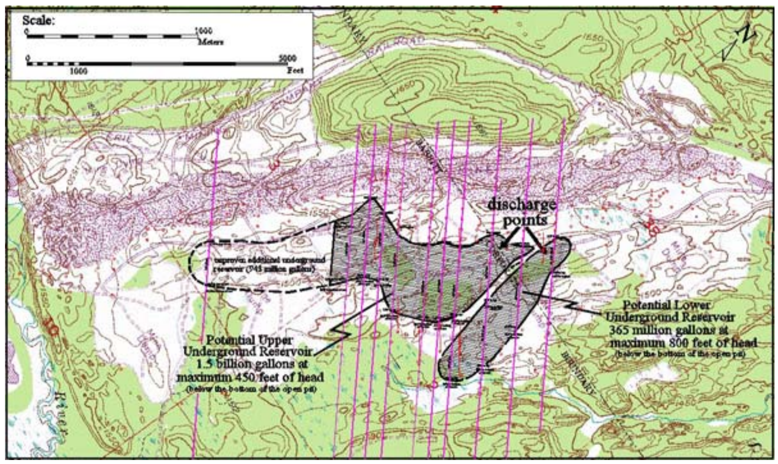
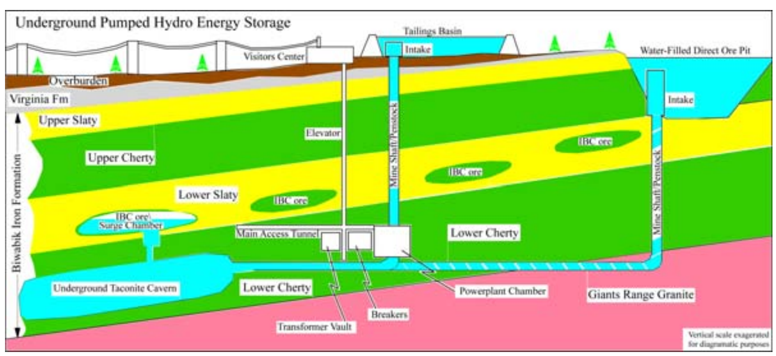
NRRI/RI-2011/02

PRELIMINARY EVALUATION OF ESTABLISHING AN UNDERGROUND TACONITE MINE, TO BE USED LATER AS A LOWER RESERVOIR IN A PUMPED HYDRO ENERGY STORAGE FACILITY, ON THE MESABI IRON RANGE, MINNESOTA

by

Mark J. Severson





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Cover Photo Captions

Top Photo: Location of the Dunka Pit taconite mine (stippled magenta-colored pattern) relative to a potential underground taconite mine (black cross-hatched areas) that could be used as a lower reservoir(s) in a PHES.

Bottom Photo: Cross-sectional view of a potential Underground Pumped Hydro Energy Storage system on the Mesabi Iron Range; whereby, an underground cavern (to be used as a lower reservoir) could be developed by mining taconite iron ore. This cavern could be connected to an upper reservoir (an existing tailings basin, or alternatively, an existing water-filled surface mine pit) via a mineshaft/penstock.

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EXECUTIVE SUMMARY

Ten sites, with some deep drill hole information, were crudely evaluated for their potential to establish a deep-seated underground taconite mine that would be located to the immediate south of the Mesabi Iron Range. Such a mine would produce a cavern that could be used as a lower reservoir in a Pumped Hydro Energy Storage (PHES) facility that would be connected to a surface reservoir (abandoned water-filled mine or tailings basin) via a mine shaft. The lower reservoir would be excavated from ore that would help to reduce the costs of producing the cavern.

Out of the ten evaluated sites, there are four candidates that appear to be the most enticing with regards to establishing an underground mine in areas that would not be mined using conventional open pit methods. These higher priority candidates are:

1. Taconite area – mining of a taconite ore body on the west end of the Mesabi Iron Range could produce a cavern up to up 140 feet high, with a holding capacity of 14 billion gallons (43,200 acre-feet), and a maximum head of 700 feet below the surface;
2. Cliffs-Erie area – mining of metamorphosed high-grade taconite from the eastern Mesabi Iron Range could produce one or two caverns, each up to 90 feet or more high, with a maximum head of 1,235 feet below the surface;
3. Northshore area – mining of metamorphosed high-grade taconite from the eastern Mesabi Iron Range could produce a cavern up to 150 feet high (based on crude data), with holding capacity of 7.8 billion gallons/24,045 acre-feet (based on 150 foot high cavern), and a maximum head of 600 feet below the surface; and
4. Dunka Pit area – mining of metamorphosed high-grade taconite from the eastern Mesabi Iron Range could produce one or two caverns, separated by a fault zone as follows:
   a) an upper underground cavern/reservoir
      - up to 110 feet high,
      - with a holding capacity of 1.5 billion gallons/4,635 acre-feet (with potential to expand to the south),
      - with a maximum head of 450 feet below the water-filled and abandoned Dunka Pit taconite mine;
   b) a lower underground reservoir
      - up to 90 feet high,
      - with a holding capacity of 365 million gallons/1,120 acre-feet,
      - with a maximum head of 800 feet below the Dunka Pit taconite mine.

While these four sites have sufficient drilling to make preliminary estimates on water holding capacities, more drilling would be needed to fully assess their ore potential.

In the event that any of the above four sites are eliminated due to conflicting land uses, any of the other six sites discussed in this report could be chosen for underground mining. These sites are classified as "lower priority" only because detailed drilling to define the full potential of an underground mine is lacking. Out of this lower priority group, the Eveleth area would be the next best candidate. The lowest priority candidates would be the Two River Reservoir area and McKinley area.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF PLATES

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INTRODUCTION

This report is written in conjunction with an IREE-sponsored project whose overall purpose is to determine the potential of creating an energy storage site on the Mesabi Iron Range of northeastern Minnesota that would combine wind-generated energy with a pumped hydro energy storage (PHES) facility. Such a system would utilize wind-generated energy to pump water to an upper reservoir during off-peak hours, and the PHES facility would generate hydro-electric energy via transfer of water from the upper to a lower reservoir during peak hours. On the Mesabi Iron Range there are numerous abandoned mine pits and underground workings (direct shipping ore mines of the pre-1960s), and related stockpiles and tailings basins, that could serve as either upper or lower reservoirs in a PHES facility. Mining of iron-rich magnetic taconite ores on the Mesabi Iron Range continues into the 21st century and some of these mines, and related tailings basins, could also conceivably be used as potential reservoirs in the future. Any of the above types of mine pits, underground workings, stockpiles, and tailings basins, in tangent with topographic highs along the Mesabi Iron Range, may possess the desired head differential needed for an effective PHES facility. Overall, the IREE project presents a unique opportunity for the Mesabi Iron Range to use a PHES facility that is in close proximity to Minnesota Power's DC transmission line from North Dakota wind resources.

The purpose of this report is to conduct a preliminary, and non-economic, review of the area located to the immediate south of the Mesabi Iron Range, where there is some potential to develop future underground mine sites. These sites would be deep-seated taconite ore bodies that could later be used as a lower reservoir that would be linked to an upper reservoir at the surface via a mine shaft/penstock(s). In this scenario, originally envisioned by Dr. Don Fosnacht of the NRRI, the mining of taconite to produce an underground cavern may allow for a very low cost, efficient creation of the lower reservoir. A benefit of this approach would be to reduce or even eliminate future mineral rights considerations since the resource would be removed from areas outside of current open pit mining limits.

The concept of establishing an underground taconite mine on the Mesabi Iron Range is not a new idea and was first examined in the 1960s. Pfleider and Yardley (1963) concluded that the economic feasibility for such an endeavor was attainable at the time and proposed a "lane and pillar" method for extracting the ore. Later work by Pfleider and Scofield (1967) agreed with the original findings, and they modeled an underground mine at 1,700 feet that also used a similar "lane and pillar" technique (but with parallel lanes driven parallel to the dip of the ore body). The mine would consist of several blocks, and the lanes in each block would be 925 feet long by 85 feet high. They assumed that "… the roof, supported by 25 ft. wide pillars and extensive rock bolting, would hold over a 75 ft. lane width" (Pfleider and Scofield, 1967, p. 70). In such a system, about 25% of the ore would be left in the each block of the underground cavern after mining was completed. **[Note** that a more conservative estimate of 50% pillar material left in the mine is used in this report to be able to withstand the repeated dewatering events of a PHES system. This scenario is not based on any known tests, and additional drilling, RQD measurements, and detailed rock mechanic tests of the various rock units would be needed to supply this type of information.**]** As recently as 2000, Larry Zanko and Steven Hauck of the NRRI proposed making an economic feasibility study of establishing an underground mine in the high-grade taconite ores at Dunka Pit on the extreme eastern end of the Mesabi Iron Range. As this proposal could be pertinent to eventually establishing a potential lower reservoir, their original proposal is included in Appendix A of this report.

While the possibility of establishing a deep underground mine has been considered in a preliminary manner, one major hurdle to conducting a detailed economic feasibility study of actually planning such a mine is hampered by the lack of detailed drilling in the Biwabik Iron Formation to the south of the Mesabi Iron Range. It is the intent of this report to present pertinent data regarding the depth to, and thickness of, potential taconite ore zones wherever deep drilling activities have taken place. Most of these drill holes have been logged by NRRI geologists, and the detailed geology of the Biwabik Iron Formation is discussed in Severson et al. (2009). Unfortunately, there is very limited ore grade information for these same holes. While ore grades may not be known, the geologic units that are intersected in these holes, and that are typically mined at the surface, are known and are also discussed by Severson et al. (2009). Wherever these geologic units are intersected in deep drill holes, they are treated as ore zones in this report.

