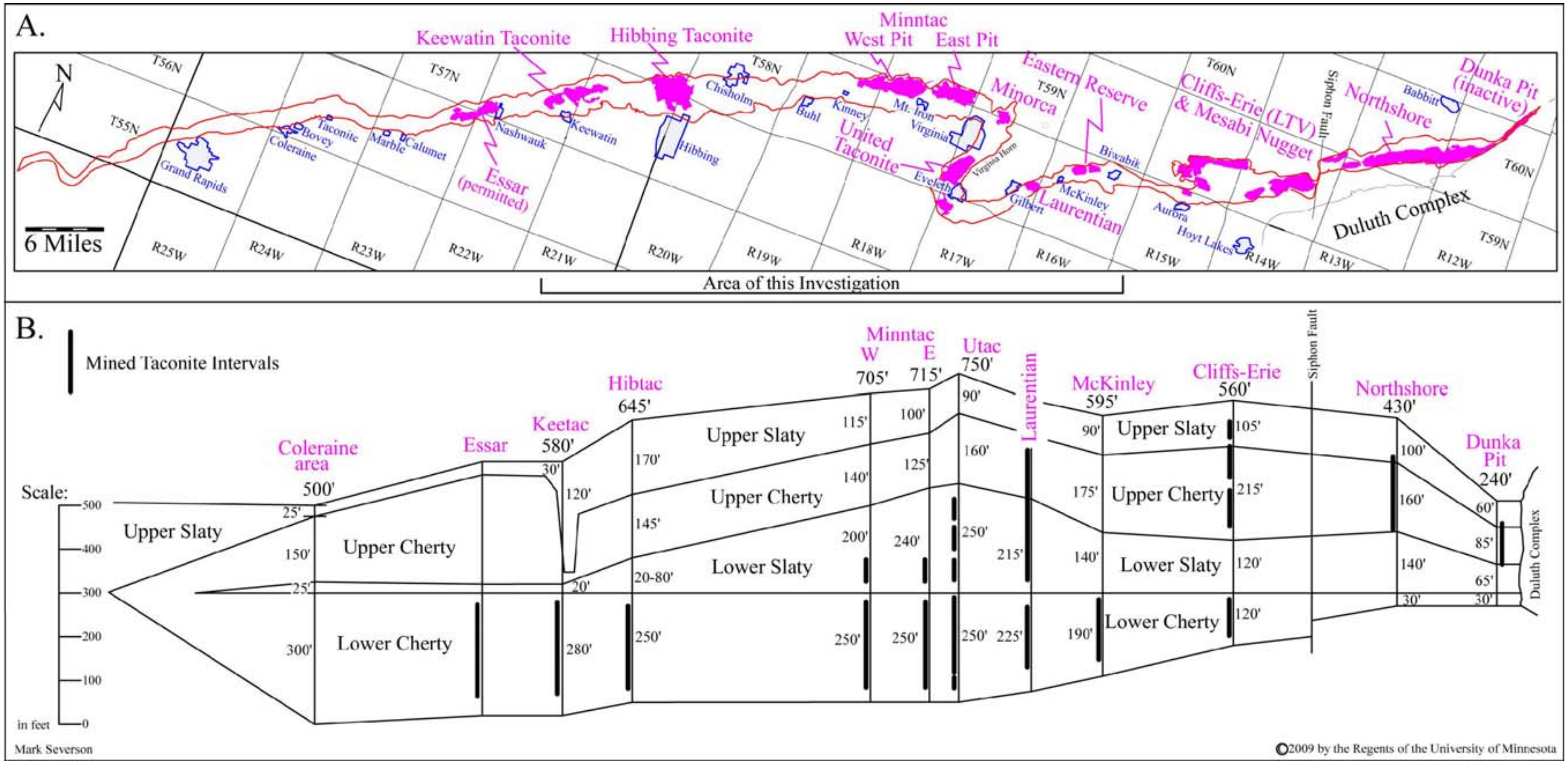


Figure 2. **(A)** Map of Mesabi Iron Range with aerial distribution of taconite pits (magenta) and cities (blue). Trend of Biwabik Iron Formation is outlined in red (modified from Jirsa et al., 2005). **(B)** Longitudinal section (looking north) of the Biwabik Iron Formation showing: average thickness of the iron-formation at each taconite operation along with the thickness of the various submembers at each operation, and mined taconite intervals represented by black bars.

Most of these historical uses were from mixtures of various waste rocks and not from specific horizons in the iron-formation. However, in the beginning of the 21st century, a local aggregate supplier, Edward Kraemer and Sons (EKS), began using in-pit crushed materials from a magnetite-poor waste rock zone in the very top of the Lower Cherty member at the United Taconite (Utac) mine. This material, originally referred to as the "TLCW" unit (Top of the Lower Cherty Waste) by Utac geologists, was found to possess excellent aggregate qualities and was given the trade name of "Mesabi Select" by EKS. [**Note** that the "TLCW" designation has now been changed to the name of LC-8 by Utac geologists.]

In 2004, the Minnesota Department of Transportation (Mn/DOT) obtained some of this Mesabi Select and used it in the construction of two cells in their Low Volume Road (LVR) test facilities, located northwest of Minneapolis/St. Paul, to demonstrate its qualities in:

1. Hot mix aggregate – used in cell 31 with results described in Zerfas, et. al (2005); and
2. Concrete mix – used in cell 54 with results described in Izevbekhai and Rohne (2008).

These reports, and more detailed work on the mineralogy of Mesabi Select (Richter, 2005), can be obtained from the Mn/DOT website at: www.mrr.dot.state.mn.us/research/mnroad_publication.

Acknowledgements

The authors wish to whole heartedly thank the geologists at each of the various mines for granting us access to drill core – in many cases before the core was consumed for grade testing purposes. These company geologists went out of their way to explain their respective submember systems and what characteristics (bedding textures, ore grades, etc.) are unique to each of the submembers. Even though we have looked at core from several of the mines, we readily admit that we are not totally familiar with all of the nuances of a particular submember, and we bow to their more experienced knowledge that was developed through the logging of hundreds of drill holes. Geologists that helped in this endeavor include: Peter Jongewaard and Phil Larson – United Taconite/Cliffs NR; Mike Orobona, Jared Lubben, Melissa Campbell, and Henry Djerlev (retired) – Hibbing Taconite/Cliffs NR; John Arola (retired) – Laurentian Mine and Eastern Reserve/ ArcelorMittal; Frank Pezzutto – Minntac/ USS; Jeff Price – Keewatin Taconite/USS; Doug Halverson and Jeff Bird – Northshore/ Cliffs NR; Alan Strandlie – LTV (Cliffs-Erie site)/Cliffs NR, and Ron Graber – Cleveland Corporate Office/Cliffs NR. Thanks are also extended to Albert Haertlein and Pete Heltunen of RGGS for giving permission to look at some of the USS holes that are now their property. We are especially indebted to Peter Jongewaard, who was our first guide in pointing out many of the characteristics of the various iron-formation submembers at United Taconite–essentially, the stratigraphic section at United Taconite became the standard to which we later compared many of the submembers at the other mines.

While we learned much about the stratigraphy at each of the mines, any deviation from the mine descriptions are ours alone, and the respective mine geologists should not be held accountable. It is through the mine geologists' efforts that we can now knowledgably talk about how the various submembers correlate with submembers in an adjacent mine, and we hope that our more regional experience, and the information presented in this report, will aid them in the future.

The primary author also wishes to thank three professors/mentors, Dr. Ralph W.

Marsden and Dr. Richard W. Ojakangas of the University of Minnesota Duluth, and Dr. G.B. Morey of the Minnesota Geological Survey, for their many discussions about the geology of the Biwabik Iron Formation and taconite mining long before the author ever looked at any drill core of this unique northeastern Minnesota rock type.

GENERAL GEOLOGY

The Mesabi Iron Range (Fig. 1) is one of the largest iron ranges in the world. It is 120 miles long, averages one to two miles wide, and is comprised of rocks that belong to the Paleoproterozoic Animikie Group. The Animikie Group on the Mesabi Iron Range [and its continuation on the Gunflint Range in northeastern Minnesota and adjacent Ontario – Fig. 1] consists of three conformable major formations: Pokegama Formation [and Kakabeka Quartzite] at the base; Biwabik Iron Formation [and Gunflint Iron Formation] in the middle; and the overlying Virginia Formation [and Rove Formation]. The Thomson Formation in the northern part of east-central Minnesota is correlative with the Virginia Formation. On the Mesabi Iron Range, these three formations display gentle dips to the southeast at an angle of 3-15 degrees. A similar stratigraphic sequence is also present to the southwest in the Emily District (Fig. 1) and consists of folded and cleaved, generally north-dipping rocks, characterized by quartzite at the base (Pokegama Formation), an iron-formation with a basal algal unit (Unit A of Morey et al., 1991), and an upper sequence of graywacke and mudstone (Virginia Formation) with common iron-formation layers at its base (Severson et al., 2003).

In models presented by Southwick et al. (1988) and Ojakangas (1994), the three Paleoproterozoic formations of the Animikie Group on the Mesabi Iron Range were deposited in a shallow sea on the northern edge/continental shelf of a northward migrating foreland basin – the Animikie basin – in response to tectonic activity to the south in the Fold-and-Thrust Belt (Fig. 1) during the Penokean orogen (1,880-1,830 Ma; Schulz and Cannon, 2007).

Ages

Age constraints for deposition of all three formations of the Animikie Group range from roughly 2,125 Ma to 1,821 Ma. The Pokegama Formation rests unconformably on the northeast-trending Kabetogama dike swarm, dated at 2,125 ± 45 Ma (Rb-Sr isochron – Southwick and Day, 1983; Beck, 1988), which gives a maximum age for deposition. A minimum age of deposition for the Pokegama Formation is 1,930 ± 25 Ma (Pb/Pb), which was obtained from quartz veins that cut the Pokegama Formation (Hemming et al., 1990). An age of 1,878 ± 2 Ma (U/Pb on euhedral zircons) has been obtained from an ash layer in the upper Gunflint Iron Formation (Fralick and Kissin, 1998; Fralick et al., 2002). An ejecta layer, related to the 1,850 Ma Sudbury impact event, has been found near the top of the Biwabik Iron Formation and at the top of the Gunflint Iron Formation (Addison et al., 2005). Zircon ages from ash layers near the base of the Virginia Formation have yielded 1,850 Ma (Hemming et al., 1996) and 1,832 ± 3 Ma (Addison et al., 2005 – the sample was collected about six inches above the base of the Virginia Formation in drill hole VHD-00-1; see Fig. 4). Zircon ages from ash layers positioned at the base of the Rove Formation, and about 70 meters above the base of the Rove Formation, have yielded ages of 1,836 ± 5 Ma (Addison et al., 2005) and 1,821 ± 16 Ma (Kissin et al., 2003), respectively. Schulz and Cannon (2007) have proposed that the age differences between the bottom of the Rove

Formation (1,836 Ma) and top of the Gunflint Formation (1,878 Ma) are indicative of a previously unrecognized disconformity and that a significant hiatus in sedimentary deposition separates the two formations. They further suggest that this hiatus represents a period of emergence between deposition of the iron-formation and the overlying clastic rocks – whether this emergence extended into the Mesabi Iron Range is unresolved at this time. Furthermore, detrital zircons with U/Pb ages of 1,780 Ma (Heaman and Easton, 2005) have been obtained from a sandstone bed about 400 meters above the base of the Rove Formation, suggesting that deposition in the northern part of the Animikie basin outlasted Penokean deformation in the southern part of the basin (Schulz and Cannon, 2007).

Pokegama Formation

At the base of the Animikie Group are clastic rocks of the Pokegama Formation. This formation has been divided into:

1. An upper member that is comprised of medium- to thick-bedded orthoquartzite beds that were deposited in a subtidal high-energy environment;
2. A middle member that is characterized by interbedded siltstone and shale that were deposited in a low-energy tidal flat environment; and
3. A lower member consisting of shale with interbedded siltstone (Ojakangas, 1983).

A basal conglomerate that contains Archean rock fragments is locally present in the lower member. Also present locally within the top of the upper member of the Pokegama Formation, especially near Biwabik, MN, are thin horizons (<2 feet thick) of chalcedonic chert and/or conglomerate with rounded chalcedonic chert clasts that often exhibit syneresis cracks and algal-related bedding features.

The Pokegama Formation ranges from locally non-existent on the east end of the Mesabi Iron Range to more than 300 feet thick on the western end of the Mesabi Iron Range. The contact of the Pokegama Formation with the Biwabik Iron Formation ranges from sharp to gradational, wherein chert layers are present in the Pokegama and detrital quartz grains are locally present in the immediately overlying iron-formation. A wedge of hematite-stained, thin-bedded, siltstone with detrital quartz grains and local magnetite-bearing zones is present in the base of the iron-formation in the Hibbing to Biwabik area (see later discussions).

Biwabik Iron Formation

The name Biwabik was chosen by Van Hise and Leith (1901, p. 356) "… because the word Biwabik is the Chippewa word for a piece or fragment of iron." Leached and iron-enriched direct ores (or natural ores) were the first materials mined from strongly oxidized pockets along fault zones in the iron-formation, with the first shipment beginning in 1892. Taconite, which is the material that is mined today using magnetic separation methods, constitutes the majority of the iron-formation and pertains to the hard, non-oxidized portions of the iron-formation. The taconite typically contains 30-40% iron and 40-50% SiO_2, plus other components (Morey, 1992). The Biwabik Iron Formation is around 175-300 feet thick in the extreme eastern end of the Mesabi Iron Range at Dunka Pit (Bonnichsen, 1968), 730-780 feet thick in the central Mesabi Iron Range/Virginia Horn area near Eveleth, around 500 feet thick in the western Mesabi Iron Range near Coleraine, and eventually exhibits a "nebulous ending about 15 miles southwest of Grand Rapids"

(Marsden et al., 1968) on the extreme western end of the Mesabi Iron Range.

Since the early 20th century, the Biwabik Iron Formation has been subdivided into four informal members referred to as (from bottom to top): Lower Cherty member, Lower Slaty member, Upper Cherty member, and Upper Slaty member (Wolff, 1917). [**Note**: for brevity's sake the word "member" is not always mentioned in this report, and they are often referred to simply as Lower Cherty, Lower Slaty, etc.] The cherty members are typically characterized by a granular (sand-sized) texture and thick-bedding (beds ≥ several inches thick); whereas, the slaty members are typically fine-grained (mud-sized) and thin-bedded (≤1 cm thick beds). Note that slaty is a miner's term to denote parting parallel to bedding in these thin-bedded rocks, and the name is not indicative of metamorphism or slaty cleavage. The cherty members are largely composed of chert and iron oxides (with zones rich in iron silicate), while the slaty members are composed of iron silicates and iron carbonates with local chert beds. Both cherty and slaty iron-formation types are interlayered at all scales, but one rock type or the other predominates in each of the four informal members, and they are so-named for this dominance. The slaty members are envisioned to have been deposited on the outer shelf as an iron-rich chemical mud in a deep-water/low-energy environment (below storm wave base) as a result of either the warming of upwelling iron-rich waters (Morey, 1993), or mixing of a stratified water column due to storm events (Pufahl and Fralick, 2004). Shoreward-moving tidal currents and storm events appear to have disrupted this chemical mud and generated granules that were transported shoreward and reworked in a shallow-water, high-energy environment to form the cherty members (Pufahl and Fralick, 2004; Ojakangas et al., 2005). Thus, the granules that comprise the cherty members are interpreted as intraclasts derived from within the basin. The repetition of the major cherty and slaty members was first interpreted by White (1954) as being the result of transgressive and regressive ocean events.

The four-fold lithostratigraphic division of the iron-formation has long been recognized, and is still used at each of the currently operating (and inactive) taconite mines along the Mesabi Iron Range (Fig. 2). However, as mining operations advanced, each of the companies further subdivided each of these members into several submembers on the basis of sedimentalogical textures (bedding-types), mineralogical changes (some of which are probably related to diagenetic changes – and metamorphic changes near the Duluth Complex), and changes in ore versus waste rock characteristics. It is at this point that the stratigraphic naming conventions of the iron-formation diverge and become less well-defined from one end of the Mesabi Iron Range to the other. This naming problem arises because each mine uses a different numbering system, or in some cases an alphabet system, to denote the various submembers. For example, some mines start numbering the submembers upward from the bottom of the iron-formation; whereas, other mines start at the top of the iron-formation and number downward. Furthermore, the actual terminology used to describe a particular bedding type that is unique to a specific submember at one mine may differ from the bedding terminology used to describe the exact same bedding type at an adjacent mine, i.e., wavy-bedded versus irregular-bedded, or one's concept of whether the rock is regular-bedded (measured in inches) or thick-bedded (measured in feet). Because each of the mines developed their submember terminology independent of (or largely independent of) an adjacent mine's terminology, the overall result was a collage of submembers that seemed similar in some areas, but vastly different in other areas.

Other differences in submember terminology that may have developed over the years include the following:

- Most of the submembers were determined in the 1960s and 1970s as the taconite mines were first developed and became operational during "boom" years. However, during "bust" years, the younger geologists that were "learning the ropes" were laid off, and several years later the older geologists retired without "passing the baton" to their non-existent replacements. Geologists were eventually hired again in some of the mines, but they had to learn how to recognize the predetermined submembers with little to no personal guidance;
- Even though the initial submember definitions were based on hundreds of drill holes (mostly shallow holes in the Lower Cherty member), those descriptions could not account for lateral or downdip facies changes that showed up in later years. A perfect example of this is the 8-3 submember at Hibbing Taconite (see later discussions);
- The geologists logging the holes for the mining companies probably had to log the holes as quickly as possible to stay ahead of rapidly advancing pit boundaries. For this reason, the geologists were not able to hang the holes on stratigraphic sections (as we were able to do in this investigation), and thus, they were not able to recognize distinct lateral and downdip facies changes;
- Over periods of time, some of the submember terminologies developed a "life of their own," and differences related to localized facies changes were continually added to the initial descriptions which eventually became a potpourri of bedding types;
- Not all of the companies adhered to a strict usage of dominantly thin-bedded zones as belonging to either the Upper Slaty or Lower Slaty members. For example, in some cases, relatively thick zones of thin-bedded rocks are classed as being submembers of the Upper Cherty, and thicker-bedded zones at depth are classed as being associated with the Lower Slaty. A good example is the UC-13 and UC-11 submembers of the Upper Cherty at Minntac which are thin-bedded and probably should have been classed as Lower Slaty submembers (see later discussions);
- Some mines appear to have had a preconceived notion of how thick a particular member or submember should be, and thus, classed it according to an average thickness rather than classing it as to its true bedding type;
- Some mines use the ore grade characteristics of particular horizons to aid them in establishing the submember nomenclature regardless of whether bedding types changed, or didn't change, across the ore grade changes. An example of this is the LC-3 and LC-2 submembers at United Taconite (see later discussions);
- In some areas of the Mesabi Iron Range (Hibbing to Grand Rapids), the uppermost units of the Lower Cherty are often strongly leached and oxidized. In these cases, it can be difficult to peer through this alteration type (often coupled with poor core recovery) and make accurate descriptions of the bedding types that are present. Thus, it is a challenge to compare bedding types in these oxidized zones to descriptions of bedding types in less oxidized rocks situated further to the east. A perfect example of this is the oxidized LC-1, LC-2, and LC-3 submembers at Keewatin Taconite and the oxidized 1-8 submember at Hibbing Taconite relative to other, less oxidized corresponding submembers at other mines; and

- Lastly, the submember terminology that works in one mine may not be applicable in an adjacent mine due to facies changes, pinch-outs, and drastic thickening and thinning of particular units. In essence, the submember descriptions as applied by each of the mines could be likened to localized "windows" that, in some cases, change laterally.

Plate I, from Zanko et al. (2003) and reproduced for this report, was the first attempt at correlating the submembers as described by each of the mines. This initial attempt used handouts (Fig. 3) obtained from each mine that describe that mine's particular stratigraphy. Key words used to describe the bedding type for each submember were "plucked" out of these handouts and added to the columns that are portrayed for each mine in Plate I. Because these stratigraphic descriptions are mainly from handouts that are not easily available, Plate I, which is now outdated, is presented herein for the historical record.

As drill holes were logged for this investigation, it became readily evident that certain key words in the mine handouts could often be re-interpreted with respect to bedding types, i.e., wavy-bedding at one mine was the same as irregular-bedding at an adjacent mine. In this manner, we were able to rebuild the stratigraphic columns for each of the mines that are now more correctly portrayed in Plate II of this report. In essence, Plate I was based on varied submember descriptions wherein the authors had very limited experience in the form of actually logging Biwabik Iron Formation drill core. Conversely, the stratigraphy portrayed in Plate II couples those early mine descriptions with actual drill core observations. Much of this report will be to describe the stratigraphy as portrayed in Plate II in more detail.

Virginia Formation

The Virginia Formation is a thick sequence of argillite, siltstone, and graywacke at the top of the Animikie Group. On the basis of lithotypes present in five drill holes, Lucente and Morey (1983) divided the Virginia Formation into two informal members – a lower argillaceous lithosome and an upper silty and sandy lithosome. The lower lithosome is approximately 600 feet thick and contains common intervals wherein black, thin-bedded, carbonaceous argillite is the dominant rock type; visible sulfides are locally present – especially in the eastern Mesabi Iron Range. These carbonaceous argillites indicate that deposition of the lower lithosome occurred by slow accumulation of black mud in deep water under anoxygenic conditions (Lucente and Morey, 1983). The distribution of specific packages of carbonaceous argillite layers within the lower lithosome are staggered and overlapped at different horizons (Fig. 4). This relationship indicates that deposition of the carbonaceous argillite packages took place in small, restricted basins, e.g., 3rd order basins that are typically several hundred meters to a few kilometers in lateral extent, within the Animikie Basin. Fine-grained, sericite-rich tuffaceous beds are locally present within the lower lithosome (Fig. 4), and in some locales these beds are up to five feet thick. Also, chert and limestone beds (and/or carbonate concretions) may be present near the base of the Virginia Formation.

The upper lithosome also consists dominantly of argillite, but it generally lacks carbonaceous argillite, and instead, contains abundant interbeds of siltstone and fine-grained graywacke that were deposited via turbidity currents in a prograding submarine fan complex (Lucente and Morey, 1983). All varieties of Bouma sequences, A through D, are exhibited by the graywacke beds.

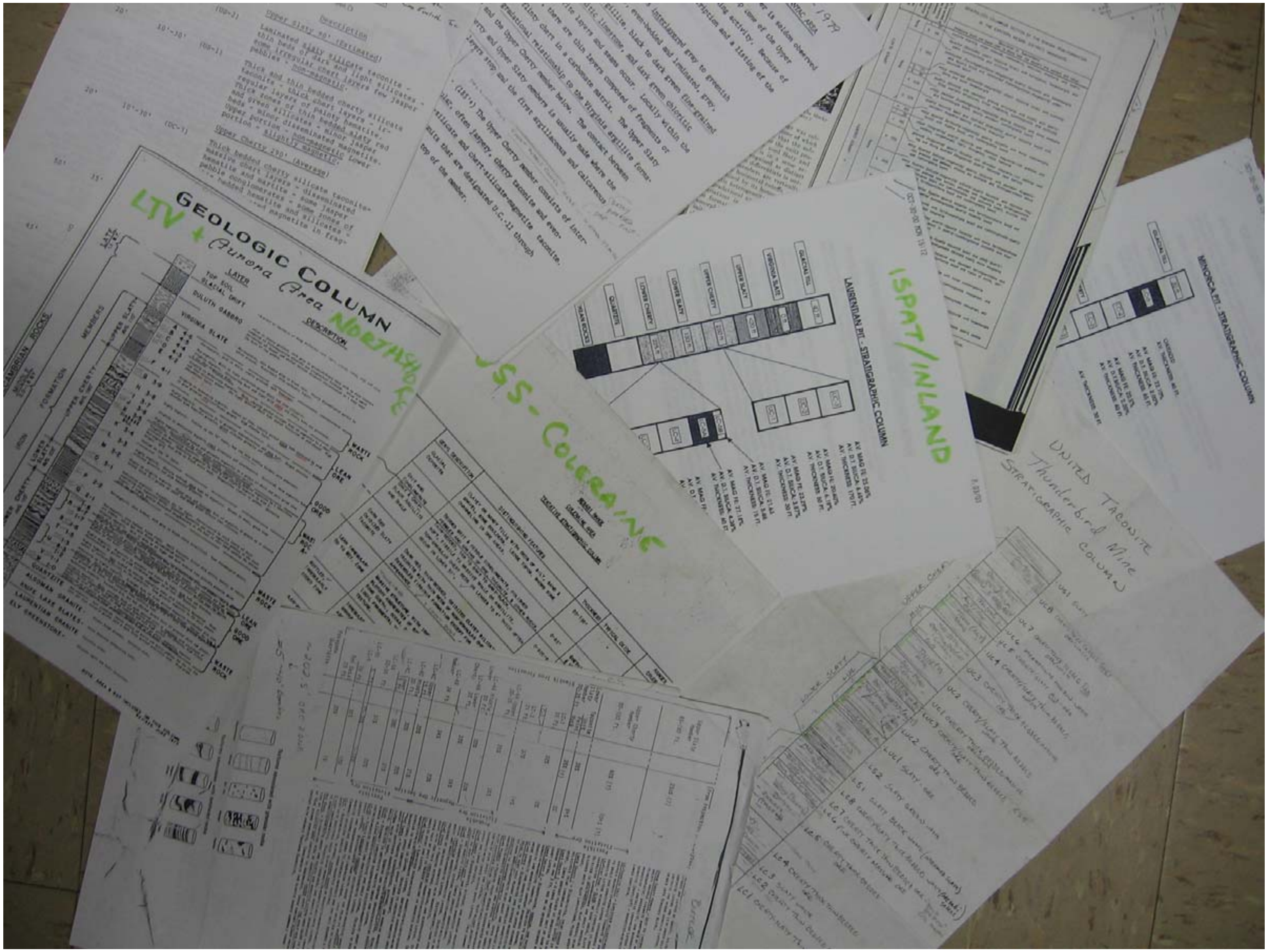
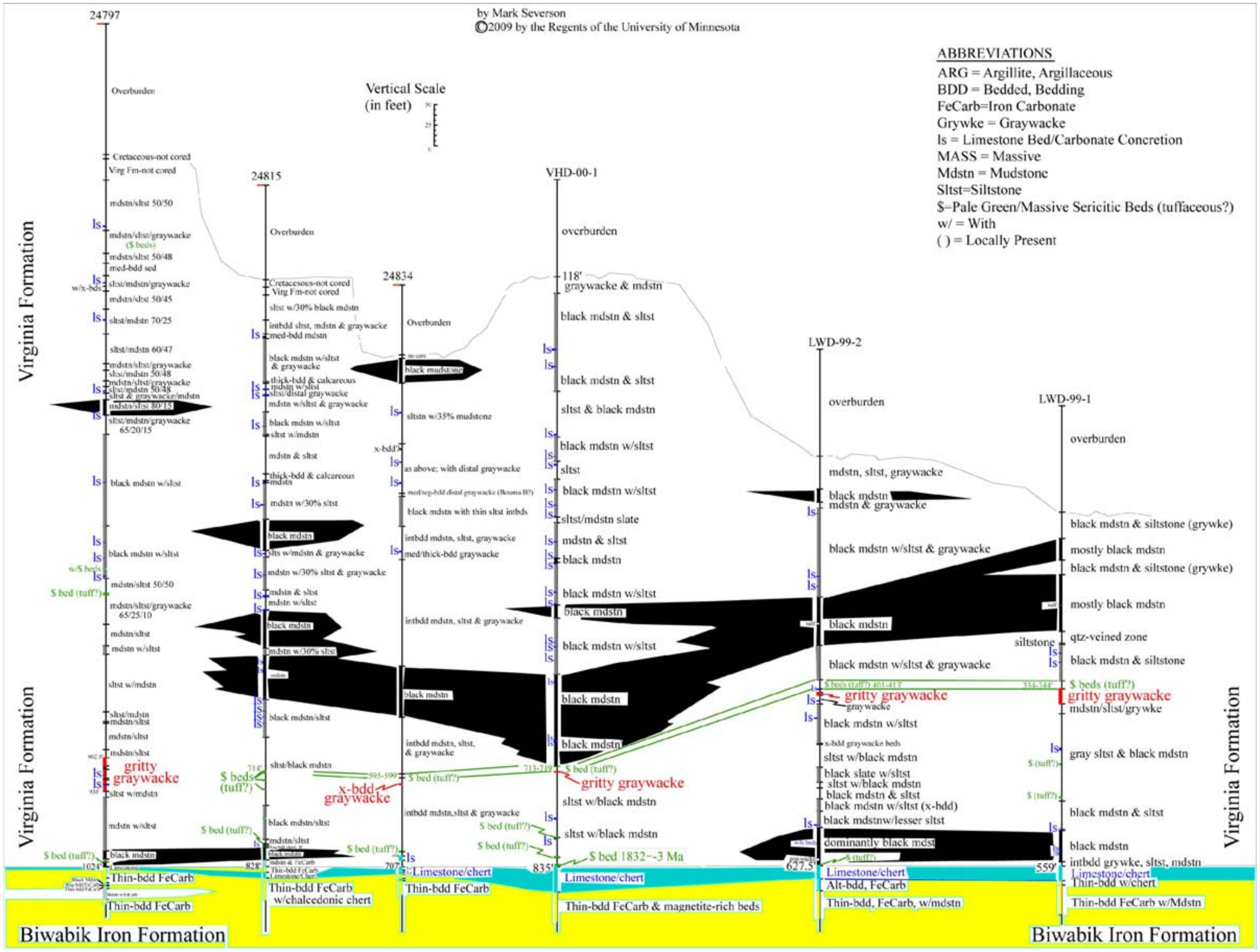


Figure 3. Photograph of the various handouts given by the mining companies that describe their submember terminology in regard to stratigraphy of the Biwabik Iron Formation along portions of the Mesabi Iron Range.



by Mark Severson

ABBREVIATIONS

ARG = Argillite, Argillaceous

BDD = Bedded, Bedding

FeCarb=Iron Carbonate

Grywke = Graywacke

ls = Limestone Bed/Carbonate Concretion

MASS = Massive

Mdstn = Mudstone

Sltst=Siltstone

$=Pale Green/Massive Sericitic Beds (tuffaceous?)

w/ = With

( ) = Locally Present

Figure 4. Correlation of geologic units within the Virginia Fm. in six deep drill holes from the central Mesabi Iron Range. All drill holes hung on the top of the Biwabik Iron Formation (bottom of figure). Zones with dominantly black mudstone/slate in the Virginia Fm. are shown in black. Fissile, pale green-colored, sericite-rich tuffaceous(?) beds are shown in green (note position of the sample wherein a 1,832 Ma age was obtained by Addison et al. (2005) in drill hole VHD-00-1). Gritty graywacke beds that are closely associated with a persistent tuffaceous unit are positioned 100-200 ft. above the base of the Virginia Fm. and are shown in red. Limestone/dolomite beds and/or carbonate concretions are shown in dark blue. A carbonate horizon containing chert and mudstone interbeds at the top of the Biwabik Iron Formation shown in light blue – note that this horizon contains, near its base, an ejecta layer related to the Sudbury impact event (1,850 Ma). Locations of drill holes portrayed in this figure are shown in Figure 48 in the appendices.

The contact with the Biwabik Iron Formation varies from sharp to highly gradational, depending on the locality. Over much of the Mesabi Iron Range, clastic argillaceous sediments are in sharp contact with a carbonate horizon at the top of the iron-formation. However, even in these instances carbonate lenses/beds may also occur near the base of the Virginia Formation, as well as in the top of the iron-formation. In addition, chert beds are also locally present in the base of the Virginia Formation, and in a few localized areas, the top of the iron-formation contains clastic argillite interbeds. At the west end of the Mesabi Iron Range (to the west of Nashwauk), the contact between the Biwabik Iron Formation and Virginia Formation is highly transitional. There, the base of the Virginia Formation contains several packages of thin-bedded carbonate iron-formation that are intricately interbedded with argillite and carbonaceous argillite. In these areas, it is difficult to place the contact accurately between the two formations, and the top contact of the Biwabik is arbitrarily placed at the zone where the carbonate iron-formation contains common chert beds and argillaceous beds become absent (Zanko et al., 2003; Severson et al., 2003).

The clastic rocks of the Virginia Formation were largely derived from Archean rocks to the north, with some contributions from older Paleoproterozoic rocks to the south (Lucente and Morey, 1983). However, limited neodymium and lead isotope data suggest that detritus in the Virginia Formation was derived mainly from a Paleoproterozoic source (2.32-1.86 Ga; Hemming et al., 1995) that was presumably located to the south in the Fold-and-Thrust Belt.

Depositional Environment

Precambrian iron-formations throughout the world have long posed problems in understanding how they formed because there are no modern day analogs for comparison. Numerous hypotheses regarding their deposition have been proposed, abandoned, and re-awakened throughout the last 100 years, and a discussion of all of them is beyond the scope of this investigation. However, there are some salient points that must be considered regarding their origins. First, iron-formations are generally grouped into two main categories: Algoman type or Superior type (Gross, 1965). The Algoman type iron-formations are generally older than 2.6 Ga, small in extent, and are associated with volcanic activity. Superior type iron-formations are: 1) generally much larger in extent and form the most extensive iron ranges in the world; 2) associated with continental margins; and 3) range from 1.8-2.6 Ga in age. The Superior type is further broken down into two types that include:

- BIF or Banded Iron-formation that:
    - is thin-bedded (or micro-banded);
    - formed in deep water well below storm wave-base;
    - is the most common of the Superior type iron-formations; and
- GIF or Granular Iron-formation that:
    - is variably-bedded (including thick-bedded);
    - formed in shallow water where they were modified by wave action (as evidenced by sedimentary structures such as cross-bedding, stromatolites, conglomerates, flat bed conglomerates, ooids, ripples, and syneresis cracks); and
    - is not as volumetrically important as the BIF iron-formations.

The Biwabik Iron Formation, which is a Superior type, contains both BIF and GIF types in the slaty and cherty members, respectively. Much larger versions of Superior type BIF are present in South Africa (Transvaal

Supergroup), Australia (Hamersley Group), and South America (Carajas Formation and Itabira Group).

One of the early problems related to deposition of iron-formation was the source of all the iron. Early debates centered on whether it was possible to derive all of the iron from weathering of pre-existing rocks, whether the ancient seas could hold all of this iron, and what caused these massive amounts of iron to eventually (rapidly?) precipitate out of those oceans. The current theory is that the primary source of iron in the seawater was related to volcanism and mantle superplume activity (Isley and Abbott, 1999), with lesser contributions from surface weathering. This connection between mantle superplumes and iron-formation deposition helps to explain why Superior type iron-formations throughout the world do not appear to be distributed evenly in time and space (Simonson, 2003). In Minnesota, rifting and volcanism associated with possible superplume activity may have taken place well to the south of the Animikie Basin in the Fold-and-Thrust Belt.

The precipitating mechanism in the deposition of iron-formations was at one time inferred to be the production of abundant oxygen in the early earth's atmosphere by cyanobacteria (Cloud, 1973). Fossilized stromatolites that are often associated with the iron-formations helped to support this concept. Some researchers (Klein, 2001) discount this "oxygen oasis" concept, and it is no longer considered to be the sole trigger in the deposition of iron-formations; however, its contribution cannot be fully discounted, and evidence for microbial involvement is increasing (Simonson, 2003; Planavsky et al., 2009 and references therein). The common lack of detrital grains in Superior type iron-formations suggests that either they were deposited beyond the range of effective offshore epiclastic influx (Trendall, 2002), and/or they were deposited in basins where nothing else was accumulating fast enough to dilute them (Eriksson, 1983).

Morey (1993 p. 12-13; and Morey et al., 1991) has proposed a mechanism for the deposition of iron-formations in Minnesota, and potentially for all Superior type iron-formations, that is quoted below and illustrated in Figure 5:

"… silica and ferrous iron from both anoxic weathering and volcanic sources accumulate in an extensive anaerobic marine basin. Upwelling of water rich in silica and iron … onto a shallow-water shelf leads to three separate but interrelated processes. First, the waters are warmed and carbon dioxide is lost, triggering the precipitation of siderite ($FeCO_3$)*. Second, nutrients in the upwelling waters stimulate the growth of protoalgae and cyanobacteria, and consequently the production of photosynthetic oxygen. The presence of that oxygen leads to the conversion of ferrous iron to ferric iron and the precipitation of insoluble ferric hydroxides, which ultimately are converted to hematite … magnetite is produced in this setting by the diagenetic breakdown of hematite (Han, 1978, 1982) via the reaction hematite + organic carbon yields magnetite +* CO_2 *(Perry et al., 1973). This reaction shows that the amount of magnetite that can form is controlled by the amount of organic carbon available in the diagenetic system. … Finally, … silica will precipitate in response to warming on a shallow water shelf … [or] … the precipitation of iron … constitutes a release of acid and a trend toward a solution that is neutral to slightly alkaline, a condition that also favors the precipitation of silica."*

In regard to deposition of the Animikie Group in Minnesota, the Pokegama Formation is interpreted to have been deposited in a tidally-influenced shallow marine setting near the shoreline (Ojakangas, 1983). In this model, depicted in Figure 6:

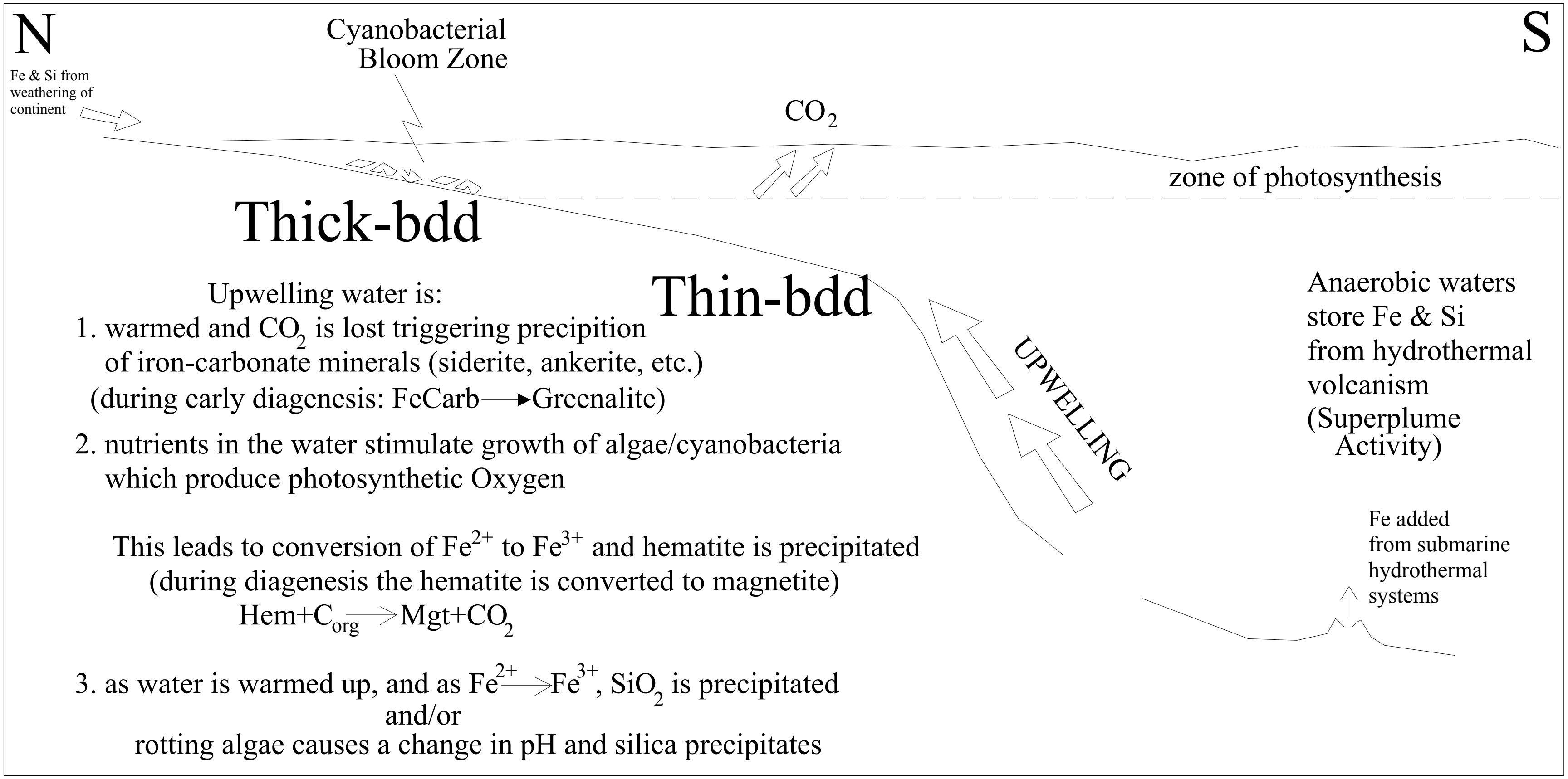


Figure 5. Proposed mechanisms for the allochemical deposition of Superior type iron-formations (modified from Morey et al., 1991).

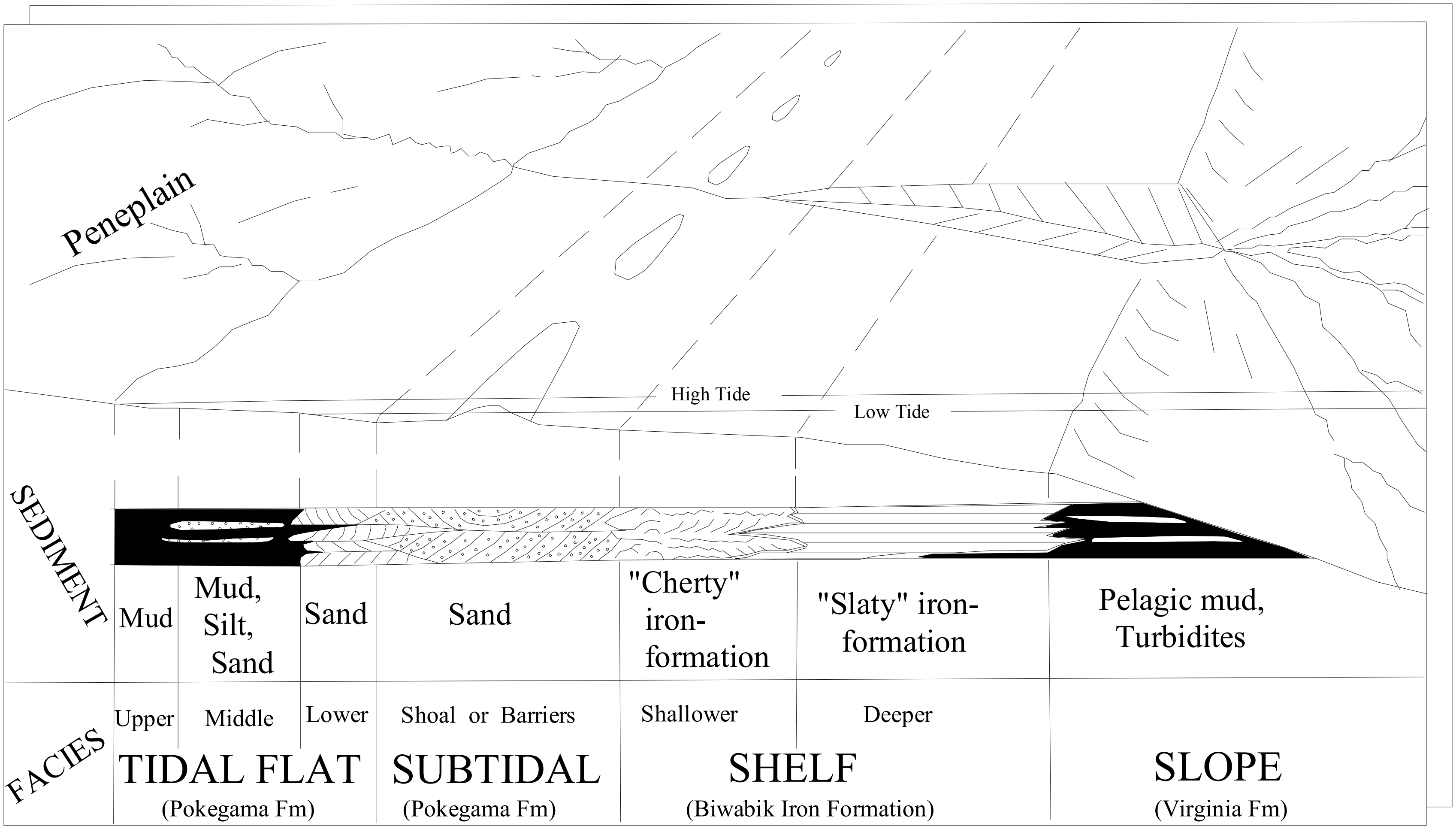


Figure 6. Sedimentation model showing lateral relationships of the Pokegama Formation, the two main types of Biwabik Iron Formation, and the Virginia Formation. Thicknesses and geography not to scale; modified from Ojakangas (1983).

1. The lower member (shale with interbedded siltstone) was deposited in the upper tidal flat;
2. The middle member (interbedded siltstone and shale) was deposited seaward in the middle tidal flat; and
3. The upper member (quartz arenite) was deposited still further seaward in a lower tidal flat/subtidal environment (Ojakangas et al., 2005).

Invoking Wather's Law, Ojakangas (1983) concluded that the Biwabik Iron Formation was synchronously deposited seaward of the Pokegama Formation, and the Virginia Formation was deposited still further offshore in a deep water euxinic environment. The slaty members of the iron-formation were deposited on the outer shelf as chemical muds, and the cherty members were deposited landward as reworked materials in a shallow marine, tidally dominated shelf (Ojakangas et al., 2005). Fluctuations in sea level, in response to episodic tectonic processes associated with the Fold-and-Thrust Belt to the south (Southwick et al., 1988), were responsible for repeated deposition of the various slaty and cherty members during periods of regression and transgression.

It has been recently postulated that deposition of the iron-formations in the Lake Superior region was halted by the Sudbury impact event at 1850 Ma (Cannon and Addison, 2007; Jirsa, 2008; Cannon and Schulz, 2009). Field and petrographic evidence for this event are clear in the Gunflint Iron Formation (Addison et al., 2005; Jirsa, 2008) and in the Paleoproterozoic iron ranges of Michigan (Cannon et al., 2009). However, an indication of this event in the top of the Biwabik Iron Formation is more subtle, possibly due to deeper water conditions that are recorded in the presently mined and drilled stratigraphic section. Thus, evidence for this event may have been largely overlooked. Possible beds, with shocked quartz grains (as well as spherules and microtektites that are often replaced by carbonate and silica) that record this event are present near the base of a carbonate layer at the top of the Biwabik Iron Formation (Addison et al., 2005, 2007). This carbonate layer, which extends from Dunka Pit to Hibbing along the Mesabi Iron Range, has been recently looked at in several drill holes (by Bill Addison, Phil Fralick, and the authors of this report in June, 2009), and evidence for the Sudbury event was noted in less than 1/3 of the holes. This evidence suggests this event is not preserved at all localities due to later reworking of the ejecta materials. Intraformational conglomerate beds are also common in the carbonate layer. It is possible that some of these conglomerates record storm events, whereas other conglomerate beds record either an early seismic shaking event or later tsunami events that typically follow meteor impacts into bodies of water. Overall, these conglomeratic beds are generally less than a few inches thick, and several horizons are often present in a single drill hole. It is difficult to separate one type of event from the other. Cannon and Schulz (2009) report the presence of shocked quartz and microcline at the top of the Biwabik Iron Formation in one drill hole (MGS-8) in the vicinity of Coleraine, MN. There, however, the top of the iron-formation is **not** well defined due to the interbedded nature of the Biwabik and Virginia formations in several drill holes (as is portrayed in Plate XV and as described by Zanko et al., 2003), and the ejecta layer can be interpreted to be at the top of an iron-formation lense in the base of the Virginia Formation. However, it is important to point out that no iron-formation lenses are present within the Virginia Formation above the Sudbury ejecta layer. Studies to more clearly define this event/time-line on the Mesabi Iron Range, as well as in the nearby Emily District and Cuyuna North Range, are ongoing, and the possibility of finding more impact-related evidence is exciting.

The Virginia Formation was deposited seaward of the iron-formation, probably in a slope-type environment, where "quiet-water" clastic mud deposits were interbedded with sandstones/graywackes related to episodic turbidity currents. The contact with the underlying iron-formation is sharp in some areas and gradational in other areas, with carbonate and thin-bedded carbonate iron-formation lenses occurring in the Virginia Formation near the basal contact zone. In several deep drill holes in the Virginia Horn area, a series of gritty graywacke beds and sericitic tuffaceous beds are present about 100-200 feet above the base of the Virginia Formation (Fig. 4). These gritty graywacke beds are anomalous in that they are slightly coarser-grained than normal, and they display sedimentary features indicative of a more energetic turbidity event – possibly related to distal volcanism and associated seismicity, or a very large storm event.

Mineralogy and Diagenesis

The Biwabik Iron Formation is comprised of various minerals as listed in Table 1. Though no thin section study was conducted as a part of this investigation, the following generalizations can be made based on megascopic observations. Fine-grained iron carbonates and iron silicates with variable amounts of magnetite and chert are common to the thin-bedded slaty submembers. Iron carbonates are also present in the cherty submembers as pink-colored mottles (up to 1 cm across) and pink- to brown-colored beds and laminae. Iron silicates are common in some of the cherty submembers, especially in the top of the Lower Cherty and in broad zones in the center of the Lower Cherty. Chert and magnetite are most evident in the cherty submembers, but both can be abundantly present in portions of the thin-bedded submembers. Calcite and dolomite are mainly restricted to carbonate beds at the very top of the iron-formation. Oxidized zones

Table 1. Common mineral names and formulas associated with the Biwabik Iron Formation (excluding the more highly metamorphosed eastern Mesabi Iron Range in proximity to the Duluth Complex).

Chert	SiO_2
Chalcedony	SiO_2
Microcrystalline Quartz	SiO_2
Magnetite	Fe_3O_4
Hematite	Fe_2O_3
Goethite	$HFeO_2$
Siderite	$FeCO_3$
Ankerite	$Ca(Fe,Mg)(CO_3)_2$
Stilpnomelane	$K(Fe^{+2}, Fe^{+3},Al)_{10}Si_2O_{30}(OH)_{12}$
Minnesotaite	$Fe_3Si_4O_{10}(OH)_2$
Greenalite	$Fe_6Si_4O_{10}(OH)_8$
Chamosite (iron-chlorite w/significant Al)	$Fe_6(Al,Si)_4\ O_{10}(OH)_8$
Talc	$Mg_3Si_4O_{10}(OH)_2$
Calcite	$CaCO_3$
Dolomite	$CaMg(CO_3)_2$

of the iron-formation contain various amounts of hematite and goethite in addition to the other minerals

On the basis of one hole located in the Virginia Horn area, McSwiggen and Morey (2008) note that in unmetamorphosed iron-formation, chamosite (iron-rich chlorite with considerable aluminum) is restricted to the Upper Slaty, Upper Cherty and Lower Slaty members. They also noted that greenalite, minnesotaite, and talc are restricted to the Lower Cherty member. However, Ojakangas reports (*in* Zanko et al., 2003) that greenalite is not common in the Lower Cherty in one hole studied in the western Mesabi Iron Range. French (1968) noted that chamosite is a major constituent of the "intermediate slate" at the base of the Lower Slaty. Other minerals not mentioned in Table 1 are those associated with more highly metamorphosed iron-formation in close proximity to the Keweenawan mafic intrusive Duluth Complex on the eastern end of the Mesabi Iron Range – this area of the iron-formation was not included in this investigation.

Morey (1992) reports, that on average, the cherty members contain more silica than the slaty members. In turn, the slaty members contain more CaO, MgO, and CO_2, indicating the importance of carbonate in the fine-grained thin-bedded rocks (Morey, 1992). The slaty members also contain more Al_2O_3, reflecting increases in stilpnomelane (Morey, 1992). Morey and Morey (1990) suggested that the stilpnomelane may be titanium-bearing based on a positive correlation between TiO_2 and Al_2O_3. These relationships suggest that the slaty members may, in part, be due to a volcanic contribution (Schmidt, 1958; Morey, 1992). Shard-like features associated with stilpnomelane have been reported to be present in the carbonaceous-rich "intermediate slate" at the base of the Lower Slaty (Morey et al., 1972; Perry et al., 1973).

The detailed origins of the various iron minerals that constitute the Biwabik Iron Formation are beyond the scope of this investigation (no petrographic work was conducted). In fact, there is controversy about which of the minerals in any Lake-Superior type iron-formation represent original precipitates as opposed to diagenetic phases (Simonson, 2003). Replacement of the granules during diagenesis has been extensive. Eh and pH are major controls on the stability of the iron minerals in both the depositional and diagenetic environments (Ojakangas et al., 2005). Klein (2005) has suggested that the original precipitate materials that were deposited were probably: hydrous Fe-silicate gels of a greenalite type composition; Na-, K- and Al-containing gels approximating stilpnomelane compositions; SiO_2 gels; $Fe(OH)_2$ and $Fe(OH)_3$ precipitates; and very fine-grained carbonate oozes. Greenalite is a mineral that is commonly reported to be primary/early diagenetic in that it exhibits no detectable replacement of any pre-existing phase (French, 1973; LaBerge et al., 1987; Simonson, 1987; Klein, 2005). Greenalite most often occurs as round-shaped granules that are <1 mm in diameter. Siderite is also reported to be early diagenetic (LaBerge et al., 1987). Primary, fine-grained hematite is present in the "basal red unit" at the base of the Lower Cherty and as concentric layers in ooids in the stromatolite horizon in the Upper Cherty (Morey, 1993). Silica, occurring as granules and ooids – often with syneresis cracks – is inferred to be a primary precipitate (LaBerge et al., 1987; Simonson, 1987). However, the silica cement in GIF-type iron-formations is inferred to be a diagenetic product, possibly related to thermal waters moving laterally out of depositional basins (Simonson, 1987).

Fine-grained magnetite is probably primary, but numerous researchers have come to the conclusion that the majority of magnetite grains, which are relatively coarse-grained and commonly euhedral, are late diagenetic in origin (LaBerge, 1964; LaBerge et al., 1987; Zanko et al., 2003) and form by the replacement of pre-existing iron silicates and iron carbonates (French, 1973). Minnesotaite generally occurs as sheaves or needles that replace greenalite (French, 1973), and is a diagenetic product as in the following reactions (Klein, 2005):

- $Fe_6Si_4O_{10}(OH)_8 + 4SiO_2 \rightarrow 2Fe_3Si_4O_{10}(OH)_2 + 2H_2O$
  greenalite chert minnesotaite
- $2Fe_6Si_4O_{10}(OH)_8 + O_2 \rightarrow Fe_3Si_4O_{10}(OH)_2 + 2Fe_3O_4 + 3H_2O$
  greenalite minnesotaite magnetite
- $FeCO_3 + 4SiO_2 + H_2O \rightarrow Fe_3Si_4O_{10}(OH)_2 + 3CO_2$
  siderite chert minnesotaite
- $Fe_{2\text{-}7}(Si,Al)_4(O,OH)_{12}\cdot xH_20 \rightarrow Fe_3Si_4O_{10}(OH)_2 + H_2O$ + minor (Na,K)
  stilpnomelane-like minnesotaite.

Stilpnomelane is a secondary mineral that commonly replaces early iron silicates, most commonly greenalite (French, 1973). French (1973) suggests that stilpnomelane formed under conditions ranging from diagenesis to low-grade metamorphism. A few occurrences of both chamosite and talc were reported by French (1973), but more recently, McSwiggen and Morey (2008) show that both minerals are common throughout portions of the Biwabik Iron Formation.

Fine-grained siderite and ankerite are probably primary, but coarser-grained variants of both minerals are secondary, as they replace earlier minerals. Ankerite mottles are a good example of this secondary replacement. In some areas, the mottles are so abundant that large patches of the iron-formation consist of massive ankerite.

Ojakangas (*in* Zanko et al., 2003) reports the following paragenetic sequence in one drill hole in the Biwabik Iron Formation of the western Mesabi Iron Range: 1) chert and greenalite granules are replaced by minnesotaite; 2) minnesotaite, in turn, is replaced by carbonate; 3) carbonate is replaced by stilpnomelane; and 4) stilpnomelane is replaced by magnetite. In addition, some granules of chert and greenalite, as well as chert cement, have been replaced by magnetite.

Methodology of Logging Drill Core

Geologists at the NRRI first began looking at the Biwabik Iron Formation in drill holes at the eastern end of the Mesabi Iron Range beginning in 1989. In these holes, the iron-formation is metamorphosed and is present as footwall rocks beneath the Duluth Complex – only the top three submembers of the Upper Slaty were typically intersected in these holes. In 2002, drill holes that intersect the entire iron-formation were logged by NRRI geologists as part of an oxidized taconite project on the western end of the Mesabi Iron Range (Zanko et al., 2003). Plate I was constructed for this particular project to show how submembers at each of the mines could be correlated from one end of the Mesabi Iron Range to the other. Holes were logged on the basis of bedding types (portrayed in Pfleider et al., 1968) and the degree of oxidation. Deep holes, situated 1-3 miles south of the Mesabi Iron Range, were logged shortly thereafter (2002-2004) and included four holes from the Mesabi Deep Drilling Project (Pfleider et al., 1968 – MGS-series holes) and three holes drilled by BHP in the Virginia Horn area. [It is important to note that these seven holes were logged before we gained a more intimate understanding of the characteristics displayed by the submembers as defined by each of the taconite mines, and these holes should be re-logged.]