Figure 1 displays ten areas along the length of the Mesabi Iron Range where deep drilling information is available, and the depths to ore zones and their estimated thicknesses are known to some degree. Each of these areas will be discussed in this report, starting at the western end of the Mesabi Iron Range and progressing eastward. Also shown in Figure 1 is a generalized stratigraphy of the Biwabik Iron Formation (BIF) that shows the four informal members (Upper Slaty, Upper Cherty, etc.) and zones where taconite ores occur (black bars). Each of the taconite mines uses a myriad of submember names for the ore and waste zones of the BIF. These are not portrayed in Figure 1 (see Severson et al., 2009 for more details) and for the sake of discussion, the ore zones will simply be referred to as:

1. Upper Cherty ore – typically mined in the eastern half of the Mesabi Iron Range at: United Taconite (Utac), Laurentian Mine, LTV/Cliffs Erie (inactive), Northshore, and Dunka Pit (inactive);
2. Uppermost IBC – channel-like lenses of “interbedded chert” (IBC) near the top of the Lower Slaty that is mined at Utac and Laurentian;
3. Middle IBC – channel-like lense of “interbedded chert” in the middle of the Lower Slaty that is mined at Utac and Laurentian;
4. Lowermost IBC – channel-like lense of “interbedded chert” near the bottom of the Lower Slaty that is mined at Minntac, Utac, and Laurentian; and
5. Lower Cherty Ore – the “bread and butter” of most of the mines on the Mesabi Iron Range consisting of several different ore types in the middle 2/3rds of the Lower Cherty member.

The remainder of this report will be a discussion of the ore types present, and depth to ore, at each of the ten sites shown in Figure 1. These discussions do not take into account the spatial placement of minerals rights and public water sources that will be more fully addressed in an ongoing GIS assessment of the Mesabi Iron Range. Furthermore, any calculations regarding the potential water holding capacities of a specific underground mine are strictly “back of envelope with a blunt crayon” and are based on limited data and assumptions. These estimates are very preliminary in nature and are only provided for future discussion purposes.

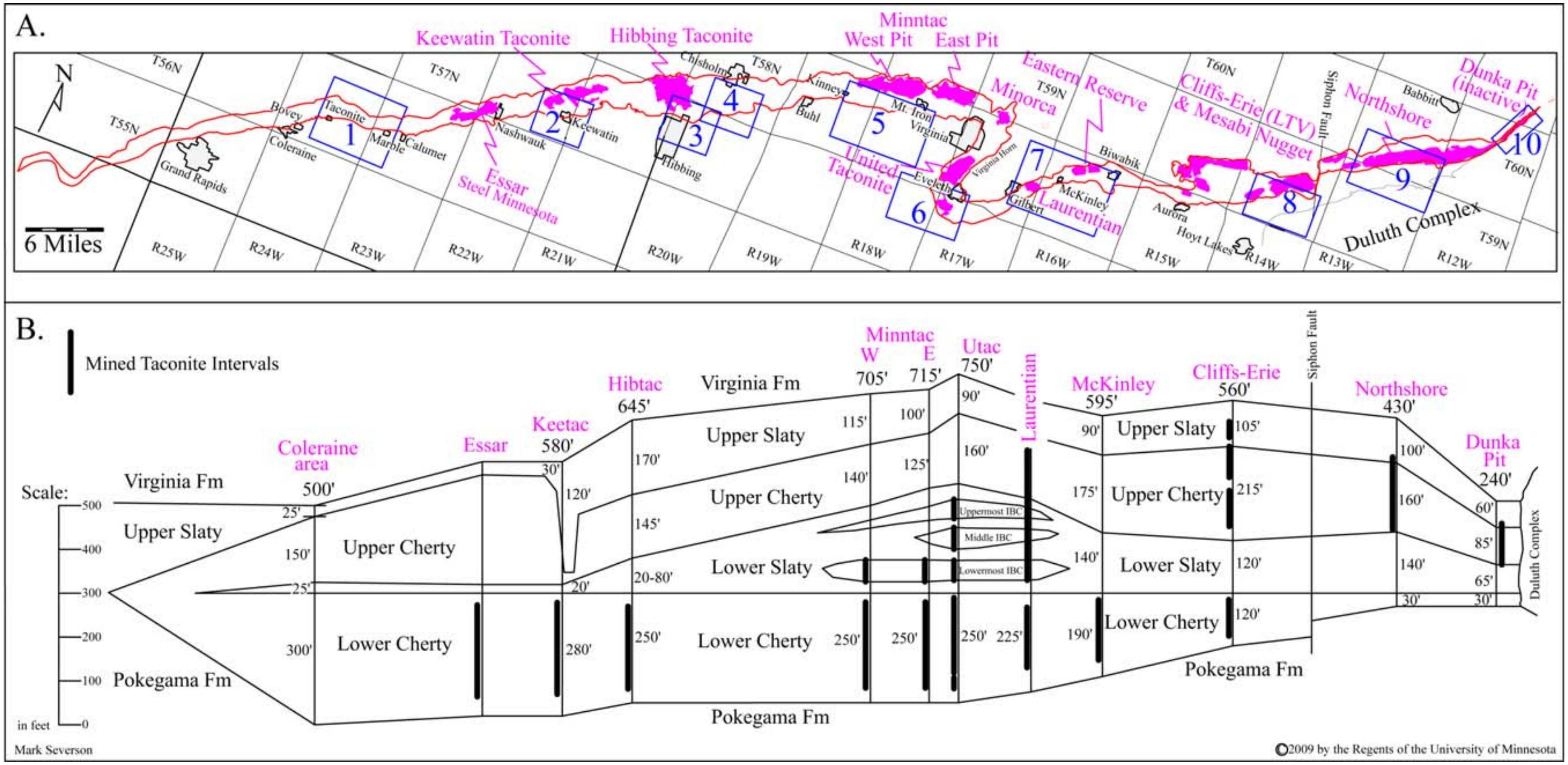

Figure 1. (A) Map of the Mesabi Iron Range with aerial distribution of taconite pits (magenta), cities, trend of the Biwabik Iron Formation (in red), and ten areas discussed in this report where underground mining of taconite could take place as follows: 1. Taconite; 2. Keewatin; 3. Hibbing; 4. Chisholm; 5. Two Rivers reservoir; 6. Eveleth; 7. McKinley; 8. Cliffs-Erie; 9. Northshore; and 10. Dunka Pit. **(B)** Longitudinal section (looking north) of the Biwabik Iron Formation showing average thickness of the iron-formation at each taconite operation, as well as the thickness of the various members at each operation, and mined taconite intervals represented by black bars. Modified from Severson et al. (2009).

Taconite Area

Most of the extreme western end of the Mesabi Iron Range has undergone wholesale oxidation to produce what has been referred to as oxidized taconite, or OXIBIF of Marsden (1977), with resources estimated at 6.8 billion metric tons to 7.9 billion long tons (Marsden, 1977 and Blake, 1983; respectively). While it is technically feasible to produce taconite pellets from this type of material, mining companies determined that it was not economically viable to do so in the 1960s (Zanko et al., 2003). Thus, most of this area will not be mined in the immediate future, and the potential to develop an underground mine in the oxidized taconite is unlikely. Furthermore, the oxidized taconite is too porous and weak to serve as a lower reservoir in a PHES system.

However, drilling by United States Steel Corp. delineated a large pod of unoxidized taconite within the area that is shown in Figure 2. Zanko et al. (2003) conducted a resource estimate for a slightly larger area than is portrayed in Figure 2 and determined that there are about 87 million long tons of unoxidized taconite present at depth in the Lower Cherty member (most of which is outlined in Fig. 2). If an underground mine were established in this area, it would be situated in rock that is much stronger than the surrounding oxidized taconite and could conceivably be used as a lower reservoir in a PHES facility. Drilling information (Fig. 2) indicates that the taconite body varies from 142 feet to 208 feet thick and is situated at 397-539 feet below the surface and extends to some unknown depth to the south. Thus,

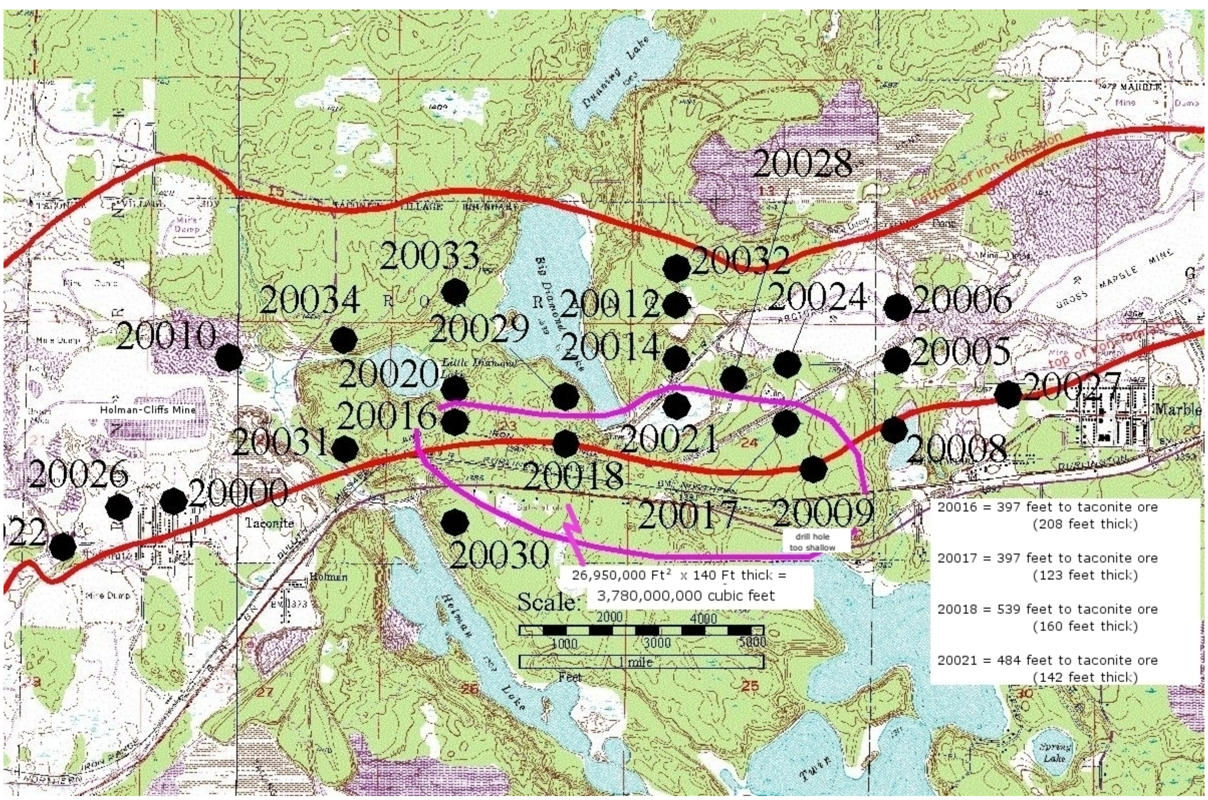

Figure 2. Taconite area with drill holes (black dots), trend of iron-formation (shown in red), and area where drill holes intersected unoxidized taconite ore (magenta ovoid – with estimated cubic foot volume) in the Lower Cherty member. Information pertaining to unoxidized taconite intercepts in four of the drill holes are shown in the inset. The unoxidized taconite body is open in the downdip direction (south), and more drilling is needed to fully define this potential resource.

an underground cavern produced in such a mine could be at least 160 feet high (140 foot average) and dip to the south with a maximum head of at least 699 feet below surface (539 feet to top of ore plus 160 feet to the bottom of the ore in hole 20018). The area defined by the drilling indicates that the underground cavern could conceivably hold about 14 billion gallons of water (43,200 acre-feet): 27 million feet^2 area x 140 feet thick = 3.78 billion feet^3 x 7.481 gal/ft^3 = 28,226,000,000 gal x 50% pillar material left in the mine.

The pros and cons of developing an underground cavern in the Taconite area are listed below.

PROS:

- Potential **underground cavern**/lower reservoir situated in unoxidized taconite resource is roughly estimated at a holding capacity of **14 billion gallons** with a **maximum head of 700 feet** below the surface (as defined by limited drilling); and
- Potential upper reservoirs are abundant in the area and include the Holman-Cliffs/Canisteo series of mines to the west (these mines are currently reaching dangerously high water levels and may soon overflow the pit limits), the Arcturus Mine to the north, the Gross Marble mine to the east, and tailings basins to the north and southwest.

CONS:

- Mineral rights are unknown, but no mining is expected in this area in the near future until an economically viable method of processing the oxidized taconite is developed;
- Public water rights regarding the upper reservoir(s) are unknown;
- More detailed drilling and rock tests are needed to fully characterize the resource and stability of the underground mine; and
- Underground cavern must be confined to the taconite ore body and must not infringe upon the more porous surrounding oxidized taconite (and/or be well-sealed).

Keewatin Area

Significant drilling activities have recently taken place in the vicinity of the Keewatin Taconite (Keetac) mine in preparation for a pit expansion in a southerly direction. Some of these holes have been logged by NRRI geologists, and the drill hole intercepts suggest that the Lower Cherty ore in this area varies from 77 to 168 feet thick depending on the amount of oxidation. The depth to the top of the taconite ore zone is around 400 feet to 520 feet deep in drill holes to the immediate north of Keewatin (Fig. 3). There is also one deep hole in the area (MGS-7 in Fig. 3) wherein the top of the Lower Cherty ore (150 feet thick) is positioned about 1,130 feet below the surface. The distribution of the holes in Figure 3, and the current Keetac open pit limits, suggests it would be possible to establish an underground mine either east of Keewatin or south of Highway 169. The most-preferred site would be to the south of Highway 169, as this area is probably well outside of current expansion limits. This mine could potentially be 160 foot high (average ore thickness of known drill holes) with a maximum head of anywhere from 350 feet to 1,280 feet below the surface (depth to top of ore + ore thickness) depending on location. The pros and cons of making an underground cavern/lower reservoir in the Keewatin area are presented below.

PROS:

- Potential **underground cavern**/lower reservoir in the Keewatin area could be up to **160 feet high** and could be located anywhere to the south of Highway 169, where the **maximum head could be as high as 1,280 feet**;

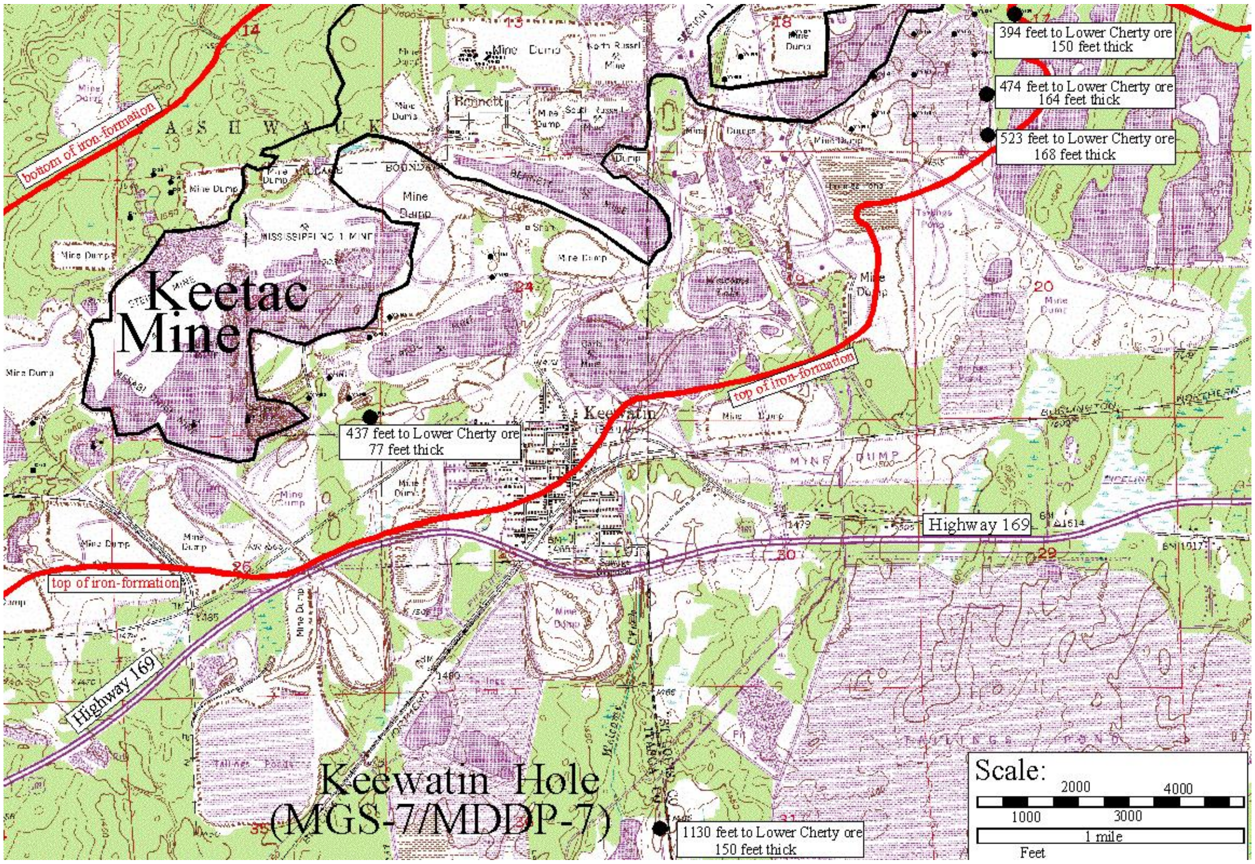

Figure 3. Keewatin area with drill holes (black dots), trend of iron-formation (shown in red), and relevant drill hole intercepts regarding depth to top of Lower Cherty ore and its thickness in select drill holes.

- There are an incredible amount of tailing basins in the area that could serve as potential upper reservoirs; and
- Open pit mining of taconite to the south of Highway 169 is unlikely to take place in the near future.

CONS:

- Amount of water in the various nearby tailings basins that is used by Keetac is unknown;
- Specifics regarding a deep-seated taconite ore zone, to be later used as a lower reservoir, are based on data from only one drill hole to the south of Highway 169; and
- More detailed drilling and rock tests are needed to fully characterize the resource and stability of the underground mine.

Hibbing Area

Recent drilling activities in lieu of a pit expansion have also taken place at the Hibbing Taconite (Hibtac) mine. Many of these holes were logged by NRRI geologists (Severson et al., 2009), and the depth to ore zones, as well as thickness of ore zones, are shown for select holes in Figure 4. The depths to ore include both the Lower Cherty ore, which is currently mined and processed at Hibtac, and Upper Cherty "ore" which is not mined at Hibtac (grade and nature of this potential ore are not publically available). Thus, for the sake of discussion, only the Lower Cherty ore is considered to be viable material to be potentially mined underground. The data presented in Figure 4 indicate that the area to the southeast of Highway 169 presents the best area to