Beginning in 2005, NRRI geologists began logging additional holes as part of an aggregate project (part of which is presented in Fosnacht et al., 2006) in the Virginia Horn area. The initial drill hole logging program was continued and expanded, and led to the more comprehensive evaluation of the aggregate potential of the Biwabik Iron Formation presented in this report. Holes were logged concurrently from the Thunderbird North Mine (United Taconite = Utac) and the McKinley Extension/East Reserve Mine (ArcelorMittal). Both Peter Jongewaard and John Arola, from each of the respective mines, were very instrumental in pointing out how they recognize each of their mine's particular submembers. At this point, the bedding types, as illustrated in Figure 7 (which is a modification of a similar figure in Pfleider et al., 1968), were developed and used in all the subsequent logging endeavors.

As just described, this project (and report) built upon the work initiated in 2005 by undertaking a slew of drill core logging campaigns on newly-drilled holes at Hibbing Taconite (Hibtac), the East Reserve/McKinley Extension near Biwabik, MN, and Keewatin Taconite (Keetac) between 2006-2009. Most of these holes have since been consumed for chemical testing purposes. Several hundred historical holes that were drilled at many locations across the Mesabi Iron Range by United States Steel Corp. (USS) were found and inventoried at Minntac. Over 50 of these holes were logged for this project. Lastly, the core from several holes drilled jointly by USS and J&L Steel were located and logged at Lerch Brothers in Hibbing, MN. The total amount of holes and total feet logged in the Biwabik Iron Formation for this and previous projects are presented in Table 2.

After several holes from a specific mine area were logged, each of the holes were then plotted on hung stratigraphic cross-sections

Table 2. Listing of amount of holes logged to date in the Biwabik Iron Formation since 2004 by NRRI personnel. The Oxtac holes were logged for a previous project in 2002 (Zanko et al., 2003). The general holes category includes the Mesabi Deep Drilling Project holes (MGS-2, 5, 7, and 8) and three holes drilled by BHP in 1999-2000. These general holes served as "cutting teeth" holes in regards to identifying the submembers as recognized at nearby taconite mining operations. MJS = Mark J. Severson, JJH = John J. Heine, MMP = Marsha Meinders Patelke, ST = Seth Trobec (a summer intern at the NRRI Coleraine Minerals Research Laboratory).

Area	**MJS holes/footage**	**JJH holes/footage**	**MMP holes/footage**	**ST holes/footage**	**Total holes/footage**
General	9/12,491 ft.	5/1,257 ft.			14/13,278 ft.
McKinley/East Reserve	28/8,515 ft.	102/22,555 ft.			130/31,070 ft.
United Taconite	9/5,346 ft.	7/4,224 ft.			16/9,570 ft.
Minntac	50/31,028 ft.	2/1,082 ft.	1/534 ft.		53/32,644 ft.
Hibbing Taconite	35/14,719 ft.		7/2,651 ft.		42/17,370 ft.
Keewatin Taconite	9/2,694 ft.	31/14,886 ft. (ongoing)		23/11,109 ft.	63/28,599 ft.
OxTac	33/14,905 ft.	34/4,046 ft.			67/18,951 ft.
Grand Total	173 holes 89,698 ft.	174+ holes 48,050 ft.+	8 holes 3,185 ft.	23 holes 11,109 ft.	**378+ holes** **152,042 ft.+**

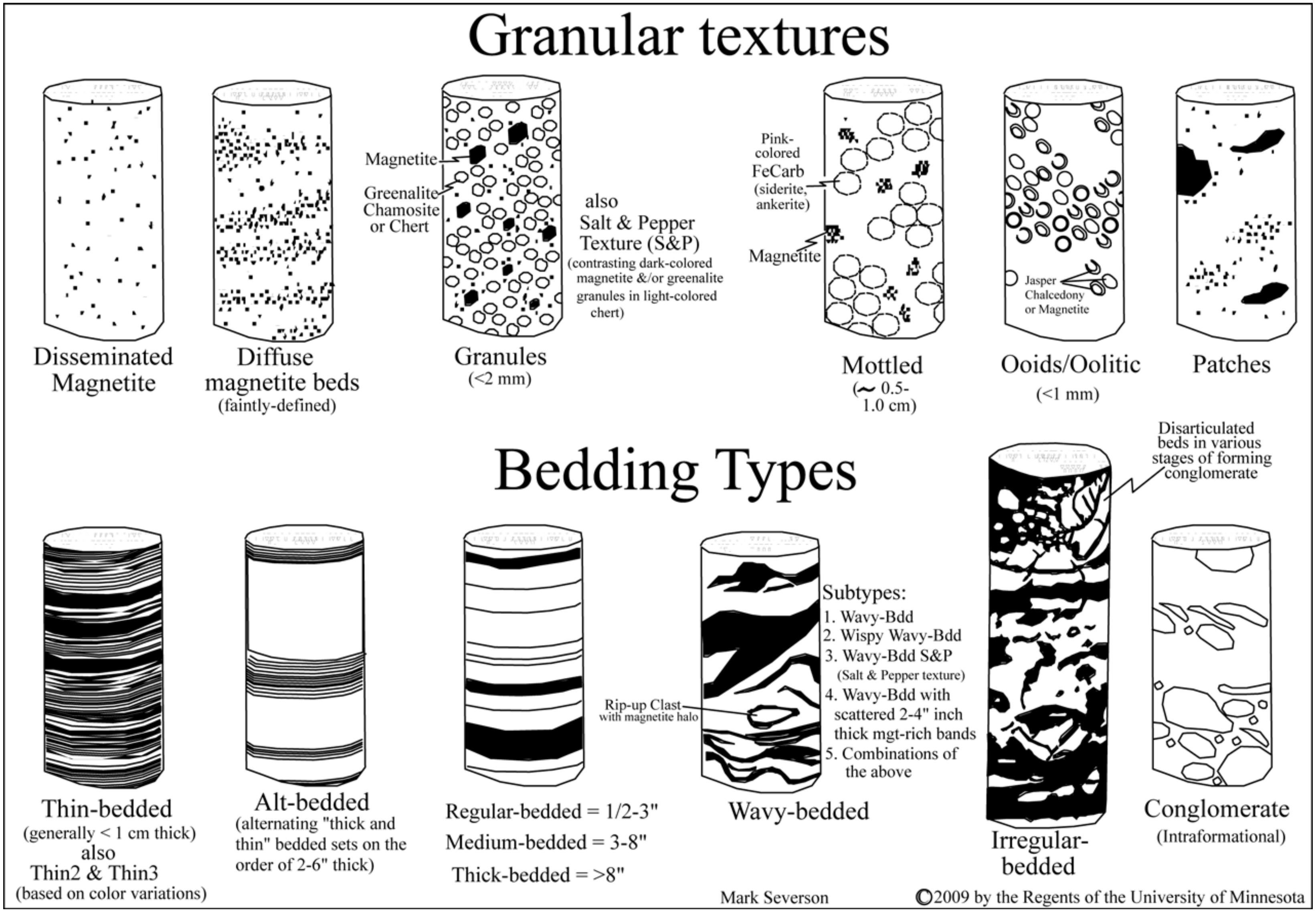


Figure 7. Template of textural and bedding characteristics of the Biwabik Iron Formation used during logging of drill core for this project. Modified from Pfleider et al. (1968).

(hung on the base of the Lower Slaty member) and individual submembers were correlated between holes. A large number of holes were used in an unbiased manner to dictate what particular characteristics were unique to each submember. These hung cross-sections, to be discussed in more detail later in this report (Plates III through XIV), were used to collectively make a generalized stratigraphic column for each mine, and in turn, each of these columns were added to Plate II. In essence, Plate II is the "Rosetta Stone" in that it can be used to illustrate how the submembers at one mine correlate with similar submembers at all of the other mines. It is important to note that the correlations presented in Plate II are unique, and they may deviate somewhat from the earlier Plate I interpretations (now outdated) based on the following:

- The geologists at each of the mines were very helpful in showing us what criterion they use to classify each of their submembers. Since we logged holes from one mine location before proceeding to an adjacent mine, it was often impossible for us to go back to the initial mine, due to time constraints, and re-look at their core for a second time to see if we could recognize a newly pointed-out submember criterion that was recognized at the second mine. This problem was compounded by the fact that many of the mines do not preserve their drill core due to storage space limitations. Thus, there was a definite **learning curve** in this investigation, and some of the earlier-logged holes should be revisited if the drill cores are still available.
- The correlations shown in Plate II are mainly based on the geologic units intersected in deep drill holes that intersect the entire iron-formation. Because many of these holes are situated downdip of the actual pit margins, it is entirely possible for there to be differences between our submember thickness determinations and previously-determined mining company-related submember thickness determinations.
- Because ore grades, and conversely the grades of the waste zones, are unknown, these data were not used as a factor in determining most of the submembers portrayed in Plate II. This situation is unfortunate and results from the fact that the mining companies are reluctant to release these types of data. The corporate submember division criterion may be completely applicable in zones where the grade changes across a boundary, but a corresponding change in the bedding type is not easily discernable across that same boundary.
- It may be possible that each of the mines treats each of the submembers as being uniform in thickness across the entire mine for mining purposes. We were not under those same constraints and based our submember divisions solely on bedding type characteristics with disregard to establishing uniform thickness determinations.
- Lastly, it is important to note that almost all of the contacts between submembers are transitional/gradational, and it is always possible to differ in where a contact is actually placed by up to 15 feet from another geologist's interpretation.

Bedding Types

For our purposes, the divisions of submembers in the iron-formation are primarily based on the bedding types recognized in drill core. We were unable to use ore/waste characteristics for division purposes as the grade testing results (magnetic Fe, Si, P, etc.) were largely unknown. Most of the texture and bedding types used in the submember divisions are illustrated in Figure 7 and are briefly discussed below. [**Note** that in almost all cases, there are **transitional contacts** between each of the following bedding types, and one type commonly grades from one to the other!]

Thin-Bedded Rocks (Thin-bdd)

Rocks that are very fine-grained and display planar beds that are less than 1 cm thick were logged as thin-bedded. These criteria apply to most of the thin-bedded iron carbonate (typically brown- to cream-colored) and/or iron silicate rocks (typically variably green-colored) that characterize the Lower and Upper Slaty members, and the herein named Basal Red Unit at the base of the Lower Cherty. This bedding type is also characteristic of some thin-bedded, chert-rich zones scattered throughout the iron-formation. In some areas, the thin-bedded rocks were further broken down into what was termed Thin3 and Thin2 as follows:

- Thin3 is defined as thin-bedded rocks wherein the following bedding sets (usually in sets less than six inches thick) alternate in combinations of three or more:
  - Brown- to cream-colored iron carbonate sets;
  - Red-colored hematite-rich sets;
  - Green-colored iron silicate sets;
  - Black-colored magnetite-rich sets (also with carbon?); and
  - Pink-colored silica-rich sets – These pink cherty sets appear to occur as silica replacement zones in the above listed green and brown sets. The pink sets can be anywhere from one inch to several tens of feet thick, and these bedding sets are randomly distributed throughout the other sets (described above). The edges of these pink sets commonly exhibit what appear to be replacement fronts that cross bedding trends. Also present in the Thin3 are pink, silica-rich, ovoid nodules (less than two inches long) that are aligned along bedding. The nodules exhibit sagged/draped beds around the nodules, as well as, replacement fronts that cross bedding trends.
- Thin2 is similar to Thin3, but only two of the above described bedding sets are present as intricate interbeds.

The possible sedimentary environment for these thin-bedded rocks would correlate with the deep water offshore zone of Figure 8.

Regular-Bedded Rocks (Reg-bdd)

This subdivision of bedding types is typically associated with cherty granular rocks that display straight- or planar-trends that range from one to three inches thick. Though not obvious in drill core, there is a suggestion that hummocky cross stratification (HCS) is present in the regular-bedded rocks. If this turns out to be HCS, and it is not related to pinch and swell of individual beds (or even to diagenesis), then the possible sedimentary environment for the regular-bedded rocks could be subtidal in the zone located between fairweather wave-base and storm wave-base, corresponding to the offshore transition zone in Figure 8. It appears this bedding type was also referred to as even-bedded in some of the mine descriptions.

Medium-Bedded Rocks (Med-bdd)

Granular cherty rocks that exhibit planar-trends and display internal bedding thicknesses that range from three to eight inches thick are described as being medium-bedded. The use of medium-bedded rocks in the early mine descriptions is uncertain, as a

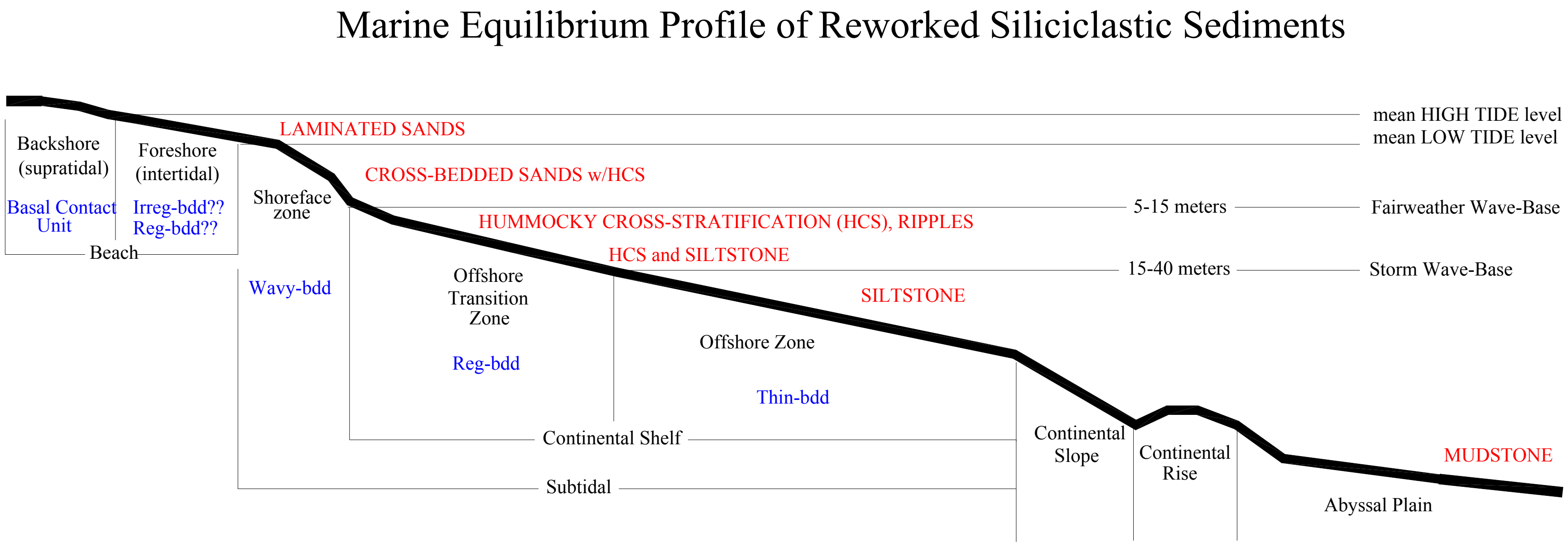


Figure 8. Marine equilibrium profile of reworked siliciclastic sediments and the possible depositional environments of specific units of the Lower Cherty member (in blue). Modified from diagram (Fig. 4.3 on page 60) and subsequent discussions in Coe et al. (2003).

thickness range for the bedding is usually not given.

Thick-Bedded Rocks (Thick-bdd)

Describes granular cherty rocks wherein the internal bedding is planar and typically greater than eight inches thick. These same rocks are also probably called massive-bedded in many of the early mine descriptions.

Combinations of Regular-, Medium-, and Thick-Bedded Rocks

As is generally the case, most of the planar-bedded, granular, cherty rocks display a range of bedding characteristics that oscillate between all three of the aforementioned bedding types. In these cases, a range of bedding types was given during logging of the core. For example, Reg/Med-bdd denotes that the bedding roughly varies from ½ to eight inches thick, Med/Thick-bdd denotes bedding varying from roughly three to over eight inches thick, Wavy/Reg-bdd denotes that the bedding changes from regular-spaced and planar-bedding to wavy-bedded, and so forth.

Alternating-Bedded Rocks (Alt-bdd)

The term "Alt-bdd" was used to describe packages of variably-bedded rock that continually alternated between fine-grained, thin-bedded sets (sets are typically one inch to three feet thick) and medium-grained, granular to ooidal, cherty sets (sets are typically ½ inch to one foot thick) in zones that persisted over several tens of feet thick. During logging, it would have been impossible and time restrictive (and probably not very instructive) to include a detailed description of the individual footages where each thin-bedded set and each cherty set occurred in the hole. Instead, it was felt that noting the **package** of alternating bedding types was more important than the location of each individual bed. However, that being said, visual estimates were made of the proportions of bedding types present in each particular Alt-bdd package. For example the ratio 60:40 denotes that 60% of the package consists of thin-bedded sets and 40% of cherty sets – the first number always refers to the amount thin-bedded sets, and the second number always refers to the amount of cherty sets. It should also be noted that the thin-bedded sets were almost always more magnetic (weakly to moderately magnetic) than the cherty sets (non-magnetic to weakly magnetic).

The possible depositional environment of Alt-bdd zones may be related to either fluxuations in sea level leading up to, and following, major transgressive or regressive events, and/or the periodic input of coarse-grained cherty materials related to storm events into a deep water, thin-bedded sedimentary environment. [**Note** that intraformational conglomerates are common to some of the cherty sets.] In some of the earlier mine descriptions, Alt-bdd units may have been described as "thick and thin" bedding. Gruner (1924) referred to this bedding type as "banded taconite."

Wavy-Bedded Rocks (Wavy-bdd)

Some of the best taconite ore zones correspond to what has typically been called wavy-bedded rocks. In this type of bedding, the magnetite is typically concentrated in bands that pinch, swell, curve, terminate, and bifurcate in a semi-random, subhorizontal fashion. The magnetite-rich bands range from <1/16 inch to four inches thick and often contain thin internal lamellae of pink-colored iron carbonates. The areas between the wavy magnetic bands are generally thicker and consist mostly of chert with disseminated magnetite; however, iron silicate-rich bands also occur, and these bands may be locally dominant in some zones – albeit very thick zones in some places. Isolated intraformational clasts of chert and iron carbonate are commonly scattered throughout this bedding type, and magnetite-rich halos are often found surrounding these clasts. Magnetite-rich stylolites, indicating a decrease in volume during diagenesis, are also locally common to portions of the wavy-bedded rocks. [**Note** that Gruner (1924, Fig. 2, p. 9) appears to have been the only geologist to have ever reported the presence of stylolites in the Biwabik Iron Formation.] Wherever these wavy-bedded rocks are seen in the mine exposures, cross-bedding is a fairly common local attribute (see figures in Ojakangas et al., 2005 for examples). These sedimentary features suggest that the wavy-bedded rocks were deposited in a subtidal shoreface zone above fairweather wave-base (Fig. 8).

The term "irregular-bedded" was commonly used by several of the taconite mines to also describe wavy-bedding. During logging of drill core, we used the term irregular-bedding for an entirely different bedding type (as described below).

Irregular-Bedded Rocks (Irreg-bdd)

The use of irregular-bedding in this investigation applies to rocks wherein the magnetite is concentrated in both wavy beds **and** irregular beds that show a variety of textures as follows:

- Magnetite is concentrated in beds that exhibit drastic pinch-and-swell thickness variations in a chaotic arrangement (as depicted in Fig. 7);
- Magnetite is concentrated in branching subvertical and subhorizontal "cracks" that could be crudely likened to dessication cracks(?);
- The rock has common intraformational conglomeratic zones that grade into medium- to thick-bedded zones that show various phases of disarticulation of individual beds to produce angular to subrounded clasts – magnetite is often the matrix material of these conglomerates and disarticulated zones; and
- Medium-bedded and thick-bedded iron silicate-rich bands are commonly interspersed with the above-described textures and bedding types.

In drill core, it is impossible to tell how all of these features relate to one another, and thus, it is difficult to envision the possible depositional environment that created this unique bedding type (not counting possible diagenetic changes). At present it is **crudely** suggested that the irregular-bedded rocks may have been deposited in the intertidal zone of Figure 8 because of their close spatial relationship to the wavy-bedded rocks.

Conglomerate

Conglomerate horizons ranging from a few inches to several feet thick are commonly scattered throughout the entire stratigraphic section of the iron-formation. There are two specific conglomerate horizons that are most commonly cited (Gruner, 1924; White, 1954). One occurs at the base of the Lower Cherty where the conglomerates are associated with algal structures. The second cited conglomerate horizon occurs within the Upper Cherty where they are also associated with algal materials. In both instances, these conglomerates occur as storm debris that are positioned between, beneath, and above algal mounds. Internally, these two conglomerate horizons, and other conglomerate horizons elsewhere in the iron-formation, are comprised wholly of intraformational clasts of: jasper, light-colored chert, black chert, thin-bedded iron-formation, iron carbonate-rich material, iron silicate-rich material, magnetite, and hematite. The clasts range from subangular to subround and are generally ¼ inch to two inches long. The long dimensions of the clasts are generally subparallel to bedding, but there are exceptions. Imbricated flat pebble conglomerates are found in a few restricted horizons.

Additionally, conglomerate horizons are common to a submember near the top of the Lower Cherty member. In this case, the rocks are irregular-bedded and contain a complete spectrum of conglomerates that range from beds that display early stages of disarticulation to form blocky clasts, to conglomerates with clasts of a single lithologic type that are angular and almost fit together, to beds with subrounded clasts of mixed lithologies.

Texturally, very-unique conglomerate horizons are present in the lower half of the Lower Slaty at the McKinley Extension/East Reserve Mine near Biwabik, MN. In this case, the conglomerates consist of black argillite clasts and iron carbonate clasts in both cherty and thin-bedded rocks that comprise the Lower Slaty (see later discussions).

Algal Horizons

Algal structures in the Biwabik Iron Formation are recognized by micro-banding that is often contorted, columnar, or ovoid with concentric rings and resembles "… the grain of an especially gnarled and knotty piece of wood" (Gruner, 1924, p. 16). Grout and Broderick (1919) were the first to assign an organic origin to these peculiar structures on the Mesabi Iron Range. The rock in which they occur is generally either a very fine-grained pink chalcedonic chert or red jasper; however, black and brown varieties are also present. Algal structures are most common near the base of the Lower Cherty and as a unique horizon within the Upper Cherty. Additional horizons have been found locally in the top of the Lower Slaty and elsewhere in the Upper Cherty. The algal horizon at the base of the Lower Cherty is present along the entire length of the Mesabi Iron Range; whereas, the algal horizon within the Upper Cherty is present only in the area to the east of Hibbing, MN (see Plate II). Continuation of this Upper Cherty algal horizon to the west is more subtle, and only scattered occurrences of algal structures, often associated with well-developed ooidal jasper zones, are found locally in several stratigraphic positions between Hibbing and Nashwauk, MN.

To date, no detailed morphological studies have been completed on these algal structures, although such studies are pending (Russell Shapiro, pers. comm., 2009). Core logging for this project suggests that the algal horizon in the Upper Cherty is characterized by columns and dome-shaped mounds in the area extending from Dunka Pit westward to Gilbert, MN. In the vicinity of the Virginia Horn (Eveleth to Virginia) and westward to Hibbing, oncolites (layered spherical growth structures) are more dominant.

Algal structures are also present in pink-colored chalcedonic bands and clasts (both <3 inches thick/across) in the Basal Red Unit. Both these bands and clasts commonly exhibit syneresis cracks that have been described as forming by shrinkage due to the dewatering of gelatinous silica precursors (Gross, 1972; Dimroth and Chauvel, 1973; Beukes, 1984).

Diffuse-bedded Rocks (Diff-bdd)

Diffuse-bedding is defined by beds wherein the concentration of disseminated magnetite gradually increases and decreases in bands ranging from ½ inch to three inches thick. Diffuse-bedding is probably the most prominent in the regular-bedded rocks near the base of the Lower Cherty.

Textures

The internal textures displayed by the various submembers in the iron-formation were also noted during logging of drill core. These textures are described in more detail below – some are illustrated in Figure 7.

Granular Texture

Upon close inspection with a hand lense, most of the cherty submembers can be seen to be comprised of small (<1 mm), well-rounded grains of greenalite, chert, magnetite, hematite, iron carbonates, and other lesser minerals that have been referred to as granules. Hook-shaped granules are also present locally. Ojakangas (*in* Zanko et al., 2003, p. 47) reports that "the granules are commonly sorted in thin laminae a few millimeters to a few centimeters thick; the result being interbedded laminae of chert granules, carbonate granules, greenalite granules and iron oxide granules." Dessication cracks in chert and greenalite granules are also common in some members (Ojakangas *in* Zanko et al., 2003). Because most of the cherty submembers are commonly granular in texture, this term was rarely used in logging, but can be inferred to be present.

Salt-and-Pepper Texture (S&P)

Salt-and-pepper texture refers to rock wherein dark granules of greenalite or magnetite are evenly dispersed in a light-colored cherty matrix. The term S&P was mainly used in this investigation to describe two submembers in the Lower Cherty as follows:

- A unit consisting of round greenalite granules (<1 mm) in a cherty matrix at the very top of the Lower Cherty – this unit is extremely magnetite-poor, makes excellent aggregate, and is referred to as "Mesabi Select" at United Taconite (also their LC-8 submember); and
- A unit consisting of considerable disseminated magnetite associated with wavy-bedded rocks in the middle of the Lower Cherty – this unit typically shows a concomitant increase in ore grade and decrease in silica content relative to other wavy-bedded units in the Lower Cherty.

Ooidal Texture

Ooidal texture, also called oolitic texture, consists of round to ovoid granules of chert, magnetite, jasper, iron carbonate, and greenalite with one or more concentrically laminated layers or coatings, i.e., cortices; no radial textures have been reported. This texture is fairly common in:

- Many of the cherty beds in the Upper Cherty;
- Both algal horizons (in the Upper Cherty and base of Lower Cherty) where ooids are extremely well-defined;
- Cherty lenses in the top of the Lower Slaty; and
- Chert bands in the Alt-bdd zones (often conglomeratic too, with jasper clasts).

Mottled Texture

Mottled taconite has a characteristic spotted or mottled appearance. The term mottles, as used in this investigation, applies to round-shaped concentrations of either iron carbonate (mostly pink ankerite) and/or magnetite that are 5-20 mm across. This mottled texture is usually superimposed on several bedding types and is most common in:

- Various submembers near the top of the Lower Cherty where they are associated with Med/Thick-bdd, Irreg-bdd, and Wavy-bdd rocks;
- Several submembers of the Upper Cherty – especially in the oxidized taconite rocks of the western Mesabi Iron Range; and
- Locally present in Reg-bdd rocks near the bottom of the Lower Cherty.

In some mines, the mottles are so abundant that the associated pink color of the mottles is readily visible in the pit walls from several hundred feet away. This texture is especially true of the LC-6 submember at United Taconite and the LC-5A submember at the Laurentian Mine (same submember near the top of the Lower Cherty, but a different numbering system).

The mottled units are readily oxidized wherein the mottles are replaced by goethite (and vugs), and the cherty units are leached and become porous and crumbly. West of Chisholm, MN, the upper-most mottled units of the Lower Cherty are commonly strongly oxidized with poor recovery zones. Also, many of the underground mines west of Chisholm apparently targeted an analogous Lower Cherty horizon, also known as the "wash ore" horizon, due to the strong oxidation and the concomitant development of "Paint Rock" at the base of the immediately-overlying Lower Slaty member.

Magnetism

The relative magnetism of the iron-formation rock types was also recorded while logging the drill core. This procedure was done with a swivel magnet held about one to one-half inches from the core with the following designations:

- Non-magnetic (or nil magnetism) – no movement of the magnet toward the core was discernable;
- Weakly magnetic – the magnet slowly moved toward, and silently touched, the drill core;
- Moderately magnetic – the magnet moved toward the core and attached to it with an audible sound;
- Strongly magnetic – the magnet rapidly moved toward the core with a loud "clunk" and stayed attached as the magnet was pulled away from the core.

STRATIGRAPHY OF THE BIWABIK IRON FORMATION

Introduction

This chapter is devoted to defining the geology of the various submembers that are present in each of the taconite mines, and how those submembers correlate from one mine to the other (in lieu of each mine's varying submember nomenclature) across the Mesabi Iron Range. All of these discussions are tied into a range-wide correlation of the submembers as portrayed in Plate II – which, in essence, is the current "Rosetta Stone" for the Mesabi Iron Range. The correlations portrayed in Plate II were derived from the detailed descriptions of the various submembers in over 378 drill holes (152,042 feet of core) from nine specific mines/areas along the length of the range. As can be seen in Plate II, there are 13 individual columns for each of the taconite mines that display that particular mine's submember nomenclature along with an attendant generalized rock type (based mostly on bedding types). The detailed geology that was used in making most of these 13 generalized columns can be viewed in Plates III through XV, which are hung stratigraphic sections (at one inch = 100 feet scale) that portray the geology in multitudinous deep drill holes from a particular mine.

In the following discussions, the specific minerals that are described as being present in specific submembers are based largely on megascopic determinations made while logging drill core. Only a select few thin sections were made to augment those determinations. Thus, the mention of minerals present should be treated as a "reconnaissance traverse" until a more detailed petrographic study of each of the submembers in multiple holes can be conducted.

It should also be stressed that almost all <u>contacts</u> between submembers are <u>transitional</u>! Thus, the placement of some contacts by different geologists logging the core could show some variability by as much as fifteen feet. From a sedimentalogical point of view, the transitional contacts are indicative of gradational changes in water depths that were ultimately responsible for deposition of the various submembers that display different bedding types.

Lower Cherty member

The Lower Cherty member is the most remarkable of all of the members of the Biwabik Iron Formation in that it displays a fairly consistent pattern of submembers from the Coleraine area to just east of the Siphon Fault (Fig. 2 and Plate II). Overall, the Lower Cherty is thickest in the vicinity of Coleraine and thinnest on the extreme eastern end of the Mesabi Iron Range, where it thins rapidly across an inferred growth fault – the Siphon Fault (Graber, 1993; Severson et al., 2003). The consistent submembers of the Lower Cherty, with some lateral and vertical variations, are depicted in Figure 9, and the variations consist of the following major units (from bottom to top) that are described in more detail below:

1. Basal Contact Unit – consisting of intricately interbedded conglomerate, chalcedonic chert, ooidal jasper, "slaty"/ thin-bedded iron-formation, and hematite-stained siltstone with detrital quartz grains;
2. Basal Red Unit – dominantly thin-bedded "slaty" iron-formation;
3. Regular-Bedded Unit;
4. Localized Thin-Bedded Unit – another thin-bedded "slaty" iron-formation that is only locally present;
5. Regular-Bedded to Weakly Wavy-Bedded Unit (or Transitional Zone) – consisting of regular-bedded to weakly wavy-bedded rocks;
6. Wavy-Bedded Unit – often subdivided into various submembers at many of the mines based on ore grade and bedding variations;
7. Variably-Bedded and/or Mottled Unit – contains mixtures of strongly mottled rocks superimposed on a multitude of bedding types;
8. Bold Striped Unit – consists of regular- to medium-bedded, iron silicate-rich, green-colored chert beds with conspicuous brown, thin-bedded, iron carbonate sets; and
9. Mesabi Select Unit – characterized by a magnetite-poor, regular- to thick-bedded, moderate green-colored chert with abundant greenalite granules and scattered brown, thin-bedded, iron carbonate sets.

<u>Basal Contact Unit</u>

Wherever the basal contact has been drilled, there are up to five rock types that are intricately interbedded in the bottom-most 0.5 feet to 30 feet of the iron-formation. In some areas, only one of these rock types may be present, and when more than one is present, any of these five rock types can occur at the very base in sharp contact with the Pokegama

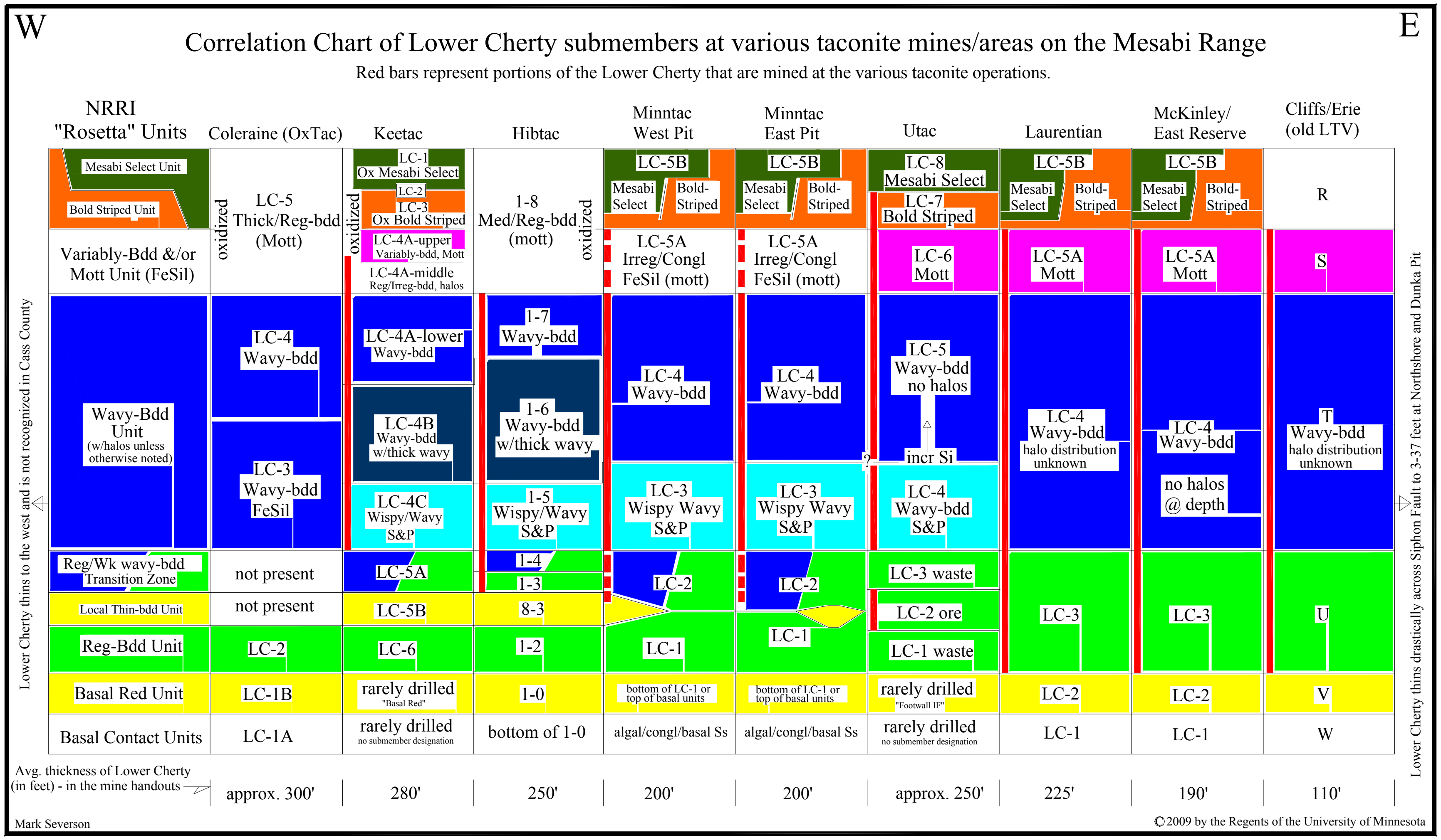


Figure 9. Correlation chart of Lower Cherty submembers at the various taconite mines/areas along the Mesabi Iron Range. Vertical red bars represent portions of the Lower Cherty that are mined at the various taconite operations. No scale implied; looking north. Contacts between all submembers are transitional/gradational! Note that the Essar mine area (old Butler/old MSI), which is located west of Keetac, is not portrayed on this figure as no drill holes have been logged at the site for this investigation; however, the submembers are reportedly similar to those at Keetac. Only two holes have been logged from the Cliffs-Erie site (old LTV mine).

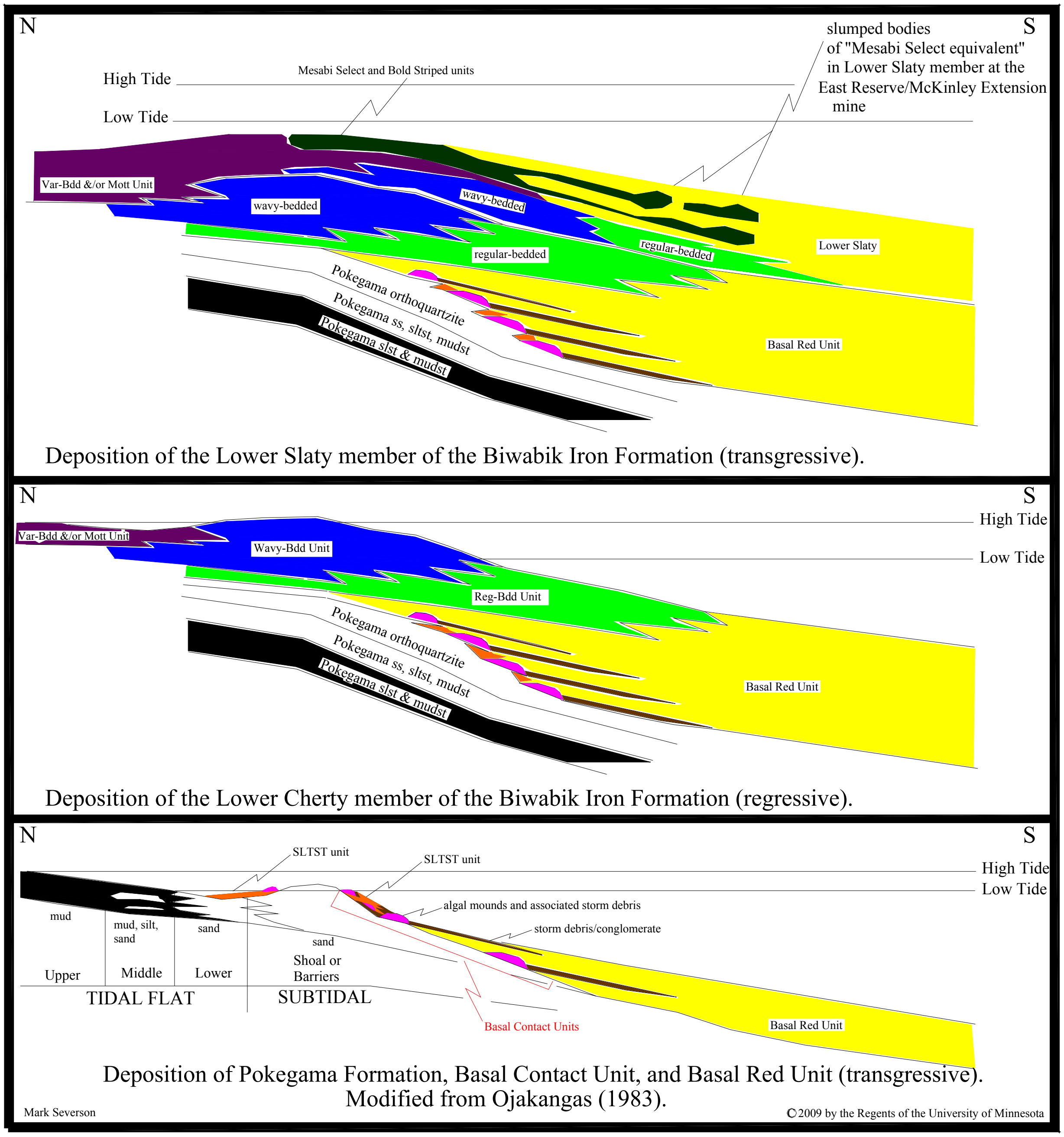
Formation. Each of these five rock types are generally non-magnetic, but localized magnetic zones and beds may be present. The five rock types of this unit are as follows:

1. *Algal chert* – Consists of light gray to pink chalcedonic chert that ranges from massive and featureless to micro-banded with weakly-contorted algal domes and/or algal columns consisting of stacked inverted cones (Fig. 10). In some areas, the massive chalcedonic chert bands exhibit quartz-filled syneresis cracks (Fig. 11). Overall, these chalcedonic chert bands range from two inches to eight feet thick. In addition, algal chert horizons, up to one foot thick, occur locally within the top ten feet of the Pokegama Formation at the Eastern Reserve/McKinley Extension mine near Biwabik, MN.
2. *Conglomerate* – Consists of subround to round, variably-colored, chert clasts (often with algal micro-banding and/or syneresis cracks), hematite clasts, and magnetite clasts in a chalcedonic matrix. The matrix is often ooidal with disseminated magnetite and hematite and also contains local syneresis cracks. These conglomerates occur in bands ranging from 1.5 feet to ten feet thick. Similar conglomerate bands, less than one foot thick, occur locally within the top ten feet of the Pokegama Formation at the Eastern Reserve/McKinley Extension mine near Biwabik, MN.
3. *SLTST Unit* (or hematite-stained siltstone wedge on the plates of this report) – Consists of thin- to regular- to vaguely-bedded rock with very fine-grained/silt-sized detrital quartz grains and iron carbonate granules in a variably iron-stained, red to green, chloritic matrix that is locally magnetic (more than often in the top few inches). The SLTST Unit commonly contains pink chalcedonic bands and clasts (often with algal micro-banding and syneresis cracks) that are generally less than three inches thick, but locally up to one foot thick. Overall, the SLTST Unit is rarely at the basal contact, except at the Eastern Reserve/McKinley Extension mine near Biwabik, MN, where it exhibits a gradational contact with orthoquartzite of the underlying Pokegama Formation, which itself is locally magnetic. The SLTST Unit ranges from three inches to over 30 feet thick; at the Eastern Reserve mine, it ranges from six inches to seven feet thick. At present, the SLTST Unit is interpreted to have been deposited in the tidal flats (or lagoon setting) behind barrier islands as depicted in Figure 6.
4. *Ooidal Jasper* – Consists of regularly-bedded rocks that are bright red and contain well-preserved red jasper ooids and jasper fragments – this rock type usually occurs as interbeds (less than a few inches thick) in all of the above three rock types, and it is occasionally found at the basal contact (where it ranges from 0.5 feet to eleven feet thick).
5. *Red-stained thin-bedded “slaty” iron-formation* – This rock type is present as thin interbeds that increase in volume upwards away from the basal contact into the overlying Basal Red Unit (see description in next section).

The intricate interbedded nature of these five rock types illustrates the synchronous deposition of clastic materials (SLTST Unit) near the shoreline mingled with deposition of biogenic-aided cherty iron-formation units (algal, conglomerate, and jasper units) in slightly deeper water, and “slaty” iron-formation deposition in still deeper water. A possible depositional environment for most of these rock types is schematically portrayed in Figure 12. Oscillations in water depth during deposition caused interfingering of the five rock types relative to the shoreline. Syneresis

Figure 10. Top view of columnar algal jasper at the base of the Biwabik Iron Formation at Pit 5E of the Cliffs-Erie site (old LTV mine). Section 36, T.59.N, R.14W.

Figure 11. Side view of syneresis cracks in chalcedonic chert at the base of the Biwabik Iron Formation at Pit 5E of the Cliffs-Erie site (old LTV mine). Section 36, T.59.N, R.14W.



Deposition of the Lower Slaty member of the Biwabik Iron Formation (transgressive).

Deposition of the Lower Cherty member of the Biwabik Iron Formation (regressive).

Deposition of Pokegama Formation, Basal Contact Unit, and Basal Red Unit (transgressive).
Modified from Ojakangas (1983).

Mark Severson

Figure 12. Diagrammatic cross-sectional sedimentation model for the Lower Cherty member and portions of the Lower Slaty member (from bottom to top).

cracks in the algal cherty beds indicate they were most likely deposited as gels in shallow water and then underwent dehydration under water. The conglomerates represent either storm debris or tidal debris formed in close proximity to the algal mounds. Eventually, the gels associated with algal, conglomerate, and jasper rock types may have formed a hard caprock-coating of biogenic cement. This "microbial glue" effectively sealed off the sandy beach-related materials of the Pokegama Formation and prevented them from being deposited in the overlying Basal Red Unit (which contains no detrital quartz grains).

At the various mines, the Basal Contact Unit, consisting of one or more of the five rock types, is referred to (according to the mine handouts, Fig. 3) as the following (see also Fig. 9 and Plate II):

- Coleraine area – variable amounts of four out of the five rock types (not including the SLTST Unit) are present in the LC1A submember;
- MSI/Butler mine – reportedly a "conglomerate" unit occurs at base of the iron-formation – the other four rock types are not mentioned in the handout (core not looked at by NRRI geologists);
- Keetac – reportedly a "conglomerate" unit occurs at base of the iron-formation – the other four rock types are not mentioned in the handout (usually not drilled and therefore not logged by NRRI geologists);
- Hibtac – includes all of the five rock types that are lumped as parts of the 1-0 submember in the handout (usually at the base of the 1-0 submember);
- Minntac – includes all five rock types that are lumped together as the "conglomerate/ algal/basal sandstone" unit in the handout;
- Inactive Minorca mine – an unknown amount of the five rock types are probably present, and these rock types are lumped as the LC-1 submember (no core remains to be logged by NRRI geologists);
- Utac – an unknown amount of the five rock types are probably present at the base of Utac's "footwall iron-formation" (usually not drilled, but noted in a few outlying holes by NRRI geologists);
- Laurentian mine – an unknown amount of the five rock types are probably present and lumped into the LC-1 submember in the handout (not seen in the pit nor preserved in drill core);
- East Reserve/McKinley extension – variable amounts of all five rock types are present in the LC-1 submember; however, the algal chert and conglomerate units are also locally present in less than one foot thick zones within the top ten feet of the underlying Pokegama Formation; and
- Cliffs-Erie site (old LTV mine) – probably contains variable amounts of four of the five rock types (excluding the SLTST Unit?), and these rock types are lumped together as the W submember in the handout.

Basal Red Unit

The Basal Contact Unit described above commonly transitions upward into a package of dominantly thin-bedded, variably-magnetic, "slaty" iron-formation (Fig. 13) that has been historically referred to as the "Basal Red" or "Red Basal" unit due to the presence of hematite (primary?) and a commonly associated red color. However, light green and brown colors may also be present, and these colors are dominant in many drill holes. In addition to the thin-bedded rocks are variable amounts of interbedded ooidal chert bands, often with conglomerate, that in places are so abundant that the rocks are described as consisting of alternating chert bands and thin-bedded sets, e.g., Alt-bdd. Chalcedonic chert

Figure 13. Photograph of thin-bedded rocks of the Basal Red Unit in drill core at the East Reserve/McKinley Extension (LC2 submember); drill hole 31-7, 212-235 feet. Note that a red color is dominant only at depth (227-235 feet) in this hole. Core in each row of the boxes = 2 feet long.

bands, nodules, and clasts, with local algal micro-banding, are also locally present. Magnetism in the Basal Red Unit is quite variable and ranges from no magnetism in the entire package, to locally magnetic, to entirely magnetic (weak to strongly magnetic range).

The thin-bedded rocks of the Basal Red Unit are inferred to be indicative of deposition in deep water in the offshore zone (Fig. 8) during a transgressive event that initially deposited the Basal Contact Unit. The chalcedonic and ooidal chert interbeds of the Basal Red Unit were deposited either due to fluctuations in sea level (the chert beds representing shallow water periods) and/or as storm event inputs (conglomeratic layers) into deep water. A hypothetical cross-sectional depiction of the depositional environment for the Basal Red Unit is depicted in Figure 12.

At the various mines, the Basal Red Unit is generally referred to as (see also Fig. 9 and Plate II) the following submembers:

- Coleraine area – LC1B submember;
- Keetac – "basal red" submember;
- Hibtac – 1-0 submember;
- Minntac – top part of the "conglomerate/algal/basal sandstone" unit or bottom of the LC-1 submember;
- Utac – an unknown portion of the "footwall iron-formation" (rarely drilled);
- Laurentian and East Reserve/McKinley Extension – LC-2 submember; and
- Cliffs-Erie site (old LTV mine) – V submember.

Regular-Bedded Unit

The next overlying unit is characterized by regular- to medium-bedded, mostly magnetic, iron-formation with minor sets of thin-bedded, fine-grained iron carbonate, and with scattered uniquely-colored pink beds; the pink color is related to ooids of iron carbonate (probably ankerite) and/or jasper (Fig. 14). There are local variations in the bedding type, and in some areas Alt-bdd zones and weakly wavy-bedded zones are present and may be dominant. Magnetism ranges from weak to moderate.

Figure 14. Photograph of drill core exhibiting the bedding characteristics of the Regular-Bedded Unit that exhibits a transitional contact with overlying weakly wavy-bedded rocks. Core shown is from the bottom portion of the Lower Cherty in drill hole 11-15 at the East Reserve/McKinley Extension. Submembers, as defined by ArcelorMittal, are the LC-3 submember (regular-bedded at 248.5-257+ feet) and LC-4 submember (wavy-bedded at +232-248.5 feet). Core in each row of the boxes = 2 feet long.

The Regular-Bedded Unit is envisioned to have been deposited on top of the Basal Red Unit during a regressive event as is depicted in Figure 12. At each of the mines, the Regular-bedded unit near the base of the Lower Cherty corresponds to the following submember nomenclatures (see also Fig. 9 or Plate II).

- Coleraine area – LC-2 submember;
- Keetac – LC-6 submember;
- Hibtac – 1-2 submember;
- Minntac – LC-1 submember;
- Utac – LC-1 and LC-2 submembers (both are very similar in appearance, but the LC-1 submember is waste rock due to low magnetic iron and contains pink ooids; whereas, the LC-2 submember constitutes ore and the pink color is less common);
- Laurentian and East Reserve/McKinley Extension – LC-3 submember; and
- Cliffs-Erie Site (old LTV) – U submember.

Local Thin-Bedded Unit

A localized transgressive event, relative to deepening water in the depositional environment, appears to have taken place in the Keetac to Hibtac area as recorded in the re-appearance of a thin-bedded "slaty" iron-formation that is similar to the Basal Red Unit. Submembers LC-5B at Keetac and 8-3 at Hibtac (Fig. 9) are both characterized by thin-bedded packages of multi-colored (red, green, gray, and brown) rock containing fine-grained iron carbonate and iron silicate with variable amounts of primary(?) hematite. Variable amounts of ooidal chert bands locally interfinger with the thin-bedded rocks, and these zones are often referred to as Alt-bdd. Magnetism in this unit is extremely variable and ranges from no magnetism to moderately magnetic; the chert interbeds are generally the least magnetic.

At both taconite mines, this particular unit is generally thin (2-10 feet thick at Keetac and a few inches to 25 feet thick at Hibtac) and may be locally absent. In fact, the local absence of this unit is apparent in the Hibtac stratigraphic column, wherein an "8-3" submember had to be added to the "1-series nomenclature" to account for this package as it became more prevalent in holes as they were drilled (note the anomalous 8-3 in the 1-system for the Lower Cherty in Fig. 9).

This same thin-bedded package is also locally present at Minntac in the upper portion of their LC-1 unit, where it occurs as Alt-bdd and Thin-bdd zones (see Plates II, XII, and XIII). However, the package is generally thin, and it is not present throughout the mine area. Thus, it was never given submember status by the Minntac geologists. This same package of thin-bedded rocks does not appear to be present at the Utac and the East Reserve/McKinley Extension areas (Fig. 9).

At Keetac, Hibtac, and possibly Minntac, this thin-bedded package grades upward into a series of regular-bedded to weakly wavy-bedded rocks, indicating the return of more shallow water conditions and a depositional environment similar to the Regular-bedded unit of the Lower Cherty.

Regular-Bedded to Weakly Wavy-Bedded Unit (or Transition Zone)

Positioned between the Regular-bedded and Wavy-bedded units is a transition zone, wherein the bedding shows a gradual upward-directed shift from regular-bedded iron-formation to weakly wavy-bedded iron-formation. Thin-bedded sets, generally less than three inches thick, of brown iron carbonate iron-formation are locally present and increase in volume toward the bottom of this unit. In addition to these characteristics, the magnetite-rich bands (weakly wavy-bedded) also contain light green iron-silicate beds (less than 1-3 cm thick) that are often referred to as "mudstone" sets by some of the mine geologists. A common pink color, related to ooids of iron carbonate and/or jasper, is also commonly noted in portions of this unit. Magnetism ranges from weak to strong, but most often is moderate to strong.

Mine submembers that correspond to rocks of the Transition Zone are as follows (see also Fig. 9):

- Coleraine area – not present/nor specifically sought while logging core;
- Keetac – LC5A submember;
- Hibtac – the following two submembers:
  - 1-3 submember = Reg-bdd to Alt-bdd with common pink colors; and
  - 1-4 submember = Reg-bdd to weak Wavy-bdd with "mudstone" interbeds and common core zones that form "poker chips";
- Minntac – LC-2 submember that often has magnetite-rich thin-bedded sets up to two inches thick (locally up to six inches thick);
- Utac – possibly the LC-3 submember, which is a waste zone, but similar in appearance to the LC-2 and LC-1 regular-bedded submembers; and
- Laurentian, East Reserve, and Cliffs-Erie site – not present/nor observed in the two holes that were logged.

Wavy-Bedded Unit

In the center of the Lower Cherty is a magnetite-rich Wavy-Bedded Unit that is the "bread and butter" of many of the taconite operations. Due to its economic significance, the Wavy-Bedded Unit has been broken down into many internal submembers based on changes in bedding thicknesses (in both the cherty bands and magnetite-rich wavy bands), ore grade changes (for example the LC-4 and LC-5 submembers at Utac), and internal textures. Internal textures generally include magnetite halos around isolated intraclasts (or a lack of them around intraclasts), magnetite-coated stylolites (some also exhibit carbon-coatings), and the increased presence of granular magnetite in the cherty bands, giving the rock a "salt-and-pepper" texture. Overall, the magnetite-rich wavy beds range from < 1/16 inch thick to bands up to three inches thick; whereas the cherty bands range from ¼ inch to 2 feet thick. Whenever the wavy bands are dominantly < 1/8 inch thick, they are referred to as wispy wavy. Typical textures present in the wavy-bedded units are displayed in Figures 14-18. The wavy-bedded units are almost always moderately to strongly magnetic except in oxidized areas and areas where channel-like bodies of silicate taconite are present (to be discussed below).

The wavy-bedded units often show localized cross-bedding features (Fig. 18), and thus, are inferred to have been deposited in the shoreface zone of Figure 8. However, the common occurrence of magnetite-coated stylolites in these same units also attests to significant volumetric changes in the rocks during diagenesis. Wavy-bedded submembers, as defined by each of the taconite mines, progressing upwards in this unit, are as follows (see also Fig. 9):

- Salt-and-pepper textured (S&P) wavy-bedded zone at base:
  - Coleraine – LC-3 submember = does not particularly exhibit a S&P texture (nor looked for), but rather consists of magnetite-rich wavy beds associated with iron silicate-rich chert bands;
  - Keetac – LC-4C submember = exhibits both wavy beds and wispy wavy beds with associated S&P texture in the cherty bands;

Figure 15. Photograph of drill core displaying typical bedding textures associated with the Wavy-Bedded Unit of the Lower Cherty. Note the pinch-and-swell thickness variations of the dark-colored, magnetite-rich wavy bands, as well as the round magnetite halos around light-colored intraclasts. Photograph of drill core from ArcelorMittal's LC-4 submember in hole 39-7 at the East Reserve/McKinley Extension (175-199 feet). Core in each row of the boxes = 2 feet long.

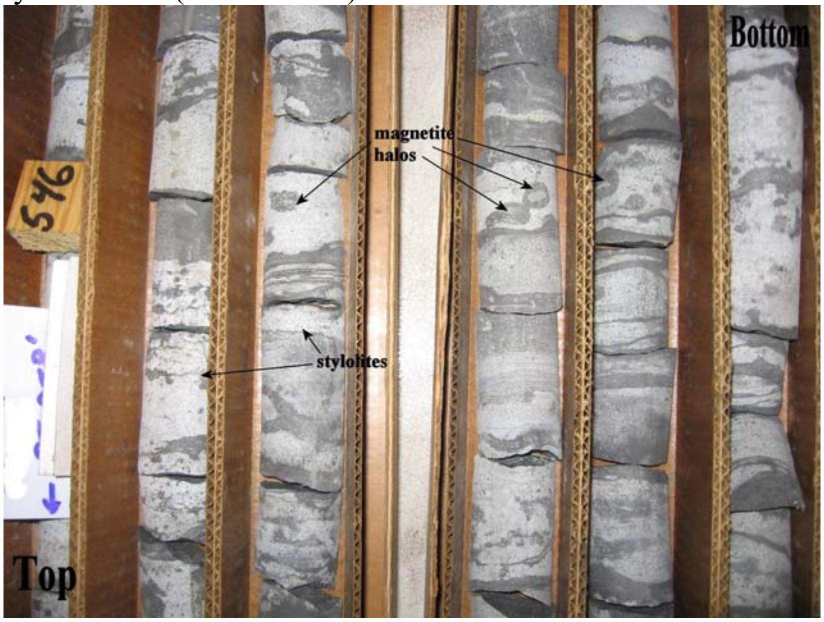


Figure 16. Close-up photograph of drill core displaying typical textures associated with the Wavy-Bedded Unit of the Lower Cherty (LC-4 submember at Minntac). Note nature of wavy magnetite-rich beds (dark), chert bands with diffuse magnetite (moderate gray), occasional magnetite-rich stylolites at contacts (center-left), and magnetite halos (dark ovoids) around cherty intraclasts. Drill hole #24426 from 546 feet through to 556 feet.