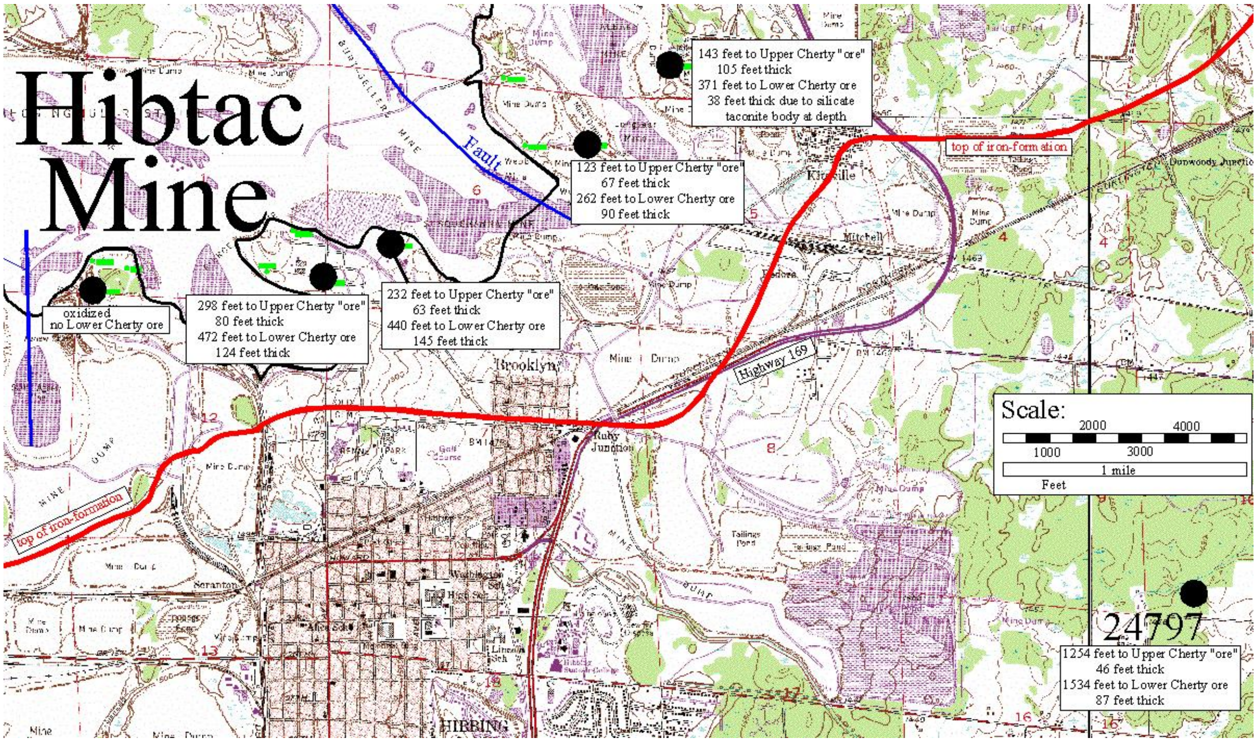

Figure 4. Hibbing area with drill holes (black dots), trend of iron-formation (shown in red), and relevant drill hole intercepts regarding depths to top of Upper Cherty "ore" and Lower Cherty ore, and their respective thicknesses in select drill holes.

establish an underground mine where the Lower Cherty ore is known to be present in drill hole 24797. This area is situated well outside of current open pit mining limits and close to a tailings basin (west of hole 24797) that could serve as an upper reservoir. The pros and cons of developing an underground mine/cavern in the vicinity of hole 24797 are presented below.

PROS:

- Potential **underground cavern**/lower reservoir in the Hibbing area could be up to **90 feet high** in the vicinity of hole 24797 where the **maximum head could be as high as 1,620 feet** below the surface (depth to top of ore + ore thickness);
- An upper underground cavern could also be developed in the Upper Cherty "ore," but based on current mining practices in the area, it is unlikely;
- There is a nearby tailings basin in the area that could serve as a potential upper reservoir; and
- Open pit mining of taconite to the southeast of Highway 169 is unlikely to take place in the near future.

CONS:

- Amount of water in the nearby tailings basin is unknown;
- Specifics regarding a deep-seated taconite ore zone, to be later used as a lower reservoir, are based on data from only one drill hole; and
- More detailed drilling and rock tests are needed to fully characterize the resource and stability of the underground mine.

Chisholm Area

The three deep drill holes in this area (Fig. 5) indicate that the depth to the Lower Cherty ore zone varies from 492 feet to 1002 feet below the surface depending on the location. If an underground mine were to be developed within the triangle outlined by the three drill holes, the cavern resulting from the mine could be anywhere from 106 feet to 151 feet high with a maximum head ranging from 604 feet to 1,153 feet below the surface. A large tailings basin is also present within this triangle, and it could serve as an upper reservoir. Pros and cons for this area are listed below.

PROS:

- Potential **underground cavern**/lower reservoir in the Chisholm area could be up to **150 feet high** (in the vicinity of hole MGS-5) where the **maximum head could be as high as 1,153 feet** (depth to top of ore + ore thickness);
- There is a nearby tailings basin in the area that could serve as a potential upper reservoir;
- There are nearby water-filled direct shipping ore pits that could serve as an upper reservoir; and
- Open pit mining of taconite in the vicinity of hole MGS-5 is unlikely to take place in the near future.

CONS:

- Amount of water in the nearby tailings basin is unknown;
- The water rights of the nearby water-filled direct shipping open pits are unknown; and
- Specifics regarding a deep-seated taconite ore zone, to be later used as a lower reservoir, are based on data from only three drill holes.

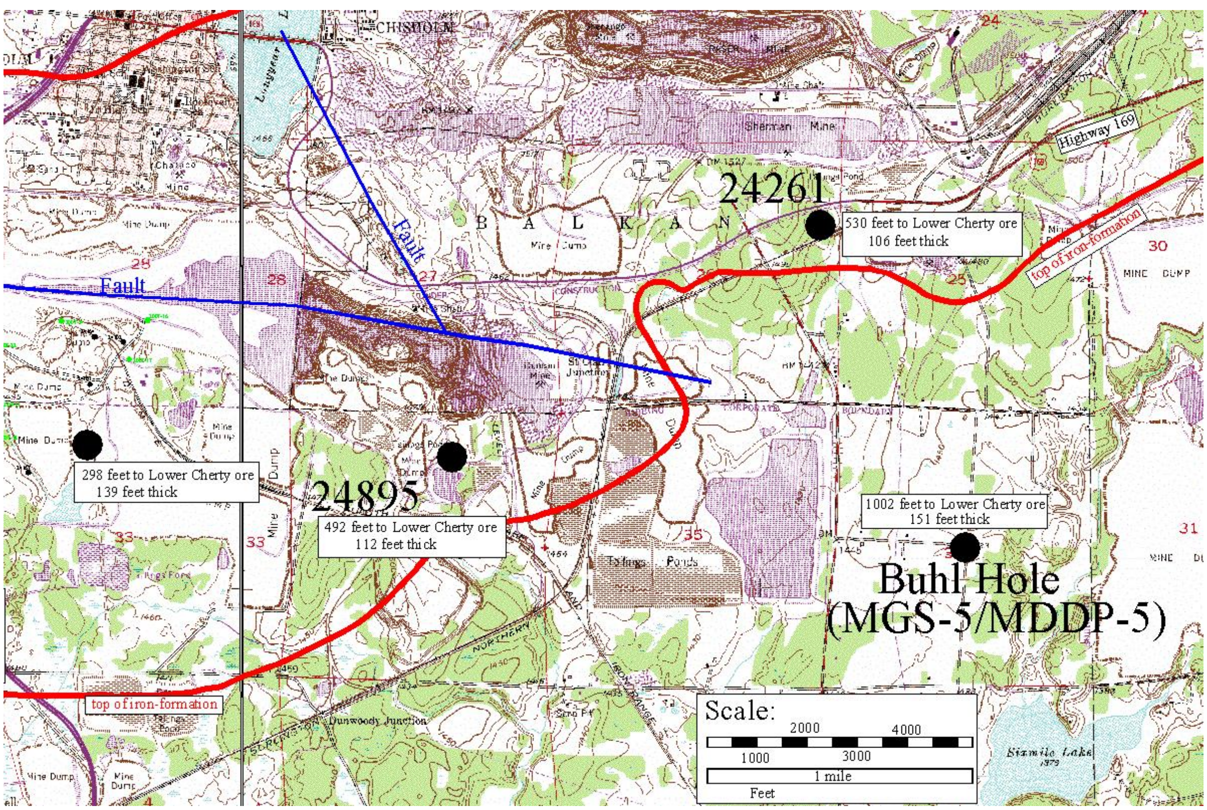

Figure 5. Chisholm area with drill holes (black dots), trend of iron-formation (shown in red), and relevant drill hole intercepts regarding depth to top of Lower Cherty ore and its thickness in select drill holes.

Two River Reservoir Area

The Two River Reservoir area, a water reservoir and recreation area owned by Minntac, is located due south of Minntac's West Pit. In this area, there are several holes to the immediate south of the West Pit, as well as, three deep drill holes that are peripheral to the reservoir (Fig. 6). The geologic units intersected in the drill holes indicate that there are several taconite ore zones that could be mined in a series of stacked underground mines that are:

1. Upper Cherty ore that is marginal material and is only locally mined at Utac (to the immediate east of drill hole VHD 00-1);
2. Uppermost IBC that is present as large lense-like bodies that are mined at Utac and vary from 39 feet to 52 feet thick in the area surrounding the reservoir;
3. Middle IBC that is present as smaller lense-like bodies that are locally mined at Utac and vary from 18 feet to 48 feet thick in the two holes to the east of the reservoir;
4. Lowermost IBC is present as large lense-like bodies that are mined at both Minntac and Utac and vary from 32 feet to 58 feet thick in the three holes to the north and west of the reservoir; and
5. Lower Cherty ore that is the main unit mined at both Minntac and Utac and varies from 127 feet to 188 feet thick in the area peripheral to the reservoir.