Figure 17. Close-up photograph of drill core displaying typical textures of the Wavy-Bedded Unit of the Lower Cherty member at Minntac (where it is named the LC-3 submember). Note the thin, magnetite-rich, wispy wavy-beds, magnetite-rich stylolites, and salt-and-pepper texture (S&P) due to disseminated magnetite. Drill hole #24426 around 615 feet deep.

Figure 18. Photograph of a fallen block of the Wavy-Bedded Unit of the Lower Cherty member exhibiting cross-bedding (submember T at this locality). Photograph taken in Pit 5E of the Cliffs-Erie site (old LTV mine).

  - Hibtac – 1-5 submember = also exhibits both wavy beds and wispy wavy beds with associated S&P texture (becomes dominantly wispy wavy-bedded towards Minntac);
  - Minntac – LC-3 submember = dominantly wispy wavy-bedded (Fig. 17) with subordinate wavy-bedded zones (both exhibit S&P texture);
  - Utac – LC-4 submember = wavy-bedded with associated S&P texture and a general lack of magnetite halos around intraclasts and with localized wispy wavy-bedded zones near the base of the submember. [**Note**: the LC-4 submember exhibits a significantly lower silica content and higher magnetic-iron content than the similar-appearing, but overlying LC-5 submember.];
  - East Reserve/McKinley Extension – LC-4 submember [probably the bottom of this submember] = wavy-bedded with no distinct S&P texture and common magnetite halos around intraclasts (in opposition to the LC-4 submember at Utac); and
  - Laurentian and Cliffs-Erie site – not present/nor specifically sought while logging the core.
- Wavy-bedded rocks with fairly common, but scattered, magnetite-rich wavy bands up to 3 inches thick:
  - Keetac – LC-4B submember;
  - Hibtac – 1-6 submember; and
  - not recognized at Coleraine, Minntac, Utac, Laurentian, East Reserve/ McKinley Extension, and Cliffs-Erie; and
- An upper, variably-spaced, wavy-bedded unit:
  - Coleraine – LC-4 submember;
  - Keetac – LC-4A-lower submember;
  - Hibtac – 1-7 submember;
  - Minntac – LC-4 submember;
  - Utac – LC-5 submember (the only one out of this group that does not exhibit common magnetite halos around intraclasts, and is lower in magnetic-iron and higher in silica content than the similar-appearing underlying LC-4 submember);
  - Laurentian and East Reserve/ McKinley Extension – LC-4 submember [probably the top portion]; and
  - Cliffs-Erie site (old LTV) – T submember.
- Silicate taconite bodies are rocks that are poor in magnetite. Silicate taconite generally occurs in two varieties. One variety consists of very wide-spaced and thin, magnetite-bearing wavy bands in otherwise medium- to thick-bedded, iron silicate-rich rock. In the second variety, wavy bands are fairly common, but the wavy bands are not magnetite-rich; rather, they consist mostly of dark-colored iron carbonates (?- no petrography conducted). Both of these rocks are generally non-magnetic to very weakly magnetic overall, but the rocks can contain internal moderately magnetic zones with increased magnetite-rich wavy beds. The overall morphology and trends of these silicate taconite bodies is unknown, as they are known mostly from wide-spaced, deep drill holes. Due to their low magnetic iron content, these rocks will eventually constitute waste zones in the Hibtac and Minntac pits as these mines advance down dip. However, the silicate taconite bodies are similar in some respects to the "Mesabi Select" aggregate, and, thus they may also be suitable aggregate material. To date, these bodies have been encountered in the following submembers:
  - Hibtac – mostly associated with their 1-5 submember and to a lesser extent the 1-4 and 1-6 submembers (to the southwest of their present mine);

- Minntac – mostly associated with their LC-3 submember, and to a lesser extent, the LC-4 and LC-5 submembers (to the west and south of their present west pit); and
- Keetac – the reported occurrence of two east-west trending, channel-like bodies (now mined out) near the top of the Lower Cherty in their LC-4A-upper, LC-4A-middle, and very top of LC-4A-lower submembers. Juneau (1979) postulated that these silicate taconite bodies were areas that resisted diagenetic alteration to magnetic taconite due to differences in either: 1) bulk chemistry; 2) carbonaceous content; 3) permeability; or 4) heat flow. He further suggested that elevated Mg contents in these bodies was the cause, but the initial source of the Mg was unknown, and the Mg could have been either original or was added during diagenesis.

Variably-Bedded and/or Mottled Unit

The Wavy-Bedded Unit of the Lower Cherty shows a transitional change upward in all of the taconite mines to a variably-bedded submember that generally consists mostly of iron silicate-rich beds that contain a **multitude** of bedding types, illustrated in Figures 19 and 20, which include:

1. Wavy-bedded – positioned mostly near the base;
2. Irregular-bedded – as discussed earlier in the first chapter, but marked by the distinct appearance of beds showing various stages of development of intraformational conglomerate beds (starting with beds showing weak disarticulation to form blocky clasts with little rotation and movement, to more highly disarticulated beds with variably-rotated clasts, to conglomerate beds with round to elongate clasts indicative of some transport);
3. Regular- to thick-bedded **iron-silicate rich** "cherty" beds – in some areas, this is the dominant feature of this unit;
4. Stylolites (magnetite- and/or carbon-coated) are present, but rare (Fig. 20);
5. Rare magnetite halos around isolated intraclasts;
6. Thin-bedded, brown, iron carbonate-rich bedded sets (up to a few inches thick) in the upper part of this unit – the iron carbonate-rich sets display an upward increase in volume towards the overlying unit, wherein they are abundant; and
7. Pink iron carbonate (ankerite) mottles are superimposed on all of the above bedding types, and in some mines, this is the dominant feature and the major criterion for submember recognition (Fig. 21).

To the west of Chisholm, this unit is not often recognized due to intense oxidation that produces poor recovery zones that consist of chunks of core that display wavy goethite-rich bands, goethite-lined vugs (originally the iron carbonate mottles), porous cherty core, and limonite-stained "sandy" core. In some areas, underground workings were actually intersected in the drill holes and pieces of old timbers and "paint rock" (from the base of the overlying Lower Slaty) were recovered from water-filled gaps during drilling.

The environment of deposition for the Variably-Bedded and/or Mottled Unit is difficult to reconcile, as it consists of a variety of bedding types that often vary drastically from one drill hole to the next. Perhaps the true nature of this unit would be more obvious if it could be observed in the pit walls. At present, it is **crudely** suggested that these variably-bedded rocks may have been deposited in the intertidal/foreshore zone of Figure 8 because of their close spatial relationship to the wavy-bedded rocks.

Figure 19. Photograph of drill core displaying the various bedding types present in the Variably-Bedded and/or Mottled Unit of the Lower Cherty (LC-5A submember at Minntac). Note the highly irregular nature of the dark-colored magnetite-rich bands and zones. Note also the magnetite-filled "cracks" across clasts (no transport indicated) and the magnetite-filled stylolites (upper right). Drill hole #24426 from 532 feet through 540 feet.

Figure 20. Photograph of drill core displaying typical intraformational conglomerate associated with the Variably-Bedded and/or Mottled Unit of the Lower Cherty (LC-5A submember at Minntac). Drill hole #24426 (from 510 feet through 518 feet) with highly irregular magnetite-rich beds and stylolites.

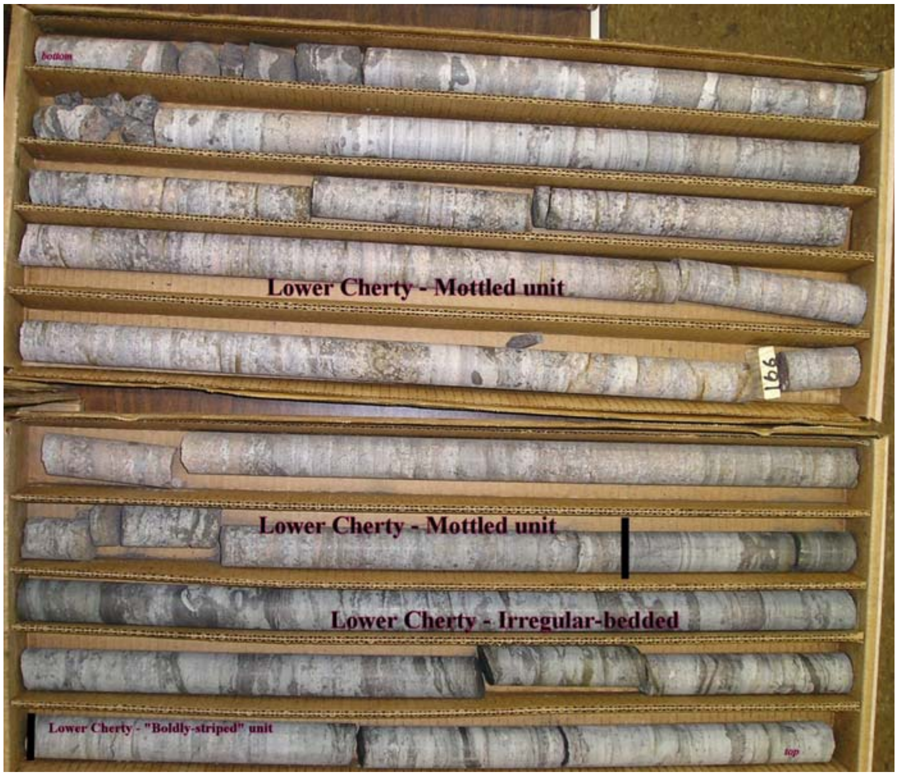


Figure 21. Photograph of drill core displaying typical pink iron carbonate mottles associated with the Variably-Bedded and/or Mottled Unit of the Lower Cherty (LC-5A submember) at the Eastern Reserve/McKinley Extension mine. Note the variability in the thicknesses of beds as well as the variability of iron carbonate mottles. Note also the irregular magnetite-rich beds (also LC-5A) located above the mottled zone, which in turn, are overlain by the Bold Striped Unit (LC-5B submember) in the top two feet. Drill hole #11-15 from 156 feet to 176 feet. Core in each row of the boxes = 2 feet long.

Variably-Bedded and/or Mottled submembers, as defined by each of the taconite mines, are as follows (see also Fig. 8):

- Coleraine area – bottom portion of LC-5 submember = strongly oxidized and not specifically recognized;
- Keetac – LC-4A-upper (LC-4Au) and LC-4A-middle (LC-4Am) = often strongly oxidized and difficult to recognize (except by Keetac geologists; wherein, LC-4Au has more halos and stylolites along with polished drill core sections of oxide-rich bands, and the LC-4Am has thicker wavy bands and thicker chert bands);
- Hibtac – bottom portion of 1-8 = strongly oxidized and difficult to recognize from other units that are also present in the 1-8 submember;
- Minntac – LC-5A submember = mottles are not as strongly developed, but intraformational conglomerates, including disarticulated beds in various stages of forming conglomerates, and iron silicate-rich cherty bands are distinct;
- Utac – LC-6 submember = strongly mottled with common thick-bedded and conglomeratic zones;
- Laurentian and Eastern Reserve/McKinley Extension – LC-5A submember = strongly mottled with a highly transitional contact downward into a strongly mottled wavy-bedded unit (their LC-4 submember); and

- Cliffs-Erie (old LTV) – S submember = mottled, medium- to thick-bedded, unit with irregular-bedded and wavy-bedded zones (only looked at in two holes).

Bold Striped Unit

The moniker "Bold Striped" was applied by Peter Jongewarrd to the uppermost mined unit of the Lower Cherty member at United Taconite. This unit consists of alternating: 1) green-colored, iron silicate-rich bands (both greenalite- and minnesotaite-rich varieties are present in 1-24 inch thick beds); 2) brown-colored, internally thin-bedded, iron carbonate-rich sets (1/2-8 inches thick); and 3) dark-gray to black magnetite-rich bands (generally less than 2 inches thick). Overall, the alternation of these three rock types of contrasting colors gives the rock a "boldly-striped" appearance that is immediately recognizable in drill core (Fig. 22) and pit exposures. In drill core, this unit is called a variety of bedding types based on the amounts of brown sets that alternate with green, iron silicate-rich bands. In other words, if the brown sets equal the green bands, the rock was called Alt-bdd; whereas, if the green bands were more dominant, the rock was called Med-bdd or Med/Thick-bdd. Other features associated with the Bold Striped Unit are:

1. The magnetite content increases downward in this unit = magnetite bands become more common, and the iron silicate-rich bands often contain considerably more disseminated magnetite with depth;
2. Stylolites (often carbon-coated) are very common at the contacts between the brown beds and iron silicate-rich bands (Fig. 23) – in some cases, greenalite granules in contact with the stylolites appear to be cut in half at the stylolite; and
3. The lower contact of this unit is transitional into the underlying Variably-Bedded and/or Mottled Unit.

It is important to note that the Bold Striped Unit displays a highly transitional contact with the spatially associated Mesabi Select Unit (see below description) that most often overlies it. However, in some drill holes, the position of the Bold Striped Unit is reversed, and it occurs above, rather than below, the Mesabi Select Unit. This reversal is because both of these units contain variable amounts of brown, thin-bedded, iron carbonate-rich sets – the main difference being that the Bold Striped has a preponderance of these sets; whereas, the Mesabi Select has noticeably less of these sets. In essence, the two units are similar, except one has more brown thin-bedded sets.

Mesabi Select Unit

The moniker "Mesabi Select" was first applied to the LC-8 submember at United Taconite in reference to its excellent aggregate characteristics (Martin, 2005; Olson et al., 2006). This unit generally occurs at the very top of the Lower Cherty and contains very little to no magnetite – thus, it is a waste rock unit that is blasted, crushed in-pit, stockpiled, and used as aggregate. As noted above, the main difference between the Mesabi Select and the Bold Striped units is the preponderance of brown-colored, thin-bedded, iron carbonate-rich sets in the Bold Striped Unit. In addition to this difference, the Mesabi Select Unit usually displays a distinctive salt-and-pepper texture (S&P) due to the presence of greenalite granules (variably replaced by minnesotaite) in a cherty matrix with little to no magnetite. Bedding in the Mesabi Select usually ranges from medium- to thick-bedded with some internal regular-bedded zones. Magnetite content

Figure 22. Photograph of drill core displaying typical Mesabi Select (480-485.5 feet) and Bold Striped (485.5-502 feet) units associated with the LC-5B submember at Minntac. Also shown are thin-bedded rocks of the Lower Slaty member (mostly dark-colored rock at 476-480 feet). Drill hole #24426 from 476 feet to 502 feet. Core in each row of the boxes = 2 feet long.

Figure 23. Photograph of drill core displaying carbon-coated stylolite at the contact between a brown-colored iron carbonate bed and a light-colored chert band with greenalite granules. Features shown are typically seen in the Bold Striped Unit of the LC-5B submember at Minntac. Drill hole #24426 at around the 492 foot depth.

shows some localized increases with depth in this unit, and when the Mesabi Select occurs below the Bold Striped, the magnetite content, based on relative magnetism, is noticeably higher.

Because the Mesabi Select and Bold Striped units often show reversed stratigraphic positions (see above description), they both must be considered to have been deposited in the same sedimentary environment. The presence of the brown-colored, thin-bedded, iron carbonate sets suggests a gradual deepening of the water relative to the underlying Irregular-Bedded/Mottled unit.

Both the Bold Striped and Mesabi Select units occur at the top of the Lower Cherty and have been identified at most of the taconite mines as the following submembers (see also Fig. 9)

- Coleraine area – top portion of LC-5 submember = strongly oxidized and rarely well preserved, thus not specifically recognized to date;
- Keetac – LC-1 submember = Mesabi Select (also mostly oxidized, except in recently-drilled holes to the south of the present mine area); and LC-3 = Bold Striped (mostly oxidized, except in recently-drilled holes to the south of the present mine area);
- Hibtac – top portion of 1-8 submember = mostly oxidized with poor core recoveries, except in six scattered, less-oxidized holes to the south and southeast of the present mined area;
- Minntac – LC-5B submember = both the Bold Striped and Mesabi Select units, or one or the other, are present in the LC-5B submember, and the two units are reversed (Bold Striped over Mesabi Select) in about 1/3 of the holes studied;
- Utac – LC-7 submember = Bold Striped, and LC-8 submember = Mesabi Select;
- Laurentian and East Reserve/McKinley – LC-5B submember = both the Mesabi Select and Bold Striped, or one or the other, are present in the LC-5B submember, and the two are often reversed (Bold Striped over Mesabi Select) in many of the holes studied; minor slate beds are also uniquely present in both units in this area ; and
- Cliffs-Erie (old LTV) – R submember = contains both Bold Striped and Mesabi Select, but in reversed positions in each of the two holes studied.

<u>Depositional Environment of the Lower Cherty member</u>

In summary, the Lower Cherty member could be likened to reworking of materials in a siliciclastic environment on the edge of a continental shelf during an initial transgressive event (Basal Red Unit) followed by a more prolonged regressive event (the bulk of the Lower Cherty). Inferred environments of deposition have been suggested, mainly for discussion purposes, for most of the submembers of the Lower Cherty and are portrayed in Figures 8 and 12. It is important to note the reworked granular materials that comprise most of the cherty submembers were solely derived from within the basin. The initial hardness of the granules at the time of deposition is unknown, but appears to have been variable as some granules exhibit a well-rounded nature, whereas other granules exhibit a flattened appearance due to a "softer" nature. Detrital quartz grains were deposited only in close proximity to the shoreline, either along beaches of barrier islands (as the Pokegama Formation) and in the tidal flats behind them (possibly the SLTST and conglomerate units of the Basal Contact Unit). Once a continuous cap of the Basal Contact Unit formed, including siliceous gels that formed a "microbial glue" that probably hardened rapidly, the detrital materials were effectively “sealed off” and were no longer added to the system.

Lower Slaty member

The GIF-type iron-formation of the Lower Cherty member is overlain by a package of BIF-type iron-formation, or thin-bedded iron-formation, that is characteristic of most of the Lower Slaty member (Fig. 24). The basal contact of the Lower Slaty member is abrupt everywhere, indicating a rapid change from shallow water deposition of the Lower Cherty to deeper water deposition of the Lower Slaty. Perhaps this abrupt change is tectonic in nature, and it is related to a series of thrusted plate collisions that took place in the Fold-and-Thrust belt to the south of the Animikie Basin. Alternatively, if superplume activity is considered to be the source of iron in the basin, perhaps a period of superplume cessation allowed for basinal subsidence and a dramatic increase in water depth to take place.

While the basal contact of the Lower Slaty member is abrupt and easily defined, the upper contact of this member is often highly gradational and less well defined. This transition is especially true in the Virginia Horn area (Fig. 2) where there are several lense-shaped bodies/channels of GIF-type iron-formation that are present within a dominantly thin-bedded rock package (green-colored lenses within the yellow-colored Lower Slaty member in Plate II). Historically, the placement of the upper contact of the Lower Slaty in the Virginia Horn area has been controversial and subject to change. Gruner (1924, p. 20) first described this placement as “somewhat arbitrary” due to the repeated alternations of cherty and slaty rocks, and he later decided (Gruner, 1946, p. 45) that the cherty alternations were lensoidal and placed these lenses in the Lower Slaty. However, White (1954) included these same lenses in the Upper Cherty. As will be seen later in this report, even the mining companies oscillated in their lithologic picks of the upper contact of the Lower Slaty. In the end, the placement of the upper contact of the Lower Slaty member in the Virginia Horn area becomes more of an academic problem. It is more important to remember that both cherty and slaty rocks show a pronounced interfingering relationship in the contact zone between the Lower Slaty and Upper Cherty members.

The various submembers of the Lower Slaty, with considerable variations in the Virginia Horn area, are depicted in Figure 25 and consist of the following generalized units (left side of Fig. 25):

1. Intermediate Slate at the base;
2. Lowermost Thin-Bedded Unit comprises all of the Lower Slaty member to the west of Chisholm and to the east of Aurora (where it includes an upper vague-bedded, non-magnetic unit);
3. Lower IBC (Lower “Interbedded Chert”);
4. Middle Thin-Bedded Unit (with a Middle IBC);
5. Upper IBC (Upper “Interbedded Chert”); and
6. Uppermost Thin-Bedded Unit.

As can be seen in Figure 25, there is considerable variation in the overall thickness of the Lower Slaty member. Towards the west end of the Mesabi Iron Range, the upper contact of the Lower Slaty is sharp and easily defined (Coleraine, Keetac, and Hibtac areas of Fig. 25). There, the Lower Slaty averages about 20 feet thick and consists of thin-bedded packages of non-magnetic iron-formation and non-magnetic carbonaceous argillite. To the immediate east of Hibtac, these same rocks are present, but show a gradual eastward thickening to 80 feet thick. In the Minntac to Laurentian mine areas (Fig. 25), there are several lenses of cherty rocks, often referred to as “interbedded cherts” or

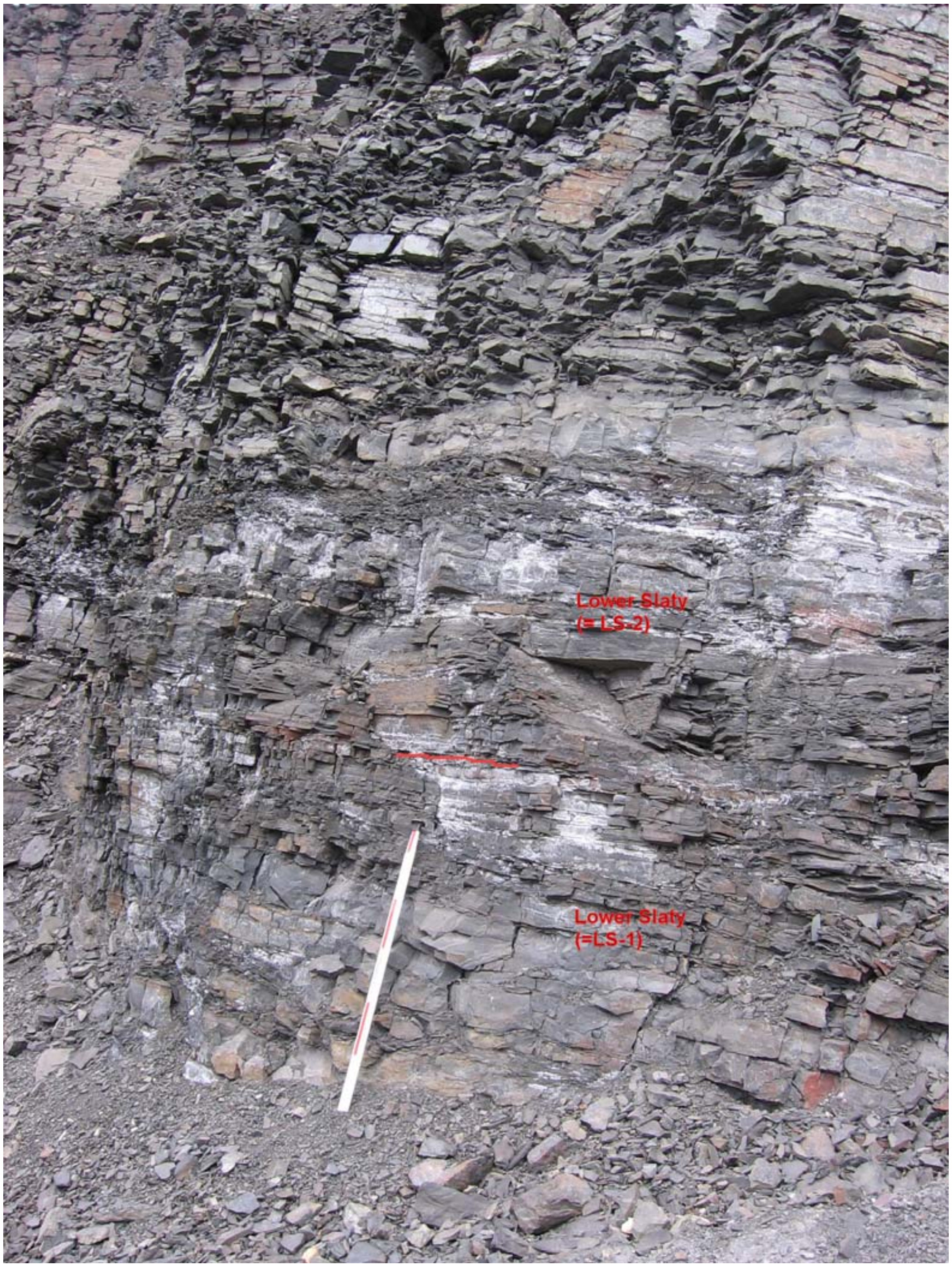


Figure 24. Photograph of a mined bench in the Laurentian Mine displaying the thin-bedded nature of the Lower Slaty member. Stadia rod is marked in one foot increments (alternating red and white bars) and is 5.5 feet long. The Intermediate Slate is present at the base of the bench (the LS-1 submember in the photograph); note the common white coating of melanterite, which is an iron sulfate derived from weathering of sulfides in the iron-formation on the subvertical joint faces. The top part of the bench is characterized by thin-bedded, non-magnetic to weakly magnetic, iron carbonate iron-formation that is characteristic of the Lowermost Thin-Bedded Unit of the Lower Slaty member (the LS-2 submember in the photograph).

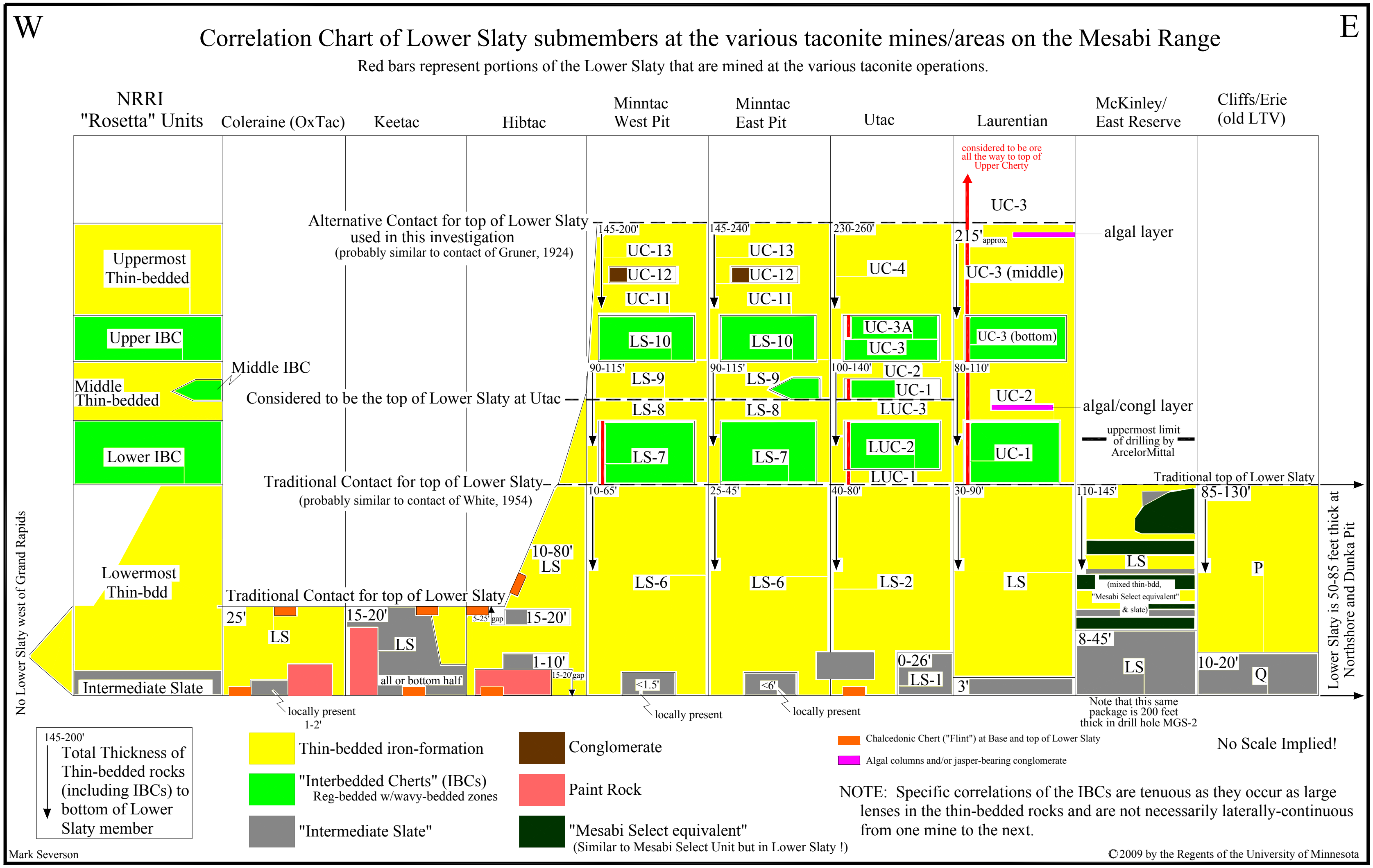


Figure 25. Correlation chart of Lower Slaty submembers at the various taconite mines/areas along the Mesabi Iron Range. Red bars represent portions of the Lower Slaty member that are mined at the various taconite operations. No scale implied. Looking North. Note the three optional contacts for the top of the Lower Slaty. The upper "alternative contact" is used in this report. Note that the Essar mine area (old Butler/old MSI), which is located west of Keetac, is not portrayed in this figure as no drill holes have been logged at this site during this investigation; however, the Lower Slaty is reportedly (mine handout) similar to the Lower Slaty at Keetac. Only two holes have been logged from the Cliffs-Erie site (old LTV mine).

IBCs, that are present in the upper portions of the Lower Slaty. Thickness determinations of the Lower Slaty are varied depending on where the top contact is placed. In this investigation, we have determined, as did Gruner (1924, 1946), that these IBCs are truly channel-like in their overall morphology and use the "Alternative Contact" of Figure 25 for the top of the Lower Slaty. This lithologic pick gives the Lower Slaty a thickness of 145 feet to 260 feet thick in the Virginia Horn area. To the east of Biwabik, MN, the upper contact of the Lower Slaty is more easily defined, due to a lack of IBCs in the upper contact zone, and the Lower Slaty exhibits a range of 85-145 feet thick.

Descriptions of each of the submembers that constitute the Lower Slaty member at each of the various taconite mines are presented in the following pages (see also Fig 25 and Plate II). Note that on Figure 25, there are several UC-designated and LUC-designated units at the top of Lower Slaty. These designations are because there is some disagreement as to the actual placement of the upper contact of the Lower Slaty at the various mines in the Virginia Horn area. The results of detailed core logging of holes in the Horn by the NRRI has shown that in almost all instances (see hung cross-sections on Plates III, IV, XII, and XIII) the green-colored IBCs of Figure 25 are channel-like in their overall morphology and occur as large, but laterally discontinuous, lenses in a sea of thin-bedded rocks. For this reason, we have included many of the UC- and LUC-designated units of the various mines in the Lower Slaty member. As of this writing, the Lower Upper Cherty (LUC) submembers at Utac (Fig. 25) are currently viewed as occurring as lenses in the Lower Slaty.

Intermediate Slate

At or near the base of the Lower Slaty member is a series of dark gray- to black-colored, thin-bedded, non-magnetic, carbonaceous argillites that have been referred to as the "Intermediate Slate." The Intermediate Slate has been inferred to be partly volcanic in origin and shard-like features, associated with stilpnomelane, have been reported to be present (Morey et al., 1972; Perry et al., 1973). However, these same shard-like features, depicted in Figure 26, while collected from the base of the Lower Slaty, are reportedly not from the carbonaceous "intermediate slate" (LaBerge, pers. comm., June, 2006). While the features seen in Figure 26 certainly appear to be shard-like, Dimroth and Chauvel (1973) have interpreted similar features in other iron-formations as being the result of compaction.

The thickness of the Intermediate Slate is not consistent throughout the Mesabi Iron Range, nor is it always present at the base of the Lower Slaty (Fig. 25). In some areas, black carbonaceous argillites (or mudstones) may be present in the following three forms:

1. Consistently at the base of the Lower Slaty in packages that range from less than one foot thick to 45 feet thick (McKinley/East Reserve mine in Fig. 25);
2. In isolated patches at the base of the Lower Slaty; and
3. In one or more isolated patches located well above the base of the Lower Slaty (Hibtac and Utac areas in Fig. 25).

Furthermore, in some areas, the base of the Lower Slaty consists of thin-bedded iron-formation with only minor thin (<1 mm)

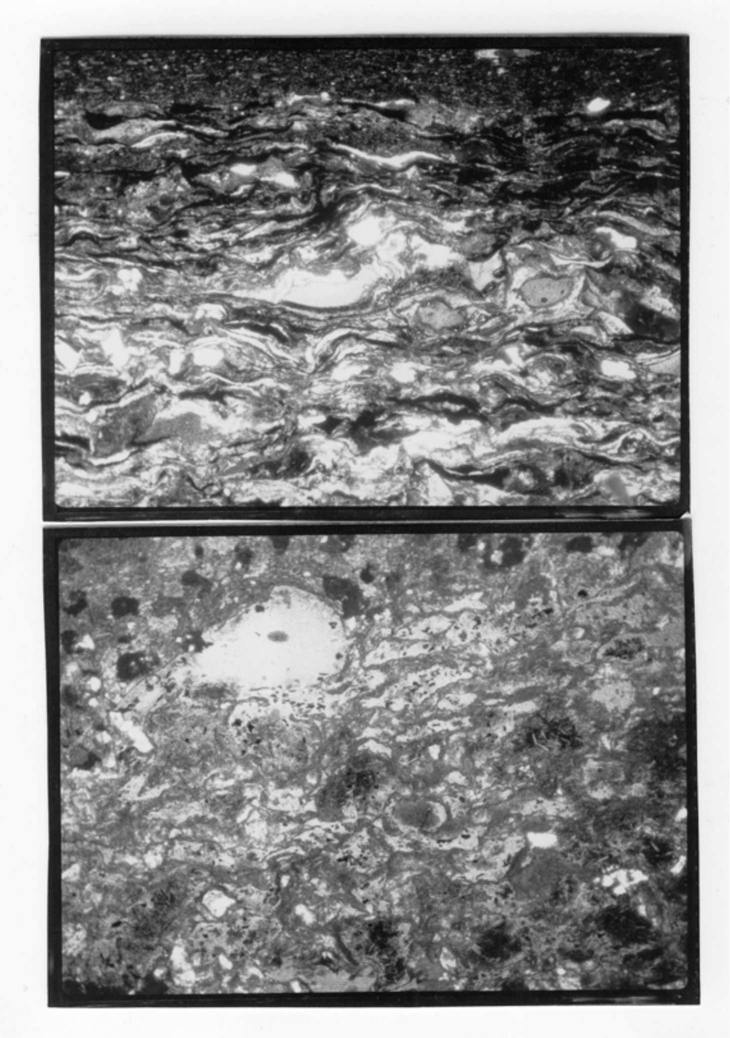


Figure 26. Scan of Polaroid photomicrographs (low power?) displaying possible evidence of volcanic shards and fragmental material in a sample collected near the base of the Lower Slaty. Courtesy of Dr. G.L. LaBerge. Thin sections made from samples collected at 1537-1543 feet (top scan) and 1524.6 feet (bottom scan) from Drill Hole #1 located to the south of Eveleth, MN. This hole has been skeletonized and is stored at the Minnesota Geological Survey in St. Paul, MN.

carbonaceous argillite beds, and in other areas only thin-bedded iron-formation is present. These variations in stratigraphic position and thickness suggest that the Intermediate Slate may have been deposited in 3rd order basins (a few hundred meters to several kilometers across) within the Animikie Basin wherever dead bacterial materials could have accumulated. Sulfides, as disseminated pyrite and as marcasite films on bedding surfaces, are commonly present in the Intermediate Slate at several locations along the Mesabi Iron Range.

Alteration and oxidation of the Intermediate Slate to combinations of white, yellow, brown, and red, iron-stained clays, often referred to as “paint rock,” is profound on the western third of the Mesabi Iron Range (from Chisholm to Coleraine – Fig. 25). This alteration often takes place in the lower half of the Lower Slaty and includes an unknown amount of thin-bedded iron-formation in addition to all or portions of the underlying Intermediate Slate. In many instances, the thin-bedded character of the paint rock is evident, but it is impossible to tell whether the protolith was thin-bedded iron-formation or thin-bedded carbonaceous argillite. Underground workings at the Lower Slaty/Lower Cherty contact were intersected in recently drilled holes in the area between Chisholm and Keewatin. Cored material recovered from these water-filled voids includes mixtures of paint rock, oxidized Lower Cherty material, and occasional wood fragments from support timbers.

The base of the Lower Slaty represents a structural accommodation zone, between units of contrasting structural competency (Lower Cherty/Lower Slaty contact), along the entire length of the Mesabi Iron Range. In almost all instances, this zone is unique in that it often contains:

1. Bedding parallel quartz veins;
2. Well-developed slickensides on multiple bedding planes with highly variable trends (sometimes at right angles to slickensides on a nearby bedding plane);
3. Localized breccia zones with quartz infillings; and
4. Localized small recumbent folds (presumably north-verging, but difficult to tell in unoriented drill core).

These structural features were probably formed during the Penokean Orogeny (approximately 1,880-1,835 Ma) due to compression associated with a series of north-directed thrusting events in the Fold-and-Thrust Belt located well to the south. In lieu of these structural features, it is not surprising that a significant amount of alteration and oxidation took place peripheral to this accommodation zone to produce the paint rocks. The timing of this oxidation event, involving either upward-moving hydrothermal fluids during the Paleoproterozoic (Morey, 1999) or downward percolating meteoric water (Leith et al., 1935), is another story and not part of this investigation.

The term "intermediate slate" is used by most of the taconite mines to denote the presence of black, carbonaceous, thin-bedded argillites at the base of the Lower Slaty as depicted in Figure 25. However, at Utac these rocks are usually referred to as the LS-1 submember, and at the Cliffs-Erie site (old LTV mine), they are known as the Q submember (Fig. 25).

Lowermost Thin-Bedded Unit

Immediately overlying the Intermediate Slate, which is not uniformly present throughout the Mesabi Iron Range (as described above), is a package of thin-bedded iron-formation containing variable mixtures of very fine-grained iron carbonates and iron silicates. The thin-bedded iron-formation is usually present in shades of green and brown (both as individual laminae and as zones up to several tens of feet thick) wherever no paint rock or oxidation is present. In most instances these rocks are not magnetic, even when not oxidized, but there are instances where the top of this package is weakly-magnetic to moderately-magnetic and decreases to non-magnetic with depth. Chalcedonic chert bands (1 inch to 1 foot thick) are fairly common in the top of this unit, and the bands decrease to rare occurrences with depth. Interbeds of carbonaceous argillite (<2 mm thick) are usually present toward the bottom of this unit (even when the Intermediate Slate is absent).

The various submember designations for this Lowermost Thin-Bedded Unit at each of the taconite mines are listed below (see also Fig. 25):

- Coleraine – LS submember = Thin-bedded rocks that are usually completely altered to paint rock with scattered less altered and oxidized zones.

- Keetac – LS submember = Thin-bedded rocks that are often completely altered to paint rock and locally contain variable amounts of "intermediate slate" (especially towards the east end of Keetac's property as defined by recent drilling).
- Hibtac – LS submember = Also characterized by thin-bedded rocks with common paint rock zones with considerable underground mine workings. Wherever the rock is not altered, it varies between green and brown colors. In some zones, the thin-bedded rock consists of alternating couplets of green (iron silicates) and black (carbon-rich?) bands less than 2 mm thick. In a few instances, the thin-bedded iron-formation is seen to display evidence of disruption and the erosional breakdown to form clasts and granules (Figs. 27 and 28) that eventually would have been transported landward to become the granules of the cherty-type iron-formation. Rare stylolites were observed at contacts with chalcedonic chert bands towards the top of this submember. The LS submember displays a gradual thickening toward the east between Hibtac and Minntac (see Plates XI and XIII).
- Minntac – LS-6 submember = Differs from the Hibtac area in that this unit is thicker and is rarely oxidized or altered to paint rock. Colors are the same as at Hibtac; including the presence of iron silicate/carbon-rich couplets. Thin2-type bedding is also fairly common, and varies from green and brown in color with pink-colored silica-rich bands that also occur as nodules and replacement fronts across bedded trends. The thin-bedded rocks of this unit are usually weakly to strongly magnetic at the top and gradually decrease to non-magnetic with depth (in all but six holes that were looked at).
- Utac – LS-2 submember = Similar to Minntac in that the thin-bedded rocks are variably magnetic at the top and decrease to non-magnetic with depth. Colors consist of mostly greens with grays.
- Utac – LUC-1 (lower Upper Cherty-1) submember = Very similar to the underlying LS-2 submember (also thin-bedded and green-colored), but it is locally strongly magnetic, and therefore, it often constitutes taconite ore.
- Laurentian Mine – LS submember = Similar to corresponding submembers at Minntac and Utac in that it is thin-bedded, green to brown in color, and it is variably magnetic at the top with decreased magnetism to nil at the base.
- East Reserve/McKinley Extension Mine – LS-submember = Incredibly different from the Lower Slaty at all of the other taconite mines! The entire thickness consists of complexly interbedded mixtures of (Figs. 29 and 30): 1) black carbonaceous argillite; 2) thin-bedded, brown, carbonate iron-formation; and 3) regular- to thick-bedded green chert that is very similar to the Mesabi Select Unit (herein called the "Mesabi Select equivalent" or MSE). All of these rock types are non-magnetic (except for a few localized zones at the top of this unit), and all rock types are combined in a multitude of textures and interbedded relationships that are outlined below:
    - o The thickest packages of black carbonaceous argillite (exhibiting a range of 8-45 feet thick) usually occur at the bottom of this unit, where it is referred to as the Intermediate Slate. However, in some locales this carbonaceous argillite layer can be as thin as a few inches;

Figure 27. Photograph of drill core displaying disrupted bedding and generation of iron carbonate intraclasts in the Lowermost Thin-Bedded Unit of the Lower Slaty at Hibtac. Drill hole #24154 at 210.5 feet to 211 feet.

Figure 28. Photograph of drill core illustrating the generation of iron carbonate granules in the Lowermost Thin-Bedded Unit of the Lower Slaty at Hibtac. Drill hole #24154 at 211 feet to 211.5 feet.

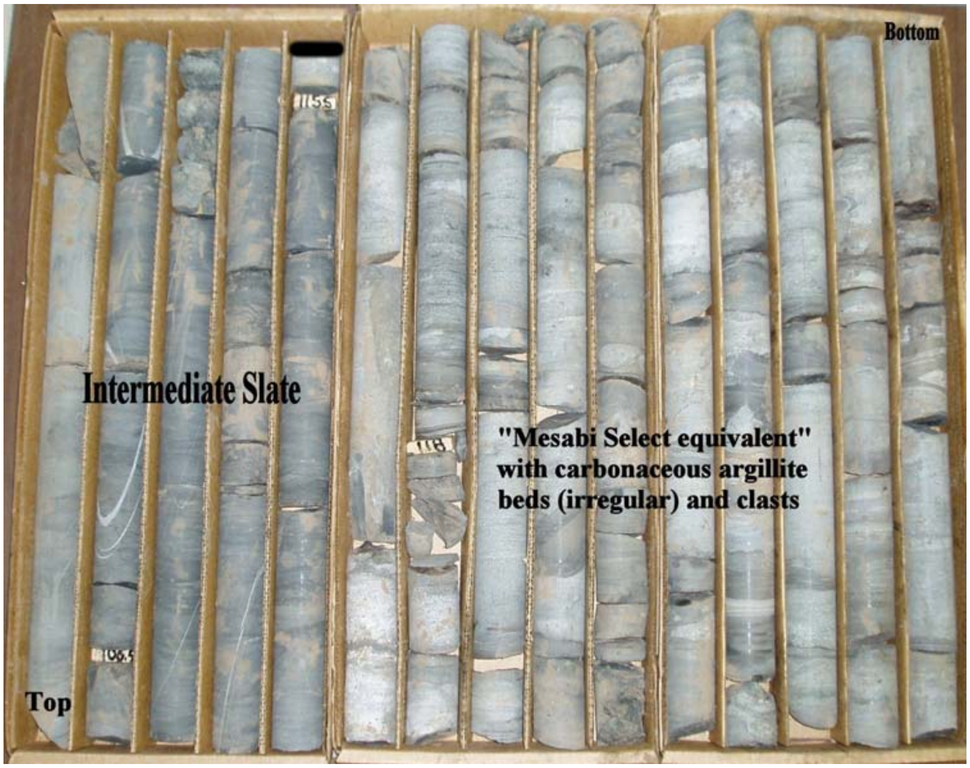


Figure 29. Photograph of drill core displaying the potpourri of rock types constituting the Lowermost Thin-Bedded Unit of the Lower Slaty at the East Reserve/McKinley Extension mine near Biwabik, MN. Drill hole #15-15 from 104.5 feet to 135 feet. Note the thick section of black-colored, carbonaceous mudstone (aka the Intermediate Slate Unit) in the left side of photo (104.5-115.5 feet). Core in each row of the boxes = 2 feet long.

Figure 30. Photograph of drill core displaying the potpourri of rock types constituting the Lowermost Thin-Bedded Unit of Lower Slaty at the East Reserve/McKinley Extension mine near Biwabik, MN. Jones and Laughlin drill hole #6549 at 134 feet to 141 feet.

  - Black carbonaceous argillite beds are also present elsewhere throughout the entire unit as irregular to planar, one millimeter thick bands in sets that range from less than one inch thick to six foot thick sets that are themselves internally thin-bedded (massive varieties with no apparent internal bedding is locally present and were called "black mudstone" during logging);
  - The "Mesabi Select equivalent" consists of abundant greenalite granules (ranging from round-shaped to locally hook-shaped) dispersed in a cherty matrix. The MSE is internally regular-bedded to thick-bedded. Overall, the textures and mineralogy displayed by the MSE are exactly the same as displayed by the Mesabi Select Unit of the Lower Cherty;
  - The "Mesabi Select equivalent" often contains sets (usually < 6 inches thick) of brown iron carbonate and black carbonaceous argillite, as well as isolated rounded clasts of iron carbonate and argillite;
  - Intraformational conglomerates are common to all three rock types and each can contain clasts of a single lithologic type or clasts of all three lithologic types (MSE, brown iron carbonate, and black argillite);
  - In some holes, the "Mesabi Select equivalent" displays variably-spaced wavy beds of brown iron carbonate ± black argillite ± brown clasts of iron carbonate;
  - All three rock types can be intricately interbedded in 2 cm to 6 inch thick bands, wherein they are logged as alternating-bedded (Alt-bdd);
  - In some holes, there are zones wherein lensoidal bands of "Mesabi Select equivalent" (<3 inches thick) alternate with carbonaceous argillite bands;
  - Micro-banded chalcedonic chert with contorted bedding (algal-mats?) and intraformational conglomerate locally occurs at the top of this unit in a few drill holes;
  - Because the Mesabi Select Unit in the Lower Cherty and the "Mesabi Select equivalent" in the Lower Slaty are identical in many respects, it is often difficult to pick the contact between the two in some holes if the intervening Intermediate Slate is very thin or absent; and
  - There are thick zones wherein the "Mesabi Select equivalent" contains features as if it had undergone slumping and soft-sediment deformation as displayed by internal brown iron carbonate sets and black carbonaceous argillite sets that are:
    - Steeply dipping (up to 40º to the core axis) and/or contorted;
    - Show indications of soft-sediment flowage around blocks of "Mesabi Select equivalent" (Fig. 31);
    - Display overall scrambled bedding trends (includes all three rock types);
    - Present as wisps and cracks (mostly the carbonaceous material in the "Mesabi Select equivalent");
    - Micro-faulted (Fig. 32); and
    - Present as small clastic dikes into the "Mesabi Select equivalent."
- Cliffs-Erie Site (old LTV) – P submember = Thin-bedded to vaguely-bedded rocks that are green-colored and show a downward decrease in magnetism in the three holes logged. Preliminary relationships seen in drill hole MGS-2 (drilled near Biwabik, MN) suggests that most of the P submember may actually correspond to a thick section of the "Mesabi Select Equivalent."

Figure 31. Photograph of drill core displaying soft-sediment deformation features (center of photo) in the "Mesabi Select equivalent" at the East Reserve/McKinley Extension mine near Biwabik, MN. Drill hole #45-9 from 54.5 feet to 67 feet. Core in each row of the boxes = 2 feet long.

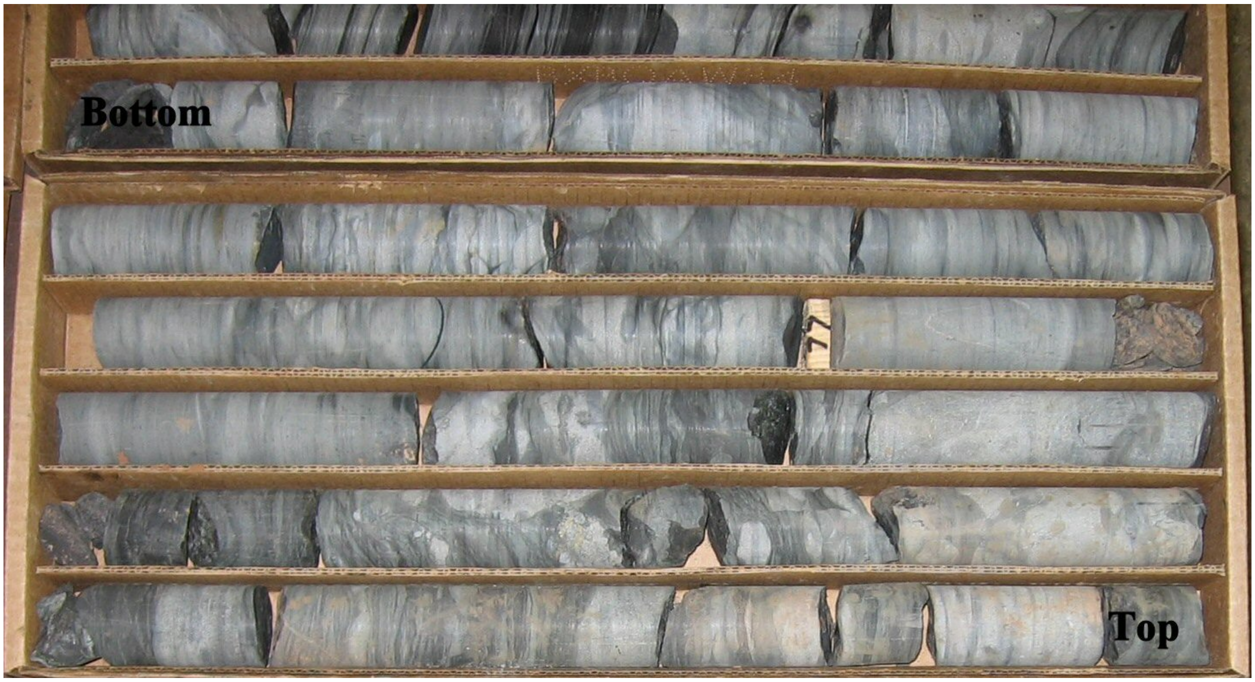


Figure 32. Photograph of drill core displaying scrambled-bedded and flowage of the black carbonaceous argillite around blocks of "Mesabi Select equivalent" at the East Reserve/McKinley Extension mine. Drill hole #39-7 from 61 feet to 84 feet. Core in each row of the boxes = 2 feet long.

The unique textures and sedimentary features in the Lower Slaty member at the East Reserve/McKinley Extension mine deserve additional discussion. First, the multitude of interbedded relationships of the three rocks is difficult to describe verbally due to the plethora of intra-related types that are present in multiple drill holes. The complicated relationships between the rock types present in most of the drill holes are shown on Plates VI through X. These plates should also be examined to gain a better understanding of the complex interbedded relationships (a picture is truly "worth a thousand words"). Second, the soft-sediment deformation features in core suggest that a good portion of the Lower Slaty in this area was formed by the slumpage of shallow water materials ("Mesabi Select equivalent") into a deeper water depositional environment (one that produced the thin-bedded iron-formation and argillite) during repeated episodes of earthquake-induced subsidence.

Lower IBC (Lower "Interbedded Chert")

In the Virginia Horn area, there are anywhere from two to three large, but laterally discontinuous sheets, of cherty iron-formation that occur as lenses in a sea of thin-bedded rocks. Detailed logging of core at Minntac (Plates XII and XIII) and Utac (Plates III and IV) have shown in many instances that these lenses laterally pinch out and/or grade into thin-bedded rocks. In the Minntac west pit (Plate XIII), the lowermost of the IBCs (Lower IBC) can be seen to cut downward in the Lower Slaty towards the west. The correlations of the various IBC units from one mine to the next on Figure 25 is tenuous as the IBCs are laterally discontinuous, and therefore, each IBC cannot be traced with certainty across the areas between the mines.

The presence of these IBCs has been known to USS geologists since the 1970s (Dr. Richard Ojakangas, pers. comm., 2007; Pete Niles, pers. comm., 2008), but there is very little documentation about the morphology of these lenses that can be found in the literature. Ojakangas et al. (2005, p.217) suggests these lenses formed as "shallow channels up to a mile wide and tens of feet deep that were cut into the Lower Slaty member and filled with sand-textured grains of iron minerals and chert in the Virginia Horn area. These grains apparently were derived from shallow water and carried seaward into the deeper water environment ... Ebb-flow tidal currents are interpreted as the erosion and transporting agent." Simonson (1985) also noted similar discontinuous GIF-type lenses in BIF-type iron-formation, and he suggested that they represent "starved" bedforms generated by storm waves and currents. Furthermore, Pufahl and Fralick (2004) suggest that such features could have formed from offshore flowing, storm-generated currents that delivered the sediment to deeper water areas.

The Lower IBC Unit of the Lower Slaty is discussed in this section. Its various submember designations at each of the taconite mines are listed below (see also Fig. 25):

- Coleraine, Keetac, Hibtac, East Reserve(?), and Cliffs-Erie site – no IBCs are present and/or have not been fully defined by drilling to date;
- Minntac – LS-7 submember = Mined for taconite ore and characterized by regular- to medium-bedded, variably magnetic (weak to strong) and variably-colored rock (greens, browns and grays) with localized wavy-bedded zones and "Mesabi Select" equivalent zones. In the west pit, the LS-7 member displays an apparent west-directed, downcutting relationship from 100 feet down to 20 feet above the base of the Lower Slaty (see Plate XIII). In the east pit, the LS-7 often grades laterally into thin-bedded, magnetite-rich rocks (see Plate XII) that display sags,

drapes, pinch-outs and possible hummocky cross-stratification (HCS) in drill core;

- Utac – LUC-2 (lower Upper Cherty-2) submember = Mined for taconite ore and characterized by regular- to medium-bedded, gray- to green-colored, moderately- to strongly-magnetic rock that laterally grades into alternating-bedded zones that in turn grade into thin-bedded zones. Relationships seen in deep drill holes to the west and southwest of the currently mined area indicate that wavy-bedding becomes the dominant feature of this submember in that direction; and
- Laurentian mine – UC-1 submember (only seen in mine exposures) = Recognized as being part of the Upper Cherty by the mine geologists and mined for taconite ore. Very similar to the LUC-2 submember in the nearby Utac mine in that it is a regular- to medium-bedded granular chert. Contains highly variable magnetic iron contents (as low as 16% with isolated pockets as high as 40% – Ojakangas et al., 2005). Not observed to be lensoidal in the pit exposures as mapped by NRRI personnel in 2006; Peter Jongewaard (pers. comm., February, 2005) observed on an earlier visit that the UC-1 was present on one mine wall, but absent from another mine wall.

Middle Thin-Bedded Unit

Rocks that are positioned between the two main IBCs (Lower and Upper IBC units of Fig. 25) consist of thin-bedded iron-formation that is weakly- to strongly- magnetic, green to gray to brown in color with common pink-colored silica-rich bands (as in the Thin2-type bedding), and minor variably oxidized red and white zones. The various submember designations for the Middle Thin-Bedded Unit of the Lower Slaty at the appropriate taconite mines are listed below (see also Fig. 25):

- Minntac – LS-8 and LS-9 submembers = No difference was noted between these two submembers in this investigation. The USS mine handout states that both are very similar except that the LS-8 submember is “noticeably more laminated”;
- Utac – LUC-3, UC-1, and UC-2 submembers = Both the LUC-3 (lower Upper Cherty-3) and UC-2 (Upper Cherty-2) submembers are currently being considered as being in the Lower Slaty at Utac. Both of these submembers are thin-bedded (as described above), and the beds are separated by a thin lense of regular-bedded chert that is mined as taconite ore. This ore zone is moderate to strongly magnetic, and it is referred to as the UC-1 submember, which on Figure 25 would be the Middle IBC;
- Laurentian – UC-2 submember = Recognized as part of the Upper Cherty, but consists of thin-bedded, green- to brown-colored rock with common bedding parallel quartz veins (up to 1 foot thick) and bedding parallel soft chlorite-rich bands. NRRI personnel (2006) also noted the presence of a jasper-rich conglomerate (one foot thick) with associated isolated algal mounds near the base of the UC-2 submember in the mine exposures.