Only the Lower Cherty ore is considered to be a viable candidate in which to develop a potential underground mine in the reservoir area for the following two reasons: 1. the Upper Cherty ore is only locally mined at the surface at Utac (actual grades

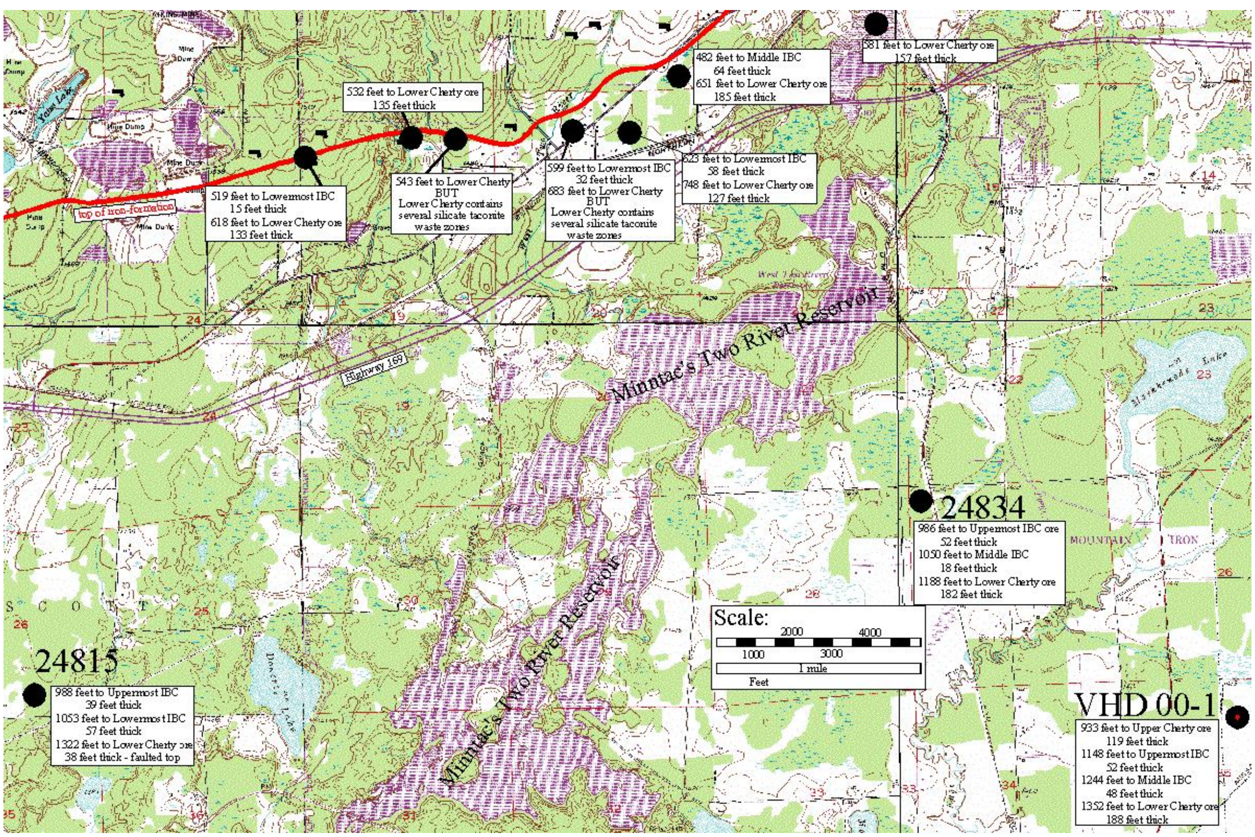

Figure 6. Two River Reservoir area with drill holes (black dots), trend of iron-formation (shown in red), and relevant drill hole intercepts regarding depths to various taconite ore horizons in select drill holes.

unknown), and it does not even constitute ore at Minntac; and 2. the various IBCs, which locally consist of very high grade materials at Utac (specifically the Uppermost IBC), exhibit drastic pinch and swell thickness changes (Severson et al., 2009) that would preclude establishing a consistent underground mining unit. While the Lower Cherty constitutes ore at most mines, it should be pointed out that there is a 1.5 mile-wide, east-west trending zone of silicate taconite that is not ore grade material and is situated about one mile to the south of Minntac's West Pit (Severson et al., 2009; and denoted by two holes in Fig. 6). In order to avoid this poor grade zone, any planned underground mine should be located to the south of Highway 169 in Figure 6. This location would place the top of the underground mined zone at depths of anywhere from 800 feet (estimated from nearby holes) below the surface along Highway 169 to depths of up to 1,352 feet below the surface near drill hole VHD 00-1. Pros and cons for this area are listed below.

PROS:

- Potential **underground cavern**/lower reservoir in the Two River Reservoir area could be up to **188 feet high** (in the vicinity of hole VHD 00-1) where the **maximum head could be as high as 1,540 feet** (depth to top of ore + ore thickness);
- There is a large recreational reservoir in the area that could serve as a potential upper reservoir; and
- Open pit mining of taconite in the vicinity of Two River Reservoir is unlikely to take ever place in the near and distant future.

CONS:

- Two River Reservoir supplies some of the water needs for Minntac;
- Two River Reservoir is a recreation site;
- Specifics regarding a deep-seated taconite ore zone, to be later used as a lower reservoir, are based on data from only three drill holes; and
- The presence of waste rocks (silicate taconite) in the Lower Cherty ore zone is disconcerting, and much infill drilling would have to take place in order to characterize the ore materials in a deep-seated underground taconite mine.

For the above reasons, consideration of the Two River Reservoir area for an underground mine should be the **lowest priority** of all the sites described in this report.

<u>Eveleth Area</u>

There are only two deep drill holes in the area to the south of Eveleth and the currently inactive Thunderbird South Mine owned by Utac, as shown in Figure 7. Both of these holes suggest that several stacked underground mines could be established in the:

1. Upper Cherty ore (material that was primarily mined at the Thunderbird South Mine (Phil Larson – pers. Comm., fall, 2008)) = 673 feet to 748 feet below the surface and 50-118 feet thick in the two holes;
2. Uppermost IBC ore = 852 feet below the surface, 54 feet thick, and present in only one of the holes;
3. Middle IBC ore = 954 feet below the surface, 50 feet thick, and present in only one of the holes; and
4. Lower Cherty ore = 1,064 feet to 1,136 feet below the surface and 195-243 feet thick in the two holes.

It is most likely that the Lower Cherty ore would be the best candidate for a potential underground mine in this area due to its better ore grade and thickness consistency. The most likely site would be in the vicinity of hole LWD 99-2 which is in close proximity to Utac tailings ponds that could serve as the upper reservoir. The pros and cons of developing an underground mine, which could serve as the lower reservoir, are presented below.

PROS:

- Potential **underground cavern**/lower reservoir in the Eveleth area could be up to **245 feet high** (in the vicinity of hole LWD 99-2) where the **maximum head could be as high as 1,381 feet** (depth to top of ore + ore thickness);
- There is a nearby tailings basin in the area that could serve as a potential upper reservoir; and
- Open pit mining of taconite in the vicinity of the two LWD-holes is unlikely to take place in the near future.

CONS:

- Amount of water in the nearby tailings basin is unknown; and
- Specifics regarding a deep-seated taconite ore zone, to be later used as a lower reservoir, are based on data from only two drill holes, albeit they are close-spaced.

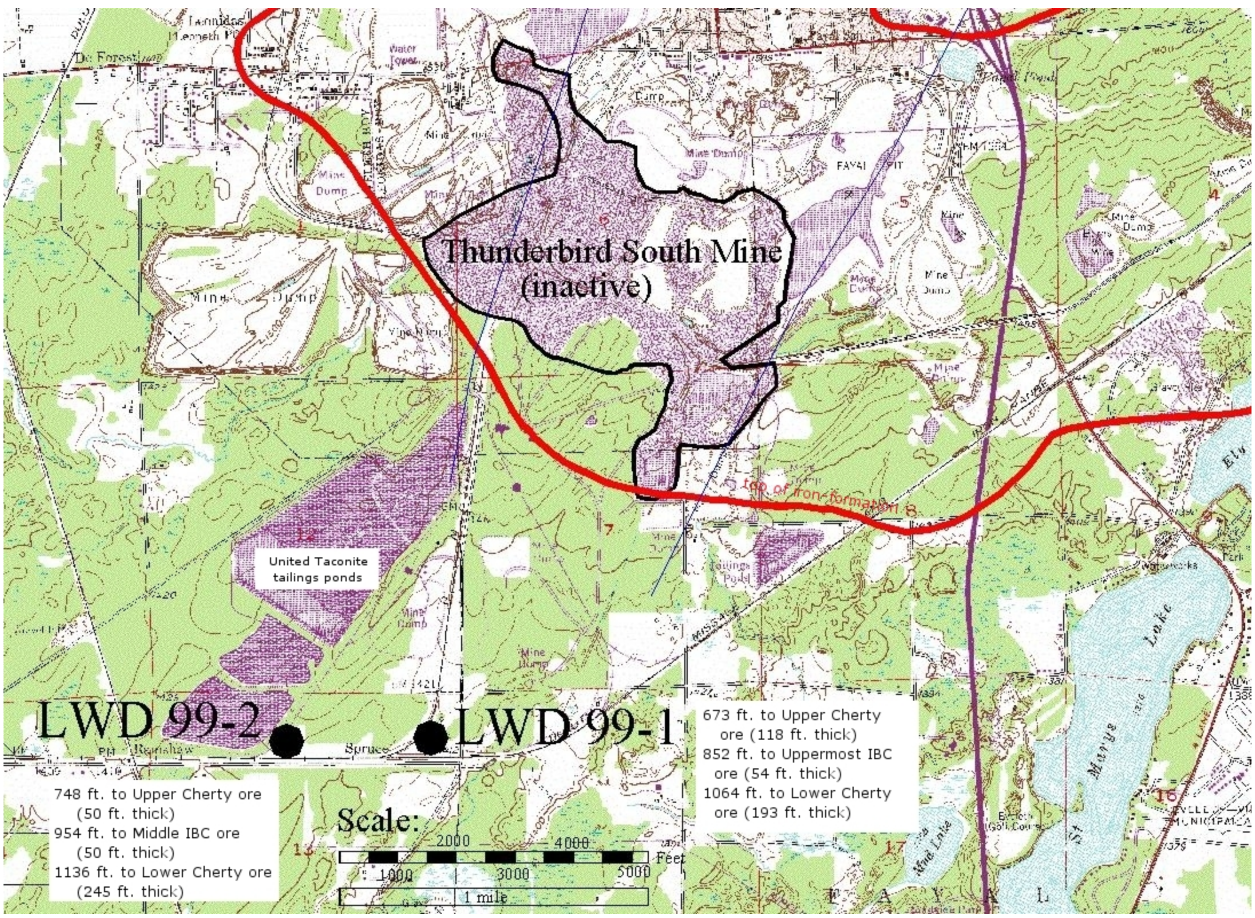

Figure 7. Eveleth area with drill holes (black dots), trend of iron-formation (shown in red), and relevant drill hole intercepts regarding depths to the various taconite ore horizons in two drill holes.