Upper IBC (Upper “Interbedded Chert”)

Near the top of the Lower Slaty in the Virginia Horn area is the third IBC lense that consists of medium- to regular-bedded, variably-colored (greens, grays, and browns) granular chert beds. This third IBC lense is moderately- to strongly-magnetic and commonly contains pink iron carbonate mottles near its base. A weakly-developed ooidal texture is locally present in these rocks. These IBC bodies show good lateral continuity at Utac (Plates III and IV), but are noticeably more discontinuous and thinner at Minntac (Plates XII and XIII). The various submember designations for the Upper IBC Unit of the Lower Slaty at the appropriate taconite mines are listed below (see also Fig. 25):

- Minntac – LS-10 submember = This IBC is very discontinuous in lateral extent and grades laterally into alternating-bedded (Alt-bdd) zones – NOT considered to be ore at Minntac (may also include the underlying LS-9 submember);
- Utac – UC3a (ore) and UC3 (waste) submembers = Both submembers are similar except for changes in ore grades, and an increase in carbonate content in the UC3a submember (Phil Larson, pers. comm., April, 2009);
- Laurentian – bottom third of their UC-3 submember = This unit is not formally recognized as being part of the Lower Slaty, but corresponds to the bottom third of their UC-3 submember where it is characterized by medium- to regular- to thick-bedded granular chert beds. Commonly contains pink mottles at the base. Mined as taconite ore at Laurentian.

Uppermost Thin-Bedded Unit

At the very top of the Lower Slaty in the Virginia Horn area is the uppermost package of thin-bedded iron-formation. These rocks are variably magnetic (weakly to strongly magnetic range, with an average of moderately magnetic) and variably colored (shades of green, gray, brown, red, and black). Chalcedonic chert bands (one inch to one foot thick), often with conglomerate zones and/or well-developed ooids, are present and show localized increases in volume (see below). It is important to note that none of the taconite mines include this particular unit in the Lower Slaty, but the thin-bedded nature of the rocks suggests that they are indeed "slaty"-type iron-formations. Furthermore, in some areas where the IBCs pinch out, this unit is vertically continuous with thin-bedded iron-formation at depth. The various submember designations for the Uppermost Thin-Bedded Unit of the Lower Slaty at the appropriate taconite mines are listed below (see also Fig. 25):

- Minntac – consists of two to three submembers as follows:
    - UC-11 submember = Thin-bedded rocks with scattered chalcedonic chert bands that are more common at the top if the overlying UC-12 submember is present, in which case, the chalcedonic bands are noticeably more conglomeratic and ooidal;
    - UC-12 submember = Characterized by a very unique conglomerate that when present is used to separate the UC-11 and UC-13 submembers (which are both thin-bedded and similar-looking). The UC-12 submember exhibits a very limited spatial extent (a single storm event?) throughout the Minntac area (see Plates XII and XIII). In the east pit drill holes (Plate XII), it can be seen to cut "upsection" where it is eventually present at the base of the Upper Cherty. Throughout Minntac, this conglomerate contains both jasper and variably-colored chert clasts that range from round-shaped to highly elongate. The amount of clasts in the conglomerate vary, and thus this horizon was logged as three varieties that include: paraconglomerate (matrix-supported), conglomerate, and flat-pebble conglomerate; imbrication is commonly observed in the latter two varieties. The matrix is usually

  magnetite-rich (moderately to strongly magnetic) and locally contains ooids of jasper and chert;
  - UC-13 submember = Thin-bedded rocks, with scattered chalcedonic chert bands, that are exactly similar to the UC-11 submember and difficult to distinguish from it if the intervening UC-12 submember is absent. If the UC-12 submember is present, there is an increase in the amount of chalcedonic bands in the bottom of the UC-13, in which case, the chalcedonic bands are more conglomeratic and ooidal.
- Utac – UC-4 submember = Thick package of thin-bedded rocks that are considered to be in the Upper Cherty member at Utac; and
- Laurentian – middle portion of their UC-3 submember = It is not formally recognized, but corresponds to the middle third of their UC-3 submember that is thin-bedded and very similar to the UC-4 submember at the nearby Utac mine. At Laurentian, all of their UC-3 submember constitutes taconite ore. A well-developed algal horizon, about two feet thick, was found within 5-8 feet of the top of this unit by NRRI geologists during pit mapping in 2007. This horizon contains columnar algal features, and it is identical in appearance to *the* algal horizon that has typically been described in the Upper Cherty member (see next section).
- East Reserve/McKinley Extension – the top of the Lower Slaty consists of a potpourri of rock types as has been described above. However, it is important to note that in several drill holes in this area, the top of the Lower Slaty contains scattered/localized chalcedonic chert bands with convoluted micro-bands suggesting that they formed as algal mats.

Depositional Environment

The depositional environment of the Lower Slaty member correlates with a deep water/offshore shelf environment below storm wave-base (Figs. 5, 6, and 9), as has been suggested by numerous individuals working on the Mesabi Iron Range. The change from shallow water sediments of the Lower Cherty member to the deep water sediments of the Lower Slaty member was abrupt, and the change could have been related to rapid tectonic subsidence associated with thrusting/collisional events in the Fold-and-Thrust Belt located well to the south of the Mesabi Iron Range, or with "collapse" of the basin associated with decreased superplume activity. The deep water conditions of the Lower Slaty were apparently short-lived on the western Mesabi Iron Range where the Lower Slaty is thin and eventually pinches out to the west. However, in the Virginia Horn area the total thickness of thin-bedded rocks that define the Lower Slaty is vastly increased and a more prolonged period of deep water deposition associated with repeated tectonic subsidence events is suggested.

The nature of the IBC lenses in the Lower Slaty member in the Virginia Horn area suggests that either:

1. Laterally-extensive channels were repeatedly eroded in the thin-bedded chemical sediments and filled with "clastic" cherty materials by ebb-flow tidal currents and/or storm-generated currents to form channel-like IBCs, each of which was eventually covered by more thin-bedded sediments [most likely scenario compared to number 2 described below];
2. There were several periods of subsidence, each resulting in a flooding surface (thin-bedded rocks) that shallowed-upward to form an IBC. This process was repeated several times to form a series of

parasequences – each consisting of thin-bedded iron-formation (deep water) that progressively grades upward into thicker-bedded iron-formation (shallow water). As a result, the thin-bedded rocks became intimately interbedded with thicker-bedded rocks that formed as laterally discontinuous IBCs that overlap in time and space. A hypothetical cross-sectional depiction of this relationship is shown in Figure 33; or

3. Combinations of the processes outlined in the first two categories.

It is impossible to tell which, if any, of these processes formed the IBCs when most of the evidence is in the form of correlations between widely-spaced drill holes, as is the case with this investigation. Future studies to understand the genesis of the IBCs should be directed at understanding the overall morphology of the "channels" by conducting detailed in-pit mapping of the wall faces. In this manner, the true lateral extents and trends of the "channels" can be mapped out, as well as the relationships to the surrounding thin-bedded rocks, e.g., do the bottom contacts of the IBCs show unconformable erosional relationships with the thin-bedded rocks.

In the Eastern Reserve/McKinley Extension area, the Intermediate Slate is locally extremely thick and indicates that accumulation of black mud in deep water anoxygenic conditions took place over a longer period than elsewhere. Also unique to this area is the potpourri of mixed sediment types in the Lower Slaty that consist of: carbonaceous argillite, thin-bedded carbonate iron-formation, and granular non-magnetic chert ("Mesabi Select equivalent"). This chaos of rock types indicates rapidly changing water depth conditions that were probably related to episodic additions of material that slumped downward from the nearby shallow water shelf (Mesabi Select Unit) during periods of earthquake-induced seismicity.

The presence of algal stromatolites at the top of the Lower Slaty in the Laurentian mine and East Reserve/McKinley Extension mine, as well as in many stratigraphic localities in the overlying Upper Cherty and Upper Slaty members, indicate that the stromatolites were becoming a much more common feature related to the development of the iron-formation over time. Overall, stromatolites in the Lower Cherty are restricted to the Basal Contact Units and the Basal Red Unit, and evidence for them is totally lacking in the remainder of the Lower Cherty. Their reappearance in the top of the Lower Slaty, and ubiquitous occurrence upwards in the Upper Cherty and Slaty members, indicates that the stromatolites eventually proliferated in an evolving sedimentary environment that was more conducive to their existence.

Upper Cherty member

The Upper Cherty member is vastly different from the Lower Cherty member in that the Upper Cherty contains very few consistent submembers that are equally present along the entire length of the Mesabi Iron Range. Differences between the two members are as follows:

- Wavy-bedded zones, which are rich in magnetite and constitute some of the best taconite ore zones of the Lower Cherty, are only locally present in the Upper Cherty to the west of Biwabik. However, wavy-bedded zones **are** extremely common in the Upper Cherty to the east of Biwabik (see Plate II)
- The Upper Cherty commonly displays an ooidal texture; whereas, ooids are only present in the base of the Lower Cherty.

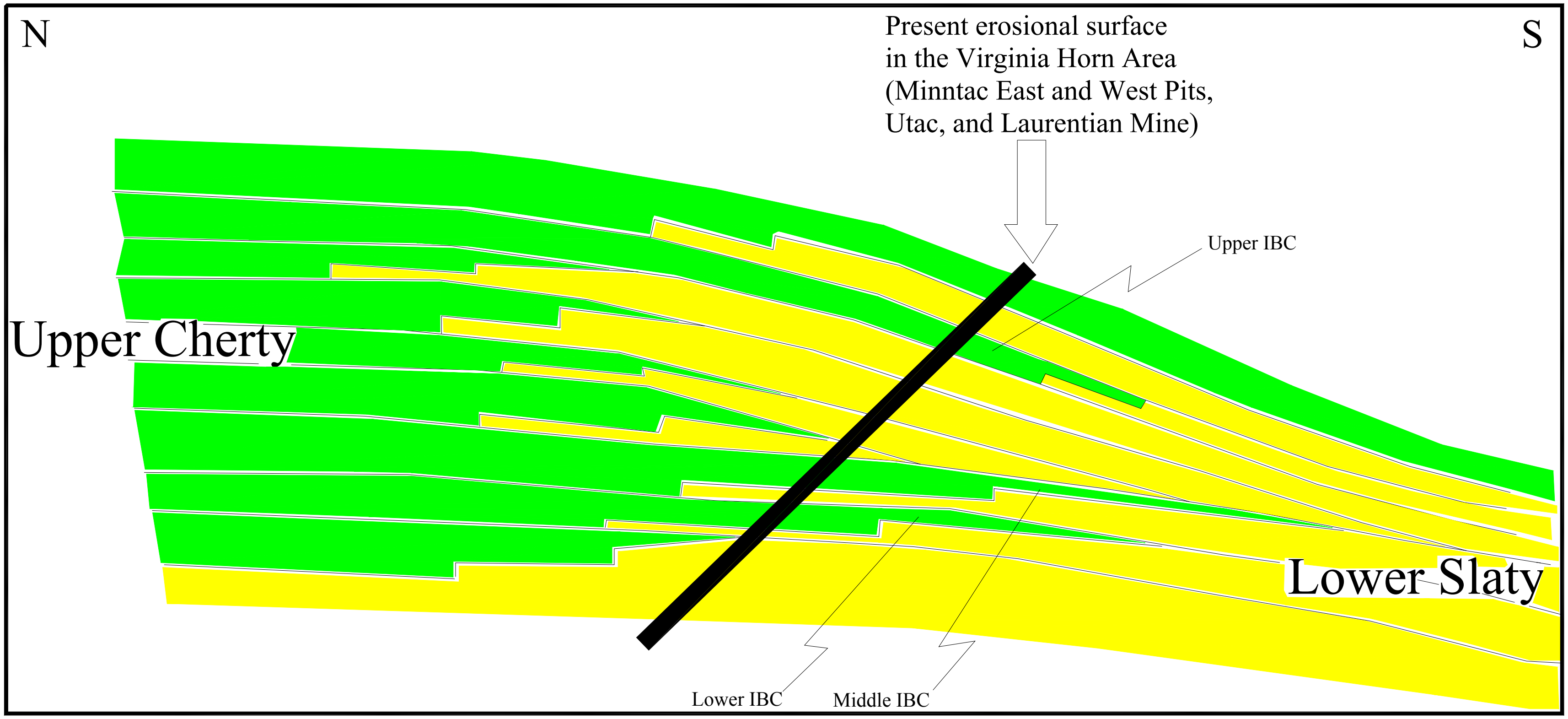


Figure 33. Hypothetical cross-section showing the interfingering relationships of Upper Cherty tongues (or "channels") in the Lower Slaty as interpreted from possible parasequences in the Virginia Horn area. The Upper Cherty tongues in this diagram are informally referred to as "Interbedded Cherts" or IBCs.

- Algal stromatolites are present in several horizons scattered throughout the Upper Cherty; whereas, stromatolites are restricted to only the base of the Lower Cherty. A major algal horizon in Upper Cherty, often colloquially referred to as the "I horizon," can be traced in scores of drill holes from Dunka pit, near Babbitt, all the way to Hibbing. It is variable in thickness, but can be up to 20 feet thick in places.
- The overall succession of rock packages in the Lower Cherty suggest gradual deepening (Basal Red Unit) followed by shallowing water depths and deposition of the remainder of the Lower Cherty by reworking of materials in a siliciclastic setting. This scenario is not the case for most of the Upper Cherty.

All of these features suggest major differences in the depositional environment between the two members. The more common occurrence of ooids and stromatolites in the Upper Cherty may be more likened to development of a carbonate platform, as has been suggested for the Paleoproterozoic Sokoman Iron Formation (Chauvel and Dimroth, 1974).

Overall, in the area of this investigation, the majority of the Upper Cherty to the west of Biwabik consists of regular- to medium-bedded rocks with common, scattered, very thin, intraformational conglomeratic lenses (usually less than two inches thick). A major algal horizon, to be discussed below, is also present throughout a good portion of the Mesabi Iron Range. Locally present in the Upper Cherty of this investigation are wavy-bedded zones, alternating-bedded zones, thick-bedded zones, and minor thin-bedded zones.

A crude correlation chart for the rock units of the Upper Cherty is presented in Figure 34. It is immediately apparent in Figure 34 that in some areas the Upper Cherty has not been divided into many submembers by the mines. This lack of division is mainly because the Upper Cherty member rarely contains taconite ore horizons, except in the Laurentian mine and further east. Therefore, definition of detailed submembers in the Upper Cherty has not been needed to the west of Biwabik. However, as the taconite mines continue to mine down-dip, definition of ore and waste zones will become more important, and submembers can be expected to be delineated in the future. It is important to note that, as of this writing, very few drill holes have intersected the entire Upper Cherty member, except in the eastern Mesabi Iron Range, and this lack of drill holes adds to the limited amount of recognizable submembers.

Also immediately apparent in Figure 34 is that the Upper Cherty shows an abrupt change in dominant bedding types in the eastern Mesabi Iron Range versus the central and western Mesabi (Laurentian to Coleraine area of Fig. 34). In the eastern Mesabi Iron Range, wavy-bedded zones are very common, and much of the Upper Cherty is mined. This drastic change in bedding types suggests a profound change in sedimentary environment in the eastern Mesabi Iron Range. Unfortunately, there are very few holes in the area where this change takes place, and it is impossible to document the sedimentary relationships associated with this change at this time.

The Upper Cherty in the area of this investigation (Biwabik to Coleraine) can be subdivided into the following preliminary units (see also Fig. 34):

1. Bottom Alternating-Bedded Unit (most common to the east of Hibbing);
2. Lower Regular-Bedded Unit (most common to the west of Hibbing);
3. Algal Unit (very distinctive and easily recognized to the east of Hibbing);
4. Upper Alternating-Bedded Unit (present only at Minntac);

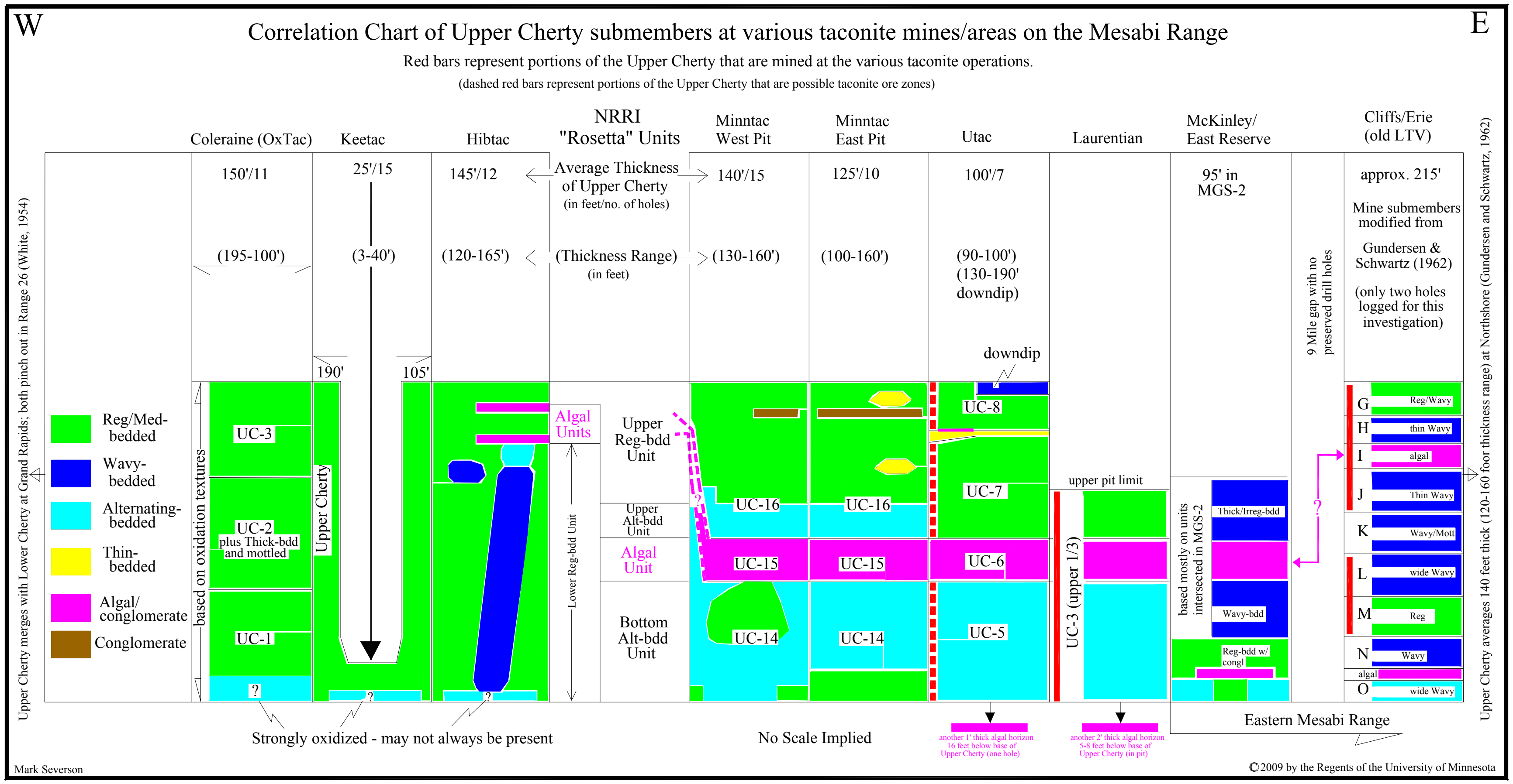


Figure 34. Correlation chart of Upper Cherty submembers at various taconite mines/areas along the Mesabi Iron Range. The vertical red bars represent portions of the Upper Cherty that are mined as taconite ore. Note that the Upper Cherty thins drastically in the central portion of the Keetac area in a valley-like morphology. Note also the distinct change in bedding types that constitute the Upper Cherty in the eastern Mesabi Iron Range. Upper Cherty submembers at Coleraine are based solely on oxidized characteristics that have been described in Zanko et al. (2003).

5. Upper Regular-Bedded Unit (all areas); and
6. A Conglomerate Horizon (at Minntac only).

Each of these units, along with mine submember designations where appropriate, is discussed in more detail below. An almost completely different set of units is present within the Upper Cherty in the eastern Mesabi Iron Range – these are only discussed briefly, as our observations are based on the geology intersected in three very widely spaced drill holes.

Bottom Alternating-Bedded Unit

At most of the taconite mines, the base of the Upper Cherty consists of alternating mixtures of thin-bedded sets of carbonate iron-formation and ooidal chert bands that are present in ratios that vary from 70:30 to 30:70. This change from dominantly thin-bedded rocks of the Lower Slaty to alternating-bedding in the overlying Upper Cherty indicates a gradual shallowing of water depth over time. In this instance, the inter-fingering chert beds represent either periodic storm debris inputs or short-lived periods of shallow water deposition. The chert bands are often conglomeratic with common jasper clasts and ooids. The thin-bedded sets occur in shades of greens, grays, reds, and pinks (with local browns), and the beds alternate with light gray to pale red chert bands. The various submember designations for the Bottom Alternating-Bedded Unit of the Upper Cherty at the appropriate taconite mines are listed below (see also Fig. 34).

- Coleraine – base of UC-1 submember = Strongly oxidized with poor core recoveries, but seen to be regular-bedded with several thin-bedded zones at the base of their UC-1 submember in a few of the less oxidized holes (Zanko et al., 2003).
- Keetac – not present, but could be obliterated by strong oxidation that is associated with the Lower Slaty.
- Hibtac – not yet recognized as a particular submember and only locally present in the eastern portion of their area (also obliterated by strong oxidation to the west?).
- Minntac – UC-14 submember = Characterized by alternating-bedded rocks, with localized regular-bedded packages near the base (especially drill holes to the south of Minntac's east pit – Plate XII).
- Utac – UC-5 submember.
- Laurentian – a portion of their UC-3 submember = Unit not recognized in the mine terminology, but corresponds to alternating-bedded rocks positioned below the Algal Unit of the Upper Cherty (as mapped by NRRI geologists in the mine exposures).
- East Reserve/McKinley Extension – present in only a few of the sparse holes that intersected the Upper Cherty in this area, and it is not yet fully defined.
- Cliffs-Erie site (old LTV mine) – O submember = Recognized as "wide wavy-bedded" by mine geologists, but consists of alternating-bedded rocks in the two holes logged for this investigation (note that both holes are located on the extreme east end of the Cliffs-Erie site).

Lower Regular-Bedded Unit

This unit is very thick and best developed in the few holes drilled through the Upper Cherty in portions of the Minntac, Hibtac, Keetac, and Coleraine areas. The rock is generally regular-bedded, gray-colored (unless oxidized as at Coleraine), and weak to strongly magnetic (unless oxidized as at Coleraine). Wavy-bedded zones can occur anywhere within this unit, but are most common toward the base of this unit (especially at Hibtac). Localized thin jasper-rich horizons with weakly convoluted micro-banding suggestive of algal mats have been noted throughout this unit at Keetac. Internal alternating-bedded units are also locally present at both Hibtac and Keetac. No specific submember designations have yet been established for this unit in the mine terminology, but it is characterized by the following relationships and textures at the following taconite mines.

- Hibtac – Thick package of regular-bedded rocks, positioned below the Algal Unit, that contains a localized, basal wavy-bedded zone (correlated in nine drill holes) that "cuts up-section" towards the east, and in turn, is locally overlain by an alternating-bedded zone (Plate XI). Overall, this entire unit exhibits a decrease in magnetism with depth.
- Keetac – Thick package of regular-bedded rocks that are drastically thin (erosional?) in the central Keetac area (as defined by recently-drilled holes - Plate XIV) and that are often strongly oxidized in close proximity to the Lower Slaty.
- Coleraine – Top of UC-1 submember and an unknown amount of the UC-2 submember. Both submembers are strongly oxidized with poor recoveries, and thus, it is difficult to distinguish true bedding types.

Algal Unit

The Algal Unit of the Upper Cherty member has long been recognized as containing colorful, red, jasper-rich stromatolites since it was first reported by Grout and Broderick (1919). The Algal Unit has often been referred to as the "I Horizon" or the "Mary Ellen Jasper." Gruner (1924) reported this single horizon extends from the far eastern end of the Mesabi Iron Range westward to the town of Nashwauk. However, in this investigation we could not trace the horizon westward with any degree of certainty past the town of Hibbing. The Algal Unit, shown in drill core in Figure 35, consists of intricate mixtures of the following:

1. Algal features are present as inverted stacked columns (often concentrated in elliptical mounds as shown in Fig. 37), algal mats and domes (weakly disrupted micro-beds), and oncolites;
2. Intraformational conglomerate (storm debris or tidal debris) with abundant jasper ooids and clasts (see Fig. 37);
3. Ooidal jasper layers;
4. Featureless chalcedonic chert bands;
5. Thin-bedded sets a few inches to a few feet thick in colors of green, brown, red, and gray;
6. Metallic, gray-colored hematite-rich beds; and
7. Black magnetite-rich beds.

All or one of the above bedding types can be present locally. Algal columns with associated intraformational conglomerates are exceedingly common from Dunka Pit to Gilbert; whereas, oncolites with associated intraformational conglomerate and lesser algal mat material are more common in the Eveleth (Utac) to Buhl (Minntac – west pit) area. Still further to the west, in the Buhl to Hibbing area, algal mats and conglomerate are dominant with rare oncolites. Magnetism in this unit is extremely variable and ranges from nil to strong. Colors in the cherty bands are mostly reds and pinks with lesser amounts of gray, green, and brown. Green and brown colors are dominant in the thin-bedded sets.

Figure 35. Photograph of drill core displaying the various textures and bedding types associated with the Algal Unit at Minntac (UC-15 equivalent). Oncolites, some with syneresis cracks, are present between the red arrows. Drill hole #24426 at 264-278 foot depth.

As mentioned above, this horizon has been reported to be present from Dunka Pit to Hibbing. However, its stratigraphic position in the Upper Cherty member is quite variable – as portrayed in Figure 34. In the area between Minntac and Hibtac (far left side of Plate XIII), this horizon can be seen to track upwards from the base of the Upper Cherty to one or two horizons at the top of the Upper Cherty near Hibtac. Toward the east, this same horizon can be traced at the base of the Upper Cherty from Minntac to the East Reserve/McKinley Extension mine near Biwabik. However, at this locale, and still further east of Biwabik, there are actually two algal horizons – a very small one near the base of the Upper Cherty and another much thicker horizon near the top of the Upper Cherty (right side of Fig. 34). It is unknown which of these two horizons corresponds to *the* Algal Unit, but the horizon near the top of the Upper Cherty is assumed to be the correct one.

The various submember designations for *the* Algal Unit of the Upper Cherty at the appropriate taconite mines are listed below (see also Fig. 34).

- Coleraine – Not observed in the strongly oxidized rocks of the Upper Cherty.
- Keetac – No continuous horizon is present, but "hints" of thin algal mats are widely scattered throughout the Upper Cherty.

- Hibtac – No specific submember designation has been chosen, but two horizons are present near the top of the Upper Cherty. Both of these horizons exhibit jasper ooids, intraformational conglomerate, and convoluted micro-banded chalcedonic chert (algal mats). Oncolites were observed in one drill hole. Black carbonaceous argillite was observed in another hole. Both of the algal horizons grade to the west into layers that contain only jasper ooids (Plate XI). These two horizons cannot be traced into Keetac.
- Minntac – UC-15 submember.
- Utac – UC-6 submember.
- Laurentian – No specific submember has been designated, but the algal unit is present, and it is located in the top third of their UC-3 submember. This algal horizon exhibits excellent jasper-rich columns and is up to 20 feet thick. It is important to note that a second and very similar algal horizon was also found fifteen feet below this horizon by NRRI geologists during detailed pit mapping (Fig. 36).

Figure 36. Photograph of geologic units associated with the top of the Lower Slaty and bottom of the Upper Cherty at the Laurentian mine. Note the presence of two algal horizons. One is positioned near the base of the Upper Cherty (UC-6 submember in the photo; approximately twelve feet thick), and the other (two feet thick within the UC-4 submember of the photo) is positioned near the top of the Lower Slaty. The UC-submember nomenclatures on this photograph are Utac designations, and these designations were applied during mapping of the pit by NRRI geologists. Conversely, the entire bench, as depicted in the photograph, is considered to be within the ArcelorMittal's UC-3 submember (see Fig. 34).

Figure 37a. Photograph of the distribution of algal mounds (white elliptical areas) in the Algal Unit at Pit 2E of the Cliffs-Erie site (I submember or “I horizon”). The mounds are lighter colored, and due to their high silica content, show positive relief in this glacially-polished exposure. The dark areas between the mounds consist of intraformational conglomerate (storm debris). Flowers and weeds for scale. Location: N ½, NW, Section 23, T.59N., R.14W., UTM 568,202E, 5,270,625N.

Figure 37b. Close up of an individual algal mound showing hundreds of finger-like structures that are convex upwards (top view). The mound is about two feet across. Same location as in Figure 37a.

- East Reserve/McKinley Extension – Only observed in a few of the holes on the property wherein the horizon is generally very thin and unimpressive in drill core when compared to exposures (now underwater) of the same horizon in the nearby Mary Ellen Mine, where historic samples consisting of bright red inverted columns were once collected.
- Cliffs-Erie site (old LTV mine) – I submember (Fig. 36); however, a much smaller algal unit and associated conglomerate is also reported to be situated between the N and O submembers (Fig. 34).

Upper Alternating-Bedded Unit

This unit is similar in all respects to the Lower Alternating-Bedded Unit except that in this case it overlies the Algal Unit. The alternation of thin-bedded sets and cherty sets is indicative of a short and very localized transgressive ocean. This unit is only present at Minntac where it corresponds to the bottom of their UC-16 submember.

Upper Regular-Bedded Unit

The upper half of the Upper Cherty consists of regular-bedded, ooidal, variably magnetic (weak to strong) rocks that exhibit various colorations that include mixtures of grays, greens, reds, and pinks with lesser browns. These rocks contain scattered conglomeratic zones – one of which can be traced with certainty in several drill holes across both the east and west pits of Minntac (Plates XII and XIII). The various submember designations for the Upper Regular-Bedded Unit of the Upper Cherty at the appropriate taconite mines are listed below (see also Fig. 34).

- Coleraine – UC-3 submember and an unknown part of the underlying UC-2 submember. It is strongly oxidized with poor core recoveries, and it is difficult to determine actual bedding types and internal relationships of both units.
- Keetac – referred to as only a portion of the Upper Cherty with no submember designation as of this writing. This unit is missing in the central Keetac area in a configuration that is suggestive of a submarine valley (Plate XIV). This valley may have been formed by either an erosional event (?), or non-deposition, and the valley was filled with thin-bedded sediments correlative with the Upper Slaty (see later discussions).
- Hibtac – referred to as only a portion of the Upper Cherty with no submember designation as of this writing. Corresponds to regular-bedded rocks above the two algal horizons.
- Minntac – corresponds to most of the UC-16 submember. A persistent conglomerate is present in the top of this submember. The conglomerate ranges from six inches to 4 feet thick, and can be traced in numerous drill holes across both of Minntac's east and west pits (Plates XII and XIII).
- Utac – corresponds to the UC-7 and UC-8 submembers. Both submembers display the same bedding characteristics, but a red color is more dominant in the UC-7; whereas, a gray color is characteristic of the UC-8 submember. In many of the holes logged for this investigation, the UC-7 and UC-8 submembers are separated by a thin-bedded zone that ranges from one foot to fifteen feet thick. Holes drilled downdip of the present mine area encountered a significant wavy-bedded zone above the UC-8 submember (Plates III and IV).
- Laurentian mine – not exposed.

- East Reserve/McKinley Extension – the entire Upper Cherty has not been drilled, but rock types present in drill hole MGS-2, located well to the south of the property, appear to be correlative with submembers of the eastern Mesabi Iron Range, e.g., at the Cliffs-Erie site, and Northshore and Dunka Pit mines.
- Cliffs-Erie site (old LTV mine) – submembers H and G. Rock types intersected in the two holes logged for this investigation (Plate II) are similar to the submembers described by Gundersen and Schwartz (1962).

Depositional Environment

Deposition of the Upper Cherty marks the second major regressive event on the northern edge of the Animikie Basin. The regular- to medium-bedded rocks associated with this member were deposited in shallow water due to reworking of "intraclasts," or granules, generated from the chemical muds of the Lower Slaty that were concurrently being deposited further from shore. There was some siliciclastic reworking of the granules in a tidally-influenced environment as evidenced by the localized presence of wavy-bedded units. This is especially true of the eastern Mesabi Iron Range, where wavy-bedded units are common. Unfortunately, the change in depositional environment from the central to the eastern Mesabi Iron Range cannot be documented as there are no known drill holes with preserved core in this critical area of change. The common occurrence of intra-formational conglomerates and ooids, which are almost exclusively associated with the Upper Cherty in the central and western Mesabi Iron Range, also indicate reworking of materials in shallow water by storm events and tidal currents.

The abundance of stromatolites in the Upper Cherty, occurring as both aerially-large fields (presumably near the shore line) and as scattered localized occurrences throughout the member, indicates that cyanobacteria activity increased and reached a peak during this period. During core logging, it was noticed that the morphological forms of the stromatolites change along the strike-length of the Mesabi Iron Range. To the east of the Virginia Horn, algal columns are common; whereas, in the Virginia Horn, oncolites and algal mats are common. Still further west, algal mats are dominant, and the Algal Unit eventually disappears in the Hibbing area. The variations in algal forms are probably related to several features that include water depth and current strength that are ultimately related to the geometry of the ancient shoreline.

Recent logging of drill holes in the central Keetac area by the NRRI has revealed that the Upper Cherty thins dramatically and exhibits a valley-like configuration in cross-section. This feature is a surprise, but a review of the plates in White (1954) revealed that this relationship had already been known at least 55 years ago. At present, this thinning is inferred to be related to erosion of the Upper Cherty at the head of a submarine canyon and will be discussed in the Upper Slaty portion of this report (below).

Upper Slaty member

The Upper Slaty is characterized by dominantly thin-bedded rocks in all locations along the Mesabi Iron Range (Fig. 38). One exception is a carbonate horizon at the very top of the Upper Slaty to the east of Hibbing. Another exception is the presence of lense-shaped bodies of regular-bedded chert that are locally present in the Hibtac and Minntac areas – in some isolated cases these lenses volumetrically account for a substantial amount of the Upper Slaty. Overall, rocks of the Upper Slaty are almost always non-

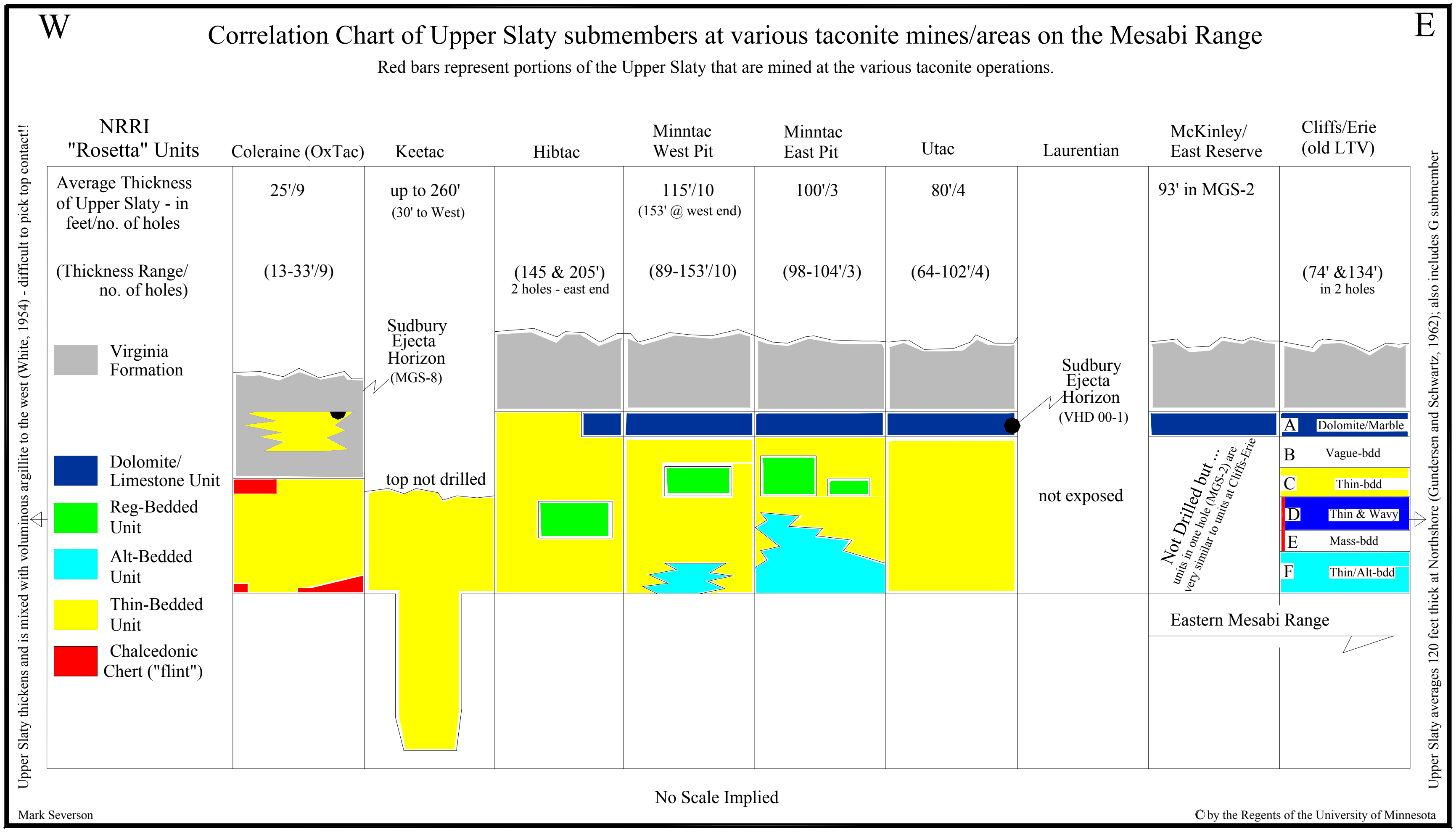


Figure 38. Correlation chart of Upper Slaty units and submembers at the various taconite mines/areas along the Mesabi Iron Range. Vertical red bars represent portions of the Upper Slaty that are mined as taconite ore. Note that the Upper Slaty exhibits drastic changes in thickness across the Mesabi Iron Range. No drill holes have been logged at the planned Essar mine (located immediately to the west of Keetac and not shown on this figure), but the Upper Slaty is reported to be 20-30 feet thick (mine handout). Only two holes have been logged from the Cliffs-Erie site (old LTV mine), and both holes confirm the presence of several submembers that have been previously recognized by Gundersen and Schwartz (1962). Submembers at the Northshore and Dunka Pit mines are similar to the submembers at the Cliffs-Erie site with some differences (see appendices). The general position of layers containing material related to the Sudbury impact event (1,850 Ma) are shown for the Utac area (Addison et al., 2005) and the Coleraine area (Cannon and Schulz, 2009). Looking North.

magnetic at the top of the member and exhibit increased magnetism with depth to moderately magnetic.

The thickness of the Upper Slaty shows considerable variation along the Mesabi Iron Range as depicted in Figure 38. To the west of Grand Rapids, the Upper Slaty is reportedly over 400 feet thick (White, 1954) and contains considerable amounts of argillaceous material (almost 300 feet) in the middle of the iron-formation (White, 1954), and placement of the upper contact, in drill holes that no longer exist, is questionable. To the east of Grand Rapids, and in the vicinity of Coleraine, the Upper Slaty is only 25 feet thick (Plate XV). However, there are several thin-bedded, iron carbonate-rich, iron-formation horizons in the immediately overlying Virginia Formation, and once again, the upper contact is picked with difficulty (see discussion in Zanko et al., 2003). In the western Keetac area, the Upper Slaty is 30 feet thick, but shows a drastic increase in thickness, at the expense of the Upper Cherty, in the central Keetac area (Plate XIV). There, recent logging of drill holes indicates thicknesses up to 260 feet thick. Two holes at Hibtac indicate that the Upper Slaty varies between 145 feet and 205 feet thick. Still further east, the Upper Slaty exhibits a gradual eastward-directed thinning from 115 feet thick at Minntac to 80 feet thick at Utac. Drill holes in the eastern Mesabi Iron Range (only three were logged for this investigation) suggest that the Upper Slaty varies from 93 to 134 feet thick. Rock types in the Upper Slaty in the eastern Mesabi Iron Range exhibit more variability, as depicted in the various submembers displayed in Figure 38, reflecting somewhat different depositional conditions than elsewhere on the Range.

As mentioned previously, the top contact of the Upper Slaty is picked with difficulty in some places due to the presence of interbedded argillite, carbonaceous argillite, and thin-bedded carbonate iron-formation in the immediately overlying Virginia Formation. This situation is especially true in the Coleraine area and further to the west. Recent logging of drill holes by the NRRI in the Keetac area has yet to encounter the top of the Upper Slaty, and the nature of the upper contact is unknown. East of Hibbing, the contact is more easily defined due to the persistent presence of a dolomite/limestone unit at the top of the Upper Slaty. But even in these cases, similar-appearing carbonate lenses are locally present in the base of the Virginia Formation and the contact is somewhat gradational in nature.

Conversely, the lower contact of the Upper Slaty is more defined, as thin-bedded rocks of the Upper Slaty are often in sharp contact with regular-bedded rocks of the Upper Cherty. In some areas, rocks at the contact zone between the two members consists of alternating-bedding, especially in the east pit at Minntac (Fig. 38 and Plate XII), indicating a gradual transition from shallow water deposition to deeper water conditions in specific areas.

The nature of bedding types in the Upper Slaty, and their internal relationships to each other, are depicted in Figure 38. Because the Upper Slaty is rarely drilled and never exposed in the mines of the central and western Mesabi Iron Range, it has not been subdivided into submembers by any of the mines (except for recognition of the carbonate unit at the top contact). However, in the eastern Mesabi Iron Range, there are multitudinous drill holes and pit exposures, and the Upper Slaty has been subdivided (Fig. 38). The major units of the Upper Slaty noted in this investigation (western and central Mesabi Iron Range) are as follows:

1. Alternating-Bedded Unit at the base of the Upper Slaty (best defined at Minntac and locally present elsewhere on the Mesabi Iron Range);
2. Thin-Bedded Unit (present everywhere);

3. Regular-Bedded Unit (present as lenses in the Thin-Bedded Unit at Hibtac and Minntac); and
4. Dolomite/Limestone Unit at the top of the Upper Slaty (present to the east of Hibbing).

These four major units of the central and western Mesabi Iron Range are described in more detail below.

Alternating-Bedded Unit

Alternating-bedded rocks, indicating a gradual deepening of water at the beginning of a major transgressive event, are commonly present at the base of the Upper Slaty. This sequence is especially evident at Minntac and possibly at the Cliffs-Erie site (Fig. 38). Alternating-bedded rocks also occur throughout the Thin-Bedded Unit of the Upper Slaty (see below). Overall, the alternating-bedding rock package is characterized by thin-bedded sets (one inch to three feet thick) that intimately interfinger with ooidal chert sets (one-half inch to one foot thick that are locally conglomeratic). Contacts between the two rock types are generally sharp and planar, but locally can be irregular and, in a few rare instances, exhibit a single stylolite. The ratios of thin-bedded sets to chert bands range from 70:30 to 30:70.

Thin-Bedded Unit

Thin-bedded, iron carbonate-rich rocks are the dominant rock type of the Upper Slaty. These rocks are generally present in shades of green and brown, but red-colored and gray-colored interbeds are also locally present. Thin chalcedonic chert beds (one-half inch to eight inches thick) are also present, and in some areas are so plentiful that the rock was logged as alternating-bedding. Thin chalcedonic bands with convoluted micro-bands (algal mats?) are widely scattered throughout this unit.

Recent logging of drill holes by the NRRI at Keetac (Fig. 38 and Plate XIV) turned up an anomalously thick package of thin-bedded rocks, with common internal alternating-bedded zones, that are associated with the Upper Slaty. In this area, the Upper Slaty exhibits a drastic increase in thickness (over 250 feet thick in some holes) at the expense of the Upper Cherty (only 3-40 feet thick in the same drill holes). Preliminary cross-sectional relationships suggest an erosional valley in the Upper Cherty that was in-filled with deep water sediments of the Upper Slaty – as has been schematically portrayed in Figure 39. Non-magnetic argillite beds, ranging from individual laminae and as packages up to 30 feet thick, are also present in the Upper Slaty in this same area and further support deep water deposition in a submarine valley. Interestingly, White (p. 25, 1954) noted this same anomalous feature which he reported as "… at Keewatin the abnormally great thickness of the overlying slaty rocks and the presence of some cherty rocks [probably correlative with the alternating-bedded zones] within the Upper Slaty member make it difficult to determine the boundaries of the members with any degree of accuracy." This statement appears to be based on one drill hole. However, this relationship is replicated in over 20 recently drilled holes that display a valley-like configuration (Plate XIV).

Regular-Bedded Unit

Regular-bedded zones, that are moderately to strongly magnetic, also occur in the middle portion of the Upper Slaty at Hibtac and Minntac. These zones are more common at Minntac, where they range from three feet to twenty-three feet thick and occur anywhere from five feet to 100 feet above the basal

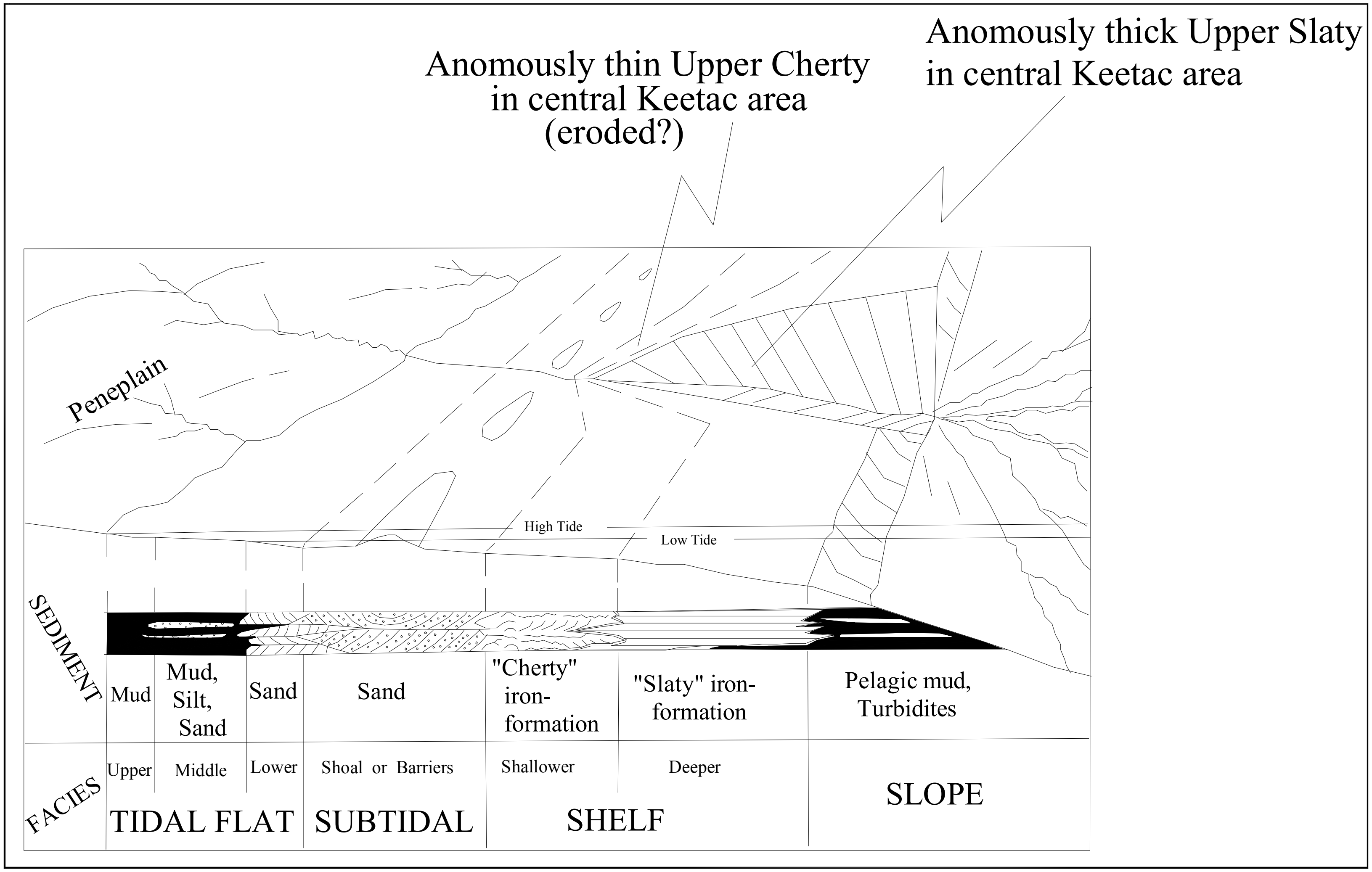


Figure 39. Sedimentation model showing lateral relationships of the Pokegama Formation, the two main types of Biwabik Iron Formation, and the Virginia Formation. A large submarine valley is inferred to have been present in the continental shelf in an area that corresponds to the present-day town of Keewatin. This submarine valley is envisioned to explain why the Upper Cherty is thin (eroded), and the Upper Slaty is anomalously thick (valley fill) in this area. Longitudinal stratigraphic sections in this area (Plate XIV) are suggestive of this valley-like morphology. Thicknesses and geography in the model are not to scale; modified from Ojakangas (1983).

contact of the Upper Slaty. The overall cross-sectional morphology of these zones, on the hung stratigraphic sections of this report (Plates XI – left side, XII, and XIII), suggest the zones occur as lenses with limited lateral extent. The zones may have been deposited as channels, or at the top of parasequences, as is envisioned for the IBCs of the Lower Slaty.

Dolomite/Limestone Unit (most often called the "A horizon")

This horizon, often referred to as the "A submember" in the eastern Mesabi Iron Range is characterized by intricately interbedded limestone, dolomite, and chert with localized carbonaceous black argillite beds (up to a few feet thick), as well as minor thin conglomerate beds with angular argillite, chert and carbonate clasts (Fig. 40). All of these rock types, or any combinations of these rock types including a single rock type, can occur in this unit in drill hole. The conglomerate beds are generally less than three inches thick, but locally occur up to one foot thick. There may be more than one conglomerate bed (Fig. 40), and when present, the conglomerate beds are usually positioned close to the top contact of the Upper Slaty.

The interbedded nature of the rock types that comprise this unit indicates simultaneous deposition of chert, carbonate, and carbonaceous muds at the end of iron-formation deposition and the beginnings of Virginia Formation deposition. However, the angular nature of the clasts in the conglomerate beds indicates that some diagenesis/lithification of all the rock types had also taken place. Thick conglomerate beds with a wide variety of clast types, shapes, and sizes are common in the top portions of the Gunflint Formation. These have been interpreted as resulting from seismic shaking in response to one of the events immediately following the Sudbury impact event (Jirsa, 2008). Whether the conglomerate beds observed in the Dolomite/Limestone Unit of this investigation are related to the same event remains to be investigated.

Depositional Environment

The Upper Slaty marks a major transgressive event in that it is dominated by thin-bedded iron-formation that was deposited in deep water. At some locales, the basal contact of the Upper Slaty consists of thick packages of alternating-bedded units, indicating a gradual deepening of the Animikie ocean; whereas, in other locales, the change took place rapidly and regular-bedded rocks of the Upper Cherty are directly overlain by thin-bedded rocks of the Upper Slaty. These differences probably reflect changes in water depth along an irregular shoreline with bays, mudflats, deltas, etc. Further still, submarine valleys extending outward from the shoreline could be invoked to explain the anomalously thick Upper Slaty and anomalously thin Upper Cherty in the central Keetac area. At this locale, the scattered chert beds in the alternating-bedded units could be related to materials that sloughed-in from the sides of the valley. The interfingering of thin-bedded iron-formation and argillite in this same area also suggests repeated periods of chemical and clastic deposition below storm wave base.

The regular-bedded lenses within the Upper Slaty probably formed as infilled erosional channels in much the same way as the IBCs formed in the Lower Slaty member. The overall trends of these lenses could help to explain their origin.

Lastly, the presence of interbedded carbonate, chert, and carbonaceous argillite at the top of the Upper Slaty indicates increasing water depth and the eventual domination of clastic deposition of the Virginia Formation

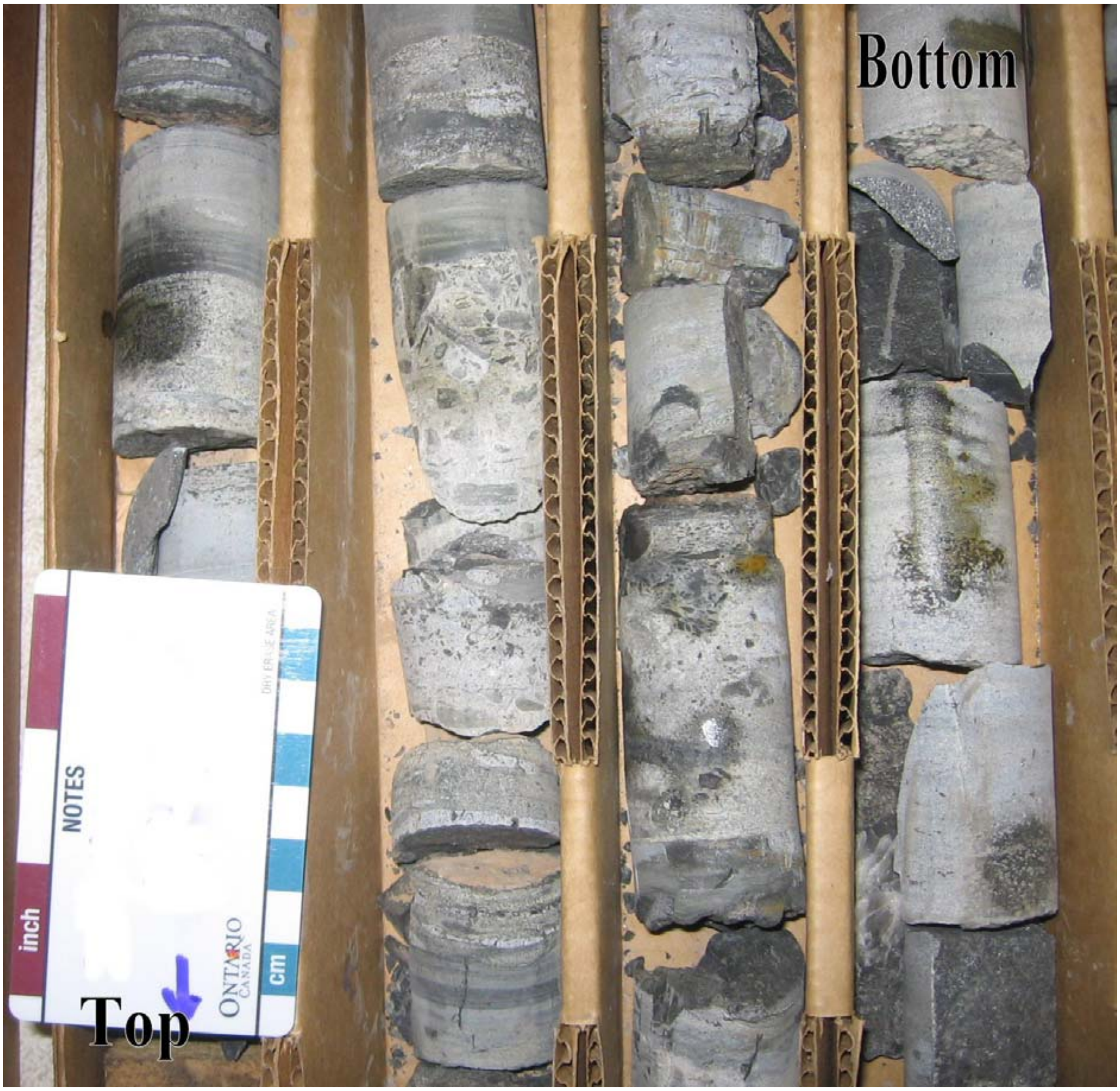


Figure 40. Photograph of drill core exhibiting bedding types associated with the Dolomite/Limestone Unit at the top of the Upper Slaty member. Note the two conglomerate beds in the center of the photo. Drill hole #24426 from 81 feet to 97 feet deep.

and the cessation of iron precipitation. The carbonate beds at the very top of the iron-formation pose several problems, and their genesis is well beyond the scope of this investigation. Several theories have been invoked to explain inorganic carbonates in the Paleoproterozoic, some of which include:

1. The carbonates were precipitated contemporaneously with biological activity (Schopf et al., 1965) – of which the association with the carbonaceous base of the Virginia Formation helps to explain;
2. The carbonates are related to higher CO_2 concentrations in the earth's primitive atmosphere (Ohmoto et al., 2004); and
3. The carbonate and chert layers at the top of the Upper Slaty are replacement products that formed during subarial exposure (P. Fralick, pers. comm., 2007, 2009).

Further still, a link to the Sudbury impact event may be possible, and detailed work is as yet inadequate to explain these iron-poor rocks at the contact between the Biwabik Iron Formation and the Virginia Formation. It is interesting to note that at the time of this writing, evidence for the Sudbury impact event has been confirmed to be present in only two holes on the Mesabi Iron Range (Fig. 38): one hole in the Virginia Horn area (Addison et al., 2005); and another hole in the Coleraine area (Cannon and Shulz, 2009). In the Virginia Horn drill hole, the impact-related materials (1,850 Ma) occur near the base of the Dolomite/Limestone unit (W. Addison, pers. comm., June, 2009). Furthermore, an age date of 1832 ± 3 Ma has been obtained from the very base of the overlying Virginia Formation (Addison et al., 2005). These age dates suggest that the Dolomite/Limestone Unit formed after the impact event sometime during an intervening 18 million year period.

Summary of Stratigraphy

This investigation has established the presence of at least 25 major units, discussed in the preceding pages and depicted in Figure 41, that comprise the Biwabik Iron Formation. Most of these units have long been recognized by the various taconite mines on the Mesabi Iron Range, but they have been called such a variety of submember names that it is often difficult to keep one straight from the other. In this report, these 25 major units have been carefully correlated in hung stratigraphic sections, and the units have been named for the bedding types that each represents. This stratigraphy was accomplished by detailed logging of over 380 drill holes spread out along 75 miles of strike length along the Mesabi Iron Range (Biwabik to Coleraine, MN). It is hoped that the mines can use these "bedding-named" units in the future to help them in their discussions with neighboring mines when comparing and contrasting their ore and waste rock types. That being said, we are NOT suggesting that the mines give up their specific submember nomenclatures. Their system of naming the various submembers has worked successfully for each of them over many years. In turn, we also used their submember systems as starting points to aid us in deciphering the stratigraphy of the iron-formation. For this reason, we looked at as much core as possible and have carefully correlated each individual submember at one mine to comparable submembers at all of the other mines. These various submember names, or "Rosetta" units, have been presented in correlation charts of Figures 9, 25, 34, and 38 in this report.

The major geologic/"Rosetta" units of Figure 41 have been proposed mainly to help simplify future discussions pertaining to the stratigraphy of the iron-formation. For example, in this report the Regular-Bedded Unit of the Lower Cherty ("Rosetta" unit) corresponds to the LC-2, LC-6, 1-2, LC-1, LC-2/LC-1, LC-3, and U submembers at each of the various mines (Fig. 9). This barrage of names is difficult to remember and cumbersome to use. Not only does one have to remember each of the submember names, but one has to also remember which submember applies to which mine. The naming of the 25 major "Rosetta" units, as defined by the bedding type that is dominant in that submember, helps to avoid this confusion.

While this report has tried to describe the highlights of each mine's submembers, it should be noted that it would be impossible to describe all of the nuances of each mine's submembers. The mine geologists who have worked with these submembers for years will easily find that some of the descriptions presented in this report are "lacking this" or "shouldn't include that," and we apologize for those omissions and errors. However, the generalities described for each of the units in

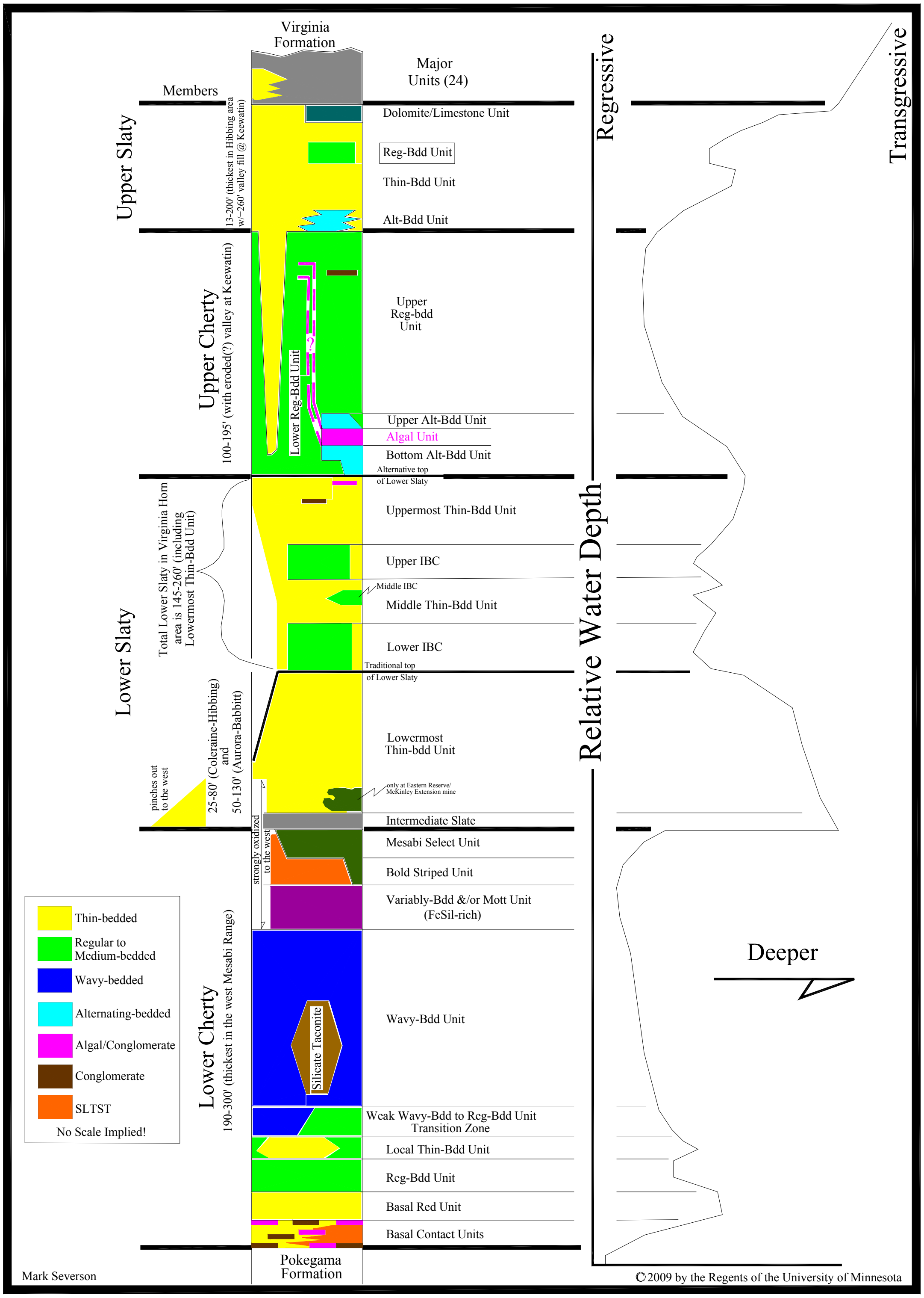


Figure 41. Summary of all of the 25 major "Rosetta" units in the Biwabik Iron Formation that have been identified and described in this report. Most of these units have corresponding submember designations at each of the taconite mines that can be seen in Figures 9, 25, 34, and 38. Note that the Upper Cherty and Upper Slaty members of the eastern Mesabi Iron Range (east of Biwabik, MN) are markedly different than what is portrayed on this figure (only two holes have been logged to the east of Biwabik). Relative water depths for each of the 25 units are shown on the right side of the figure.

this report are those that we saw at multiple sites.

Throughout this report, possible depositional environments have been suggested for most of the 25 "Rosetta" units. However, it must be repeatedly stressed that these inferred environments have been based largely on the relationships displayed in the drill cores of multiple holes. A detailed sedimentalogical study was not the primary goal of this investigation, and the suggested environments are crude comparisons to recent sedimentary systems and should only be used as starting points for future discussions. More rigorous testing of the proposed environments, in the form of field mapping the pit walls as they advance and the continued logging of more drill holes for detailed 3-dimensional analyses, need to be completed before the true nature of sedimentation can be established. Such studies may also shed light on ore grade changes that show up as down strike facies changes.

Definition of the 25 "Rosetta" units can also be used as starting points for more detailed sequence stratigraphy studies and basin analysis. There are clearly variances in some of the units and the four iron-formation members that are related to facies changes. Good examples of these differences are the following:

1. The Lower Cherty is remarkably consistent throughout most of the Mesabi Iron Range, and it exhibits a procession of units that can be related to reworking of materials in a siliciclastic environment; whereas, most of the Upper Cherty is vastly different, and it is suggestive of an entirely different depositional environment;
2. The rapid thinning of the Lower Cherty in the eastern Mesabi Iron Range, across the Siphon Fault (which is inferred to be a growth fault), suggests a unique change in depositional environment from the rest of the Mesabi Iron Range;
3. The Lower Slaty is uniquely thicker in the Virginia Horn area, possibly related to reactivation of Archean-age structures (M. Jirsa, pers. comm., 2006), and contains several "interbedded chert" lenses that were either deposited as individual parasequences or, more likey, as "cut and fill" channels;
4. The possible presence of slumped bodies of "Mesabi Select equivalent" in the Lower Slaty at the East Reserve/ McKinley Extension mine suggest unique localized responses to earthquake induced seismicity that occur only at this locality and may be related to proximity to the Siphon Fault (17 miles to the east) and/or proximity to other mapped or unmapped faults;
5. The Upper Cherty is unique in that there is increased biogenic involvement in its genesis, as suggested by increased stromatolite occurrences that in some areas form extensive "fields";
6. There is a profound difference in the Upper Cherty in the eastern Mesabi Iron Range, wherein wavy-bedded rocks are more common, versus the central and western Mesabi Iron Range, where regular- to medium-bedded rocks dominate;
7. The various forms of the stromatolites (columns, mats, and oncolites) associated with the Algal Unit suggest changes in specific areas along the shore in regards to shoreline morphology, water depth, and current strength/direction;
8. The unique presence of a submarine valley in the Upper Cherty, near Keewatin, which was filled with Upper Slaty materials; and
9. The change in the nature of the Upper Slaty in the eastern Mesabi Iron Range (with some wavy-bedded zones) in regard

to the same member in the central and western Mesabi Iron Range (no wavy-bedded zones).

As the list above indicates, there are several unique differences in the stratigraphy of the iron-formation that could give an impression of overall heterogeneity. In fact, Morey (1992) mentions this heterogeneity several times in his discussion on the chemistry of the Biwabik Iron Formation. This heterogeneity, in part, stems from the multitude of submembers used by each of the different mines, and also from previous concepts of the stratigraphy that were based on a handful of widely-spaced drill holes that were available to the public at the time. Rather, this investigation shows that there are gradual lateral facies changes that can be traced in numerous drill holes. This change is a reasonable relationship when one remembers that shorelines along continental shelves are not static, and the rocks deposited on them reflect changes in water depth, current strength, and changes in the morphology of the shoreline, e.g., the presence of bays, beaches, mudflats, estuaries, submarine valleys, etc. Thus, this investigation has found that the iron-formation is remarkably homogenous with reasonable local facies changes that take place progressively in a series of drill holes positioned along the strike of the Mesabi Iron Range.

While this project was extremely useful in characterizing the submembers of the Biwabik Iron Formation, there are still numerous questions that remain to be investigated through continued detailed core logging and petrographic studies that include the following:

- The 3-dimensional nature of some specific units, particularly the IBCs of the Lower Slaty member and the silicate taconite bodies of the Lower Cherty, need to be more fully investigated through continued logging of drill holes coupled with in pit mapping. Hopefully, such studies will map out the trends of these units. These trends could become increasingly more important as the mines continue to advance down dip.
- The ore grades associated with each of the various units/submembers should be characterized, and changes should be investigated both within and between the mines – these data are not yet available from the taconite mines due to their proprietary nature;
- Changes in mineralogy, both vertically and laterally, that are associated with each of the units/submembers should be investigated. While McSwiggen and Morey (2008) noted some interesting mineralogical trends, their data are only from two holes (one of which is in the metamorphic aureole of the Duluth Complex), and more detailed work is essential to categorizing the types and volume of minerals that are specific to each unit/submember.
- More detailed logging of drill core should continue. There are still large areas, with preserved core, where the stratigraphy of the iron-formation can be further established. These areas include:
  a) The Essar area (previously MSI) near Nashwauk;
  b) The area between Hibtac and Minntac;
  c) The Thunderbird South Mine (old Evtac mine) near Eveleth;
  d) The area between the Thunderbird South Mine and Laurentian Mine (Genoa/Sparta mine area);
  e) The Cliffs-Erie site (old LTV mine); and
  f) The metamorphosed iron-formation of the Northshore and Dunka Pit mines.
- The holes that were logged very early in this project should be relogged now that we are more familiar with the stratigraphy and submembers of the iron-formation.

This includes the Mesabi Deep Drilling Project holes (MGS-2, MGS-5, MGS-7, and MGS-8) and the BHP holes from the Virginia Horn area (LWD-99-1, LWD-99-2, and VHD-00-1).

POTENTIAL AGGREGATE HORIZONS WITHIN THE BIWABIK IRON FORMATION

Introduction

The major emphasis of this project was to delineate potential aggregate horizons within the Biwabik Iron Formation. The previous identification of "Mesabi Select" as good aggregate material (Martin, 2005; Olson et al., 2006) from a specific layer in the iron-formation was a major catalyzing driver in the search for other aggregate horizons. Several potential horizons, depicted in Figure 42, were found in this investigation and are discussed in this chapter.

Mesabi Select Unit

The Mesabi Select Unit at the top of the Lower Cherty member makes "priority one" aggregate material (Fig. 42) for two reasons. First, from a mining viewpoint, this unit is easily separated from the surrounding geologic units due to the following: 1. the overlying Lower Slaty member is easily blasted off and removed due to its very fissile nature; 2. the Mesabi Select Unit, which is noticeably thicker-bedded and much more indurated, is then drilled, blasted and removed selectively as it is a waste rock that contains virtually no magnetite; and 3. the Mesabi Select Unit has to be removed anyway as it is positioned above the taconite ore zones of the Lower Cherty. The second reason is that the Mesabi Select Unit has performed well in the tests that have been conducted on it by Mn/DOT thus far. It is a very indurated silica-rich rock that generates angular particles when crushed, thereby giving it good friction qualities in hot mix asphalt (HMA), and it exhibits a unit weight (~160 pounds/ft^3) that is about 10% heavier than typical HMA in Minnesota (Zerfas et al., 2005).

Richter (2005) has characterized the mineralogy and rock types of the Mesabi Select Unit from crushed stockpiled materials collected at Utac. He found that this unit consists of three main rock types:

1. Silica-rich component (about 60% of the sampled material by volume) that can be further broken down into:
   - Type I – ferruginous materials (about 46% by volume) consisting of cherty particles with varying amounts of greenalite granules;
   - Type II – minnesotaite-rich materials (about 9% by volume) consisting of particles that are rich in minnesotaite and appear to be simply minnesotaite-rich varieties of Type I materials [wherein the greenalite has been replaced by minnesotaite]; and
   - Chert-rich materials (5-10% by volume) that are texturally similar to the Type I materials, but have lesser concentrations of minnesotaite and greenalite;
2. Carbonate-rich component (about 19% by volume) that can be further broken down into:
   - Siderite-rich materials (about 10% by volume) consisting of particles where the mineral assemblage is dominated by siderite, stilpnomelane, and iron oxides with minor minnesotaite and greenalite/chamosite;

     Cherty siderite materials (about 9% by volume) that are similar to the siderite-rich materials, but are finer-grained and consist mostly of cherty minerals that are ≥ siderite; and

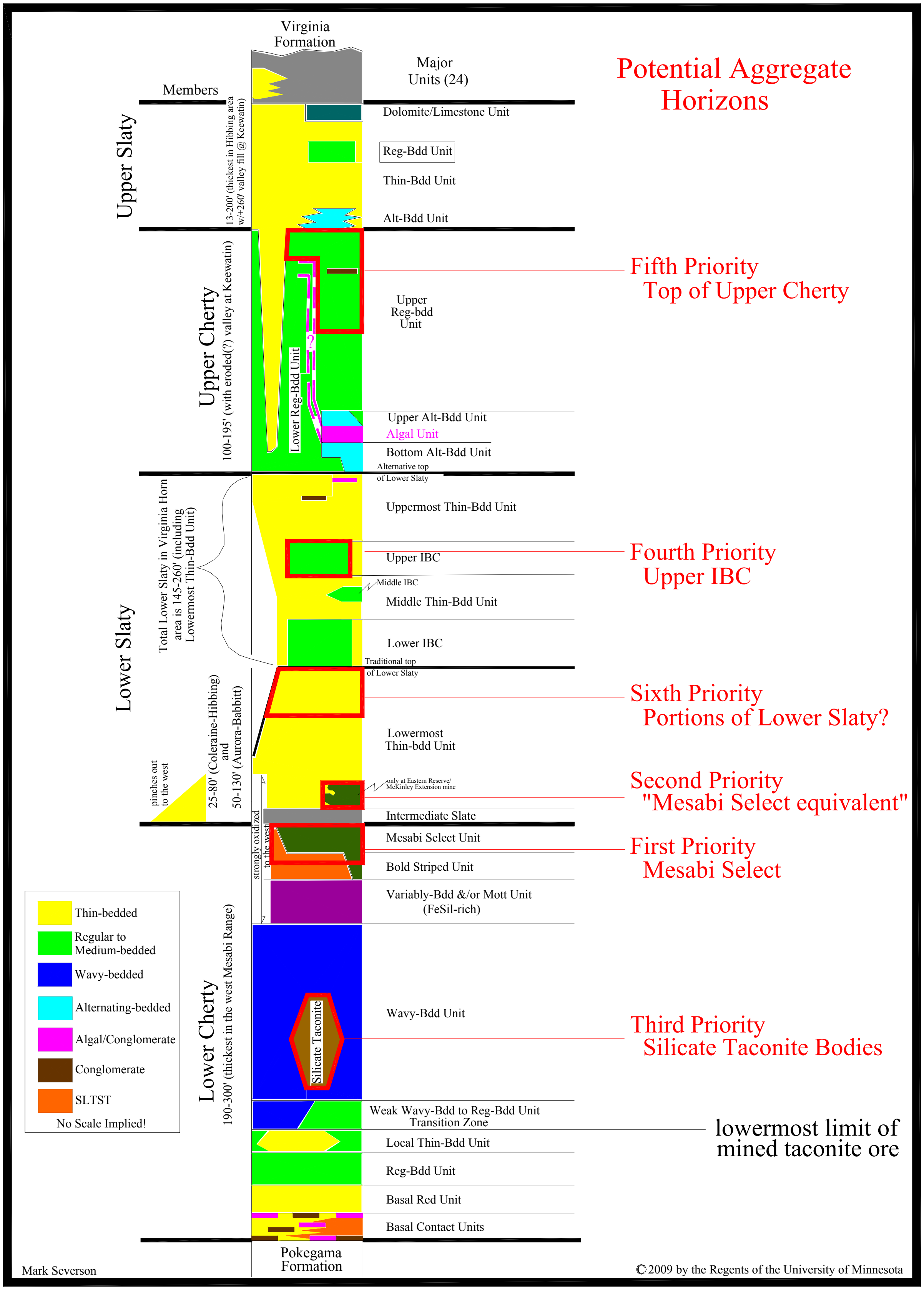


Figure 42. Potential aggregate horizons, listed according to relative priorities, in the Biwabik Iron Formation that were defined in this investigation. No vertical scale implied.

  - Meta-Siderite-rich materials (about 2% by volume) consisting of particles that are rich in coarse-grained iron carbonates that display a preferred grain shape orientation [probably from zones rich in iron carbonate mottles]; and

3. Magnetite-rich components (about 5-10% by volume) consisting of particles rich in magnetite [probably from either the Mesabi Select or Bold Striped units that show an increase in magnetite content with depth].

Overall, Richter's (2005) descriptions of the various components match quite well with our observations of the Mesabi Select Unit. We also noted the dominant granular greenalite-rich character with lesser beds wherein greenalite is extensively replaced by minnesotaite. These two rock types would be identical to Richter's Type I and II materials; respectively. Richter's (2005) "carbonate-rich component" is related to the varying proportions of iron carbonate-rich, thin-bedded, brown sets that we also saw in drill core. In fact, in some areas the Mesabi Select Unit contains enough of these thin-bedded sets that it is often logged in drill core as the underlying Bold Striped Unit (see descriptions in the previous chapter). Thus, the percentages that Richter (2005) gives, for his two main components, can be expected to show more variability elsewhere depending on where the material is obtained, and the amount of Bold Striped Unit that is contained within the stockpile. Richter (2005) also made other observations based on his thin-section study, which we also observed in the drill core, which include: 1) the presence of stylolites; and 2) the presence of anthraxolite (carbon-rich mineral).

In our investigation, we found that the Mesabi Select Unit, along with varying proportions of the Bold Striped Unit, occurs at several locations with sufficient thickness to constitute aggregate materials that can selectively be mined and set aside. Areas with good potential are:

- Minntac west pit – LC-5B submember (both Mesabi Select and Bold Striped units; in some cases in reversed stratigraphic order) where it is 20-35 feet thick;
- Minntac east pit – LC-5B submember (as above) where it is 15-25 feet thick;
- Utac mine – LC-8 submember (Mesabi Select Unit) where it is about 20 feet thick, and possibly contains portions of the underlying Bold Striped Unit that often makes taconite ore grade and averages about 14 feet thick;
- Laurentian mine – LC-5B submember (both Mesabi Select and Bold Striped units; in some cases in reversed stratigraphic order) where it is about 15-30 feet thick (as measured in the pit walls); and
- East Reserve/McKinley Extension mine – LC-5B submember (both Mesabi Select and Bold Striped units; in some cases in reversed stratigraphic order) where it is 15-30 feet thick.

It is important to note that the Mesabi Select Unit is extensively oxidized and friable to the west of Buhl, MN, and thus, cannot be used as aggregate from the Hibtac and Keetac operations.

"Mesabi Select equivalent"

Recent logging of drill core by the NRRI from the East Reserve/ McKinley Extension mine (Fig. 43) has outlined a significant amount of material that is very similar in texture and mineralogy to the Mesabi Select Unit of the Lower Cherty. In this case, the similar material occurs in the overlying Lower Slaty Member and is herein referred to as "Mesabi Select equivalent." Fortuitously, both the Mesabi Select Unit and "Mesabi

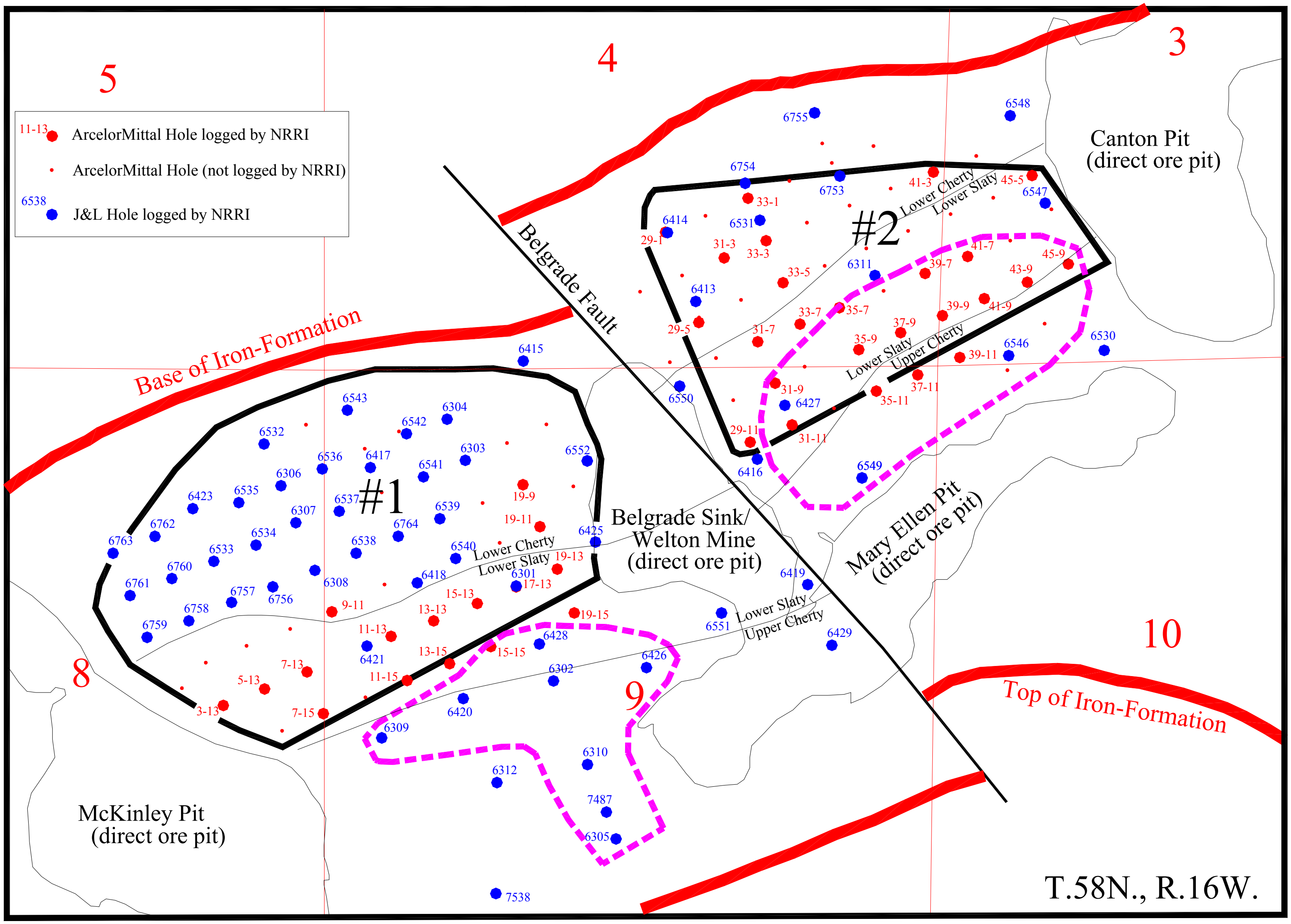


Figure 43. Drill hole location map for the Eastern Reserve/McKinley Extension mine showing crude pit limits (in black) for pits #1 and #2. Areas with significant amounts of "Mesabi Select equivalent" materials that are situated down dip of the planned pits, and could potentially be mined and used as aggregate, are outlined in the dashed areas (magenta color). More details regarding drill hole numbers/colors, core logged by NRRI personnel, and the locations of various cross-sections through the property can be found in Plate XVI of this report. Location of drill holes from John Arola (ArcellorMittal holes) and Peter Jongewaard (J&L holes).

Select equivalent" occur in close vertical proximity to each other with variable amounts of the Intermediate Slate between them. Thus, both could be mined collectively and stockpiled for use as aggregate. In some areas, the intervening Intermediate Slate is only three feet thick (drill hole 41-7; Fig. 43; Plate X); whereas, in other areas, the Intermediate Slate is as much as 52 feet thick (drill hole 31-11; Fig. 43; Plate VIII).

While the above statements paint an optimistic picture, there are several points to consider if the "Mesabi Select equivalent" material is to be used as aggregate. These points are listed below.

- The entire Lower Slaty at this location consists of highly variable amounts of: 1) "Mesabi Select equivalent;" 2) thin-bedded carbonate iron-formation; and 3) carbonaceous argillite (which is usually thicker at the base where it is called the Intermediate Slate). All of these rock types are not magnetic, and therefore, constitute waste materials that must be removed to access the Lower Cherty taconite ores.
- In some areas, the Lower Slaty contains very little "Mesabi Select equivalent" material; whereas in other areas, considerable amounts of "Mesabi Select equivalent" are the dominant rock type. A perfect example of the latter is the occurrence of up to 105 feet of "Mesabi Select equivalent" in drill hole 43-9 (Fig. 43; Plate IX).
- There are always some carbonaceous argillite beds and wisps in the "Mesabi Select equivalent." These argillites vary from <1 mm thick to a few feet thick and could generate tabular particles when blasted and cause contamination problems in the potential aggregate. However, when this material is blasted it may be possible that the argillite beds could become pulverized and lost as dust particles; thereby, causing no problems in the potential aggregate.
- In some areas, more than one zone of "Mesabi Select equivalent" is present in a single drill hole. These zones can be quite thick, and they are often separated by variable amounts of intervening carbonate iron-formation and carbonaceous argillite. A perfect example of this relationship is the presence of two thick aggregate zones in drill holes 37-11 and 39-11 (as shown in Plate V; Fig. 43).
- Most of the zones where significant thicknesses of "Mesabi Select equivalent" occur are positioned down dip of the present proposed ultimate pit limits (Fig. 43). If this material could be sold as aggregate, it could change the economics of the current stripping ratio, and effectively move the ultimate pit limits much further to the south for both pits.

For all of the above reasons, the quality and quantity of "Mesabi Select equivalent" materials in specific areas of the mine site will need to be carefully monitored and grade-controlled. The plates of this investigation (Plates V through X) specifically show areas where significant thicknesses of "Mesabi Select equivalent" materials are present, as well as, areas where these materials are lacking. Similarly, numerous cross-sections have been constructed through the property (both pits) that also show where good aggregate zones occur and where they are insignificant (Plates XVII through XXXV). Two fence cross-sections (Plates XXXVI and XXXVII) were also constructed and summarize where the best and thickest potential aggregate zones are located relative to the two pits.

The pertinent cross-sections of the area that are found in this report (Plates XVII through XXXV) could eventually be incorporated into a mining software program to generate the volume of potential aggregate materials that are available (not done for this investigation). Specific gravity (density) measurements of the "Mesabi Select equivalent" materials, collected by the NRRI from intervals in three drill holes (33-11, 39-9, and 41-9), could be used in this exercise. The density results are included in the McKinleySpecGrav.xls file on the CD that accompanies this report (Appendix B). A discussion of how the density determinations were made is presented in Appendix B. In addition, magnetic susceptibility readings (in 10^{-3} SI units), taken with an Exploranium KT-9 instrument, were obtained by the NRRI on the same drill holes/intervals and are included in the McKinleyMag.xls file on the CD that accompanies this report (Appendix B).

Sampling of thick zones with "Mesabi Select equivalent" from sawn drill core in three drill holes was also conducted for this investigation (the same zones where the above mentioned density determinations and magnetic susceptibility measurements were made). Sampled intervals are listed in Table 3. Permission to sample the core was granted to the NRRI (by John Arola), and the core was sawn in half (by NRRI personnel). One half of the core was retained by the NRRI, and the other half was consumed by ArcelorMittal for grade testing purposes (results are not known). The half-core samples retained by the NRRI will be crushed, and some aggregate tests will be conducted by Mn/DOT with results to be documented in a later Mn/DOT report. Hopefully, these tests will give some preliminary indication of whether the argillaceous interbeds have any deleterious effect on the aggregate potential of the "Mesabi Select equivalent."

Silicate Taconite

Silicate taconite bodies are present in the Lower Cherty Member at two taconite mines, Minntac and Hibtac, and constitute a "third priority" potential aggregate. In both instances, the silicate taconite is situated in the Wavy-Bedded Unit, which usually constitutes ore, and the silicate taconite would eventually need to be removed and stockpiled during mining activities. However, at both of the mines, the silicate taconite bodies are positioned well to the south of present-day pit limits and would not be mined for several years. A description of the silicate taconite bodies at the two mine locations follows.

Silicate Taconite at Minntac

The largest amount of silicate taconite, that was delineated in this investigation, is positioned to the south of Minntac's West Pit (Fig. 44). At this locale, magnetite-poor rock was intersected in at least seven drill holes, which are portrayed on the hung stratigraphic section of Figure 45. The silicate taconite intervals in the holes of Figure 45 define a subhorizontal zone that corresponds to Minntac's LC-4, LC-3, and LC-2 submembers (called LC-4W, for LC-4 "waste," and LC-3W during logging by the NRRI). As can be seen in Figure 45, there are considerable amounts of waste or lean ore at either end of the silicate taconite body (holes 24210 and 24379) that, in turn, are connected by a 24-31 foot thick band, giving an overall "dumbbell-shaped" appearance. The silicate taconite in the "dumbbell" is generally characterized by medium- to thick-bedded chert rather than magnetite-rich wavy-bedded rocks (typical of the LC-4 submember) or "salt-and-pepper" textured magnetite-rich rocks (typical of the LC-3 submember). Wavy magnetite-rich beds are locally present over short intervals (usually less than five feet thick), but they are not very common. Also, the chert bands of the silicate taconite contain a high percentage of iron silicate minerals rather than disseminated magnetite. Overall, these rocks range from non-magnetic to weakly magnetic

Table 3. Listing of sampled half core (sawn) collected from various intervals in three drill holes from the Eastern Reserve/McKinley Extension mine near Biwabik, MN. Note that these samples were specifically collected from zones where the "Mesabi Select equivalent" (regular- to thick-bedded greenalite granule-bearing chert) is dominant. The term slate is applied to black, carbonaceous argillite.

Drill Hole	Interval (in feet)	Description
35-11	77-87	"Mesabi Select equivalent" with 3% slate beds and 12.5% brown iron carbonate sets (both < 5 inches thick).
35-11	87-97	"Mesabi Select equivalent" with 0.2% slate beds and 20% brown iron carbonate sets (both < 5 inches thick).
35-11	97-107	"Mesabi Select equivalent" with 2% slate beds and 5% brown iron carbonate sets (both < 1 inch thick).
35-11	125-135	"Mesabi Select equivalent" with 6% slate beds and 13% brown iron carbonate sets (both < 1 inch thick). Bedding is soft-sediment deformed.
35-11	135-145	"Mesabi Select equivalent" with11% slate beds and 11% brown iron carbonate sets (both < 1 inch thick). Bedding is soft-sediment deformed.
35-11	145-156	"Mesabi Select equivalent" with 9% slate beds and 21% brown iron carbonate sets (both < 1 inch thick). Bedding is soft-sediment deformed with slate rich zone at 148-149 feet.
39-9	57-67	"Mesabi Select equivalent" with 0.5% slate beds and no brown iron carbonate sets.
39-9	67-77	"Mesabi Select equivalent" with 3% wispy slate beds and 3.5% brown iron carbonate sets.
39-9	77-82.5	"Mesabi Select equivalent" with 3% wispy slate beds and 6% brown iron carbonate sets.
39-9	106.5-115	"Mesabi Select equivalent" with 3.5% wispy slate beds and 1% brown iron carbonate sets (mostly at 112.5-113.5'). Bedding is soft sediment deformed.
39-9	115-125	"Mesabi Select equivalent" with 1% wispy slate beds and 7% brown iron carbonate sets. Bedding is soft sediment deformed.
39-9	125-134	"Mesabi Select equivalent" with 2% wispy slate beds and 3% brown iron carbonate sets. Bedding is soft sediment deformed.
41-9	135-145	"Mesabi Select equivalent" with 4% slate beds (up to 3 inches thick) and 4% brown iron carbonate sets. Bedding is soft sediment deformed.
41-9	145-155	"Mesabi Select equivalent" with 3% slate beds (up to 4 inches thick) and no brown iron carbonate sets. Bedding is soft sediment deformed.
41-9	155-165	"Mesabi Select equivalent" with 3% slate beds (<1 inches thick) and 2% brown iron carbonate sets. Bedding is soft sediment deformed.

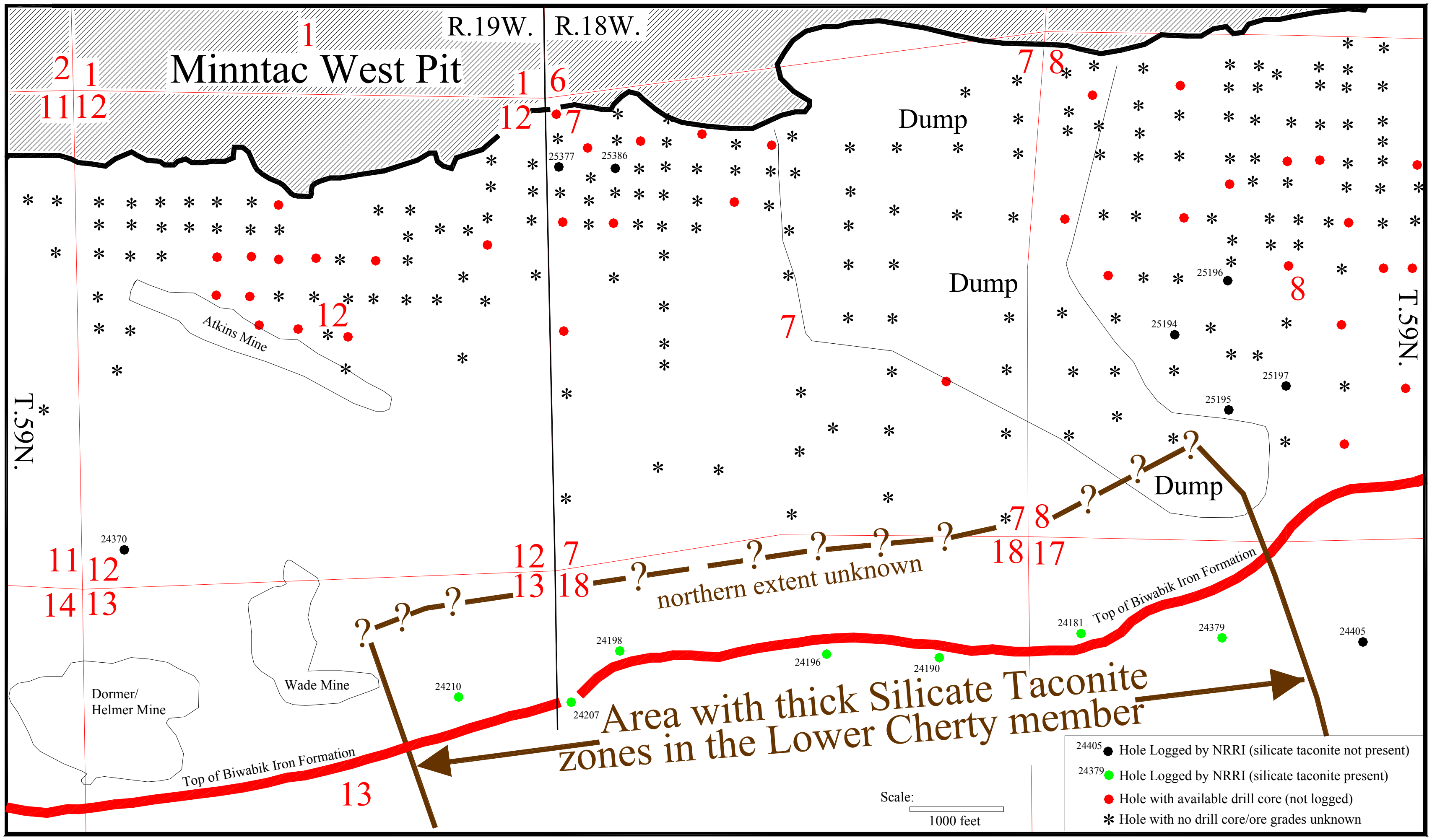


Figure 44. Known aerial distribution of silicate taconite in the Lower Cherty member in drill holes located to the south of Minntac's West Pit. The northern extent of this body is not known and could be further defined in several holes, some of which have preserved drill core, located in sections 7 and 8 (T. 59N., R. 18W.) and section 12 (T. 59N., R. 19W.). Note that over 150 feet of silicate taconite are present in holes 24379 and 24210 at the east and west margins of the body respectively; whereas, 24-31 feet of silicate taconite are present in the intervening holes (see also Fig. 45).

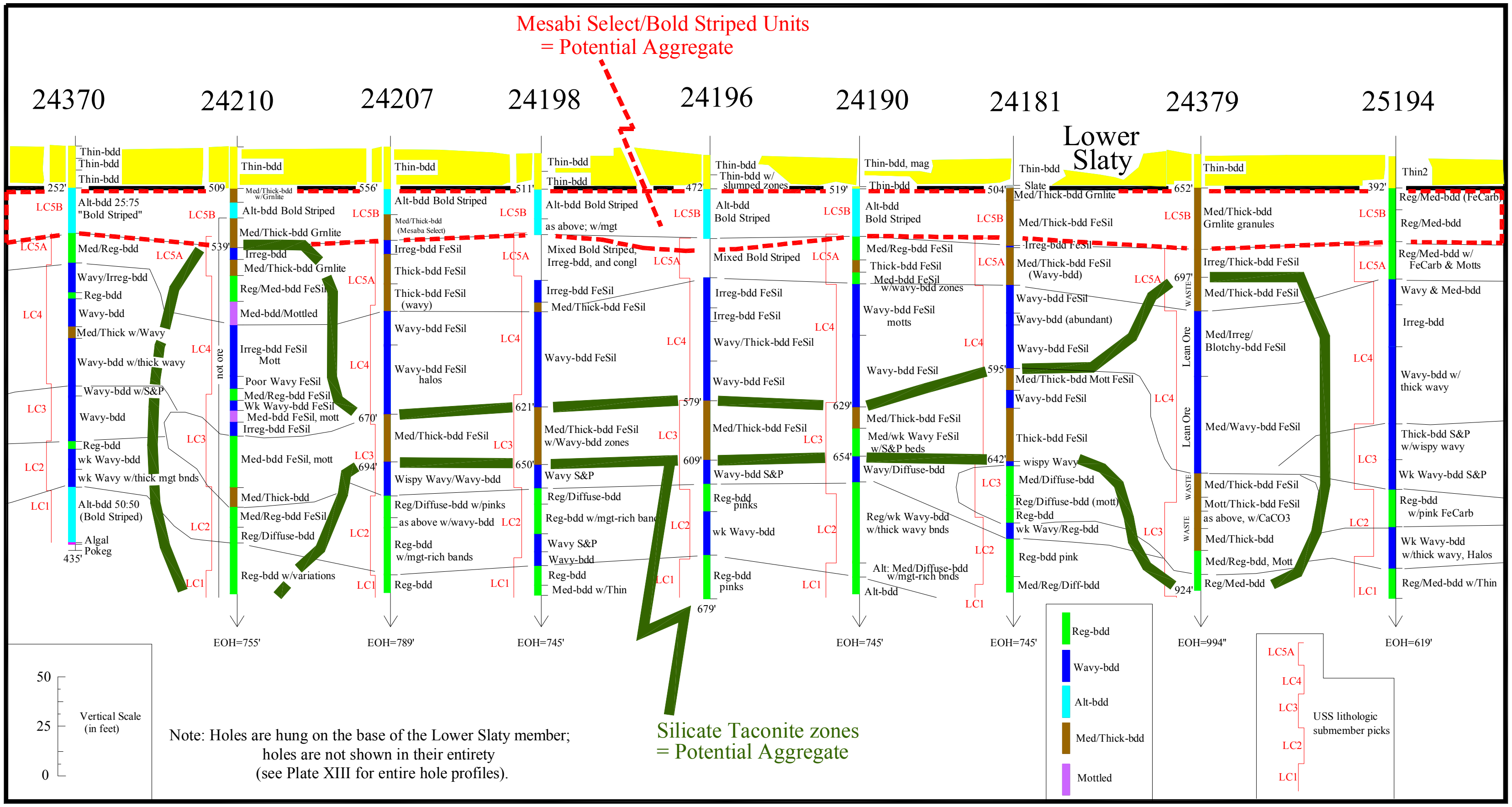


Figure 45. Hung stratigraphic section (looking North) of nine holes along the southern edge of Minntac's West Pit property showing the distribution of potential silicate taconite zones (outlined in green in a "dumbbell" shape) in the LC-4 and LC-3 submembers (USS terminology). Note the anomalous presence of wavy-bedded zones (blue colored) in LC-2 submember beneath the handle of the "dumbbell." Potential aggregate associated with the Mesabi Select and Bold Striped units at the top of the Lower Cherty member is also shown (see discussion in previous section of this report). Notations depicting "lean ore" or "not ore" for some of the drill holes are based strictly on the rock's relative magnetism and **not** on assay data, which are proprietary in nature and thusly unknown to the NRRI.

with moderately magnetic zones, and thus, would constitute either waste zones or lean ore zones (**Note** that the results of Minntac's ore grade tests are unknown, and the "waste/lean ore" category is based solely on the degree of magnetism exhibited by the core during logging).

The northern extent of the silicate taconite body is unknown, and the limits of the body shown in Figure 43 are based solely on the known distribution in seven holes. These limits could be modified if existing drill core to the north were logged (Fig. 44), and **if** grade testing results for other holes to the north (Fig. 44) were known. Any new limits delineated by such a study could be used to define the tonnage of potential aggregate materials, and could also affect future mine planning along the margins of the silicate taconite body. It is interesting to note that the thickness of the handle of the "dumbbell" roughly corresponds to a mine bench, and thusly, this material could easily be set aside during future mining activities.

The origin of this silicate taconite body is unknown, and preliminary results suggest that it may be related to both the original depositional environment and to concomitant diagenetic changes. Depositional features include the more thick-bedded nature of the silicate taconite in the handle of the "dumbbell" and the anomalous presence of good ore zones, corresponding to wavy-bedded zones, beneath the "dumbbell" handle in the underlying LC-2 submember, which is typically not wavy-bedded (Fig. 45). Diagenetic features include a paucity of magnetite halos and magnetite-bearing stylolites in the silicate taconite, as well as in the wavy-bedded rocks positioned above the "dumbbell" handle. Future studies should be directed at defining the overall morphology of this silicate taconite body (**if** the grade testing results were available) and defining changes in bedding types in drill holes that are positioned within and surrounding the body.

Silicate Taconite at Hibtac

A silicate taconite body within the Lower Cherty member was recently discovered in four holes located to the southeast of Hibtac by the NRRI (and, coincidentally, by Hibtac; T. Campbell, pers. comm.., 2009). These four holes, shown in Figure 46, define a NNE-trending "channel" wherein magnetite-poor rocks are present rather than the typical ore-grade materials of the Wavy-Bedded Unit (corresponding to Hibtac submembers 1-6, 1-5, and 1-4). The rocks in these four holes, shown in Figure 47, are characterized by medium- to thick-bedded iron silicate-rich chert with fairly common wavy-bedded to weakly wavy-bedded zones. However, even when present, the wavy bands are magnetite-poor and consist of dark green-colored iron silicates(?) with associated brown iron-carbonate sets. Magnetite-rich halos and magnetite-rich stylolites, which are common to the Wavy-Bedded Unit, are rare in the silicate taconite body. Furthermore, the occurrence of halos and stylolites also show a definite decrease in the overlying wavy-bedded rocks. The channel-like morphology of the silicate taconite body, as well as the paucity of halos and stylolites above and within the body, give a preliminary suggestion that the body was originally related to a depositional feature with a chemical signature(?) that eventually prevented the formation of magnetite during diagenesis.

The silicate taconite body ranges from 42 feet to 87 feet thick. The position of this channel-like feature at almost a right angle to the iron-formation trend indicates this silicate taconite body will be eventually mined out and stockpiled in order to reach good taconite ore on both sides of the "channel." If future tests of this material indicate that it makes good aggregate material, the cost of mining it out could be offset by aggregate sales.

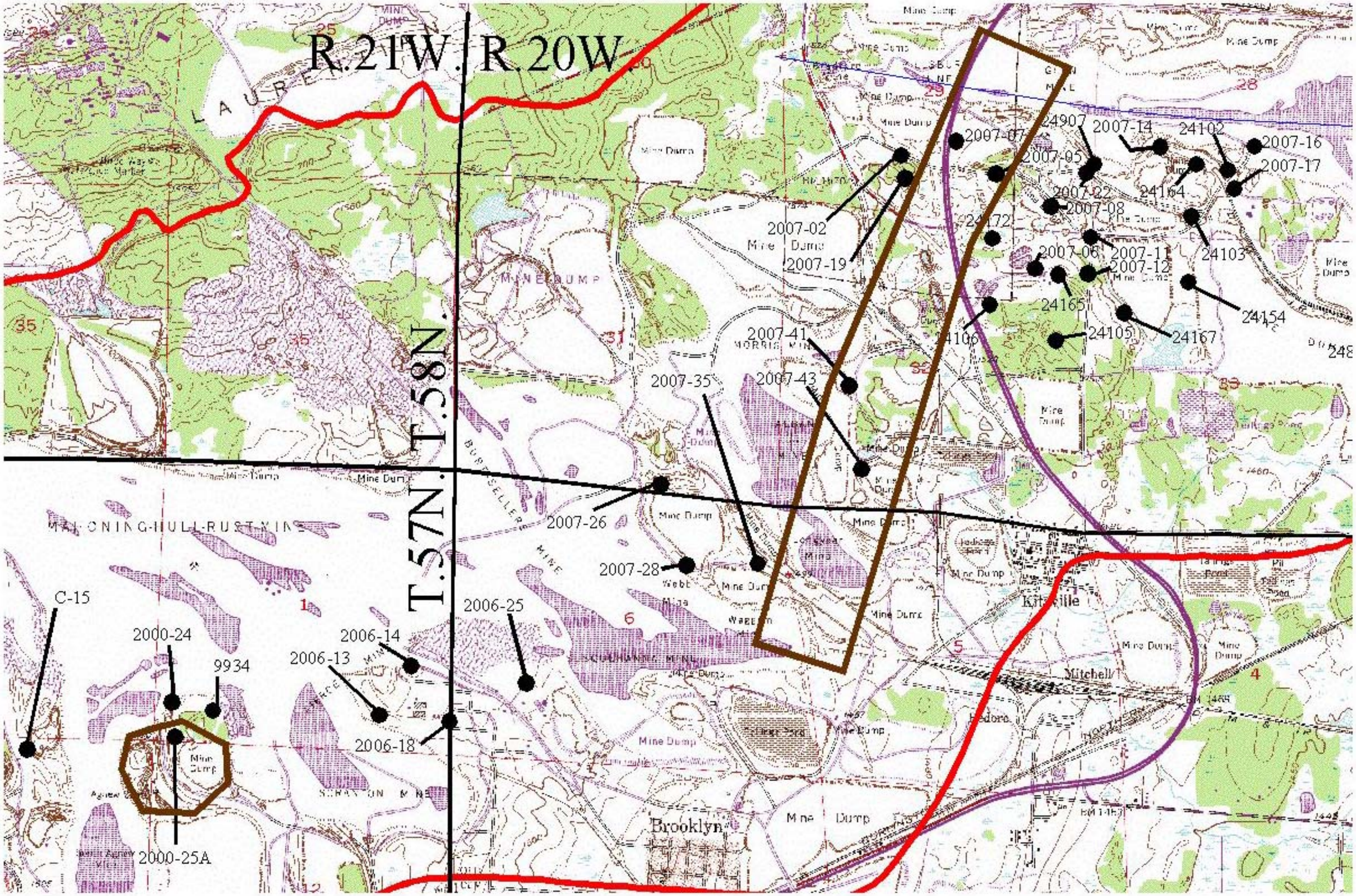


Figure 46. Known aerial distribution of a "channel-like" silicate taconite body (outlined in brown) in four drill holes located to the southeast of Hibtac's current pit. Drill hole locations courtesy of Hibtac.

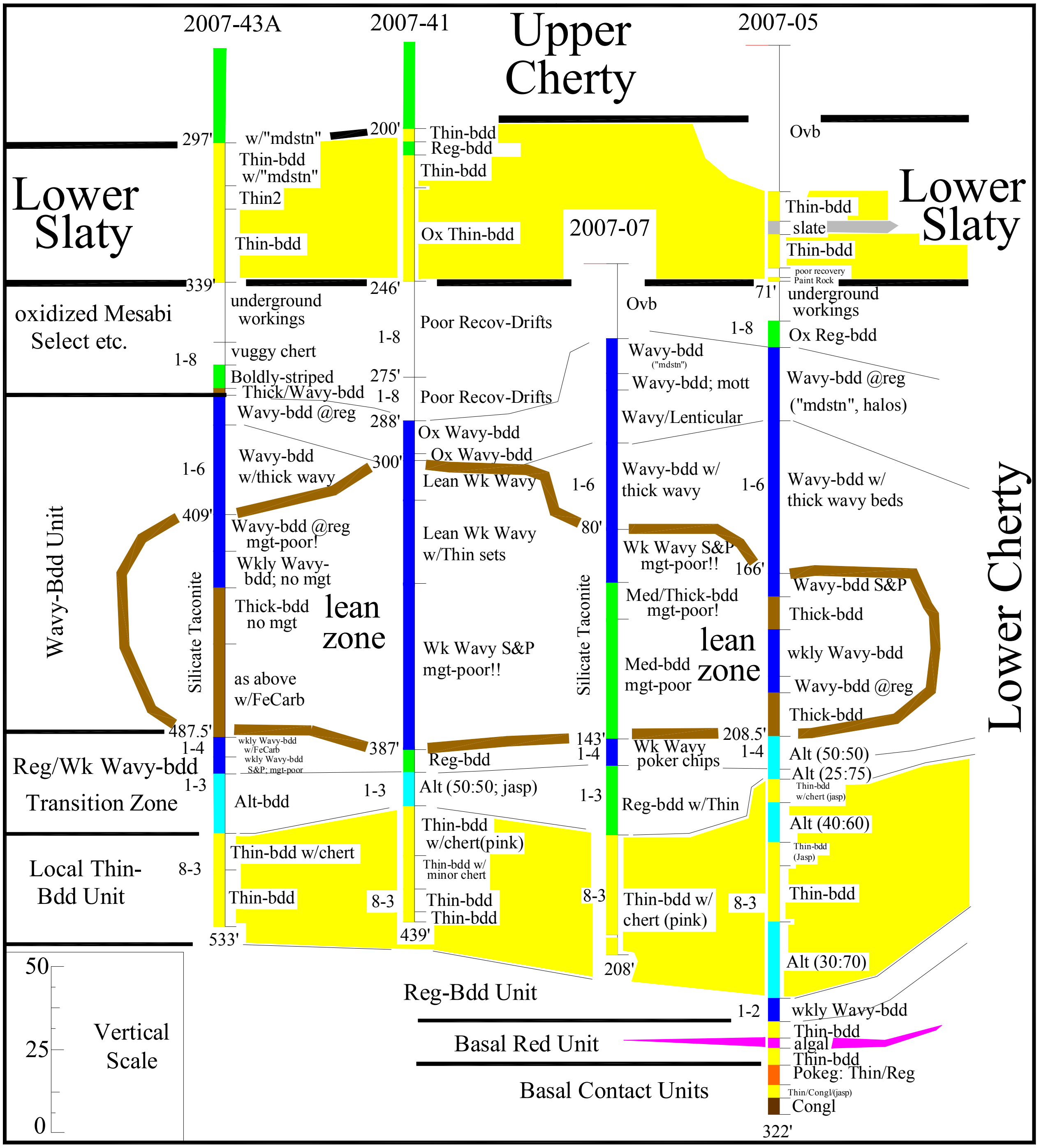


Figure 47. Hung stratigraphic section of four holes (looking NW) that intersected significant intervals of magnetite-poor silicate taconite (outlined in brown) rather than typical magnetite-rich submembers of the Wavy-Bedded Unit of the Lower Cherty at Hibtac (correlative with Hibtac submembers 1-7, 1-6, 1-5, and 1-4). The designation of "lean ore" on this figure is based solely on the degree of magnetism that was noted during core logging by the NRRI – grade test results conducted by Hibtac are unknown. Drill hole profiles modified from Plate XI. Looking North.

Another silicate taconite body was also intersected in a hole drilled much further to the west in 2000 (hole 2000-25A – Fig. 46). As this material has been intersected in only one hole, the trend of this silicate taconite body is unknown.

Upper IBC Unit at Minntac (West Pit)

Most of the three IBC units of the Lower Slaty member are mined as taconite ore except for the Upper IBC Unit at Minntac (their LS-10 submember and possibly the LS-9 submember), which makes it a fourth priority candidate for potential aggregate material. The Upper IBC Unit is sporadically present in drill holes in the eastern half of Minntac's West Pit (Plate XIII), where it varies from 20 to 64 feet thick. The top of the Upper IBC Unit is positioned about 45 feet below the top of the Lower Slaty member, with a range of 15-63 feet below the top of the Lower Slaty. Rocks that characterize this IBC are typically regular- to medium-bedded with diffuse magnetite and common conglomeratic zones. These rocks are usually strongly magnetic (moderate to strongly magnetic range), but are apparently not mined as taconite ore (**Note** that grade testing results are unknown, and the Upper IBC may have too high a silica content to be treated as ore). *If* the Upper IBC does not constitute taconite ore, then it would make good aggregate materials due to:

1. Its regular- to medium-bedded nature would generate angular particles during blasting and removal;
2. The particles would have a high density due to the high magnetite content; and
3. The overall thickness of this unit would allow for it to be selectively blasted and removed as one or two mine benches.

Upper Regular-Bedded Unit of the Upper Cherty member

As the taconite mines continue to mine in a down dip direction, more and more of the Upper Cherty member will need to be removed. As of this writing (2009), very little of the top half of the Upper Cherty constitutes taconite ore to the west of the Siphon Fault, and thus portions of the Upper Cherty could be a fifth candidate for potential aggregate material. Most of the bottom half of the Upper Cherty (including the Alt-Bedded units, Algal Unit, and Lower Regular-Bedded Unit – Figs. 41 and 42) are either too thin or contain too many thin-bedded zones to make good aggregate. Conversely, the Upper Regular-Bedded Unit of the Upper Cherty (Figs. 41-42) is typically thicker bedded (regular- to medium-bedded range), and in most cases, appears to be not magnetic enough (weak to strongly magnetic range) to constitute taconite ore (**Note** that grade testing results are unknown!). The various submember designations for the Upper Regular-Bedded Unit of the Upper Cherty member that could be considered to be potential aggregate materials at the appropriate taconite mines are listed below.

- Hibtac - referred to as only the Upper Cherty with no submember designation as of this writing. Corresponds to regular-bedded rocks, but does contain magnetite-rich wavy-bedded zones (Plate XI) that could eventually be considered to be taconite ore.
- Minntac – corresponds to most of the UC-16 submember.
- Utac – corresponds to the UC-7 and UC-8 submembers. Both submembers display the same bedding characteristics, but a red color is more dominant in the UC-7. The

top of the UC-8 submember, or possibly an overlying UC-9 submember, contains magnetite-rich wavy-bedded zones in a down dip direction that could eventually be considered to be taconite ore.

[As a sidebar, the Algal Unit of the Upper Cherty member could be a potential dimension stone source due to the presence of unique and bright red-colored stromatolites.]