McKinley Area

There are only two holes regarding the nature and thickness of potential underground taconite ore horizons in the McKinley area as shown in Figure 8. These data suggest that an underground mine located to the south of the iron-formation subcrop (south of the “top of iron-formation” line in Fig. 8) could be positioned anywhere from 411 feet to 2,037 feet below the surface depending on the site chosen for such a mine. The mined material would most likely be the Lower Cherty ore, but materials could also be mined from the Upper Cherty and Uppermost IBC (both were intersected at depth in drill hole MGS-2). The great depth to the top of the Lower Cherty ore in the vicinity of hole MGS-2 (2,037 feet) would preclude developing an underground mine at this site and any underground mine would most likely be developed in the area between Highway 135 and the iron-formation subcrop. Such a site could use any of several nearby abandoned mine pits (McKinley, Welton, Mary Ellen, or Canton mines) to be used as an upper reservoir.

Projections of geologic units from the recently opened Eastern Reserve taconite mine indicates that an underground mine located near the red dot in Figure 8 would be around 1,000 feet below the surface. The average ore thickness in the nearby Eastern Reserve, for the Lower Cherty ore, is about 155 feet thick (Severson et al., 2009). Thus, an underground mine at the site of the red dot could produce a cavern, or series of caverns, up to 155 feet high with a maximum head of 1,155 below the surface.

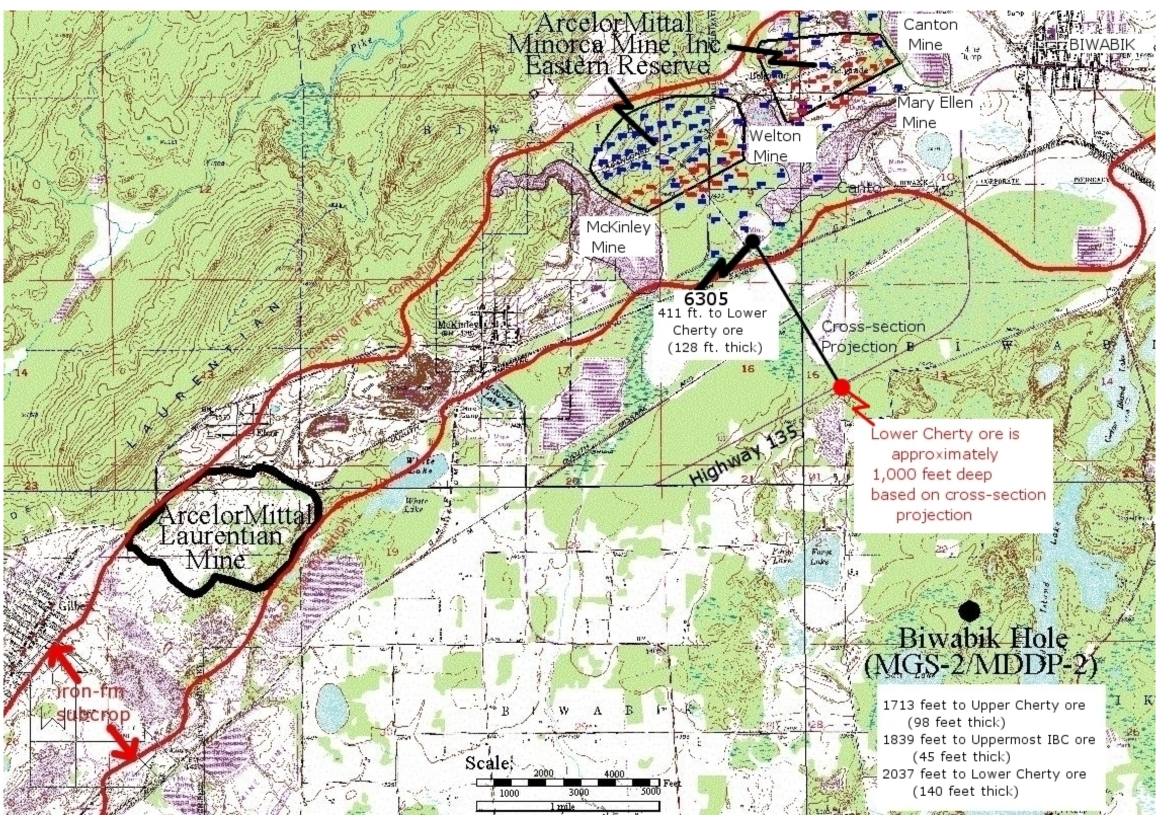

Figure 8. McKinley area with drill holes (black dots), trend of iron-formation (shown by red lines), and relevant drill hole intersections regarding depths to the various taconite ore horizons in two drill holes. The projected depth to Lower Cherty ore at the red dot is based the southern projection of a cross-section presented in Plate 25 of Severson et al. (2009). Three active open pit taconite mines operated by ArcelorMittal are shown, as well as abandoned direct shipping ore pits.

The pros and cons of developing an underground mine, which could serve as the lower reservoir, are presented below.

PROS:

- Potential **underground cavern**/lower reservoir in the McKinley area could be up to **155 feet high** (based on projections from the north) where the **maximum head could be as high as 1,155 feet** (depth to top of ore + ore thickness);
- There are several nearby abandoned mines, and tailings basins, in the area that could serve as a potential upper reservoir; and
- Open pit mining of taconite in the vicinity of the red dot in Figure 8 is unlikely to take place in the near future.

CONS:

- The potential underground site has not been drilled, and any statements regarding depth to ore and thickness of ore zones are based purely on projections of geologic units;
- The site would be in close proximity to a recently opened taconite mine, the Eastern Reserve (also called Pit 2), and dewatering activities at the mine could affect both lower and upper reservoirs in a PHES facility (it has been speculated by the public that these dewatering activities caused a drop in water level at the "Lake Ore Be Gone" recreational site near Gilbert, MN); and
- The above statements would cause this site to be classed as a **low priority** site.

Cliffs-Erie Area

A portion of the Cliffs-Erie area, as presented in Figure 9, is in close proximity to the intrusive Duluth Complex that metamorphosed the iron-formation. A similar situation is also present further east where metamorphism produced high-grade, and coarse-grained, taconite ore that is, and was, mined at the Northshore and Dunka Pit operations, respectively. There are several drill holes in the vicinity that crudely indicate depths of 155-890 feet to the top of the Upper Cherty ore and 450-1,140 feet to the top of the Lower Cherty ore depending on location (see Fig. 9). The range of thicknesses of mined taconite in this area is reportedly 80-150 feet thick for the Upper Cherty ore and 45-95 feet for the Lower Cherty ore (Severson et al., 2009). The NRRI has recently received permission, from RGGS Lands and Minerals, to conduct a geological study of the core for many of the drill holes shown in Figure 9. Thus, a much better idea relative to true depths to the ore zones, and their relative thicknesses in each hole, will be forthcoming once all data and core are acquired in the near future.

The data available at present suggest that two potential ore zones could be mined underground in the Cliffs-Erie area (Fig. 9). The cavern created by mining the Upper Cherty ore could be up to 150 feet high with a maximum head of roughly 1,040 feet below the surface depending on the specific area that is chosen, e.g., in the vicinity of hole 17700. Similarly, a cavern created by mining the Lower Cherty ore could be up to 95 feet high with a maximum head of roughly 1,235 feet below the surface (again in the vicinity of hole 17700). The pros and cons of developing an underground mine, which could serve as the lower reservoir, are presented below.

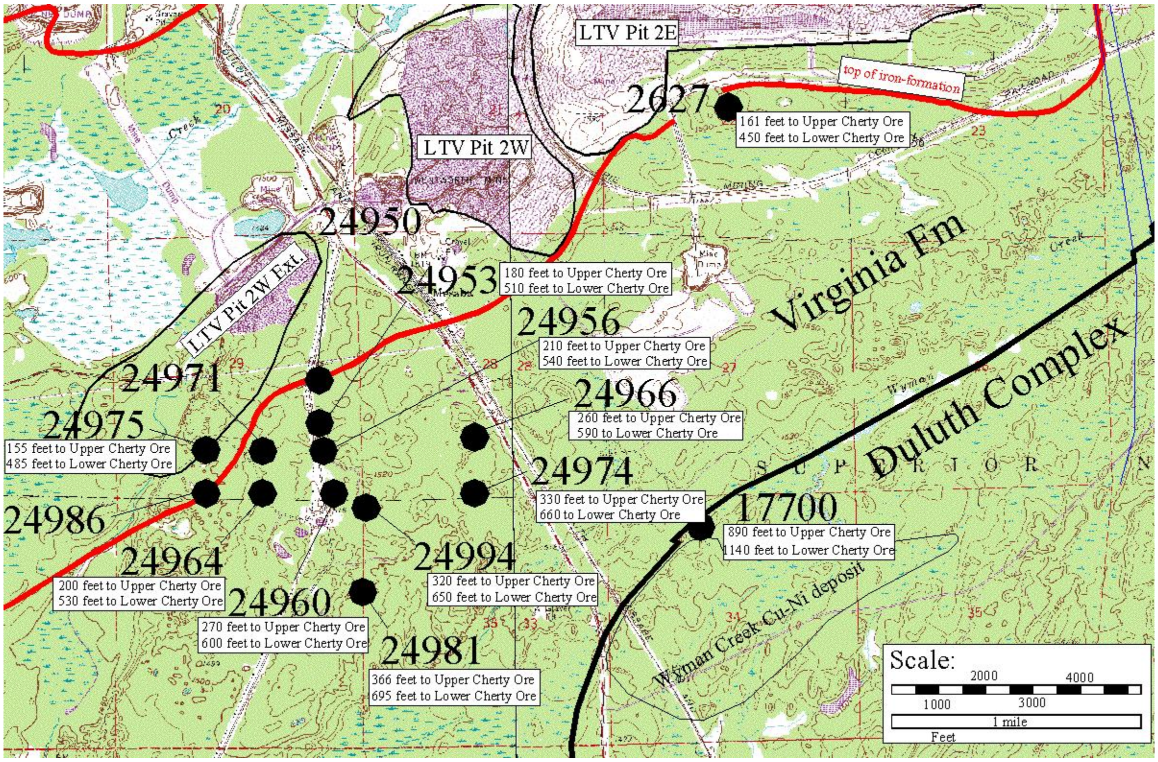

Figure 9. A portion of the Cliffs-Erie area with drill holes (black dots), trend of iron-formation (red lines), and relevant drill hole intersections regarding depths to the various taconite ore horizons. The depths to the Upper Cherty ore and Lower Cherty ore are crudely approximated from archived geologic logs of the drill holes that do not include any ore grade data. The thickness of ore grade material present in each drill hole is also unknown.