Uppermost Portions of the Lower Slaty

The lowest priority potential aggregate material identified in this investigation corresponds to thin-bedded rocks at the top of the Lower Slaty member. These rocks are typically weakly to moderately-magnetic, thus generating particles with a high density, but their thin-bedded nature may generate too many tabular particles to be of any use as aggregate. At present, all of this material is removed as waste and set aside during mining operations. Thus, it would be optimal to find some sort of use for this material; however, because it may generate too many tabular particles, a very low priority has been assigned to it in this investigation. The various submember designations for the uppermost portions of the Lower Slaty that could be considered to be potential aggregate materials at the appropriate taconite mines (very low priority!) are listed below:

- Hibtac – top of their LS submember to the east and southeast of the presently mined area (these rocks are strongly oxidized to the south and west of the mine site, and they would never make good aggregate).
- Minntac – the UC-11, UC-12 (conglomerate), and UC13 submembers with a lesser potential associated with the underlying LS-9 and LS-8 submembers; and
- Utac – UC-4 submember – thick package of thin-bedded rocks that are considered to be in the Upper Cherty member.

Summary of Potential Aggregate Horizons

In addition to the already recognized Mesabi Select material, six potential aggregate horizons have been identified in this investigation, and these horizons have been assigned relative priorities (1 through 6). The first two priorities correspond to the Mesabi Select and “Mesabi Select equivalent.” Both are waste materials that are easily singled out and removed during current blasting and stripping operations. The third priority, silicate taconite bodies, will eventually be encountered as the mines expand in a down dip direction. These bodies will also be easily singled out and removed during mining operations. The fourth and fifth priorities (Upper IBC Unit of the Lower Slaty and Upper Regular-Bedded Unit of the Upper Cherty, respectively) could be treated as either waste or ore, depending on grade testing results that are unknown, and these bodies could also be singled out and stockpiled during current mining operations. The sixth and lowest priority corresponds to thin-bedded and variably magnetic rocks associated with the uppermost portions of the Lower Slaty member. The use of these thin-bedded rocks as aggregate is highly questionable due to their potential to generate tabular particles during blasting and removal. In essence, use of this sixth priority will be highly dependent on their tested characteristics.

It is important to stress that the three-dimensional trends of the silicate taconite bodies in the Lower Cherty, and the Upper IBC Unit of the Upper Slaty, are completely unknown. Both are channel-like in their overall morphology, and their trends could greatly affect how peripheral taconite ores are mined, as well as the overall tonnage of potential aggregate materials that they represent.

SAMPLING OF POTENTIAL AGGREGATE HORIZONS WITHIN THE BIWABIK IRON FORMATION

Four bulk samples were collected from Utac's Thunderbird North Mine and ArcelorMittal's Laurentian Mine (two samples from each) during the spring of 2005. Each sample consisted of rock materials placed into two 55 gallon drums, and each sample was collected from a specific horizon(s) immediately after a particular mine bench was blasted. The sampling procedure for all bulk samples consisted first of draping a 100m tape over the blasted piles, then collecting pieces of rock along the tape, from top to bottom, and placing them in 5 gallon plastic buckets that were used to fill the two 55 gallon steel drums. All samples were collected by hand from materials touching the tape and under 6 inches in size. After completing the first sampling trip along the tape, the tape was then moved to a new position on the same pile and sampling resumed. With four people collecting from the pile, five tape repositions were needed to fill the two 55 gallon drums. A GPS location for each blasted pile that was sampled was taken at the center of the pile. After collection, the samples were delivered to Coleraine Minerals Research Laboratory for processing and later to Mn/DOT for specific aggregate testing (Beaudry and Richter, 2008). The locations and type of material constituting each of the bulk samples are listed in Table 4. Drill core from the McKinley Extension/East Reserve Mine was also sampled (and has been previously discussed - see Table 2), but has yet to be tested by Mn/DOT.

Testing results of the materials listed in Table 4 by Mn/DOT (Beaudry and Richter, 2008) indicate that all of the samples met the specifications for tests regarding: Los Angeles Rattler (LAR), flatness and elongation, and magnesium sulfate. All but the LC-5A sample passed tests in accordance with ASTM C 260 and ASTM C 1293 standards. These tests are designed to test the potential for "alkali silica reaction" (ASR) in concrete that

Table 4. Listing of bulk samples collected in 2005 from the Thunderbird North Mine (United Taconite) and the Laurentian Mine (ArcelorMittal Steel).

Mine	**Sample Number**	**Location** (state plane NAD27-feet)	**Type of Material**
Laurentian	Bulk TAC AGG 2005-01	2164055.331E, 365044.847N	Variably-Bedded and/or Mottled Unit (LC-5A submember) – note that sampling of the LC-5B submember was initially intended
Laurentian	Bulk TAC AGG 2005-02	2161996.458E, 363470.064N	Near base of Lower Slaty (LS submember; **not** including the Intermediate Slate Unit)
Thunderbird North	Bulk TAC AGG 2005-03	2139511.460E 364011.002N	Mesabi Select Unit (LC-8 submember)
Thunderbird North	Bulk TAC AGG 2005-04	2138641.082E, 364498.841N	Middle of Lower Slaty (LUC-1 and LS submembers)

ultimately causes premature failure of the concrete. The LC-5A sample, which was actually collected from an ore horizon, failed these last two tests miserably due to its high magnetite and silica contents. The LC-5A sample was collected inadvertently from the wrong mine blast (the LC-5B submember, or Mesabi Select Unit was the intended target sample) due to a mix up at the mine site. However in hindsight, collection of the LC-5A sample serves to illustrate that ore materials from the taconite mines may not be suitable as aggregate materials due to their more "cherty" nature and high magnetite content (high specific gravity).

CONCLUSIONS AND RECOMMENDATIONS

This investigation has, for the first time, allowed for creation of a "Rosetta Stone" that ties all of the taconite mine's submember terminologies into a coherent system whereby the submembers of one mine can be compared to an adjacent mine's submembers. In order to simplify the barrage of submember names used at each of the various mines, we propose that the mines also use the terminologies for the 25 "Rosetta" units of the Biwabik Iron Formation, as depicted in Figure 41, that were established in this investigation. Most of these 25 units have long been recognized by the various taconite mines on the Mesabi Iron Range, but they have been called such a variety of submember names that it is often difficult to keep one straight from the other. In this report, these 25 "Rosetta" units have been carefully correlated in hung stratigraphic sections, and the units have been named for the bedding types that each represents. It is hoped that the mines can use these "bedding-named" units in the future to help them in their discussions with neighboring mines when comparing and contrasting their ore and waste rock types.

Throughout this report, possible depositional environments have been suggested for most of the 25 "Rosetta" units. However, these inferred environments have been based largely on the relationships displayed in the drill cores of multiple holes. A detailed sedimentalogical study was not the primary goal of this investigation, and the suggested environments are crude comparisons to recent sedimentary systems and should only be used as starting points for future discussions. More rigorous testing of the proposed environments, in the form of mapping the pit walls as they advance and the continued logging of more drill holes for detailed 3-dimensional analyses, need to be completed before the true nature of sedimentation can be established. Such studies may also shed light on ore grade changes that show up as down strike or down dip facies changes.

Definition of the 25 "Rosetta" units can also be used as starting points for more detailed sequence stratigraphy studies (Appendix D) and basin analysis. There are clearly variances in some of the units, and major members, that are related to facies changes and/or changes in shoreline morphology. Good examples of these differences are the following:

1. The Lower Cherty member is remarkably consistent throughout most of the Mesabi Iron Range, and it exhibits a procession of units that can be related to reworking of materials in a regressive siliciclastic environment; whereas, most of the Upper Cherty, also formed during a regressive event, is vastly different and suggestive of an entirely different depositional environment;
2. The rapid thinning of the Lower Cherty member across the Siphon Fault suggests a unique change in the depositional environment in the eastern Mesabi Iron Range relative to the rest of the Mesabi Iron Range;

3. The Lower Slaty member is uniquely thicker in the Virginia Horn area, and it contains several "interbedded chert" lenses that were either deposited as individual parasequences or, more likey, as "cut and fill" channels;
4. The possible presence of slumped bodies of "Mesabi Select equivalent" in the Lower Slaty member at the East Reserve/McKinley Extension mine suggest unique localized responses to earthquake induced seismicity that occur only at this locality that may be related to proximity to the Siphon Fault (17 miles to the east) and/or proximity to other mapped or unmapped faults;
5. The Upper Cherty member is unique in that there is increased biogenic involvement in its genesis as suggested by increased stromatolite occurrences that, in some areas, form extensive "fields;"
6. There is a profound difference in the Upper Cherty member in the eastern Mesabi Iron Range; wherein, wavy-bedded rocks are more common, versus the rest of the Mesabi Iron Range, where regular- to medium-bedded rocks dominate;
7. There are spatial changes in the various forms of stromatolites associated with the Algal Unit of the Upper Cherty member that suggest there were initial changes in specific areas along the depositional shoreline with regard to water depth, and/or current strength, and current direction;
8. The unique thinning out of the Upper Cherty member, near Keewatin, MN, suggests the presence of a submarine valley (eroded Upper Cherty member) that was filled with materials of the Upper Slaty member;
9. The change in the nature of the Upper Slaty in the eastern Mesabi Iron Range (with some wavy-bedded zones) in regard to the same member in the central and western Mesabi Iron Range (no wavy-bedded zones) also suggests a spatial change in the depositional environment; and
10. The Upper Slaty member appears to have been deposited in two separate basins, within the Animikie basin, with the division between the two basins located in the Minntac East Pit area (see Appendix D).

While this project was extremely useful in characterizing the submembers of the Biwabik Iron Formation, there are still numerous questions that remain to be investigated through continued detailed core logging and petrographic studies that include the following.

- The 3-dimensional nature of some specific units, particularly the IBCs of the Lower Slaty member and the silicate taconite bodies of the Lower Cherty, need to be more fully investigated through continued logging of drill holes coupled with in pit mapping. Hopefully, such studies will map out the trends of these units. These trends could become increasingly more important as the mines continue to advance down dip.
- Ore grades associated with each of the various units/submembers should be characterized and changes should be investigated both within and between the mines; however, these data are not yet available from the taconite mines due to their proprietary nature;
- Changes in specific iron silicate and iron carbonate mineralogy, both vertically and laterally, that are associated with each of the units/submembers should be investigated. At present, these types of data are limited to a handful of drill holes, and more detailed work is essential to categorizing the types and volume of

minerals that are specific to each unit/submember.

- More detailed logging of core should continue. There are still large areas, with preserved core, where the stratigraphy of the iron-formation can be further established.

In addition to the already recognized Mesabi Select material, five potential aggregate horizons have been identified in this investigation that have been assigned relative priorities (1 through 6). The first two priorities correspond to the Mesabi Select and "Mesabi Select equivalent." Both are waste materials that are easily singled out and removed during current blasting and stripping operations. Materials from the Mesabi Select Unit at United Taconite have passed all aggregate tests thus far, and the "Mesabi Select equivalent" (MSE), which is mineralogically similar, should show similar testing results. However, the MSE shows extreme local variations with respect to carbonaceous argillite content, and materials stockpiled for aggregate use would have to be closely monitored. The third priority, silicate taconite bodies, will eventually be encountered as the mines expand in a down dip direction. They will also be easily singled out and removed during mining operations. For the most part, the silicate taconite bodies exhibit low magnetite content and a high iron silicate/chert ratio. Thus, they are likely to pass ASR-related tests. The fourth and fifth priorities (Upper IBC Unit of the Lower Slaty and Upper Regular-Bedded Unit of the Upper Cherty, respectively) could be treated as either waste or ore, depending on grade testing results which are unknown, and could also be singled out and stockpiled during current mining operations. The sixth and lowest priority corresponds to thin-bedded and variably-magnetic rocks associated with the uppermost portions of the Lower Slaty member. The use of these thin-bedded rocks as aggregate is questionable due to their potential to generate tabular particles during blasting and crushing. However, even in this case, the method used to crush these thin-bedded rocks could be modified to alleviate this problem.

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APPENDIX A:

LOCATION MAPS OF DRILL HOLES LOGGED AT THE VARIOUS MINING OPERATIONS, ALONG WITH STRATIGRAPHIC COLUMNS SHOWING THE DISTRIBUTION OF THE MINE SUBMEMBERS

Abbreviations used in the stratigraphic columns:

Alt-Bdd = Alternating thin-bedded and thick-bedded sets
Arg = Argillite
Bdd = Bedded, Bedding
Carb = Carbonate
Dolo = Dolomite
Bnds = Bands
Chalc = Chalcedonic
Ch = Chert, Cherty
Cl = Chlorite, Chloritic
Congl = Conglomerate, Conglomeratic
FeCab = Iron Carbonate
FeSil = Iron Silicate
Gran = Granular
Graph = Graphite, Graphitic
Hem = Hematite, Hematitic
Intraform = Intraformational
Irreg-Bdd = Irregular-Bedded
Jasp = Jasper, Jasperoidal
Ls = Limestone
Mag = Magnetic
Mass-Bdd = Massive-Bedded
Mdstn = Mudstone
Med-Bdd = Medium-Bedded
Mgt = Magnetite
Mott = Mottled, Mottles
Qtz = Quartz
Reg-Bdd = Regular-Bedded
Sept = Septarian/Syneresis Cracks
Sid = Siderite, Sideritic
Ss = Sandstone
Sltst = Siltstone
S&P = Salt and Pepper Texture
Thick-Bdd = Thick-Bedded
Thin-Bdd = Thin-Bedded
w/ = with
( ) = Locally Present

Appendix A-1: Regional Drill Holes

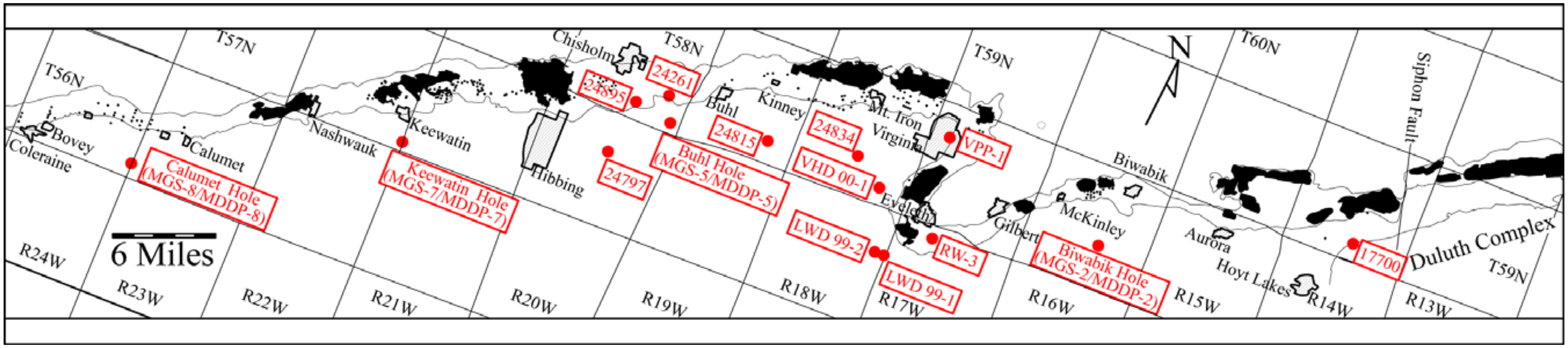


Figure 48. Location map of logged drill holes that are considered to be regional in nature (in red), in addition to holes logged at each of the mine areas (small unlabeled black dots). Note that the MGS/MDDP-series holes (Mesabi Deep Drilling Project holes) and VHP/LWD-series holes (BHP holes) were logged in the NRRI's formative years whilst learning the various submembers as defined at each taconite mine; these drill holes should be relogged again. Note also the paucity of holes that were logged in specific areas that include: Biwabik eastward to the Siphon Fault; Gilbert to Eveleth area; Buhl to Chisholm area; and Keewatin to Calumet area. All of the holes shown on this figure, except for 24261 and 24895, are stored at the Minnesota Department of Natural Resources core storage facilities in Hibbing, MN, and are available to the public.

Appendix A-2: Coleraine Drill Holes

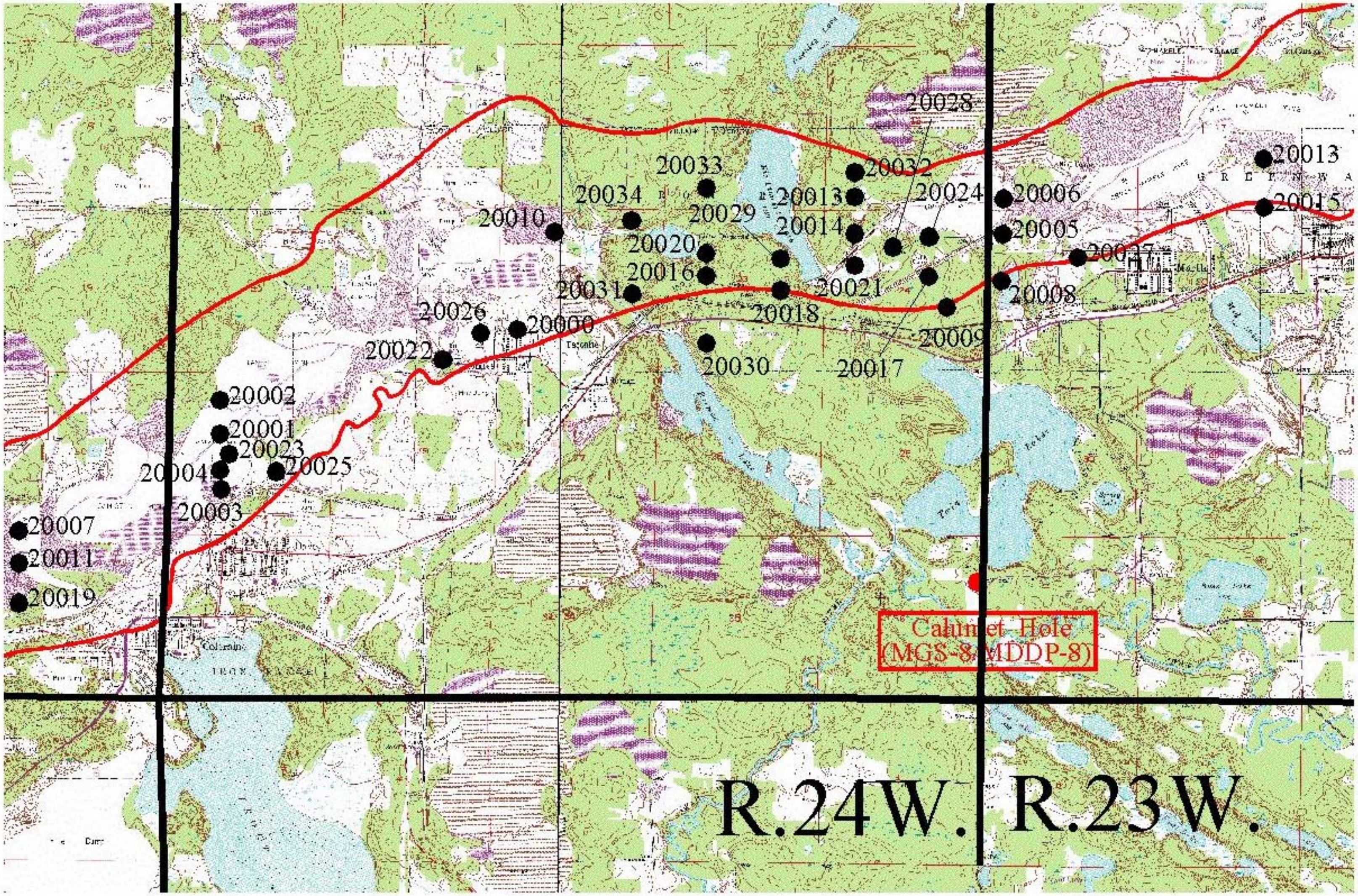


Figure 49. Location map of deep drill holes logged for an earlier oxidized taconite investigation. The detailed stratigraphy of Biwabik Iron Formation noted in these holes is included in Plate XV and is discussed in detail in Zanko et al. (2003). Note that the geology intersected in drill hole MGS-8, a regional drill hole, is also portrayed on Plate XV. All holes are in T.56N., R.23 & R.24W. Trend of the iron-formation shown in red.

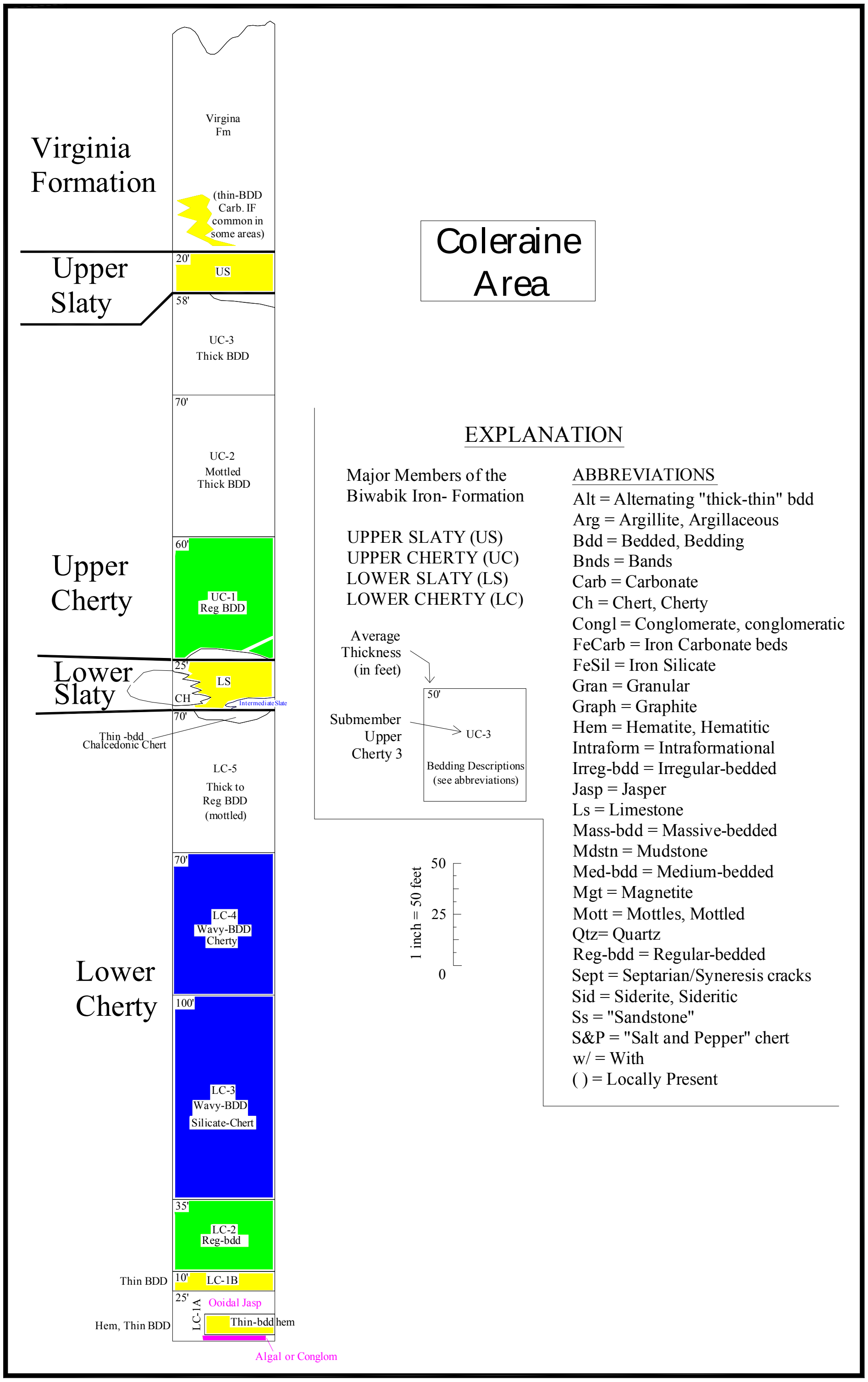


Figure 50. Simplified stratigraphic column of the Biwabik Iron Formation in the Coleraine area showing submember nomenclature as devised by United States Steel Corporation, and the detailed logging of 16 deep drill holes by the NRRI (Zanko et al., 2003). Note that the Upper Cherty member is often strongly oxidized with associated poor core recoveries, and the true bedding nature of the UC-1, UC-2, and UC-3 submembers is largely unknown.

Appendix A-3: Essar/Butler/MSI Drill Holes

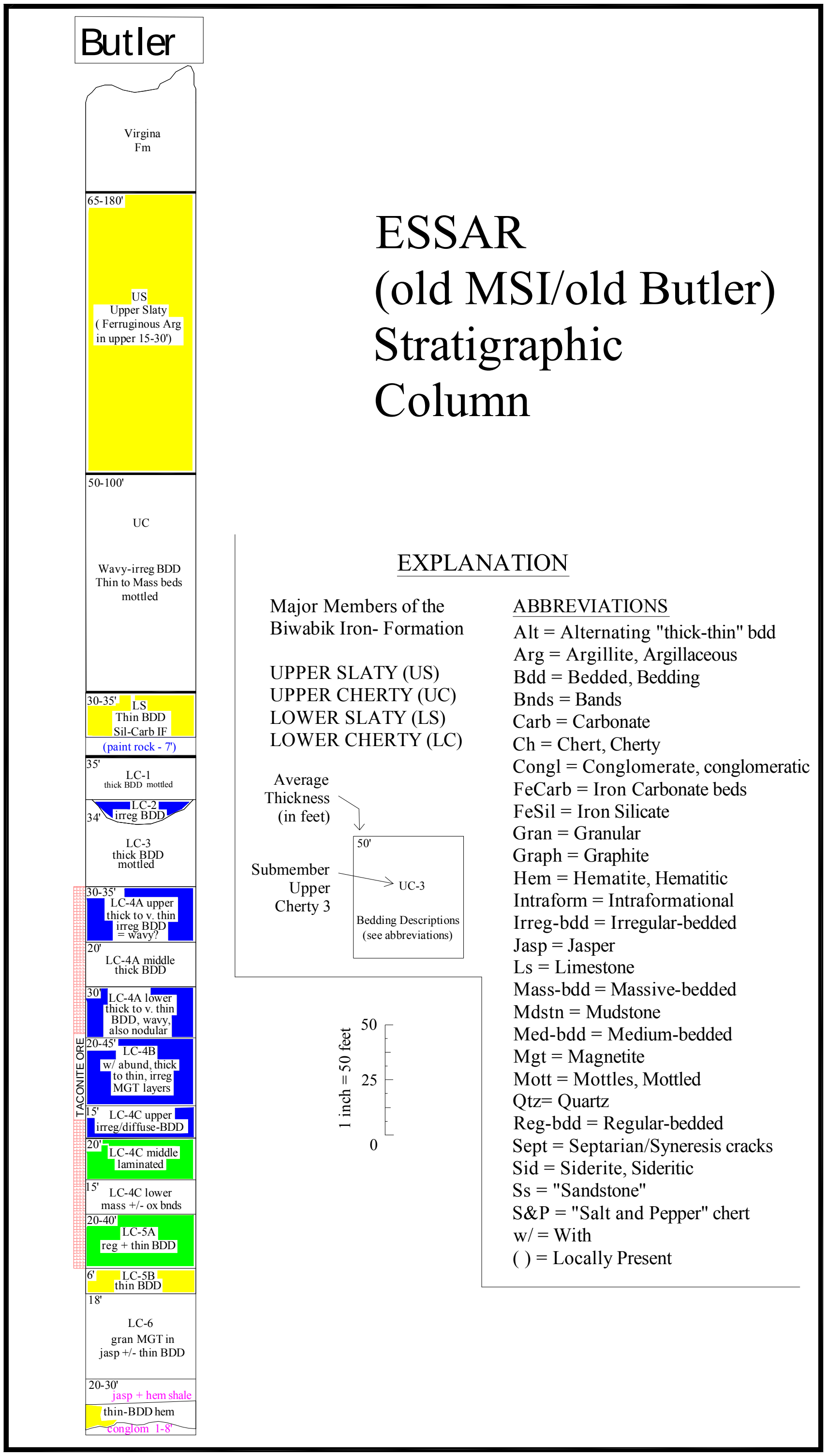


Figure 51. Stratigraphic section of the Biwabik Iron Formation at the planned Essar (MSI) mine (old Butler Mine). Note that the submember nomenclature as portrayed in this figure was defined by M.A. Hanna Mining Company geologists. No holes were logged in this area by NRRI geologists as part of this investigation.

Appendix A-4: Keetac Drill Holes

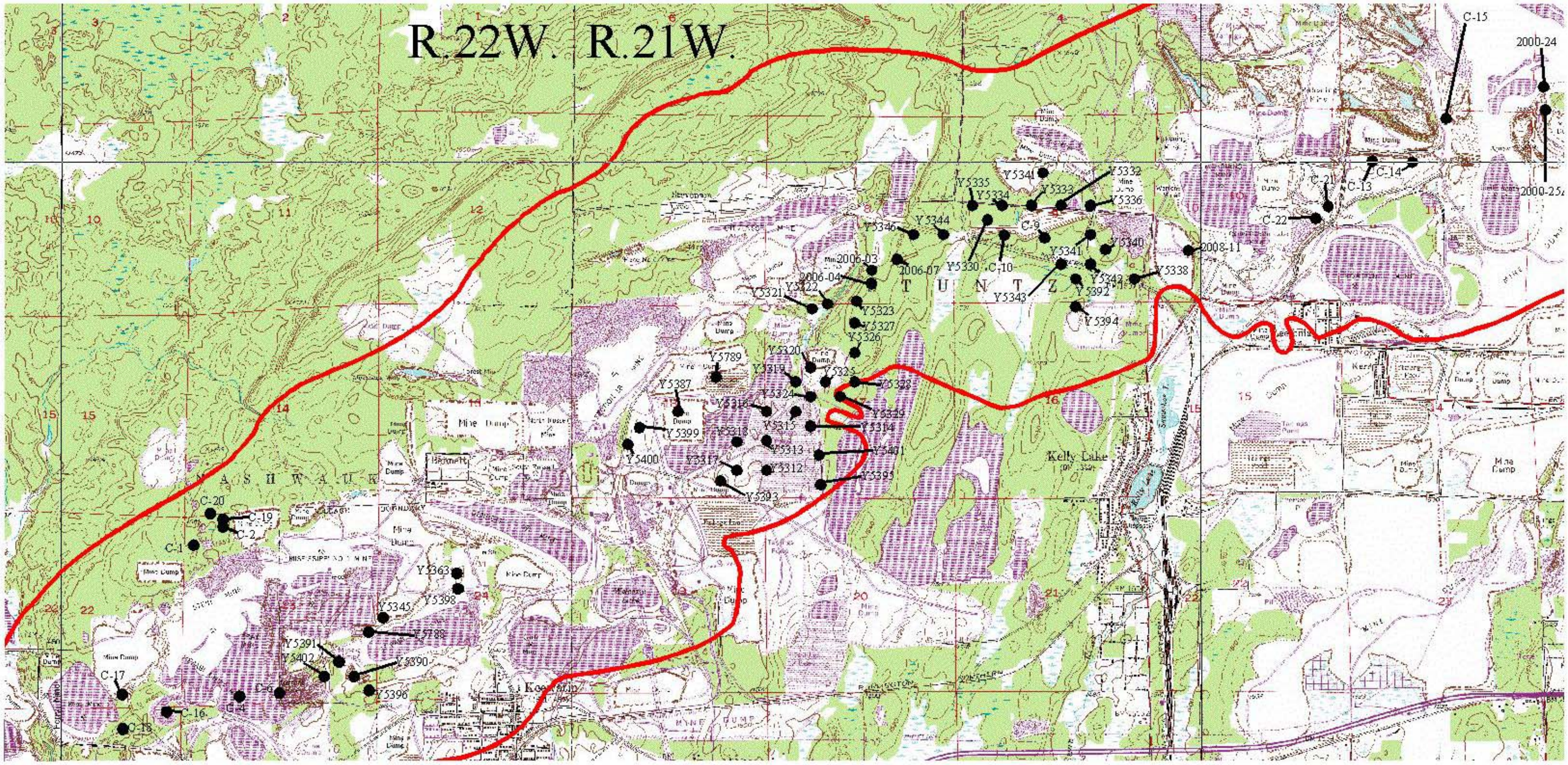


Figure 52. Location map of all drill holes logged by the NRRI in the Keetac Mine area (old National Mine) in 2008. Note that around 30 more drill holes were logged for USS by NRRI geologists in 2009. Drill logs for these holes have not yet been released, and thus, their locations are not shown on this map. All holes shown on this map are in T.57N., R. 21 & 22 W. Note also that holes 2006-03, 2006-04, and 2006-07 (in Section 8, T.57N., R. 21W) were drilled by Hibtac. This map overlaps with Figure 55 on the right/east side. Trend of the iron-formation shown in red.

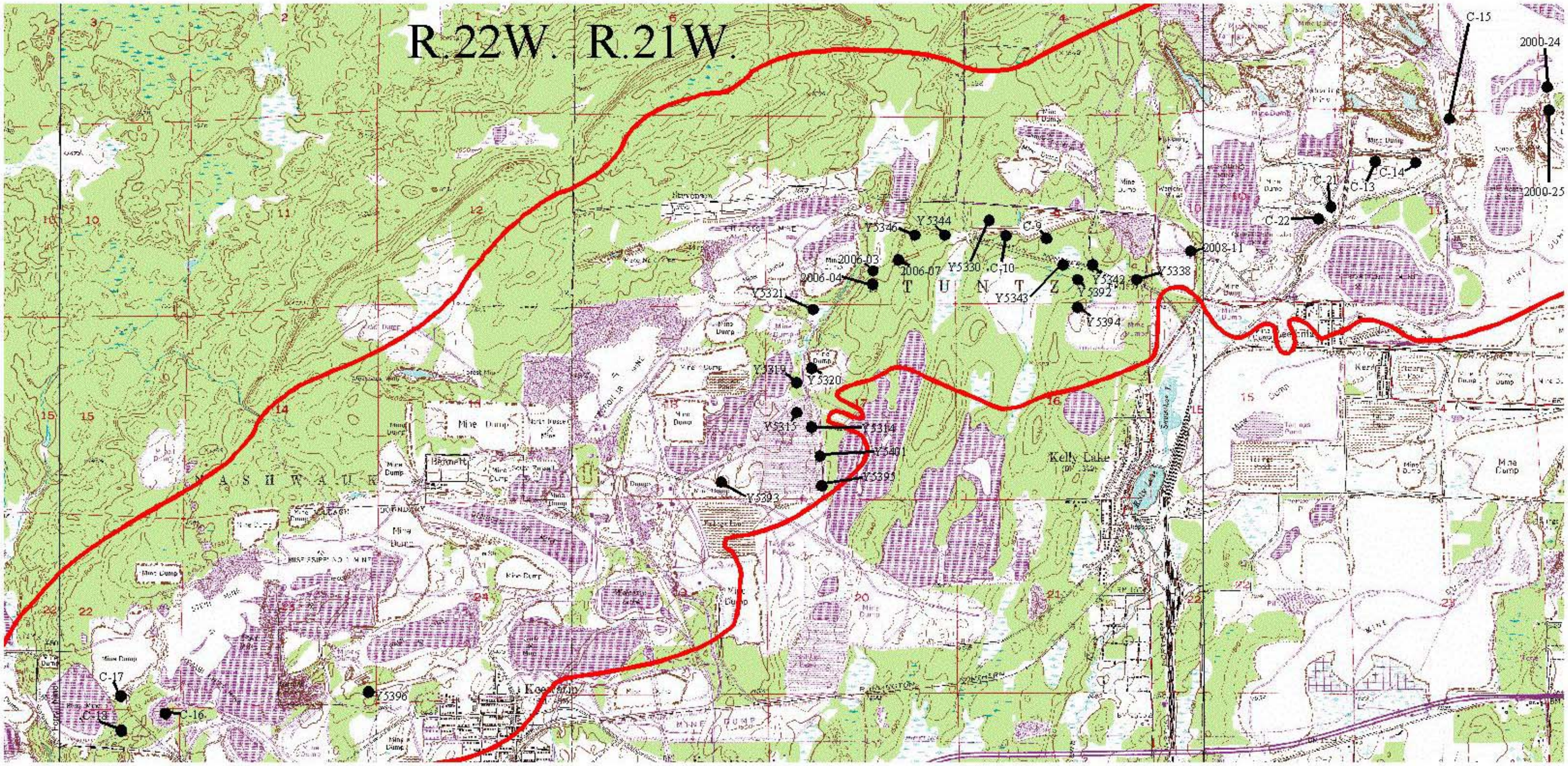


Figure 53. Location map of drill holes logged by the NRRI in the Keetac Mine area that have been correlated on the hung stratigraphic section of Plate XIV. Note that the geology intersected in drill hole MGS-7, a regional hole, is also portrayed on Plate XIV. It is important to note that Plate XIV is preliminary in nature since all of the holes logged in Keetac area have not been correlated on additional hung stratigraphic sections.

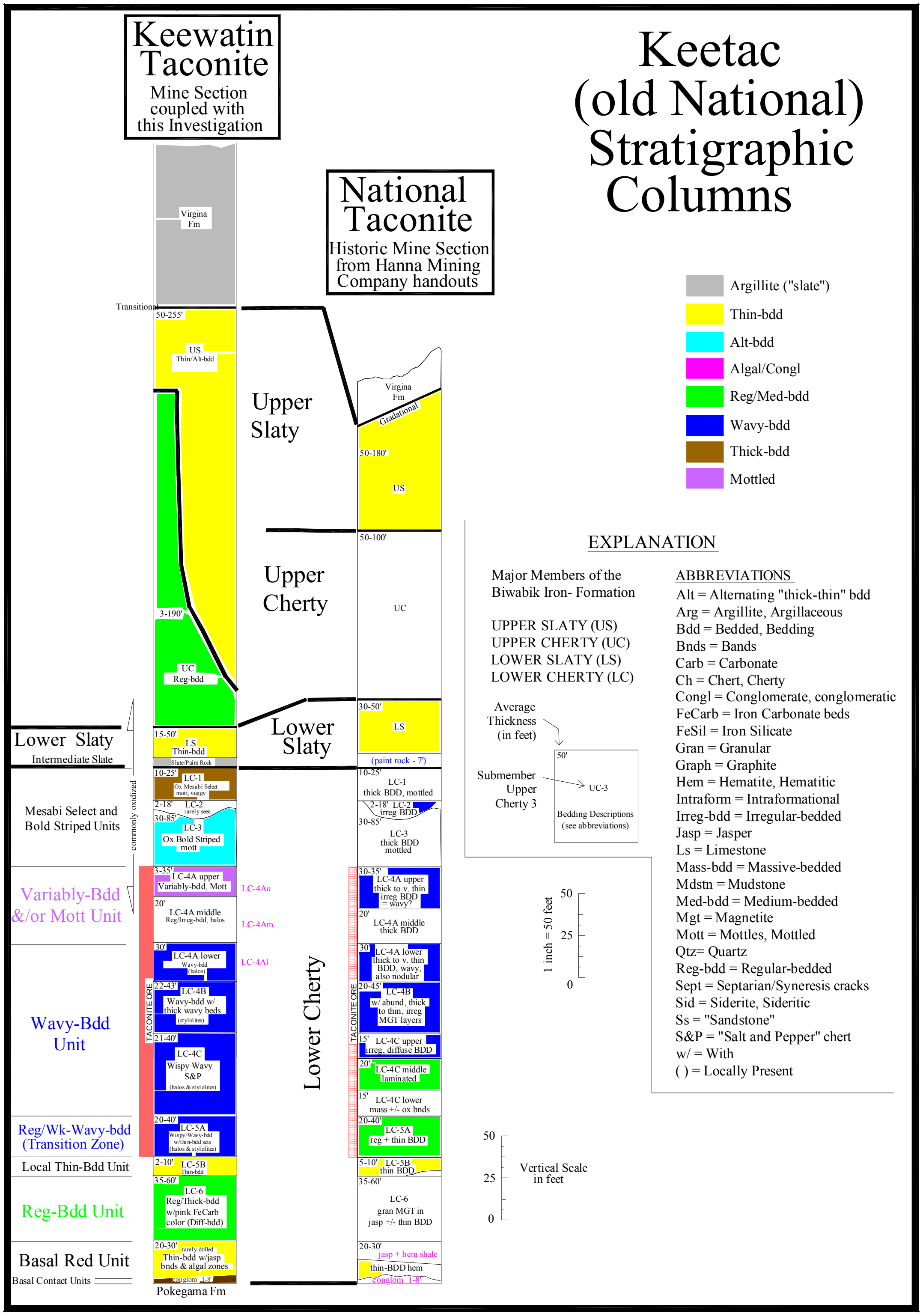


Figure 54. Comparison stratigraphic columns of the various iron-formation submembers at Keetac as determined by Hanna Mining Company geologists (right column) versus a slightly different interpretation (left column) as determined by the more recent logging of over 32 drill holes by NRRI geologists. Note that several of the submembers at the top of the Lower Cherty member (submembers LC-1, LC-2, LC-3, and LC-4Au) are strongly oxidized except in more recently drilled deep drill holes along the southern edge of the current mine boundary.

Appendix A-5: Hibtac Drill Holes

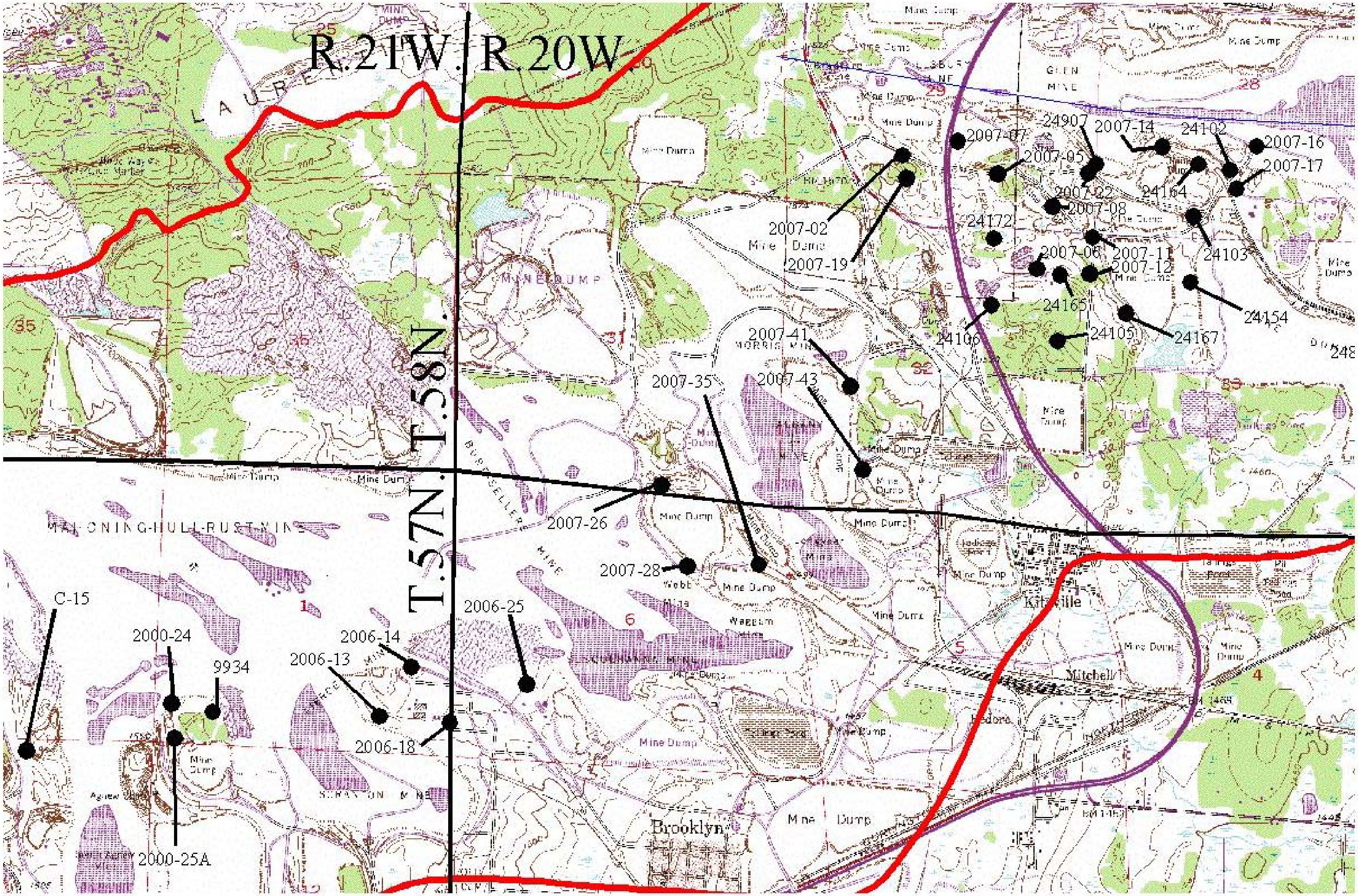
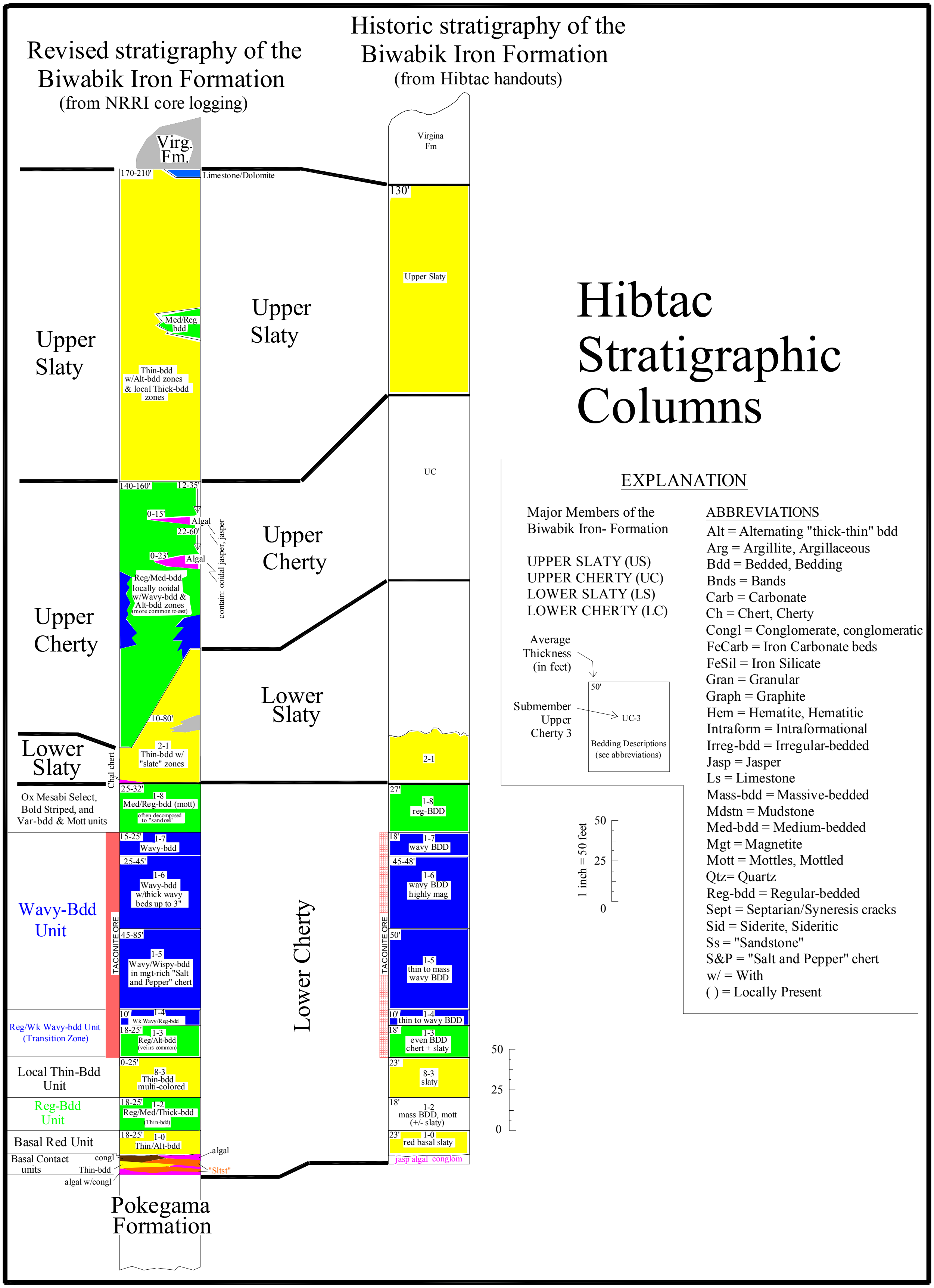


Figure 55. Location map of drill holes logged by the NRRI in the Hibtac Mine area that have been correlated on the hung stratigraphic section of Plate XI. Note that the geology intersected in regional drill holes MGS-5, 24797, and 24895 (not shown on this figure) are also portrayed on Plate XI. This map overlaps with Figure 52 on the left/west side. Trend of the iron-formation in red.



ABBREVIATIONS

Alt = Alternating "thick-thin" bdd
Arg = Argillite, Argillaceous
Bdd = Bedded, Bedding
Bnds = Bands
Carb = Carbonate
Ch = Chert, Cherty
Congl = Conglomerate, conglomeratic
FeCarb = Iron Carbonate beds
FeSil = Iron Silicate
Gran = Granular
Graph = Graphite
Hem = Hematite, Hematitic
Intraform = Intraformational
Irreg-bdd = Irregular-bedded
Jasp = Jasper
Ls = Limestone
Mass-bdd = Massive-bedded
Mdstn = Mudstone
Med-bdd = Medium-bedded
Mgt = Magnetite
Mott = Mottles, Mottled
Qtz= Quartz
Reg-bdd = Regular-bedded
Sept = Septarian/Syneresis cracks
Sid = Siderite, Sideritic
Ss = "Sandstone"
S&P = "Salt and Pepper" chert
w/ = With
( ) = Locally Present

[See figure caption on next page.]

Figure 56 Comparison stratigraphic columns of the various iron-formation submembers at Hibtac as determined by Hibbing Taconite Mining Company geologists (right column) versus a slightly different interpretation (left column) as determined by the more recent logging of 32 deep drill holes by NRRI geologists. Note that much of the Lower Slaty, Upper Cherty, and Upper Slaty members have only recently been drilled by Hibtac, and thus, no detailed submembers have yet been broken out by Hibtac.

It is interesting to note that the 8-3 submember was not present in many of Hibtac's early drill holes, positioned along the northern edge of the current mine, and was not originally given a specific submember designation until it was encountered in deeper holes in subsequent years. Thus, the 8-3 designation is used rather than the typical 1-series designation as is used for all the other Lower Cherty submembers. The 8-3 submember corresponds to the Local Thin-Bedded Unit that has been intersected in numerous holes extending from the west edge of Keetac, through Hibtac, and to the east edge of Minntac.

Appendix A-6: Minntac Drill Holes

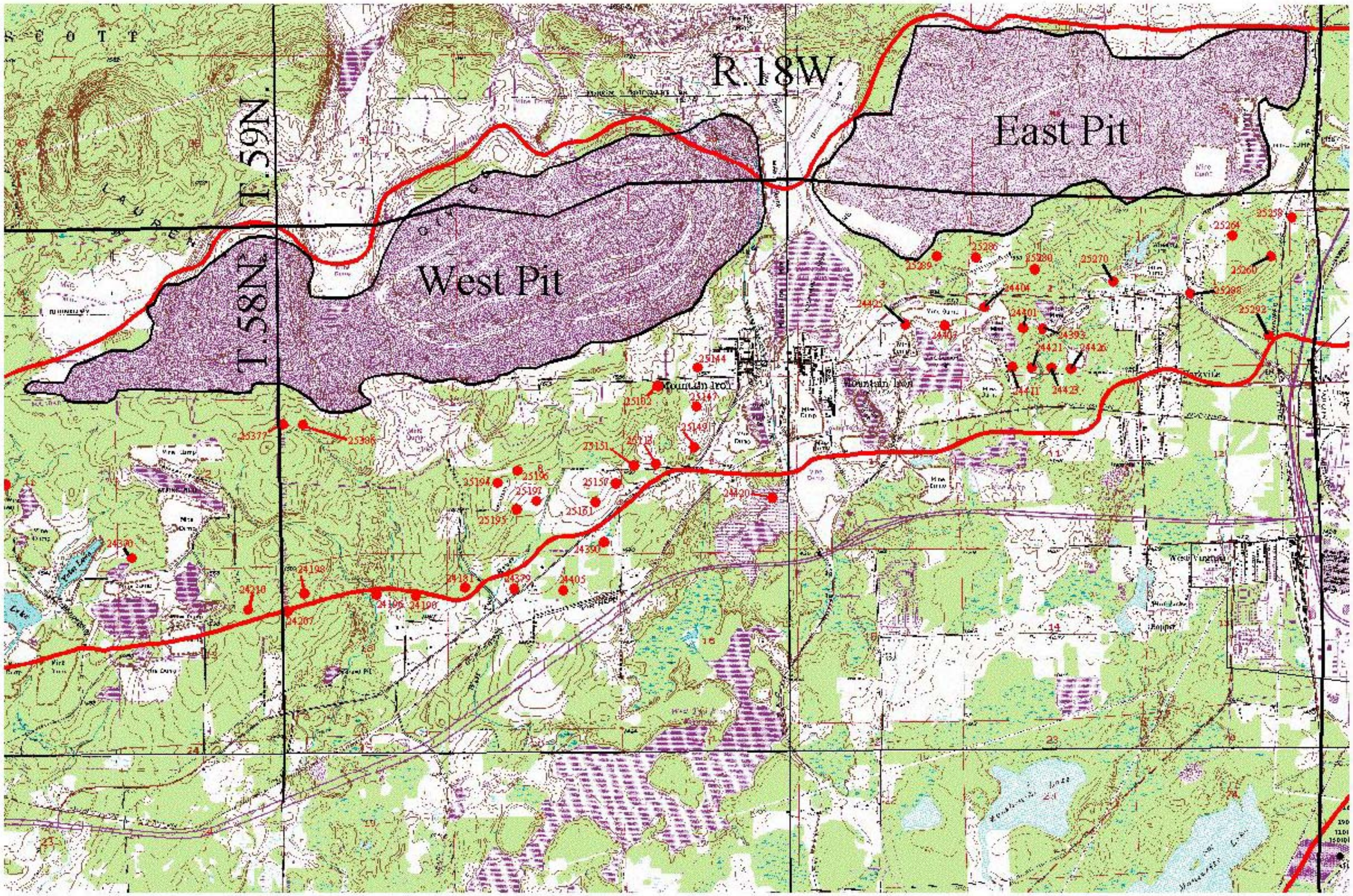


Figure 57. Location map of all drill holes logged by the NRRI in the Minntac Mine area that have been correlated on the hung stratigraphic section of Plates XII and XIII. Note that the geology intersected in regional drill holes 24261, 24815, 24895, and VPP-1 (not shown on this figure) is also portrayed on Plates XII and XIII. This map has been further broken down into the next three drill hole location maps (Figs. 58-60). Trend of the iron-formation in red. Note that the iron-formation stratigraphy described in this report for Minntac's East and West Pits is based solely on units observed in drill core; no in-pit mapping was ever conducted.

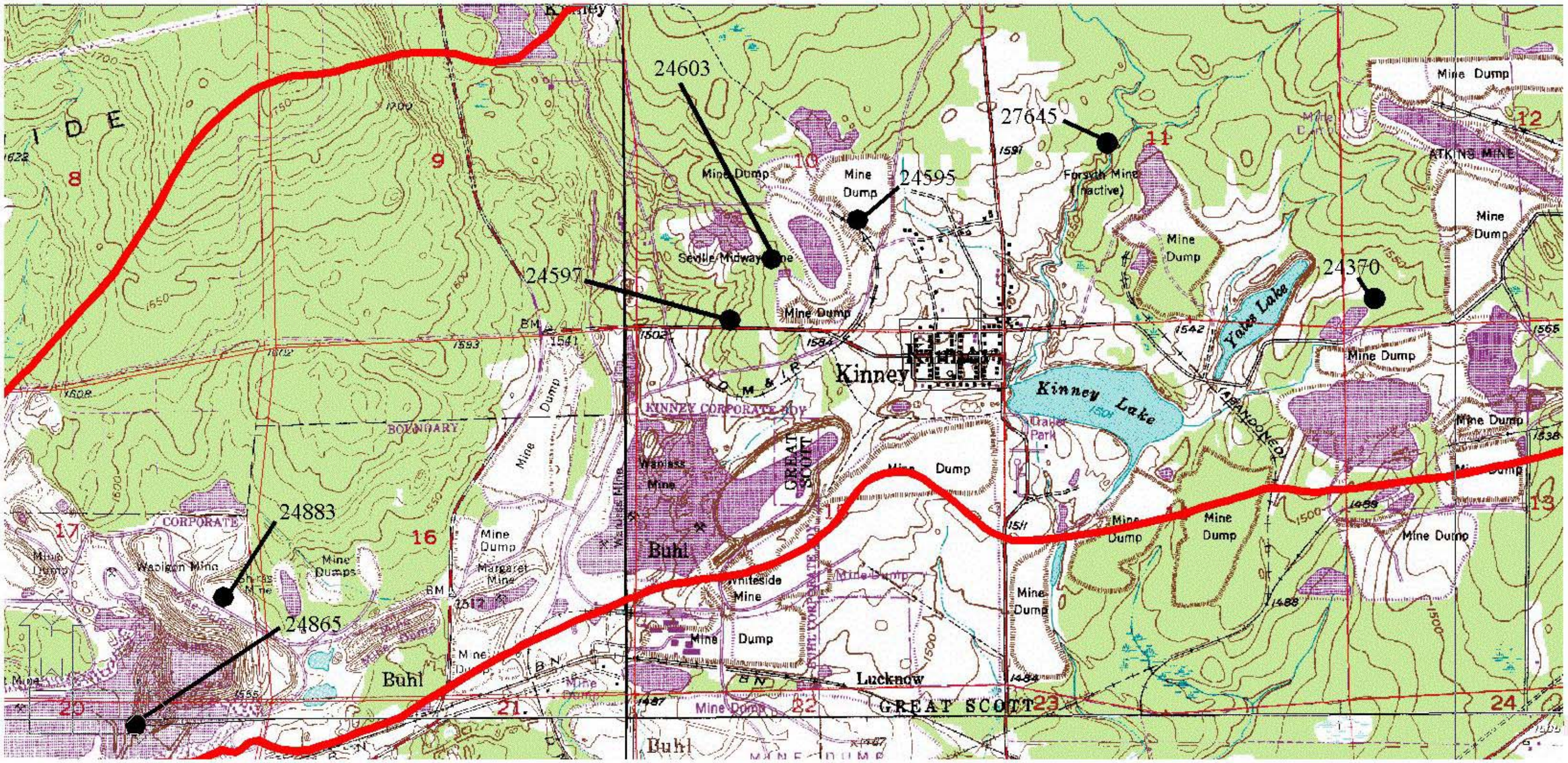


Figure 58. Location map of all drill holes logged by the NRRI to the immediate west of the Minntac Mine area in the Chisholm to Kinney area. These holes are correlated on the left side of Plate XIII.

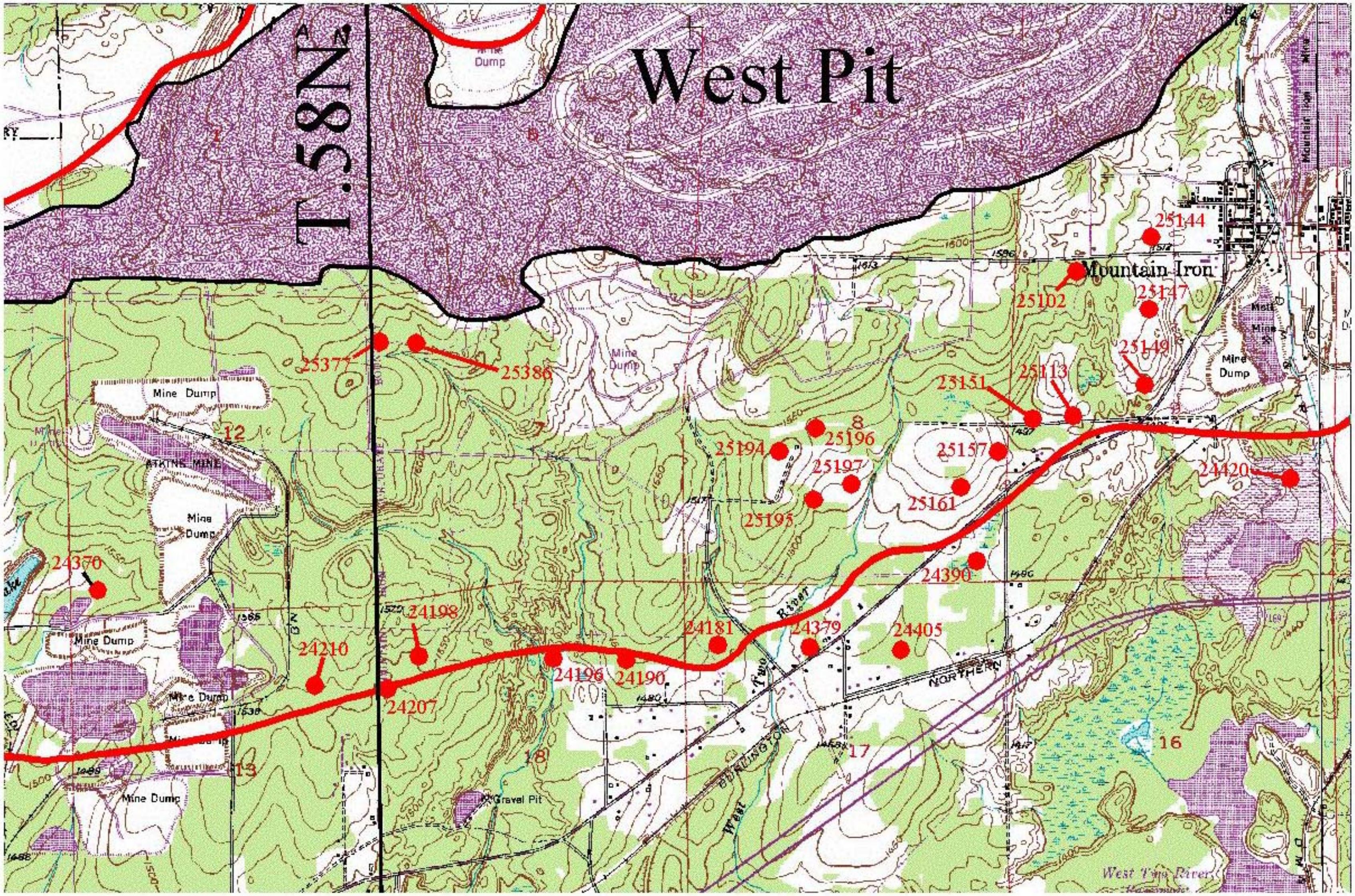


Figure 59. Location map of all drill holes logged by the NRRI to the south of Minntac's West Pit. These holes are correlated on the hung stratigraphic section of Plate XIII.

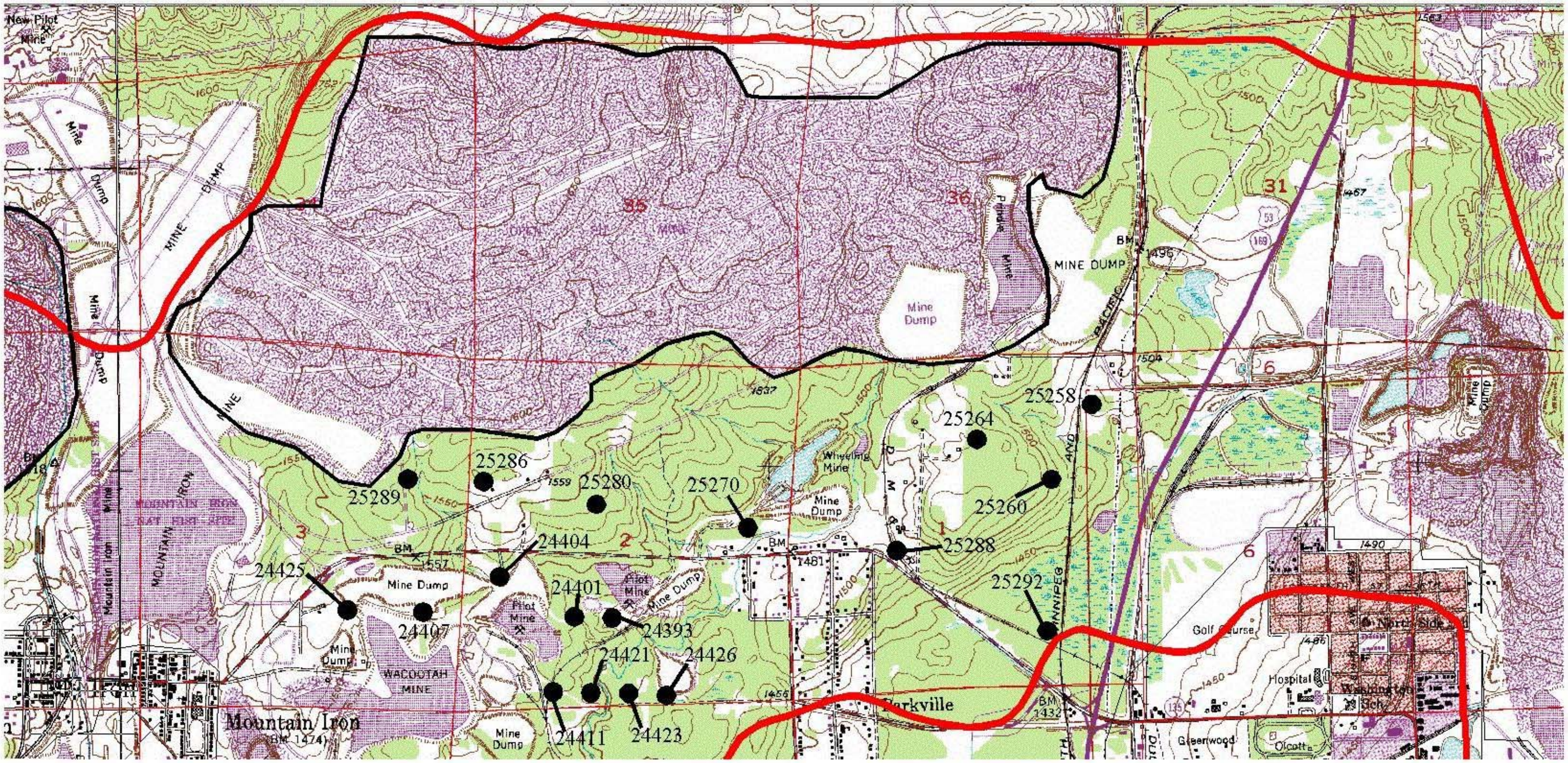
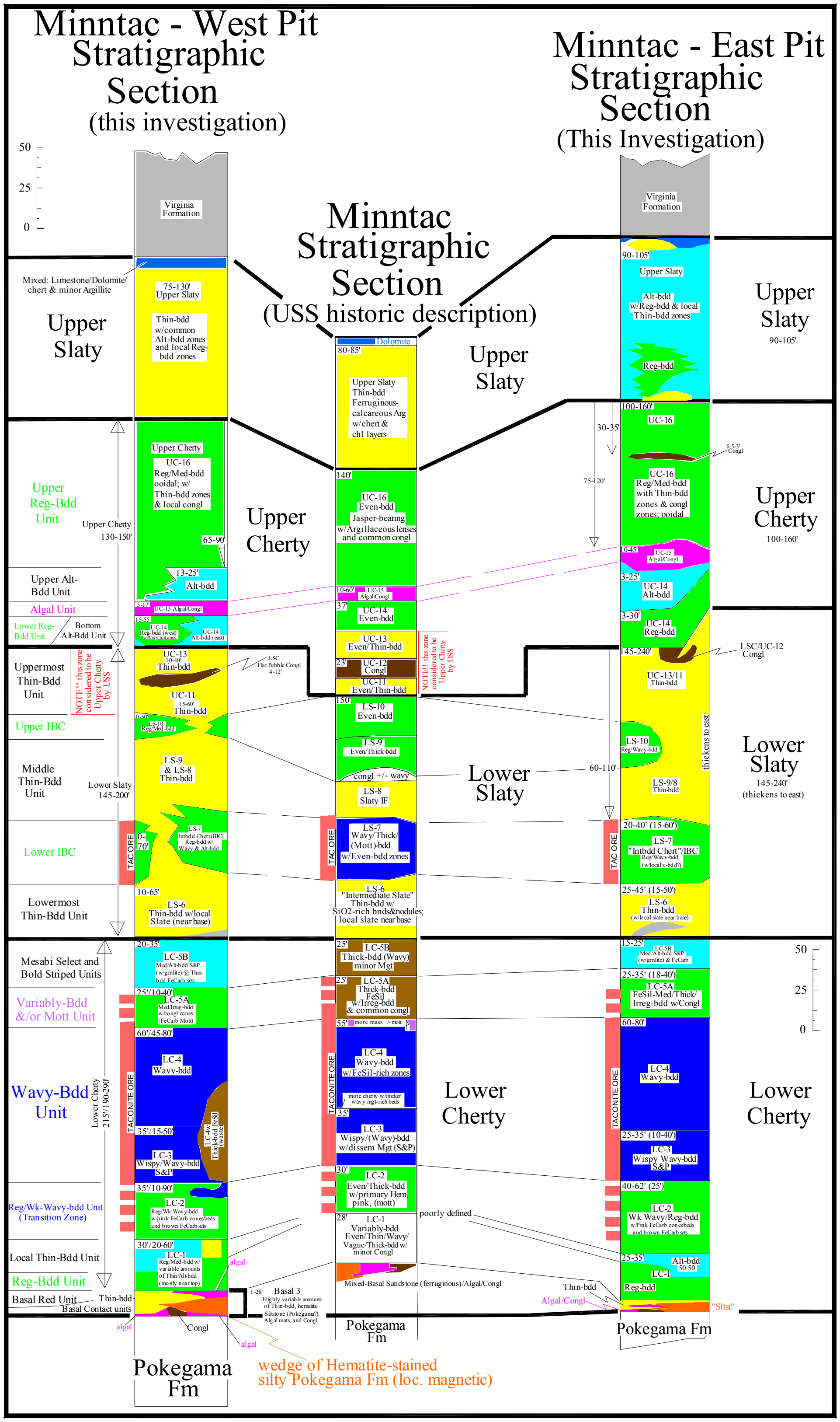


Figure 60. Location map of all drill holes logged by the NRRI to the south of Minntac's East Pit. These holes are correlated on the hung stratigraphic section of Plate XII.



[See figure caption on next page.]

Figure 61. Comparison stratigraphic columns of the various iron-formation submembers at Minntac as determined by United States Steel Corporation's geologists (center column) versus a slightly different interpretation (right and left columns) as determined by the more recent logging of 50 down dip deep drill holes by NRRI geologists. There are a few particular items to note in this figure, and in Plates XII and XIII that include:

- Submembers UC-13, UC-12, and UC-11 are considered to be part of the Upper Cherty member by USS; whereas, the NRRI has determined that UC-13 and UC-11 are thin-bedded units that should be classified as Lower Slaty submembers. Both of these submembers correspond to the Uppermost Thin-Bedded Unit of the Lower Slaty. Note that these three submembers were not consistently placed in the Upper Cherty member by USS geologists – as evidenced by the red-lines (denoting USS lithologic picks) on the left side of drill holes in Plates XII and XIII;
- The LS-9 submember is described by USS as being "even to thick-bedded" **and** as being similar to the LS-8 submember (thin-bedded), except that LS-8 is "noticeably more laminated." The NRRI was not able to resolve these profoundly different descriptions and lumped the LS-9 and LS-8 submembers together; and
- The contact between the LC-2 and LC-1 submembers is described as being "poorly defined" by USS. The NRRI noted that in most of the deep holes, these two submembers are separated by a 1-25 foot thick Alt-Bdd to Thin-Bdd unit that corresponds to the Local Thin-Bedded Unit of the Lower Slaty. This unit was not recognized by USS because it is not consistently present throughout their property (note the lack of this unit in the center of Plate XIII).

Appendix A-7: Utac Drill Holes

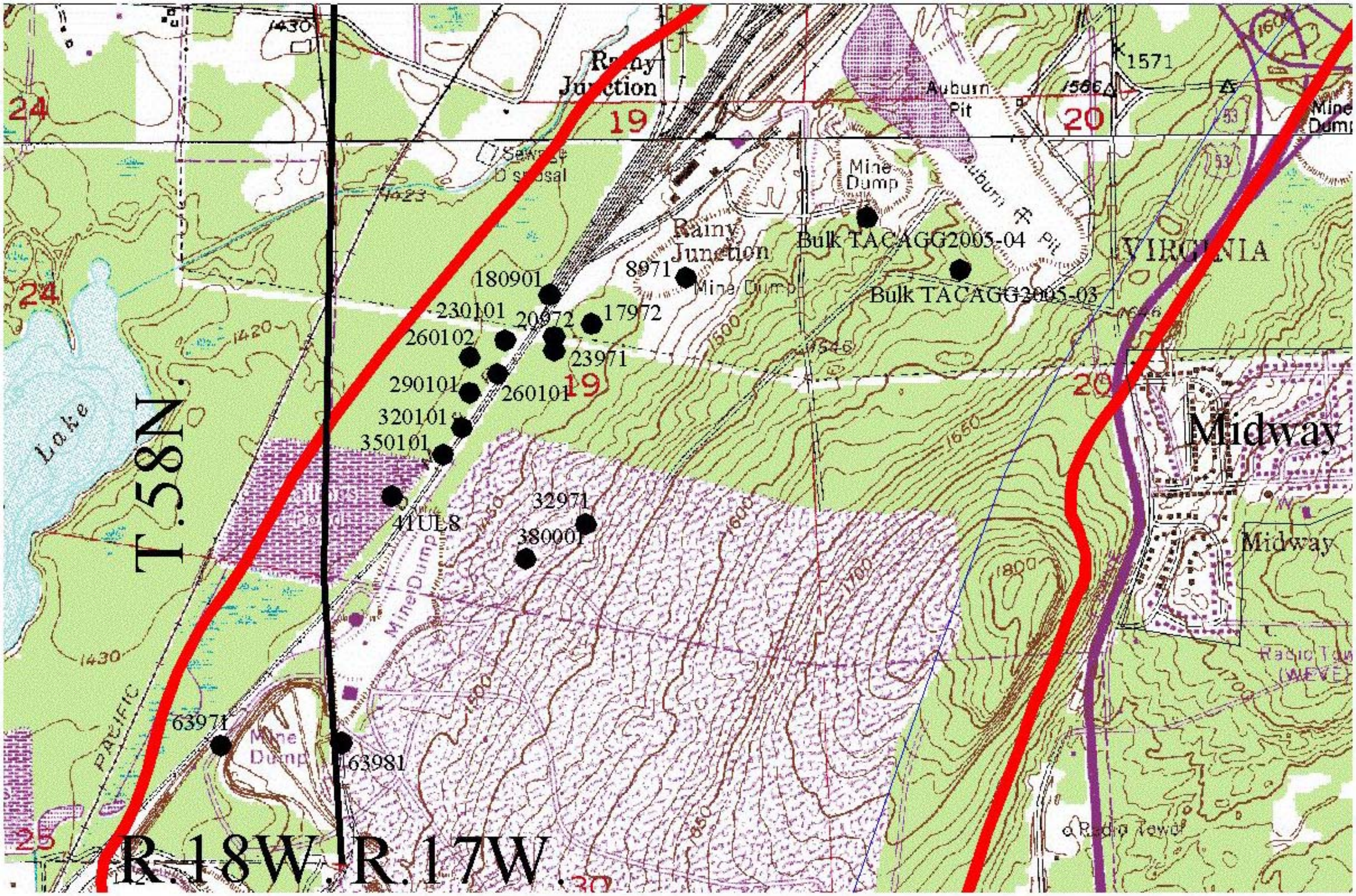
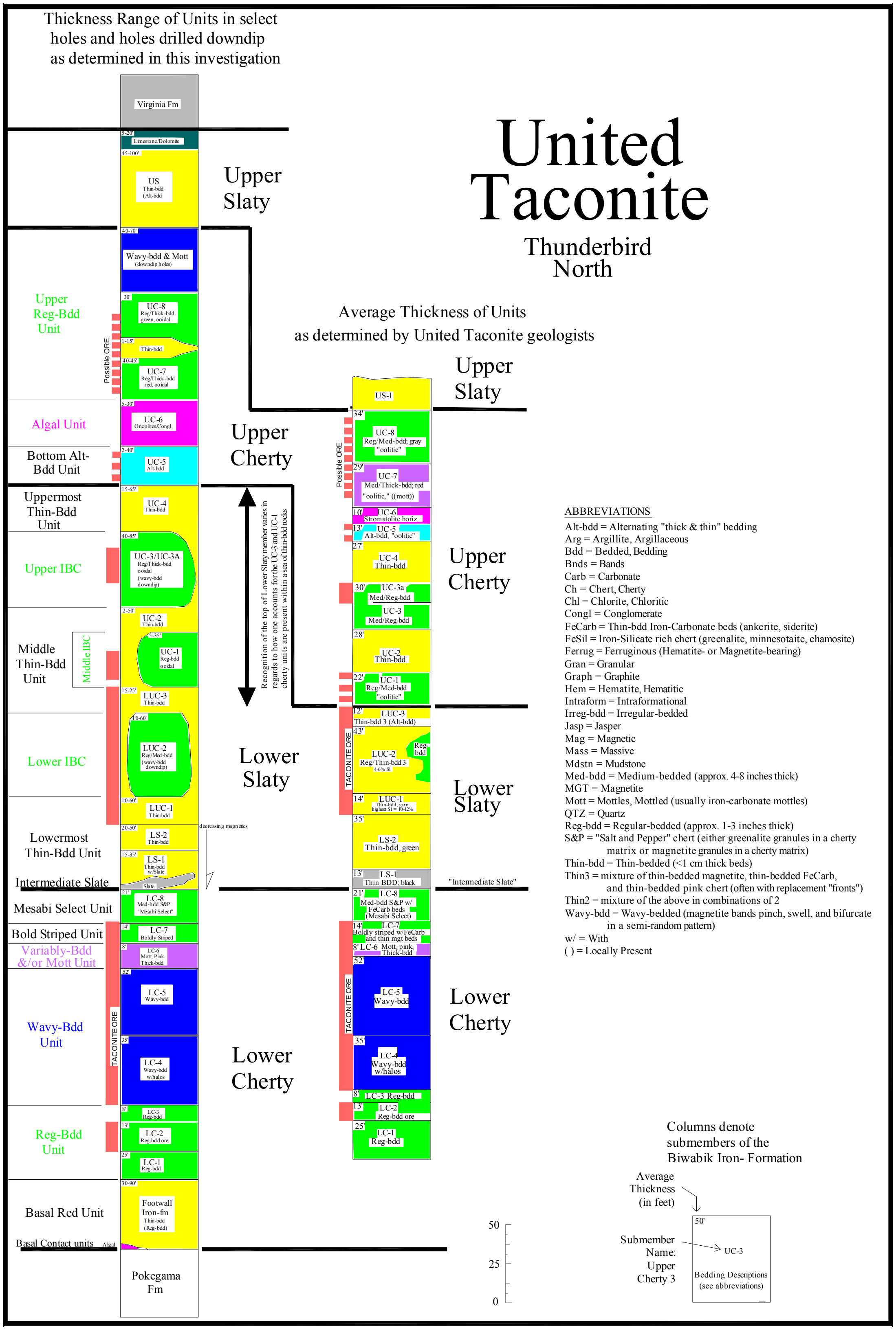


Figure 62. Location map of all drill holes logged by the NRRI in the United Taconite/Thunderbird North Mine area that have been correlated on the hung stratigraphic section of Plates III and IV. Note that the geology intersected in regional drill holes 24834, VHD 00-1, LWD 99-1, LWD 99-2, and RW-3 (not shown on this figure) are also portrayed on Plate III. All of the holes shown on this map are located in Section 19, T.58N., R.17W., except for hole 63971 which is located in Section 25, T.58N., R.18W. Locations of the two bulk samples collected from this mine are also portrayed on this map. Trend of the iron-formation in red.



ABBREVIATIONS
Alt-bdd = Alternating "thick & thin" bedding
Arg = Argillite, Argillaceous
Bdd = Bedded, Bedding
Bnds = Bands
Carb = Carbonate
Ch = Chert, Cherty
Chl = Chlorite, Chloritic
Congl = Conglomerate
FeCarb = Thin-bdd Iron-Carbonate beds (ankerite, siderite)
FeSil = Iron-Silicate rich chert (greenalite, minnesotaite, chamosite)
Ferrug = Ferruginous (Hematite- or Magnetite-bearing)
Gran = Granular
Graph = Graphite
Hem = Hematite, Hematitic
Intraform = Intraformational
Irreg-bdd = Irregular-bedded
Jasp = Jasper
Mag = Magnetic
Mass = Massive
Mdstn = Mudstone
Med-bdd = Medium-bedded (approx. 4-8 inches thick)
MGT = Magnetite
Mott = Mottles, Mottled (usually iron-carbonate mottles)
QTZ = Quartz
Reg-bdd = Regular-bedded (approx. 1-3 inches thick)
S&P = "Salt and Pepper" chert (either greenalite granules in a cherty matrix or magnetite granules in a cherty matrix)
Thin-bdd = Thin-bedded (<1 cm thick beds)
Thin3 = mixture of thin-bedded magnetite, thin-bedded FeCarb, and thin-bedded pink chert (often with replacement "fronts")
Thin2 = mixture of the above in combinations of 2
Wavy-bdd = Wavy-bedded (magnetite bands pinch, swell, and bifurcate in a semi-random pattern)
w/ = With
( ) = Locally Present

[See figure caption on next page.]

Figure 63. Comparison stratigraphic columns of the various iron-formation submembers at Utac as determined by United Taconite geologists (right column) versus a slightly different interpretation (left column) as determined by the more recent logging of 17 deep down drip drill holes by NRRI geologists. There are a few particular items to note in this figure, and in Plates III and IV that include:

- The Wavy-Bdd & Mott unit at the top of the Upper Cherty (left column) is apparently only present in holes positioned well to the west and south of the present mine site (see Plate III);
- Within the Upper Cherty submembers, there are thickness differences between the Utac column (right side) and the NRRI column (left side). These variations are probably related to the fact that Utac obtained the average thicknesses from many holes in their mine area; whereas, the NRRI obtained their averages from lesser holes and from deep holes positioned well outside (down dip) of the mine area;
- Utac considers the UC-4, UC-3, UC-2, and UC-1 submembers to be positioned in the Upper Cherty member; whereas the NRRI has determined that the UC-1 and UC-3 submember to be present as channel-like "interbedded cherts" (IBCs) in the Lower Slaty member; and
- Thin-bedded rocks that correspond to the Basal Red Unit are rarely drilled at Utac, and thus, these rocks are not portrayed on their stratigraphic column (right side).

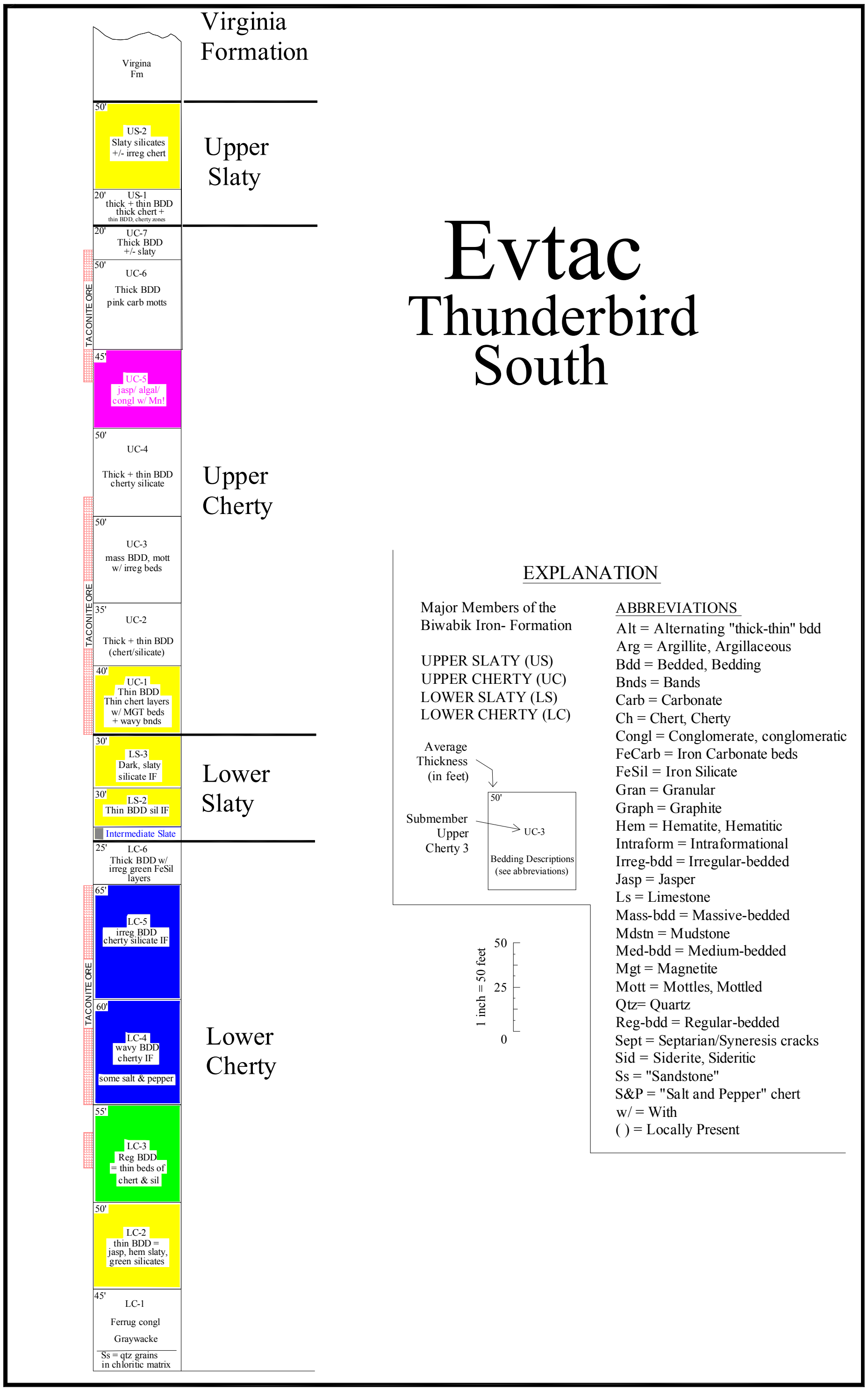


Figure 64. Stratigraphic section of the Biwabik Iron Formation at the inactive Evtac Thunderbird South Mine. Note that the submember nomenclature as portrayed in this figure was defined by Evtac geologists. No holes were logged by NRRI geologists as part of this investigation. Most of the ore at the Thunderbird South mine was reportedly obtained from the Upper Cherty member (Phil Larson – pers. comm., fall, 2008).

Appendix A-8: Laurentian Mine

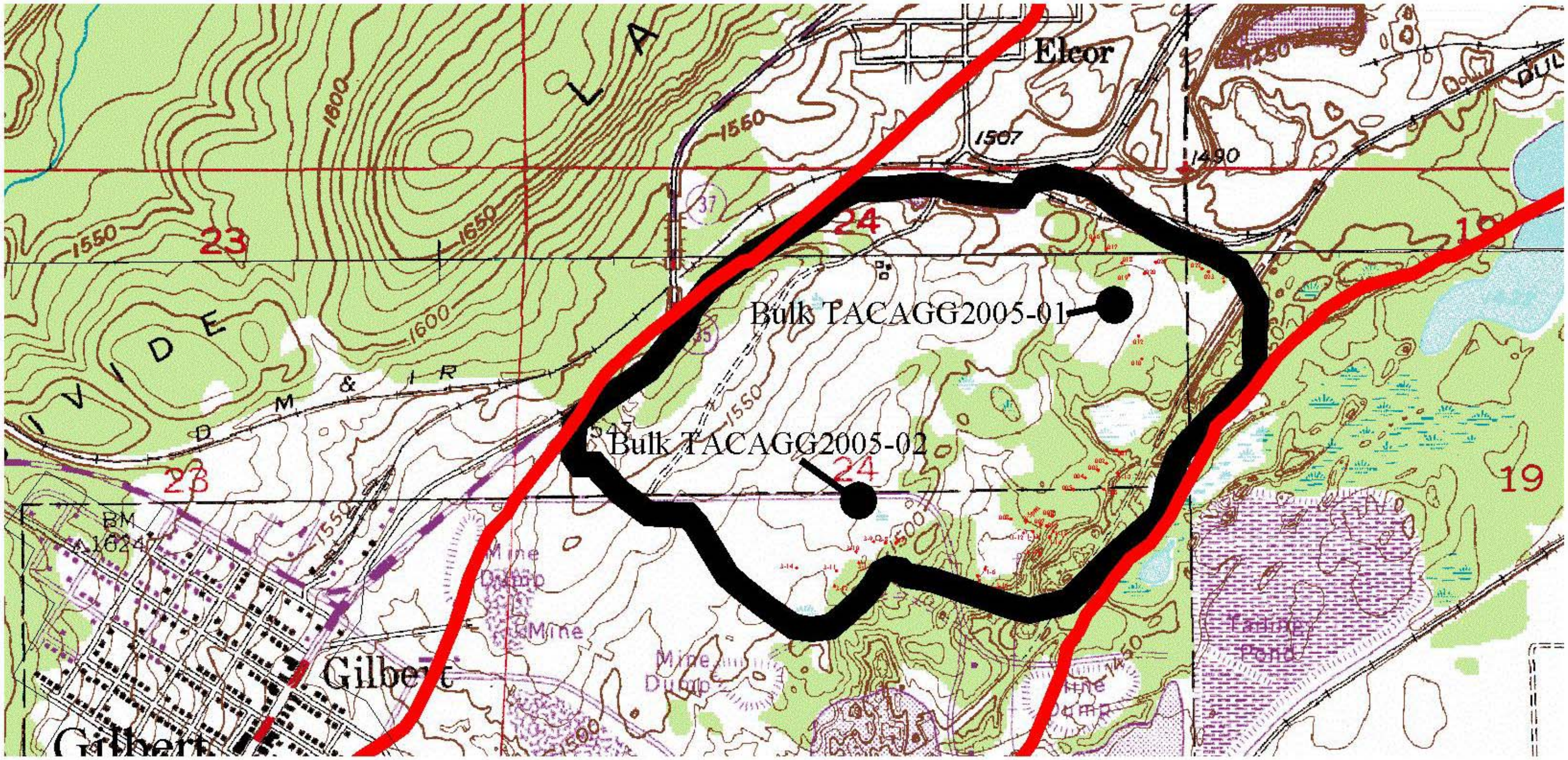


Figure 65. Location map (T.58N., R.17W.) showing the mine boundaries of the Laurentian mine, the location of two bulk sample collection sites (large black dots), and locations of in-pit stratigraphic measurements that were taken at several locations (very small, illegible red text points) along the south and east walls. Note that no drill holes have been preserved from this site, and submember thicknesses were obtained solely from in-pit measurements. Trend of the iron-formation in red.

Figure 66. Overall view, looking north, of the Laurentian Mine taken from the uppermost bench of the south wall.

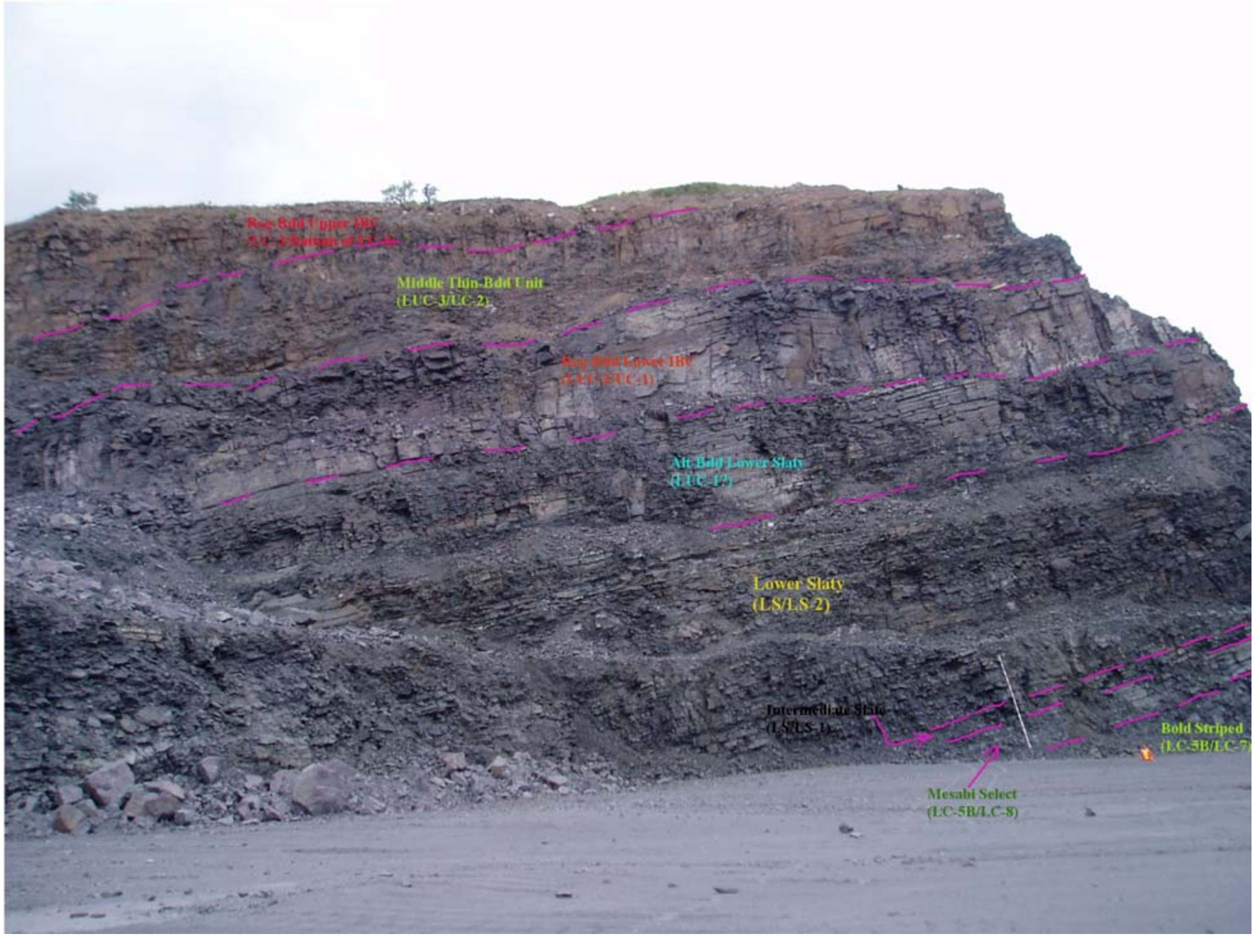


Figure 67. Photograph of the southwestern wall of the Laurentian Mine showing several submembers of the iron-formation (25 foot stadia rod for scale). The method used to map out the submembers included placing a stadia rod against the mine face, recording thickness measurements of submembers in the vicinity of the rod, and taking a digital photograph at each site to determine additional thickness measurements for submembers positioned well above the stadia rod (using the rod as a scale to measure incremental footages). Both Utac and Laurentian submember designations (listed respectively in the parentheses) were used to map the units that are shown on this photograph.

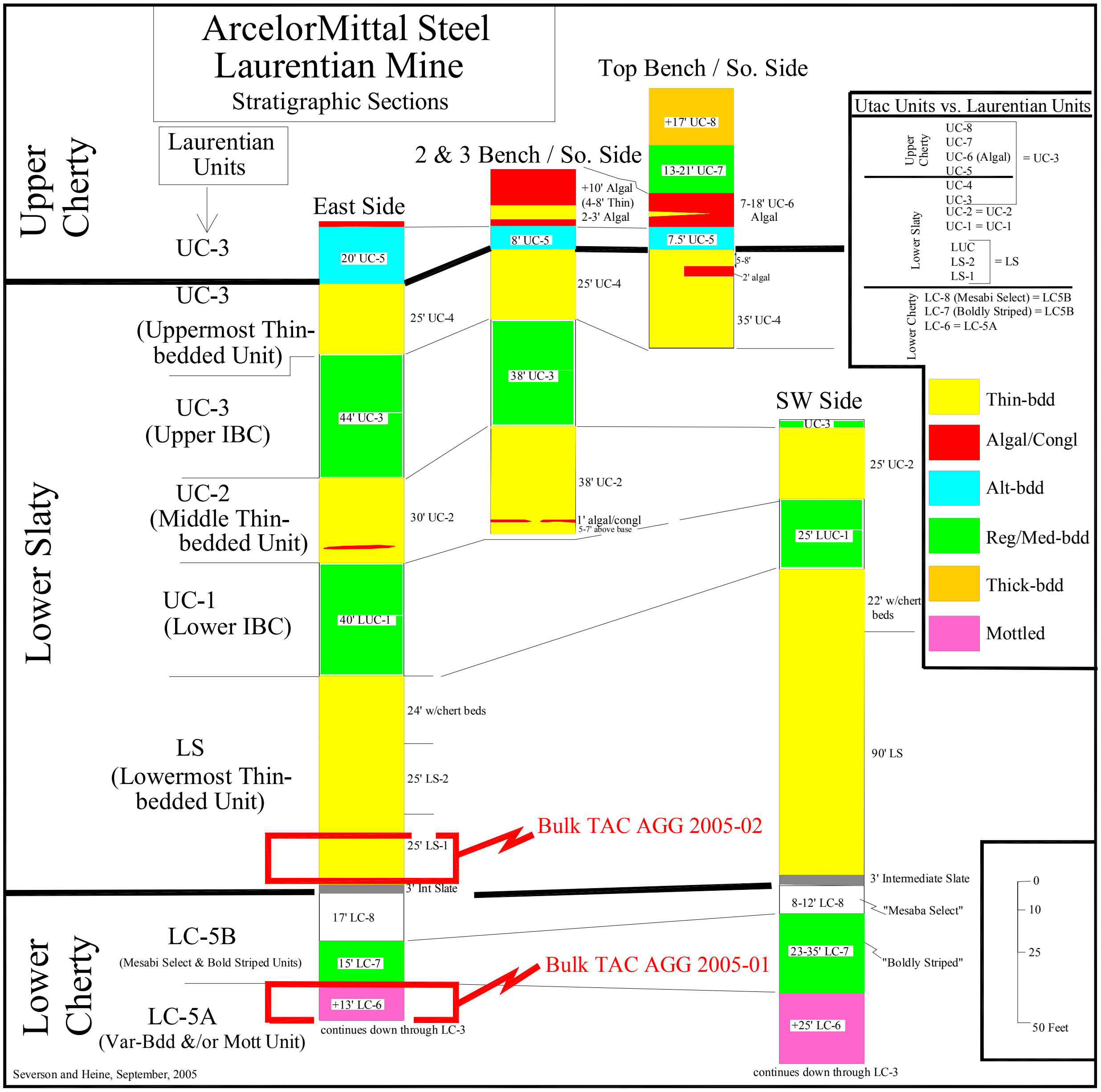


Figure 68. Summary diagram showing the thicknesses of various submembers along several benches and different mine faces of the Laurentian Mine. Both Utac and Laurentian submember designations were used during in-pit mapping (see upper right side of this figure for specific correlations between the two systems). Also shown on this figure (left side – in parentheses) are the major units of the iron-formation as determined by the NRRI in this investigation. Note that ArcelorMittal considers their UC-1 and UC-2 submembers, and a good portion of the UC-3 submember, to be positioned in the Upper Cherty. Correlations by the NRRI indicate that these submembers are actually situated in the Lower Slaty, and ArcelorMittal's UC-1 and bottom portion of the UC-3 correspond to the Lower IBC and Upper IBC Units of the Lower Slaty, respectively. Generalized stratigraphic positions of the two bulk samples collected from the Laurentian Mine are shown.

Appendix A-9: East Reserve/McKinley Extension Mine

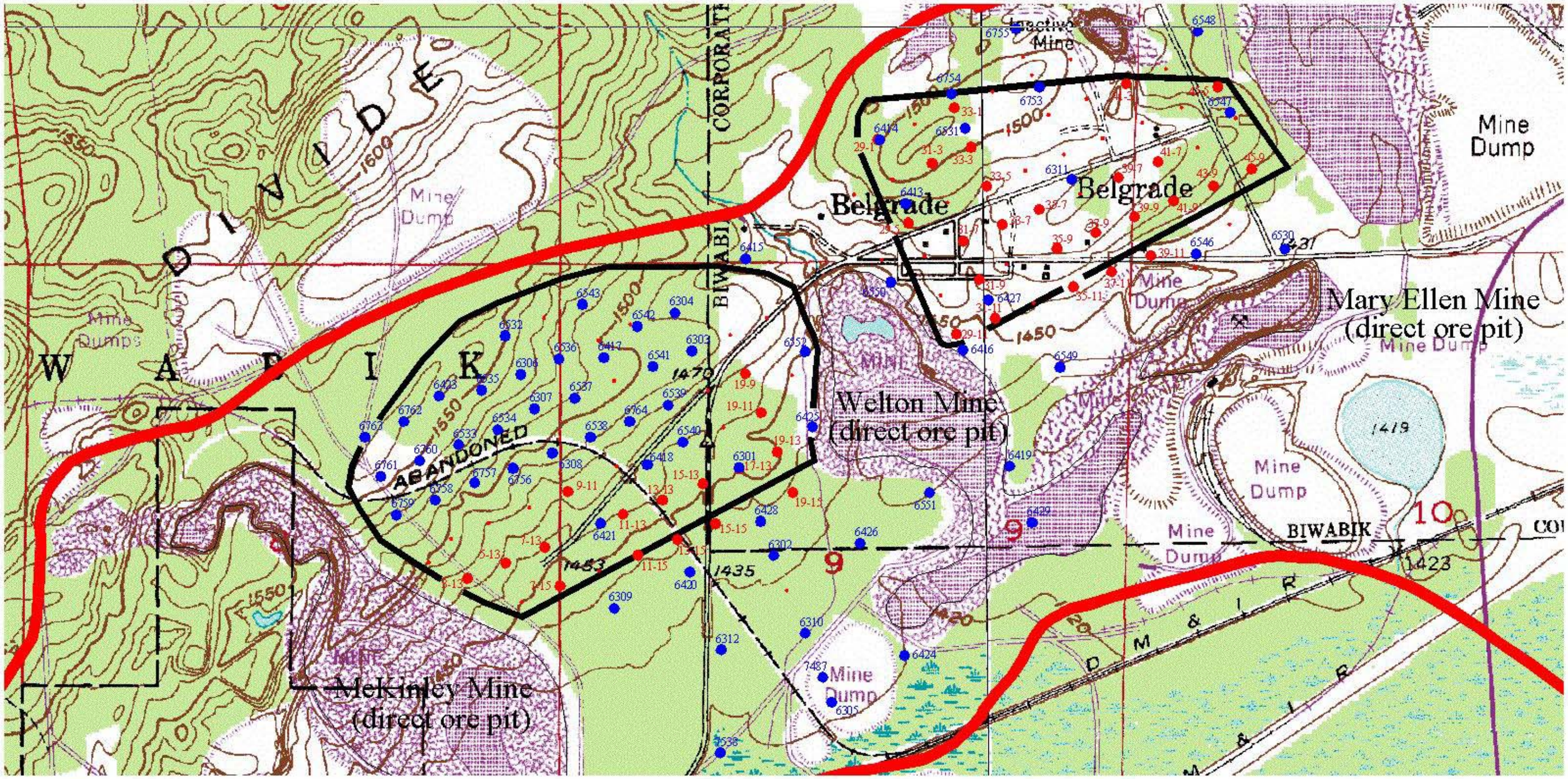
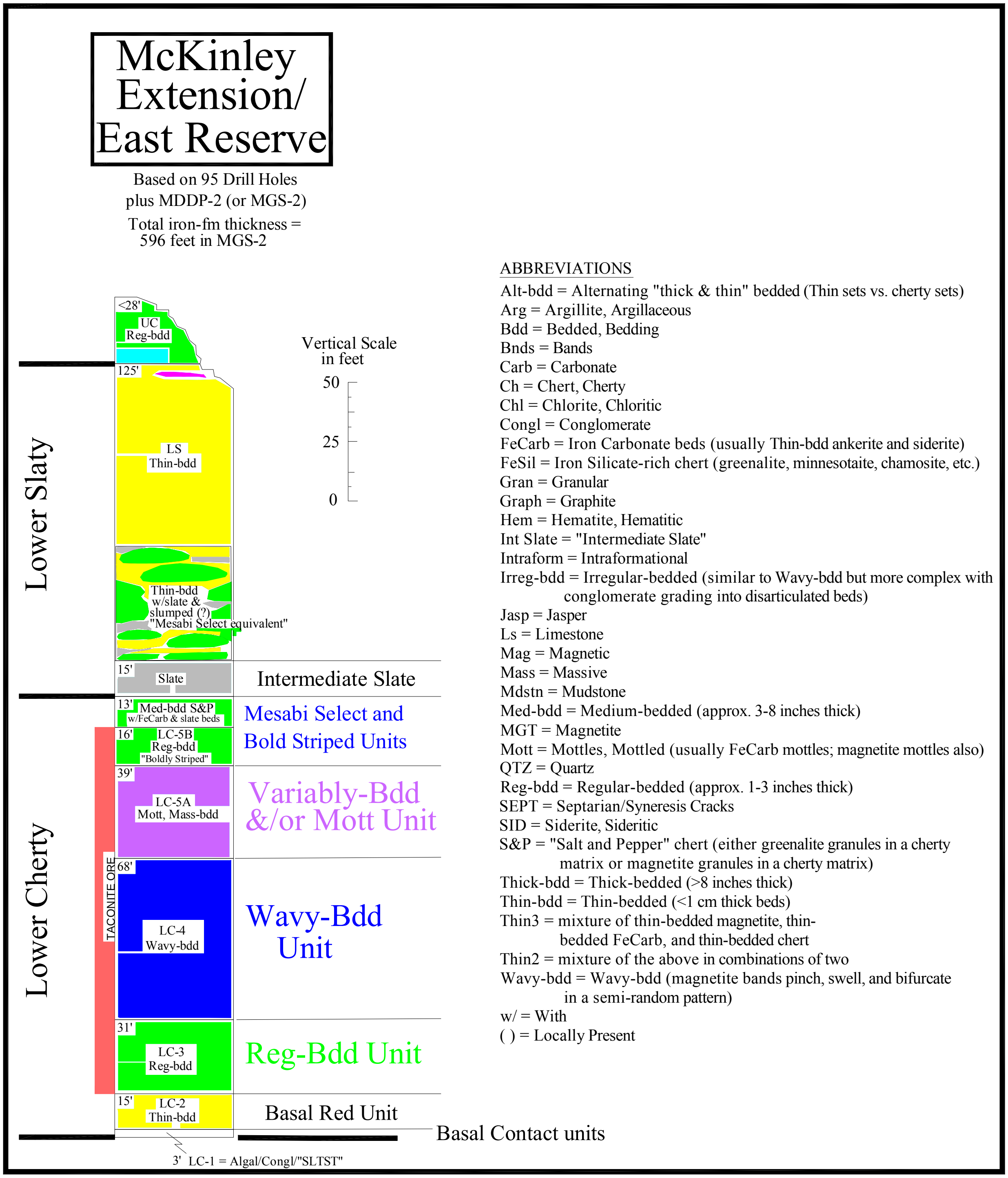


Figure 69. Location map (T.58N., R.16W.) of all drill holes logged in the East Reserve mine area. Proposed mine boundaries of Pits #1 (west) and #2 (east) are shown in black. Red dots represent drill holes drilled by ArcelorMittal that were logged by the NRRI. Very small red dots represent holes drilled by ArcelorMittal, but the holes were consumed for grade testing purposes before they could be logged by the NRRI. Blue dots represent holes drilled by the Jones and Laughlin Mining Company (many were jointly drilled with USS) that were logged by the NRRI (core stored at Lerch Brothers facility in Hibbing, MN). All of the holes logged by the NRRI are presented in the hung cross-sections of Plates V to X and north-south cross-sections of Plates XVII to XXXVIII that are staggered across the property. Note the geology intersected in regional drill hole MGS-5 (not shown on this figure) is also portrayed on Plate V. Trend of iron-formation shown in red.



ABBREVIATIONS

Alt-bdd = Alternating "thick & thin" bedded (Thin sets vs. cherty sets)
Arg = Argillite, Argillaceous
Bdd = Bedded, Bedding
Bnds = Bands
Carb = Carbonate
Ch = Chert, Cherty
Chl = Chlorite, Chloritic
Congl = Conglomerate
FeCarb = Iron Carbonate beds (usually Thin-bdd ankerite and siderite)
FeSil = Iron Silicate-rich chert (greenalite, minnesotaite, chamosite, etc.)
Gran = Granular
Graph = Graphite
Hem = Hematite, Hematitic
Int Slate = "Intermediate Slate"
Intraform = Intraformational
Irreg-bdd = Irregular-bedded (similar to Wavy-bdd but more complex with conglomerate grading into disarticulated beds)
Jasp = Jasper
Ls = Limestone
Mag = Magnetic
Mass = Massive
Mdstn = Mudstone
Med-bdd = Medium-bedded (approx. 3-8 inches thick)
MGT = Magnetite
Mott = Mottles, Mottled (usually FeCarb mottles; magnetite mottles also)
QTZ = Quartz
Reg-bdd = Regular-bedded (approx. 1-3 inches thick)
SEPT = Septarian/Syneresis Cracks
SID = Siderite, Sideritic
S&P = "Salt and Pepper" chert (either greenalite granules in a cherty matrix or magnetite granules in a cherty matrix)
Thick-bdd = Thick-bedded (>8 inches thick)
Thin-bdd = Thin-bedded (<1 cm thick beds)
Thin3 = mixture of thin-bedded magnetite, thin-bedded FeCarb, and thin-bedded chert
Thin2 = mixture of the above in combinations of two
Wavy-bdd = Wavy-bdd (magnetite bands pinch, swell, and bifurcate in a semi-random pattern)
w/ = With
( ) = Locally Present

Figure 70. Stratigraphic column of the various iron-formation submembers at the East Reserve/McKinley Extension mine, using ArcelorMittal's submember nomenclature (designators within the column), as determined by the recent logging of 96 drill holes by NRRI geologists.

Appendix A-10: Cliffs-Erie Site (old LTV/Erie mine site)

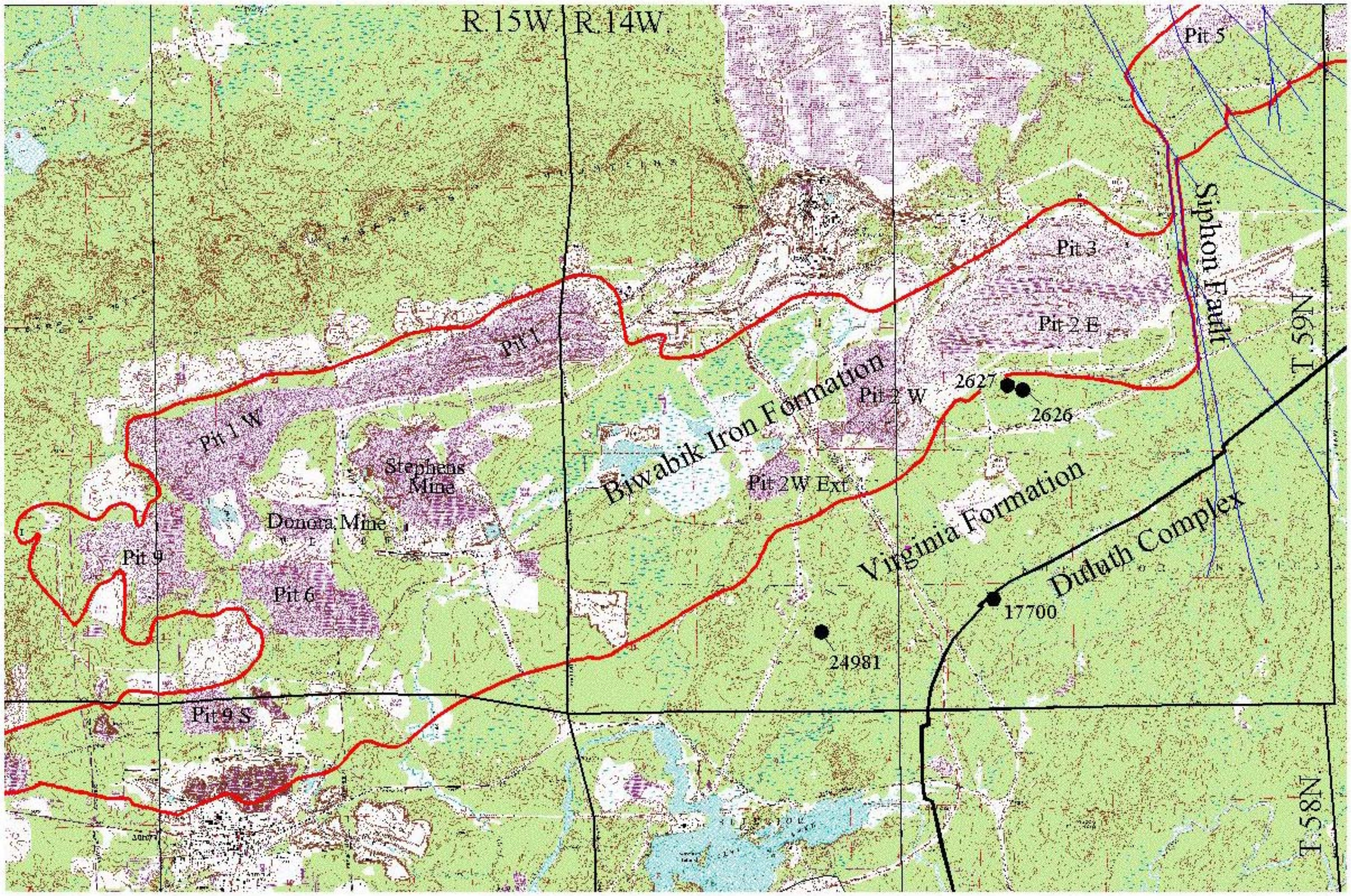


Figure 71. Location map of the various pits and preserved drill holes at the Cliffs-Erie Site. Trend of the iron-formation shown in red. Note the almost complete lack of preserved drill core from this area. Drill holes 24981 (stored at Minntac) and 2627 (stored at the MDNR in Hibbing) were logged for this investigation, and both drill holes are portrayed in the hung stratigraphic cross-section of Plate II and in Figure 66. Drill hole 2626 (stored at the MNDR) has not yet been logged by the NRRI. Drill hole 17700 has been logged by the NRRI, but because it has been heavily sampled, for studies pertaining to metamorphism of the iron-formation by the Duluth Complex, significant portions of the core are missing, and it has not been portrayed in any plates or figures of this report. The core storage location for this hole was unknown for a several decades until its discovery by Mr. Al Dzuck of the MDNR in the mid 1990s – it is now stored at the MDNR in Hibbing. Drill hole 17700, drilled jointly by INCO and USS (Severson and Heine, 2007) was collared in the Duluth Complex, penetrates the Biwabik Iron Formation, and it was terminated in Archean greenstone.