PROS:

- There are two potential underground mines that could be developed, and later used as a lower reservoir in a PHES, in either the Upper Cherty or Lower Cherty ores in the Cliffs-Erie area as follows:
  - **Underground cavern**, or series of caverns, in the **Upper Cherty ore** could be up to **150 feet high with a maximum head as high as 1,040 feet** below the surface; and
  - **Underground cavern**, or series of caverns, in the **Lower Cherty ore** could be up to **95 feet high with a maximum head as high as 1,235 feet** below the surface; and
- There are several nearby abandoned taconite mines (LTV Pits 2W and 2E) in the area that could serve as a potential upper reservoir.

CONS:

- The depths listed to potential underground ore zones, and thickness of ore zones, are crude and will be refined as data are acquired in the immediate future;
- Reopening of LTV Pit 2W Extension (Fig. 9) is currently being investigated by Mesabi Nugget, but they are encountering permitting difficulties; and
- Cu-Ni mining could take place within one mile to the southeast at the Wyman Creek deposit (which is one of the poorer-grade disseminated sulfide deposits in the Duluth Complex) and in the event that such a mine is established any dewatering activities at Wyman Creek could affect both the upper and lower reservoirs of a potential PHES facility in this area.

Northshore Mine Area

A portion of the Northshore mine area, as presented in Figure 10, is in close proximity to the intrusive Duluth Complex that metamorphosed the iron-formation and produced a high-grade, and coarse-grained, taconite ore. There are several drill holes in the vicinity that crudely indicate depths of 80 feet to 1,240 feet to the top of the Upper Cherty ore (the Lower Cherty is thin and not mined at Northshore) depending on location (see Fig. 9). The range of thicknesses of mined Upper Cherty ore at Northshore is reportedly 135-150 feet thick (Severson, et al., 2009). The NRRI has recently received permission, from RGGS Lands and Minerals, to conduct a geological study of the core for many of the drill holes shown in Figure 10. Thus, a much better idea relative to true depths to the ore zones, and their relative thicknesses in each hole, will be forthcoming once all data and core are acquired in the near future.

The available data suggest that the best place to establish and underground mine would be in the area between drill holes 25402 and 25403 (on the south) and 25416 and 24517 (on the north). This location would position the mine close to: 1. Northshore's mothballed Crusher #2; 2. close to the inactive and water-filled portion of the Peter Mitchell taconite mine to be used as an upper reservoir; and 3. place it to the north away from the planned stockpile for PolyMet's NorthMet Cu-Ni deposit. If such a site were chosen, the underground mine could produce a cavern, or series of caverns, 150 feet high that dips to the south with a maximum head of 650 feet below the surface. The pros and cons of developing an underground mine, which could serve as the lower reservoir, are presented below.

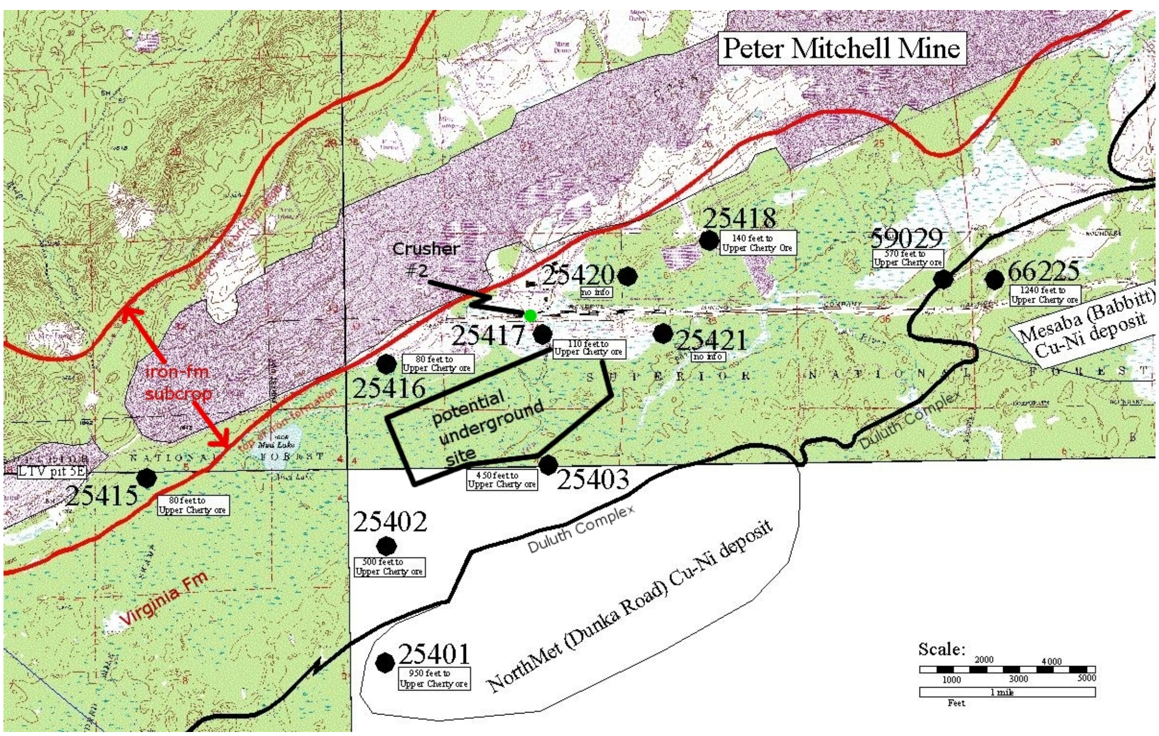

Figure 10. A portion of the Northshore/Peter Mitchell mine area, which is currently inactive and water-filled, with drill holes (black dots), trend of iron-formation (red lines), and relevant drill hole intersections regarding depths to the Upper Cherty ore. These depths are crudely approximated from archived geologic logs of the drill holes that do not include any ore grade data. The thickness of ore grade material present in each drill hole is also unknown.

PROS:

- If an **underground mine** were developed at the site shown in Figure 10, the cavern could be **up to 150 feet high**, with a **maximum head of 600 feet** below the surface (depth to top of ore + ore thickness at drill hole 25403). Crude calculations indicate that such a mine would be around 14 million ft^2 x 150 ft high = 2.1 billion ft^3 x 7.481 ft^3/gal = 1,571,010,000,000,000 gal x 50% pillar material left for support = around **7.855 billion gallons (24,045 acre-feet) of holding capacity** (this is based on the assumption that the ore zone is up to 150 feet thick, and this thickness would need to be confirmed for the drill holes shown in Fig. 10);
- Crusher #2 could be reactivated and used for the underground mining activities;
- The abandoned portion of the Peter Mitchell mine to the immediate north could serve as an upper reservoir; and
- Nearby Mud Lake, which is inaccessible to the public and surrounded by swamps, could serve as an upper reservoir (unlikely as this would destroy wetlands and require significant permitting time and effort).

CONS:

- The depths listed to potential underground ore zones, and thickness of ore zones, are crude and will be refined as data are acquired in the immediate future;
- Future plans regarding reopening the adjacent portion of the Peter Mitchell mine by Northshore are unknown and another upper reservoir site could be required;
- The site is situated in close proximity to two Cu-Ni deposits (NorthMet and Babbitt deposits), and their potential dewatering and blasting effects on the lower reservoir should be taken into account; and
- The overlying Virginia Formation contains sulfide-bearing zones and the underground mine/reservoir would have to be well sealed to prevent contamination from surrounding surface and groundwater that would be in contact with the sulfide-bearing zones.

Dunka Pit Mine Area

While exploring for Cu-Ni deposits in the Dunka River area, numerous drill holes encountered highly metamorphosed iron-formation beneath the intrusive Duluth Complex. Drilling revealed that metamorphism enhanced both the physical and grade properties of the taconite to produce some of the highest grade material on the Mesabi Iron Range. The Erie Mining company followed up on this discovery and established the Dunka Pit mine (Fig. 11) that was operated until 1995. Part of the reason the mine closed is that stripping operations eventually exposed sulfide-bearing rocks of the overlying Virginia Formation and Duluth Complex and treatment of run-off from the resultant stockpiles and exposures became too expensive to treat for environmental reasons. However, a significant tonnage of ore remains at depth. Crude estimates indicate that 50 to 100 million tons of ore remain (Graber, pers. Com., 2000). A more detailed study to determine the economic feasibility of establishing an underground mine was proposed for Dunka Pit in 2000 (see Appendix A) but has yet to receive funding.