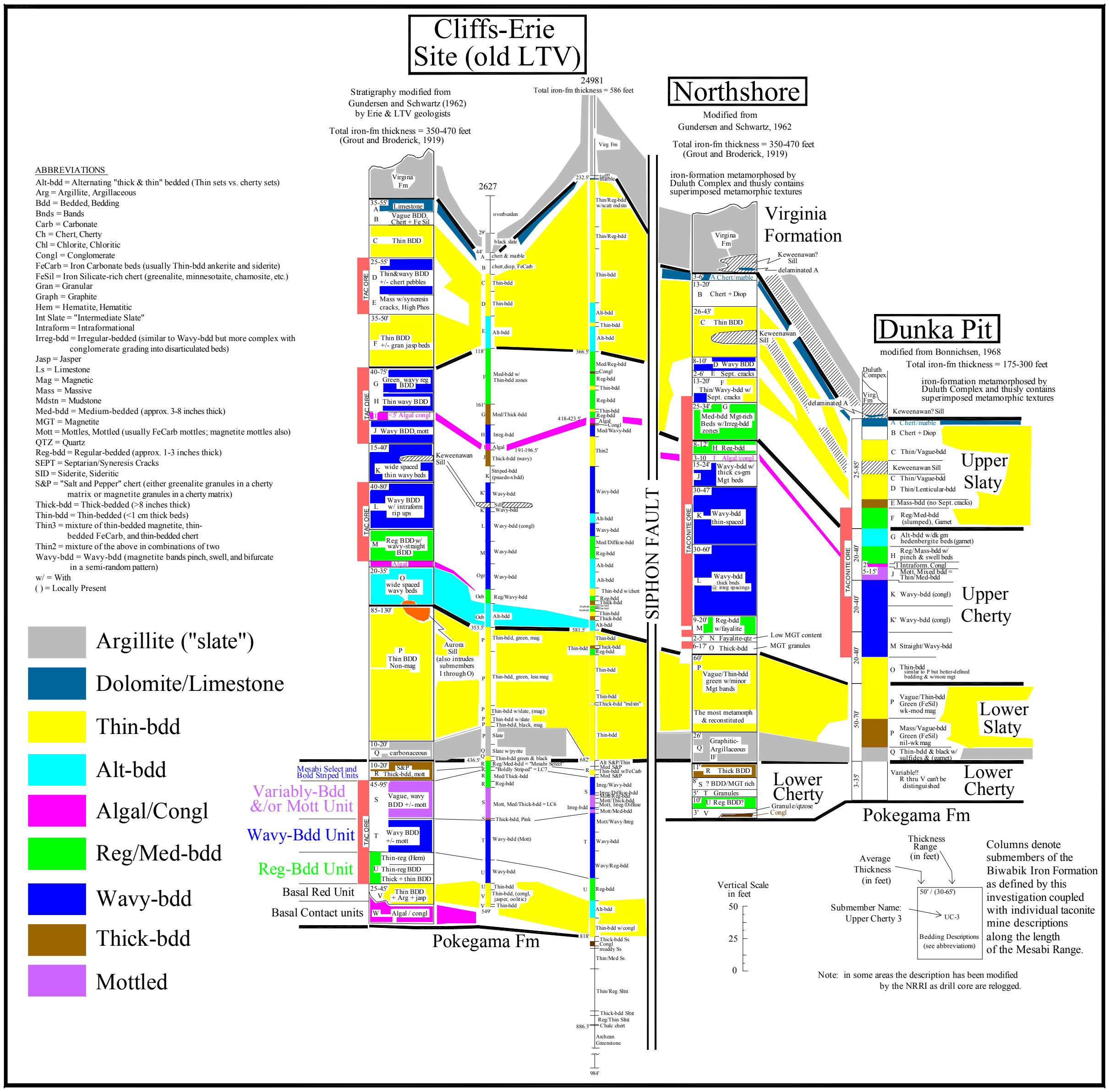


Figure 72. Stratigraphic columns showing submember nomenclatures for the Cliffs-Erie Site, Northshore/Peter Mitchell Mine, and Dunka Pit. Only two holes have been logged from this area by NRRI geologists and are shown on this figure. Note that the G submember is considered to be positioned in the Upper Slaty member at Northshore (due largely to the work of Gundersen and Schwartz, 1962); whereas, the G submember is considered to be within the Upper Cherty member at Cliffs-Erie and Dunka Pit (LTV modified the stratigraphy of Gundersen and Schwartz, 1962).

APPENDIX B:

SPREADSHEET FILES
(ON CD IN BACK POCKET OF THIS REPORT)

The following spreadsheets are included on the CD in the back pocket of this report:

1. *McKinleyMag.xls* = listing of magnetic susceptibility readings (in 10^{-3} SI units) collected from selected intervals in three drill holes that contain significant amounts of "Mesabi Select equivalent" from the East Reserve/McKinley Extension mine.
2. *McKinleySpecGrav.xls* = listing of density results (specific gravity) collected from selected intervals in three drill holes that contain significant amounts of "Mesabi Select equivalent" from the East Reserve/McKinley Extension mine.

The graduated cylinder method (GCM) was used to make specific gravity, or density (g/cm^3), determinations on whole drill core samples. This process first involved collecting a sample of whole drill core that consisted of several pieces of consecutive core in 1-2 foot long core runs. This sample was weighed on a Mettler PM 16 digital scale capable of measuring to 0.1 grams. The sample was measured up to three times, and the average weight was recorded in grams. Next, a 500 mL, plastic graduated cylinder was partially filled with deionized water, and the initial water value in mL was recorded (the cylinder's volume could be read to within ±5 ml). Then the sample of drill core was placed into the cylinder, and the new displaced level of water in the cylinder was recorded. This second reading was used to determine the volume of the sample that was calculated by subtracting the initial volume reading from the second reading. All values were recorded on a spreadsheet. The specimen's weight, in grams, was then divided by its volume to obtain the specific gravity (density) of the sample.

Specific Gravity = Core (specimen) Weight/Core (specimen) Volume

A major advantage to this method is that relatively large pieces of core could be used instead of very small pieces or chips that are required in the use of the Jolly Balance. All data pertaining to specific gravity measurements can be found in *McKinleySpecGrav.xls*.

APPENDIX C:

IMAGES USED IN FIGURES
(ON CD IN BACK POCKET OF THIS REPORT)

The CD in the back pocket of this report contains copies of pictures used in the following figures: 4, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 27, 28, 29, 30, 31, 32, 35, 36, 37a, 37b, 40, and 67. See captions in the text for each of the corresponding figures for an explanation.

APPENDIX D:

SEQUENCE STRATIGRAPHY STUDY OF THE BIWABIK IRON FORMATION

“Sequences stratigraphy is a methodology for analyzing and predicting the distribution of rocks and their properties within a framework of time equivalent surfaces” – from T. Demko’s 2005 sequence stratigraphy class

INTRODUCTION

Sequence stratigraphy is a method of interpreting the sedimentary rock record that was developed in the 1970s. This method identifies time boundaries (chronostratigraphic surfaces) and genetically related sedimentary deposits that develop during changes in sea level. When sea level drops, erosional surfaces (unconformities/sequence boundaries) and regressive deposits are formed. As sea level rises, marine flooding surfaces and transgressive deposits develop. Significant sedimentary surfaces are used in sequence stratigraphy to segregate the rock record into packages of *contemporaneously deposited* sediments. Using information from the significant surfaces in conjunction with the sedimentary packages provides a better understanding of changes in the depositional environment reflected by the sedimentary record (Coe et al., 2003).

An initial effort to develop a sequence stratigraphic framework for the Biwabik Iron Formation is presented in this appendix. The detailed core log for LWD 99-1, and various depictions of the general hung stratigraphy (from Plate II), but hung at four time intervals, were utilized for this evaluation. From these data, it appears that deposition changed across the Mesabi Iron Range with the basin appearing more stable during deposition of the Lower Cherty and Lower Slaty than in the Upper Cherty and Upper Slaty time. One larger, deeper basin is observed during deposition of Lower Slaty, and by Upper Slaty time, it appears that deposition may have taken place in two shallower basins. It will be evident that much additional work with lots of detail remains to be done in order to further evaluate the ideas presented here.

The Biwabik Iron Formation is typically divided into four members: Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty. Ojakangas et al. (2001) outlines the second-order and third-order stratigraphic sequences for the Biwabik Iron Formation. Second order sequences are bound by major unconformities, and third-order sequences are the based on the members-rock type (cherty/slaty). Ojakansas states “Third-order cycles of 1 – 10 m.y. or fourth-order cycles of 0.2 – 0.5 m.y. duration may be contained within the iron formations of the Animikie . . . groups.” This study begins to look at the third and potential fourth-order sequences.

BACKGROUND

As a sediment package is deposited, it can incorporate signatures that, if preserved, provide clues as to its origin, environment of deposition, response to sea level change, water depth, energy regime, sediment supply, and other conditions. Divisions created by unconformities and flooding surfaces related to changes in sea level are time lines (surfaces). Sequence stratigraphy is a method of evaluating sedimentary units that uses time lines to subdivide the rock record into genetically related successions of sedimentary rock layers. In Posamentier and Allen (1999), they reference Mitchum’s (1977) definition of sequence as “a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bound at its top and base by unconformities”. “. . . can form in marine settings in response to cyclic changes in relative sea level, i.e., accommodation, due to a combination of tectonism and eustacy." The principle that allows sequence stratigraphy to predict the location of specific sedimentary packages is Walther's Law. It states that in an undisturbed vertical sequence of sedimentary rocks, the sedimentary beds that are observed were originally deposited next to each other horizontally. Unconformities and flooding surfaces are two surfaces used to identify time lines that reflect changes in sea level.

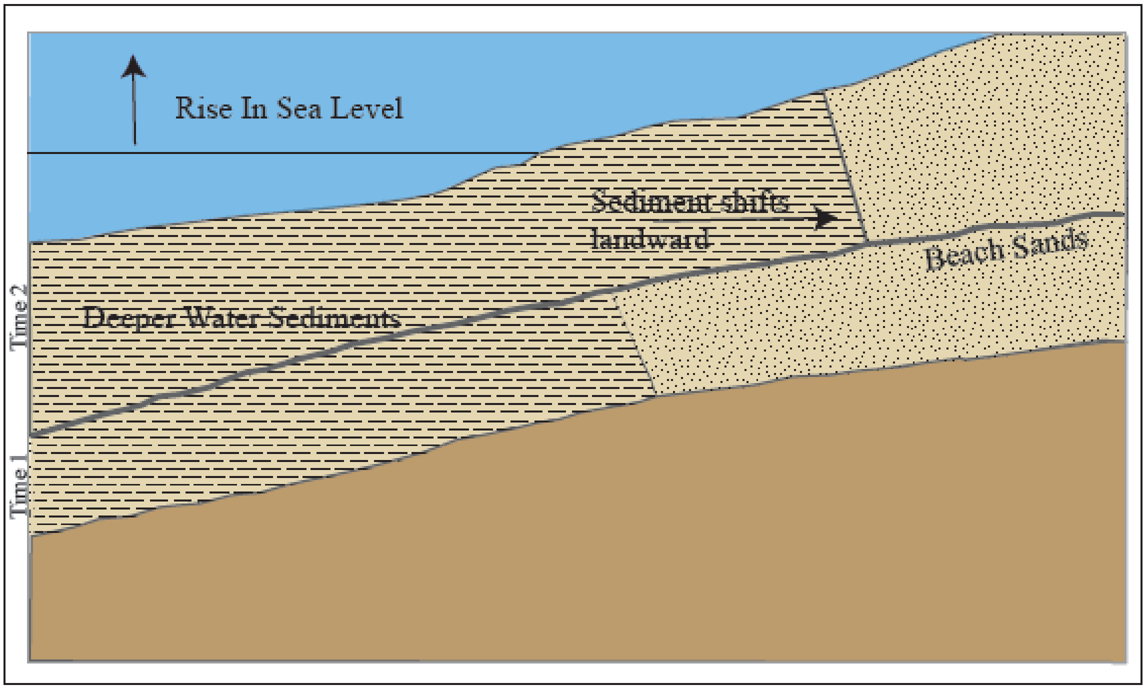


Figure D-1. Shift of sediment along a shoreline in response to a rise in sea level.

A simple analogy for sequence stratigraphy is to think of the sediment types a person would encounter as they walked across the current sediment surface at the bottom of a large lake. A variety of sediment/rock could be encountered along that time surface. Bedrock surfaces, glacial deposits, beach sands, deeper water silts/clays and river sediments could all potentially be encountered. The variety of sediment would be determined by the location and would be indicative of the depositional environment at that location, but they would all be deposited contemporaneously. Over time, the site of these types of sediments can shift (Fig. D-1). For example, if lake level rises, over time the beach deposits from Time 1 become covered by deeper water deposits such as silts and clays (Time 2). The change in sediment creates a new surface or time line.

To initiate construction of a sequence stratigraphic framework for the Biwabik Iron Formation, detailed core logging needs to continue. Data from many boreholes, especially holes that extend through the iron-formation (including portions of the Pokegama and the Virginia Formation) from across the Mesabi Iron Range, need to be included. Core up and down the depositional dip from the Mesabi Iron Range would need to be logged and incorporated as well. Observations regarding composition, texture, grain size, bedding structures, form, fossils, associations, and other items need to be recorded. Also, outcrops/mining cuts need to be described, as some features are not as evident in core.

METHODS

According to Posamentier and Allen (1999), the method of sequence stratigraphic study includes the following steps:

1. Establish paleogeographic setting;
2. Interpret depositional systems and facies using all available data (looking for coarsening upward, fining upward trends);
3. Subdivide the stratigraphic successions through identification of Maximum Flooding Surfaces (MFS) and Sequence Boundaries (SB); and
4. Analyze facies stacking patterns and identify systems tracks.

A limited attempt has been made on steps 1 – 4 for this study.

Definition of a couple of terms mentioned above are listed below and come from Posamentier and Allen (1999) book.

- Maximum Flooding Surface (MFS) – "… the surface of deposition at the time the shoreline is at its maximum landward position." A key surface.
- Sequence Boundary (SB) – unconformity and its correlative conformities. A key surface.
- Facies Stacking Patterns – "…based on analysis of depositional environments and their vertical stacking pattern." Does Walther's Law apply, or are there sharp changes that create boundaries in sediment?
- System Tracts – "…identify the systems tracts that "fill" the space between these surfaces (key surfaces)." The sediments that constitute the sequence can be subdivided into distinct stratigraphic units that are deposited during specific phases of the relative sea-level cycle. "The boundaries between system tracts form key stratigraphic surfaces . . . and represent breaks in the continuum of sedimentation." Figure D-2 depicts the subdivisions on a relative sea level curve.

Most of the core logged for this project was done for aggregate definition and used characteristics such as bedding and mineralogy, similar to megascopic divisions used by the mining companies. Detailed logging was completed on several cores, however, not all cores intersected the entire section of Pokegama, Biwabik, and Virginia Formations. Core from borehole LWD 99-1 is located in the area of the Virginia Horn, and it was logged for both mining and sequence stratigraphic purposes. A stratigraphic column was created using observations such as grain size, "Slaty" rock, "Cherty" rock, and the form of the cherty grains. The new submember units for this hole are also provided near the stratigraphic column as a reference to look for patterns of coarsening or fining upward trends in the submembers.

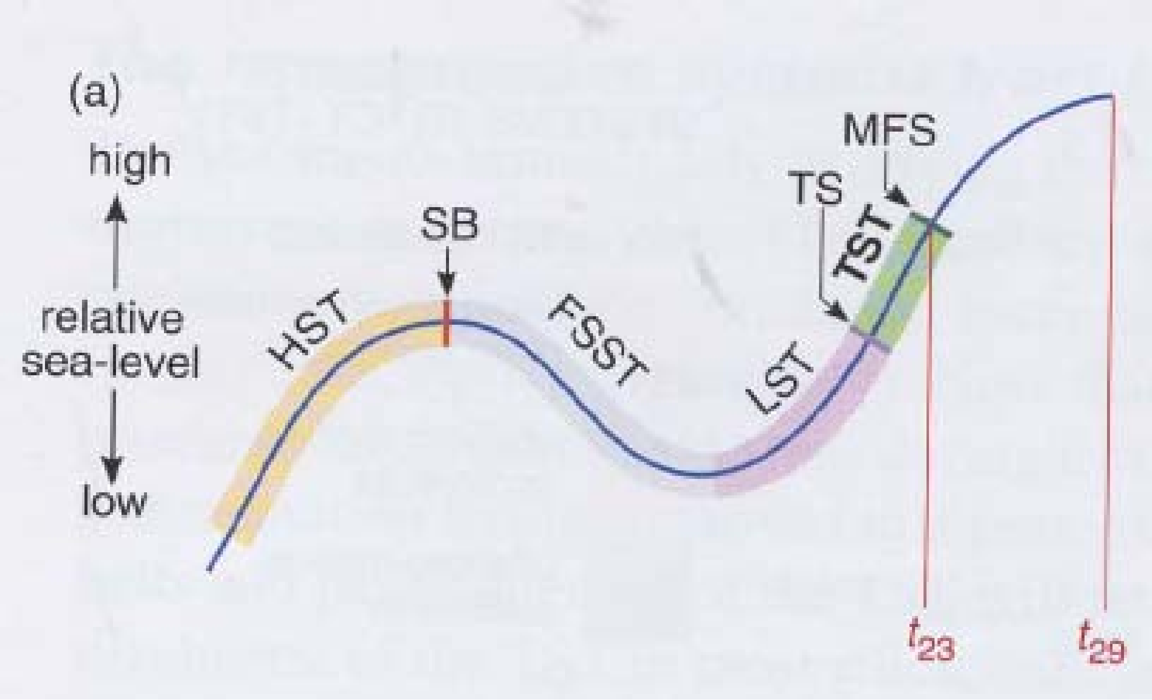


Figure D-2. Systems tracts utilized in sequence stratigraphy analysis displayed on one cycle of relative sea level rise and fall. Highstand Systems Tract (HST), Falling Stage Systems Tract (FSST), Lowstand Systems Tract (LST), and Transgressive Systems Tract (TST). Bounding surfaces SB, MFS, and Transgressive Surface (TS), from Coe et al. (2003).

There are typical features associated with various facies and depositional environments. Water depth, as well as, location on shelf and slope can be interpreted from these features. A brief review is given in Figure D-3 for shallow sea clastic storm and tidal deposits as well as for carbonate ramps. Using the revised submember nomenclature presented in this report, an attempt was made to assign submembers from the Lower Cherty and Lower Slaty to potential depositional environments. Upper Cherty and Upper Slaty members are not as well understood or studied. Therefore, these members have not been linked to a specific depositional environment in Figure D-3. Observations from core logging, including bedding characteristics, are the basis for selecting an environment, as depicted in Figure D-3.

Four generalized cross sections hung on different datum were created using Plate II. Datum used includes the top of the Pokegama, bottom of Lower Slaty, top of Lower Slaty, and top of Upper Slaty. Using the depositional environments assigned to the submembers and Walther's Law, an attempt to create time lines of genetically related sediment was used for correlation.

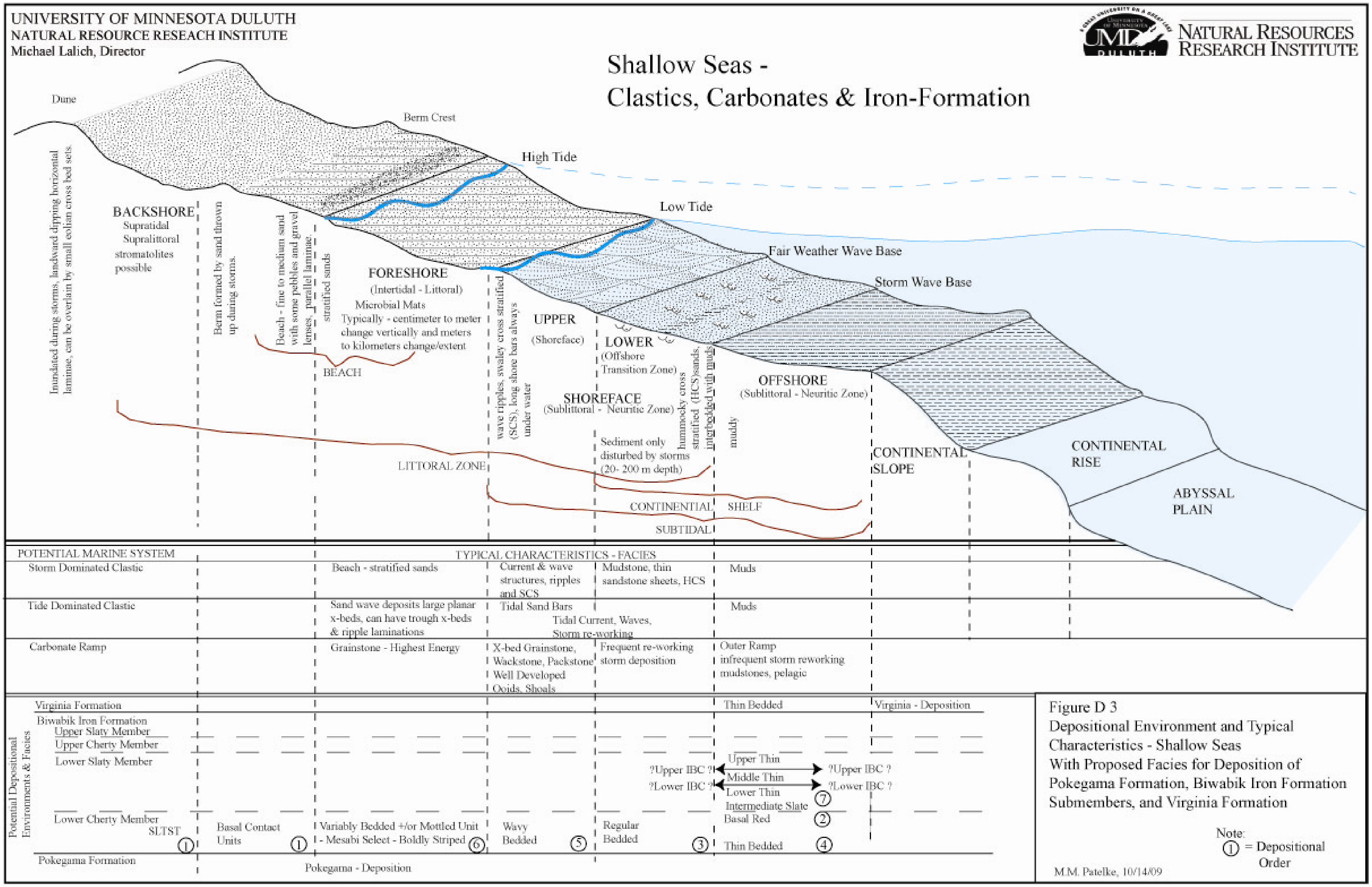


Figure D-3. Cross sectional view – facies division in a shallow sea. Compiled from sources including Boggs (2001), Leeder (1999), Nichols (1999), and Pratt et al. (1992).

RESULTS

Detailed Core Logging

Figure D-4 includes two stratigraphic columns for LWD 99-1 that present the member and submember boundaries, as well as, details such as grain size and texture. Cherty textures include: grainstone – oolitic; wackstone-oolitic/granules, granules, and the generic term cherty rock when grain boundaries are difficult to see by hand lense. Muddy/Slaty rocks refer to fine- to very fine-grained sediments. Mixed mud/chert units represent where very thin layers of "muddy" and "cherty" rocks alternate back and forth frequently. Grain size trends are also depicted on this figure to show zones of coarsening upward, fining upward, and aggredation (grain size appears stable when sedimentation and accommodation space are in balance, . . . sediment builds vertically, and the depositional environment does not shift (Nichols, 1999, p. 265). A copy of the grain size card (Fig. D-5) used for logging is included to provide the definition for terms. In addition, a catalogue of thin sections collected from LWD 99-1 is included with this report as Appendix F. It contains scans of thin sections, photos of the core sample, XRD traces, descriptions, and mineralogy for each sample.

Generalized Cross Sections

Figure D-3 places the submembers of the Lower Cherty and Lower Slaty in proposed depositional environments. The data used to select these environments were limited.

In attempting to reconstruct the progression of deposition along the Biwabik Iron Formation, four cross-sections, using four different chronostratigraphic boundaries/surfaces as datum lines, were constructed and are presented in Figures D-6, D-7, D-8, and D-9. These cross-sections use the generalized submembers presented in Plate II. The columns are a combination of observations of core and mine pit walls that generalize the geology at the location given. No specific drill holes or mine faces were used for the reconstruction.

Figure D-6 hangs the stratigraphic columns on the top of the Pokegama Formation. This hung section assumes the basin configuration is relatively flat along the contact, and the iron-formation began to form on top of the Pokegama Formation at the same time. In most core, the contact between the Pokegama and the Lower Cherty was seen to be conformable. In the Area 5 pit at the former Cliffs-Erie site, a possible local unconformity was observed in the mining floor. Lower Cherty stromatolites and algal material were observed to be above the Giant's Range Granite. However, in other places in the same pit the Pokegama Formation is observed directly below the Lower Cherty. Review of additional core and mine pits would be required to determine if the unconformity extends for any distance. Deposition of iron-formation begins with thin-bedded material and some algal deposits interpreted as proximal to the shore and the Pokegama deposits.

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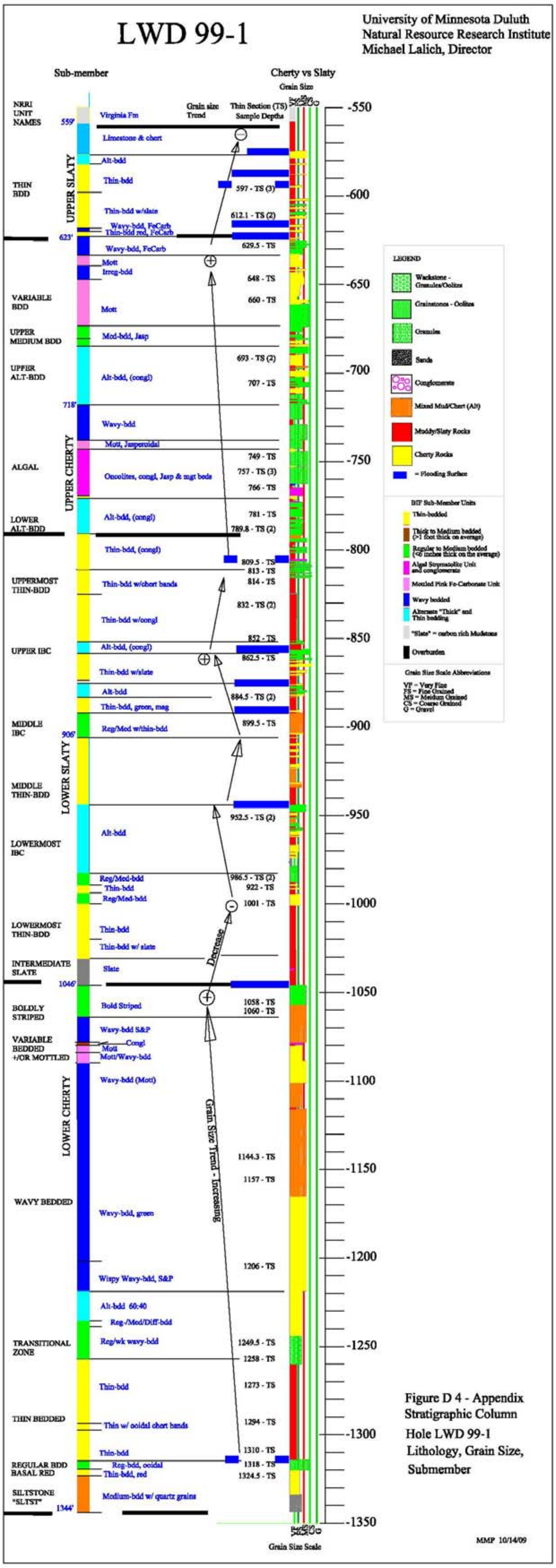
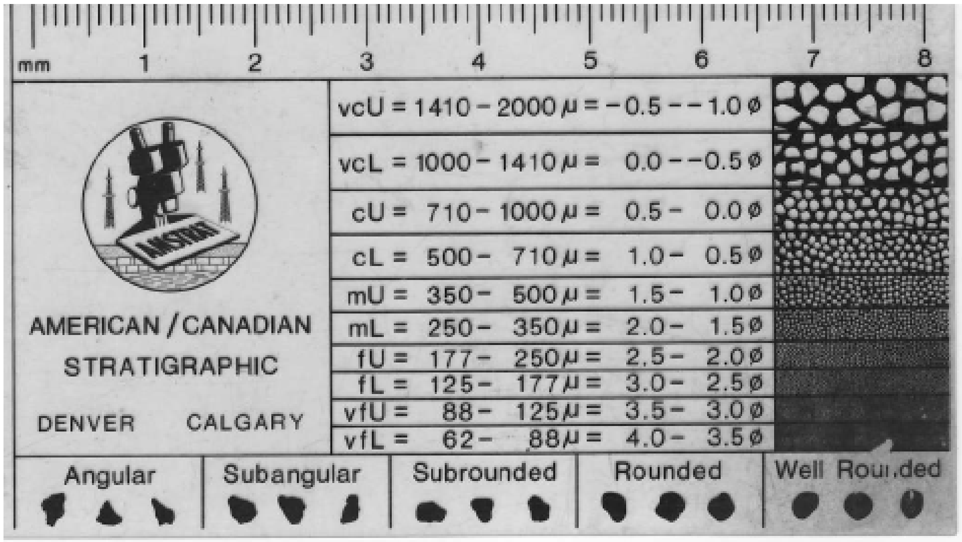


Figure D-4. Stratigraphic columns for LWD 99-1. A stand-alone pdf version of this figure is located on the CD included with this report.



vcU = 1410 - 2000 μ = -0.5 - - 1.0 ø
vcL = 1000 - 1410 μ = 0.0 - - 0.5 ø
cU = 710 - 1000 μ = 0.5 - 0.0 ø
cL = 500 - 710 μ = 1.0 - 0.5 ø
mU = 350 - 500 μ = 1.5 - 1.0 ø
mL = 250 - 350 μ = 2.0 - 1.5 ø
fU = 177 - 250 μ = 2.5 - 2.0 ø
fL = 125 - 177 μ = 3.0 - 2.5 ø
vfU = 88 - 125 μ = 3.5 - 3.0 ø
vfL = 62 - 88 μ = 4.0 - 3.5 ø

Figure D-5. Grain size card. Examples of abbreviation meaning: vcU = very coarse upper, cL = coarse lower, mU = medium upper, vfL = very fine lower. The grain size for a sample can be expressed as a range. For example, a sand could range in grain size and be described as coarse lower to medium upper (cL – mU). The terms Upper and Lower subdivide grain size, i.e., very coarse, coarse, medium, fine, and very fine, into measured size ranges. Medium Upper (mU) refers to grains with sizes between 1.5-1.0 phi (ø) units), as displayed on the card.

Figure D-7 is hung on the base of the Lower Slaty – the Intermediate Slate as in Plate II. Offshore deeper water deposits (Thin-Bedded) appear initially on top of the Pokegama and are followed by general shallowing upward of depositional environments. However, near the top of the Lower Cherty, prior to the deposition of the Intermediate Slate, the basin appears to be deepening between Hibtac and McKinnley. Lowershore face deposits, represented by the Regular-Bedded Unit, appear and persist until deposition of thin-bedded Intermediate Slate. During this same period, shallower depositional environments, characterized by Variably-Bedded and Thick-Bedded Units, appear to develop east of McKinnley and west of Hibtac. It needs to be noted, though, that the top of the Lower Cherty is oxidized to the west, and only three holes from the eastern end of the range were logged.

Figure D-8 depicts deposition up to the top of the Lower Slaty. While the pick for the contact between the Lower Slaty and Upper Cherty can vary depending on the person logging, it is a good approximation for the switch from fine-grained “slaty” deposits to predominantly “cherty” deposits. Offshore to slope deposits persist for a longer duration roughly between Hibtac and McKinley Extension. Channels of cherty material deposited in the thin-bedded material can be seen in this area. Thinner offshore deposits of the Lower Slaty are seen west to the Coleraine area and east from Cliffs-Erie to Northshore. Sea level shallows upward above the Lower Slaty to form the Upper Cherty.

Figure D-9 is hung on the contact between the Upper Slaty and the Virginia Formation. Sea level deepens upward from the top of the Upper Cherty and into the Virginia Formation. Two separate basins (possibly second order basins) are indicated in the Upper Slaty of this figure. Thicker Thin-Bedded material deposits appear to shift to the west and also appear to be more consistent with deposition of fine grained sediment. The amount of Thin-Bedded material pinches out at the Minntac East Pit. A second, but shallower, basin is located to the east of Minntac.

DISCUSSION

Core from borehole LWD 99-1 was logged for submember characteristics, as well as, a more detailed observation of the sediment. Characteristics recorded included bedding thickness, bedding type, sorting, grain size, and texture of the cherty zones. General observations for the bedding types are presented in Table D-1.

Table D-1. General observations for bedding types – Submembers.

BEDDING TYPE	GRAIN SIZE RANGE	NOTES
Thin-Bedded	Very Fine Upper – Fine Lower	
Wavy-Bedded	Medium Upper – Medium Lower	Chert w/ hard to see grain boundaries in Lower Cherty. Oolites and granules present in wavy beds in Lower Slaty and Upper Cherty.
Regular-Medium-Bedded	Medium Upper – Medium Lower	Cherty forms hard to see grain boundaries to granules.
Algal	Medium Upper – Medium Lower, Some fine grained beds.	Oolites common, conglomerate at base in Upper Cherty. Sequence of beds moving up the core: Thin-Bedded – Alt Bedded – Algal – Wavy.
Mottled	Fine Upper – Medium Upper	Granules and cherty layers with hard to see grain boundaries.
Alt Bedded	Very Fine – Coarse Lower	Cherty forms vary, from hard to see grain boundaries to granules to oolites.

Grain size can be used as an indicator of changing sea level/depositional environment with coarsening upward trends being equated with shallowing upward and more energy. However, there are other explanations for grain size increases, such as turbidite and overbank deposits. For example, the coarser grained material in the Lower Slaty near the location of LWD 99-1 is interpreted to be channel deposits based on mine pit wall exposures. However, additional texture information and more than one data point need be used to define true sea level fluctuations.

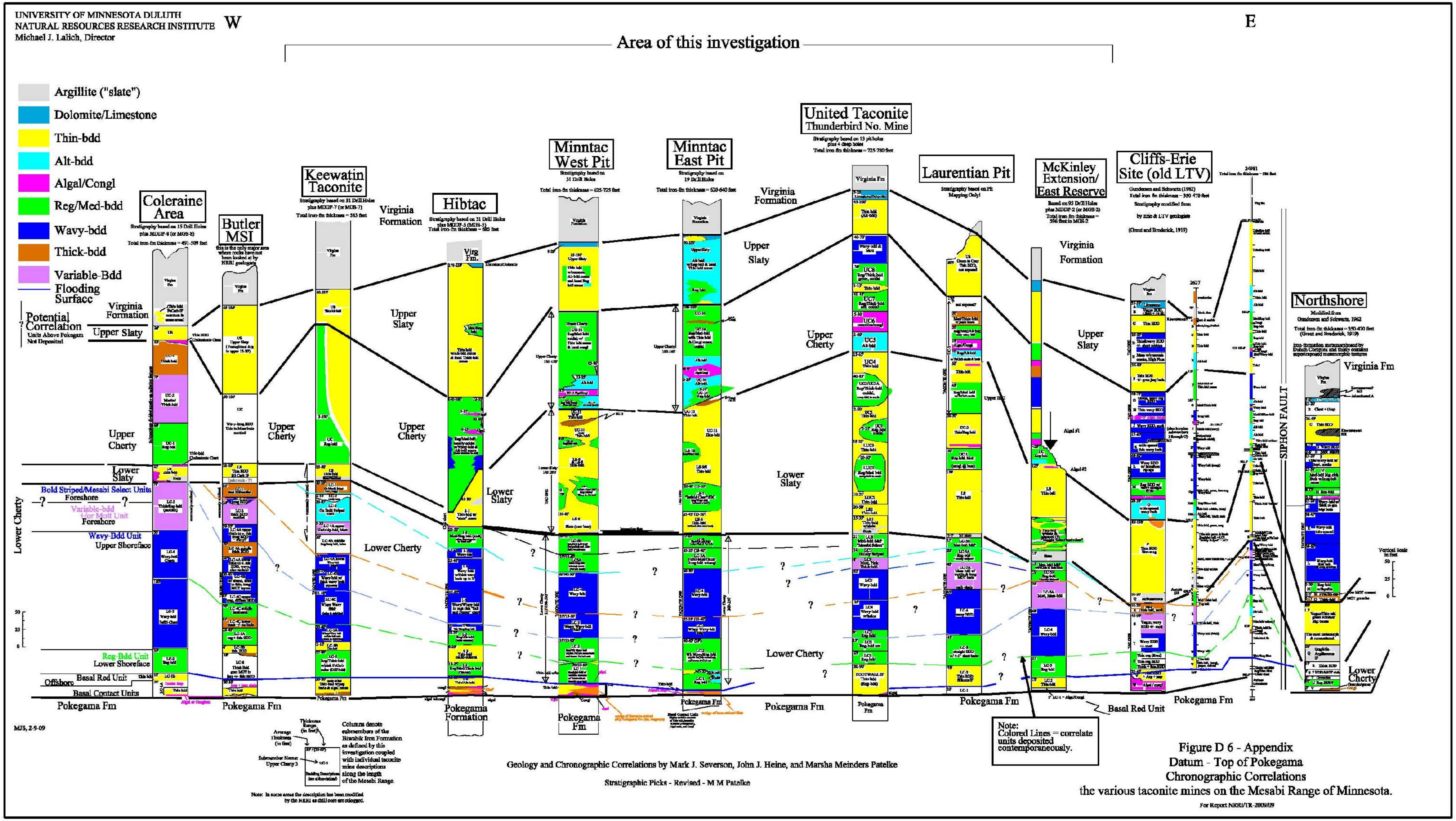


Figure D-6. Generalized cross-section hung on the top of the Pokegama Formation (1 of 4). A stand-alone PDF version of this figure is located on the CD included with this report.

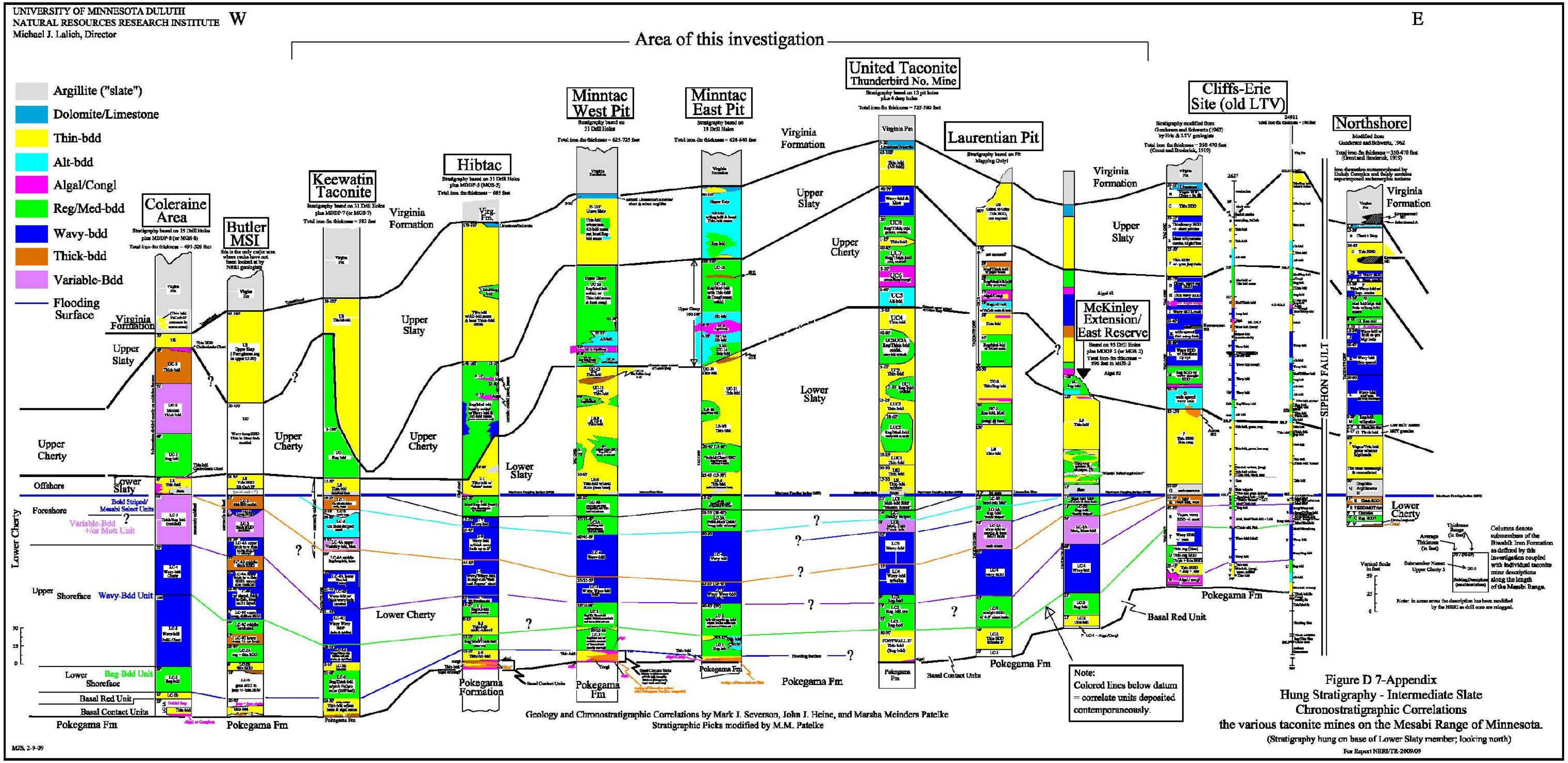


Figure D-7. Generalized cross-section hung on the Base of the Intermediate Slate (2 of 4). A stand-alone PDF version of this figure is located on the CD included with this report.

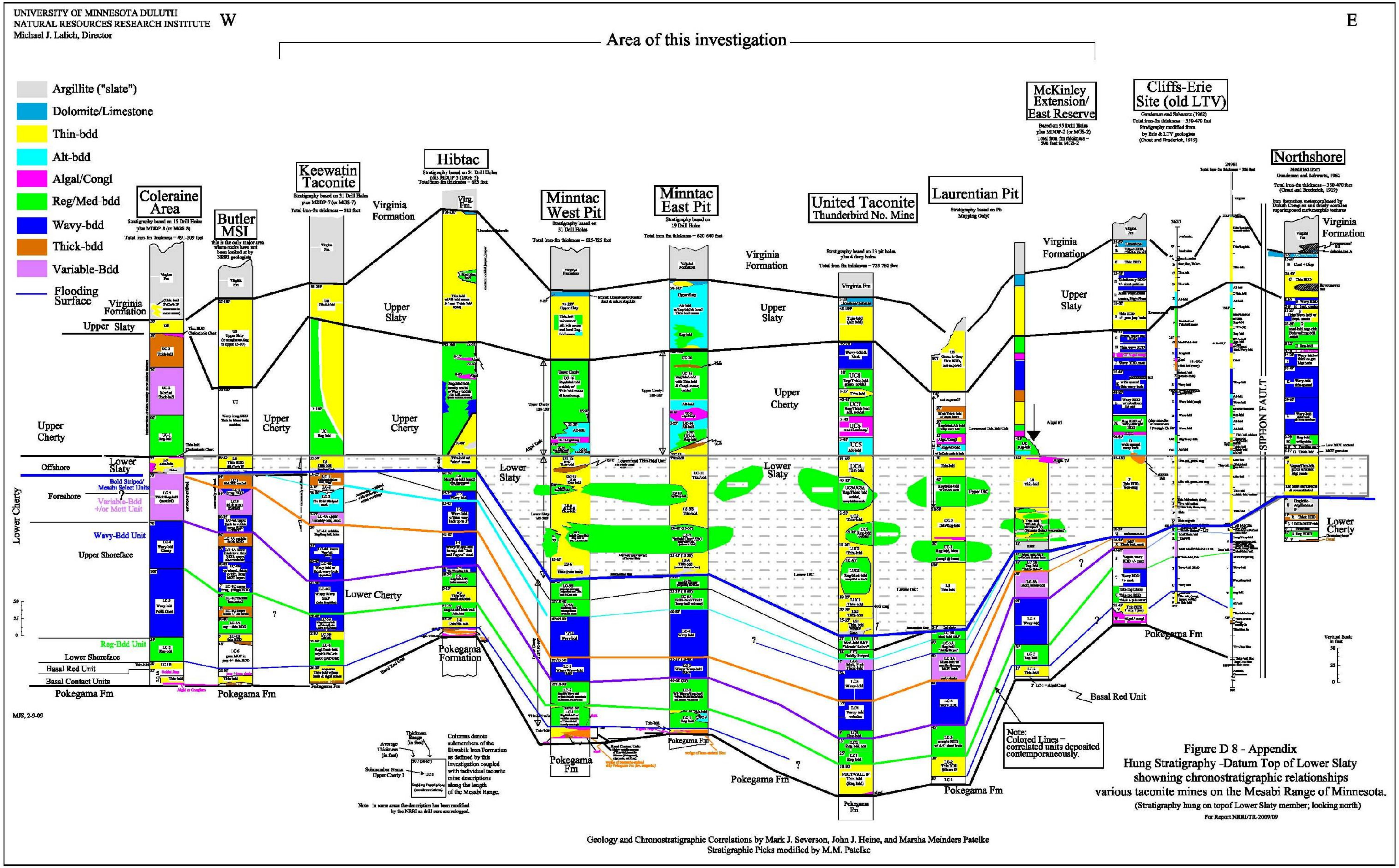


Figure D-8. Generalized cross-section hung on the top of the Lower Slaty (3 of 4). A stand-alone PDF version of this figure is located on the CD included with this report.

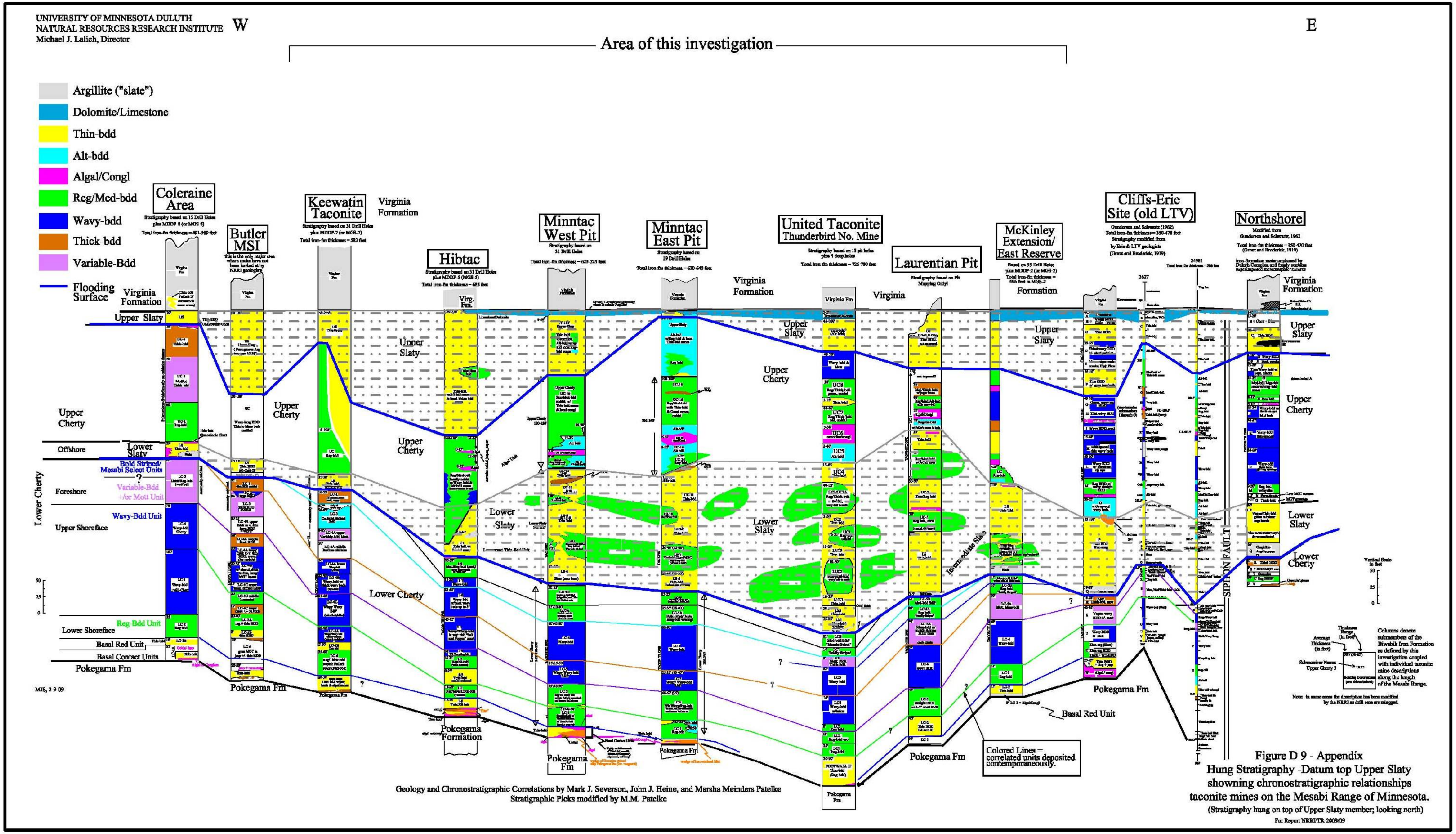


Figure D-9. Generalized cross-section hung on top of Upper Slaty (4 of 4). A stand-alone PDF version of this figure is located on the CD included with this report.

As defined by Van Wagoner et al. (1990), "A marine-flooding surface sharply separates deeper-water rocks, such as shelf mudstones, above, from shallow-water rocks, such as lower-shoreface sandstones, below." Using this definition and grain size data from LWD 99-1, several flooding surfaces are observed and are marked on Figure D-4 with a blue line. Thin-Bedded Units tend to correlate with the fine-grained material, and the Thin-Bedded deposits are located above the flooding surfaces. Thicker packages of the fine-grained sediments are present near the bottom of the Lower Cherty, at the Intermediate Slate, in the Lower Slaty and in the Upper Slaty suggesting transgressions during these periods of deposition. Flooding surfaces can be divided into transgressive flooding surfaces (TS) and maximum flooding surfaces (MFS). Definitions for each of these terms by Posamentier and Allen (1999) are presented below.

> <u>Transgressive Surface</u> – "…is commonly used interchangeably with flooding surface. The distinction between these terms lies in the word transgressive, which refers to the direction of shoreline movement (i.e., landward), . . . surface marking the onset of significant and extended periods of transgression . . ."
>
> <u>Maximum Flooding Surface</u> – "…refers to the surface of deposition at the time the shoreline is at its maximum landward position (i.e., the time of maximum transgression)."

Neither of the surfaces can be identified with much confidence due to the lack of detailed core descriptions, and lack of cores completed near or at the shoreline and backshore environment. It is possible, however, that the Intermediate Slate and its correlative deposits are a transgressive surface.

Coarsening upward trends suggest progradation of the shoreline into the basin. Several intervals of coarsening upward grain size trends capped by a flooding surface (fine grained, thin bedded) are observed in LWD 99-1, and the longer intervals are associated with the Lower and Upper Cherty deposits, third order sea-level cycle sequences (per Vail et al. (1977), in Van Wagoner et al. (1990), 1 to 5 million year duration from one period of sea-level fall to the next sea-level fall). Grain size trends also suggest that several fourth order sequences (100,000s year sea-level fall-rise-fall duration) might be delineated with additional data from additional cores.

A potential depositional history for the Biwabik Iron Formation based on the generalized cross-sections and proposed depositional environments follows. Remember, the cross-sections are constructed along strike – potentially parallel to shore. Few drill holes have been completed perpendicular to shore, up and down depositional dip, through the Pokegama to the Virginia Formation.

Lower Cherty deposition began with the placement of siltstone and basal contact unit sediments in near shore, or possibly behind a barrier bar (Figs. D-3, D-6), environments. These submembers contain finer grained sediment. Algal deposits are present in some locations. The Basal Red Unit, also a fine-grained unit, is interpreted to have been deposited in deeper water, possibly an offshore environment, and represents a Flooding Surface. Water depth deepened during Regular-Bedded deposition, and then began to shallow upward through the Wavy-Bedded Unit. Sea level begins to drop between Hibtac and McKinley Extension with deposition of regular-bedded sediments. Lower Cherty sedimentation appears to be fairly similar across the basin with most areas transitioning upward from Thin- to Regular- to Wavy-Bedded deposits. Appearance of the Intermediate Slate signals a rise in sea level across the Mesabi Iron Range, with all locations depositing thin-bedded sediment (Fig. D-7).

Figure D-8, hung on the top of the Lower Slaty, depicts a basin that is deepening with a thick accumulation of offshore Thin-Bedded deposits between Hibtac and McKinley Extension. As discussed in the main body of this paper, cherty channel deposits are present in this area of the Lower Slaty, and these channel deposits were likely deposited in the area of the Offshore and Continental Slope environments. Thin-Bedded material thins to the east and significantly thins to the west.

Correlations were not completed for submembers of the Upper Cherty. The sequence of submember deposition is more variable across the Mesabi Iron Range. Based on the cross-section (Fig. D-8), it appears that west of United Taconite the basin was deeper. Thick packages of Regular-Bedded Unit deposits are dominant. To the east the basin appears to shallow based on the presences of Algal and Wavy-Bedded Units. There is more variation in the number of submembers that are deposited.

The Upper Slaty Thin-Bedded submember sediment appears to be deposited in two separate basins that are separated by a basin floor high near the Minntac East Pit (Fig. D-9). Thin-Bedded deposits are thicker in the basin to the west, but deposits in both basins are not as thick as the Lower Slaty.

CONCLUSIONS

Deposition of sedimentary rocks can be considered the filling of a hole. Factors influencing deposition can include changes in subsidence, sedimentation, and relative sea level. From Figures D-7 and D-9, it appears that areas of subsidence had shifted from a single basin near the center of the Mesabi Iron Range during Lower Slaty time to two smaller sedimentary basins (possibly second order basins) at the east and west ends of the range. The mechanism for this geometry was not explored and it would require additional work.

As mentioned above, there are four steps, according to Posamentier and Allen (1999), in a sequence stratigraphic study. Brief conclusions for these steps are presented below.

1. Establish paleogeographic setting -
   a. According to Ojakangas et al. (2001), the Biwabik Iron Formation was deposited on a shallow tidally influenced shelf on the northern side of the Animikie Basin, a foreland basin.
2. Interpret depositional systems and facies using all available data (looking for coarsening upward, fining upward).
   a. Depositional environments ranging from foreshore to lower shoreface were applied to the Lower Cherty and Lower Slaty submembers of the Biwabik Iron Formation. Environments have not been applied to deposits in the Upper Cherty Units. Water depths are implied by the location of deposition.
   b. Coarsening and fining upward trends are observed in the stratigraphic column for core LWD 99-1. Major trends coincide with grain size implied by the cherty and slaty names

of the formation members. Frequently alternate bedding observed in core implies fluctuation of water depth/sediment as a transition from, or, to either deeper water (slaty) or shallow water (cherty).

   c. All available data have either not been reviewed or not obtained, i.e., detailed core logging. Additional core logging and mine pit wall observations need to be completed to interpret the depositional environments with more confidence.

3. Subdivide the stratigraphic successions through identification of Maximum Flooding Surfaces and Sequence Boundaries
   a. MFS and SB have not been identified due to the geographic distribution of available core. However, using the data reviewed for this report, there are horizons that are suspect and should be evaluated further with more data.
4. Analyze facies stacking patterns and identify systems tracks
   a. Stacking patterns have been reviewed for core from LWD 99-1. More detailed logging needs to be completed on additional core.
   b. Systems Tracks have not been identified and additional work will be required to identify these with certainty. Ojakangas (2001) states that Wolff (1917) had interpreted the following as individual third order depositional sequences: Lower Cherty; Lower Slaty and Upper Cherty; Upper Slaty members.

APPENDIX E:

LISTING OF SPECIFIC DRILL HOLES LOGGED FOR THIS INVESTIGATION

(on CD in back pocket of this report)

A listing of locations for most of the holes logged for this investigation is presented in *Mesabi-DH-Loc-Header-NRRI-TR-2009-09* (on CD in back pocket of this report). A complete listing of the lithologies logged for the holes presented in this data base will be included in an upcoming NRRI report by Severson et al. (2009). Note that not all the holes logged in Coleraine, MN are listed in this data base. For a complete listing, please see the Oxtac report by Zanko et al. (2003).

APPENDIX F:

CATALOGUE OF THIN SECTIONS COLLECTED FROM LWD 99-1

(on CD in back pocket of this report)