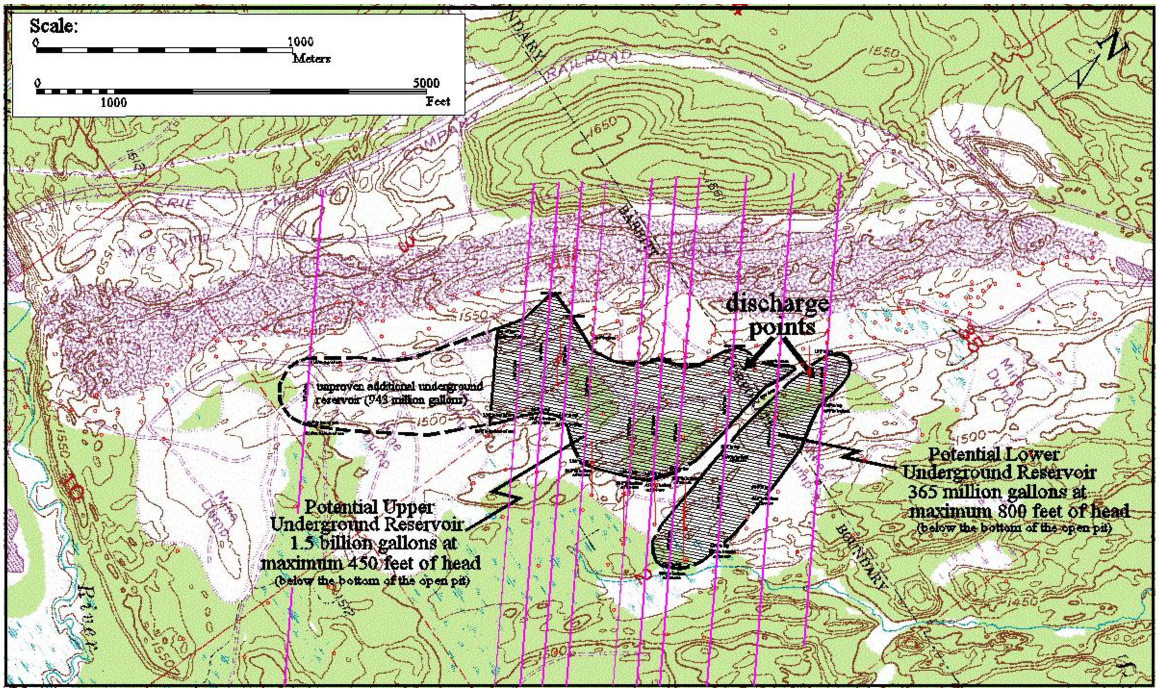

Figure 11. Location of the Dunka Pit taconite mine (stippled magenta-colored pattern) relative to a potential underground taconite mine (black cross-hatched areas) that could be used as a lower reservoir(s) in a PHES. Note that two underground mines/reservoirs are shown on the map, an upper underground reservoir and a lower underground reservoir, that are separated by a major fault – the underground reservoir on the right corresponds to the down-dropped side of the fault. See Plates I through XIII for more details regarding cross-sections (magenta-colored lines) showing drill holes, down-dip ore projections, faults, and blocked off underground ore grade zones.

More recently, 29 cross-sections across the mine were prepared by Severson and Hauck (2008). The distribution of the cross-sections in relationship to the open pit mine are portrayed in Figure 11 and Plate I. Most of these cross-sections are included in this report (Plates II through XIII), and they can be used to show the continuation of the taconite ore at depth beneath the Duluth Complex. The cross-sections have been modified for this report in that they show projected ore grade blocks at depth based on known grades in nearby shallow drill holes. The cross-sections were further enhanced to show possible underground mine pit limits that could be collectively used to crudely estimate the volume of water that an underground cavern could hold when used for the lower reservoir of a PHES facility. However, there were certain assumptions that were made in preparing these cross-sections and estimates:

1. continuous intervals of >25% magnetic iron in the drill holes are assumed to be ore for this exercise (material with >20% magnetic iron was mined from the open pit);
2. these continuous ore grade intervals, which range from 80 feet to 110 feet thick, are shown in each cross-section for:
   a) Erie drill holes, with known grades, that are positioned close to but outside of, and down-dip of, the open pit limits;
   b) Drill holes in the Duluth Complex that intersected taconite ore at depth (no grade tests were conducted on most of these holes, and the assumed

ore thickness for these holes is based on up-dip Erie drill holes in the same cross-section);

c) Areas where no drilling is available, but relationships in adjacent cross-sections indicate that taconite ore is most likely present (in these cases, the assumed ore thickness for the projected area is based on up-dip Erie holes in the same cross-section); and

d) Based on the above ore thickness relationships, each cross-section shows blocks where ore grade material is anticipated and an underground mine could be established;

3. the lowest part of Dunka Pit is assumed to be at an elevation of 1260 feet above sea level (based on a 1990s-vintage pit map) – the potential PHES facility discharge points that are labeled on Figure 11 and Plate I are positioned at this lowest point;
4. the above mentioned 1260 foot elevation is displayed on each cross-section – for the sake of discussion, it is assumed that <u>all</u> of the water in the open pit will be used to fill the underground excavation up to this elevation (this is a conservative estimate as the open pit probably contains much more water than the holding capacity of the underground excavation); and
5. the maximum head was determined for each cross-section by measuring the distance from the 1260 foot elevation to the deepest portion of the ore body (the distance to both the top and bottom of the ore body are listed for each cross-section on Plate I) .

Using the assumptions listed above, the surface area (square feet) of the underground excavation below the 1260 foot elevation was determined for each cross-section. This number was then multiplied by the area of influence for each cross-section to obtain a cubic foot volume. The cubic foot volume was converted to gallons (cubic foot = 7.481 gallons) to obtain the preliminary holding capacity. This capacity was then multiplied by 50% pillar material, left in the underground cavern for support, to obtain a crude maximum holding capacity. The results from this exercise are shown in Tables 1 and 2. The pros and cons of developing an underground mine that could serve as the lower reservoir are presented after the tables.

Table 1. Water holding capacity calculations for the upper underground reservoir at Dunka Pit. Note that the 7200 cross-section is not included in the estimate as this cross-section is well removed from the area where cross-sections are more plentiful.

Cross-Section/Plate	Area of upper underground cavern in cross-section (Ft^2)	Width of cross-section influence (Ft)	Volume of cavern in each cross-section (area x width = Ft^3)	Volume of cavern in each cross-section (Ft^3 x 7.481 = gallons)	Water-holding capacity in each cross-section with 50% pillars left for support (gal)
7200/Plate 2 (not included in estimate total)	88,588	2,850 (based on one isolated cross-section!)	252 million	1.89 billion	943 million gallons (in possible extension zone to the south)
9900/Plate 3	116,435	300	34.9 million	261 million	130 million
10200/Plate 4	88,603	300	26.6 million	199 million	100 million
10500/Plate 5	96,311	300	28.9 million	216 million	108 million
10800/Plate 6	159,913	450	71.9 million	538 million	269 million
11400/Plate 7	120,839	450	54.5 million	407 million	204 million
11700/Plate 8	185,790	300	55.7 million	417 million	208 million
12000/Plate 9	108,197	450	48.7 million	364 million	182 million
12600/Plate 10	114,235	600	68.5 million	513 million	256 million
13200/Plate 11	38,064	400	15.2 million	114 million	57 million
13800/Plate 12	Not present	na	na	na	na
			Total = 404.9 million ft^3 ÷ 43,560 ft^3/acre x 0.50 pillars left = 4,650 acre-feet		**Total = 1.51 billion gallons**

Table 2. Water holding capacity calculations for the lower underground reservoir at Dunka Pit. The true thickness of the taconite ore in cross-sections 12000 and 12600 is purely based on projections and would need to be refined by additional drilling.

Cross-Section/Plate	Area of lower underground cavern in cross-section (Ft^2)	Width of cross-section influence (Ft)	Volume of cavern in each cross-section (area x width = Ft^3)	Volume of cavern in each cross-section (Ft^3 x 7.481 = gallons)	Water-holding capacity in each cross-section with 50% pillars left for support (gal)
12000/Plate 9	46,650	450	21.0 million	157 million	78 million
12600/Plate 10	52,350	600	31.4 million	235 million	117 million
13200/Plate 11	67,266	400	26.9 million	201 million	100 million
13800/Plate 12	37,400	500	18.7 million	140 million	70 million
			Total = 98 million ft^3 ÷ 43,560 ft^3/acre x 0.50 pillars left = 1,125 acre-feet		**Total = 365 million gallons**

PROS:

- If an **underground mine** were developed down-dip of the Dunka Pit mine, two caverns could be produced:
  - An upper reservoir, up to 110 feet high, with a **maximum head of 450 feet** below the deepest portion of the open pit mine and a **holding capacity of 1.51 billion gallons** (the mine/cavern could also be extended in a southerly direction and include an additional 943 million gallons – based on very limited data, e.g., cross-section 7200),
  - A lower reservoir, up to 90 feet high, with a **maximum head of 800** feet below the deepest portion of the open pit mine and a **holding capacity of 365 million gallons**;
- Mining-related infrastructure (power lines and railroad lines) could easily be re-established;
- Neither of the potential underground reservoirs would ever be mined by conventional open pit methods as they are situated beneath stock piles at the surface (white areas in Fig. 11);
- The abandoned, water-filled Dunka Pit could serve as the upper reservoir; and
- Rock exposures of the iron-formation are present in the walls of the open pit and joint measurements, and rock samples, could easily be obtained for structural integrity and rock mechanic studies.

CONS:

- The depths listed to potential underground ore zones, and thickness of ore zones, are fairly well constrained, but additional drilling in the down-dip direction would be needed to confirm the true nature of the ore zones;
- Future plans regarding the use of the site as a brownfield and Cu-Ni processing site by Twin Metals are unknown, although Twin Metals holds the surface rights;
- If the water in the abandoned Dunka Pit mine exhibits elevated sulfate contents, and if it were used for the upper reservoir, the entire PHES system would have to be well sealed to prevent leakage into nearby Birch Lake;
- Portions of the taconite are sulfide-bearing as indicated by drilling along the extreme down-dip edge of the iron-formation, e.g., Plates 9 through 12, and these areas would have to be better defined by additional drilling and avoided during underground mining activities;
- The underground mine should not encroach upon the overlying, sulfide-bearing Virginia Formation and Duluth Complex rocks; and
- The underground mine should avoid the fault zone that separates the two potential ore bodies as this ground is highly fractured and porous.

CONCLUSIONS

Ten sites, with some deep drill hole information, were crudely evaluated for their potential to establish an underground taconite mine that could be used in a PHES facility to the immediate south of the Mesabi Iron Range. The concept is that the payback from the mine would produce a very low cost efficient cavern that could be used as the lower reservoir. Out of these ten sites, there are several candidates that appear to be the most enticing with regards to establishing an underground mine in areas that would not be mined using conventional open pit methods as follows:

1. Taconite area = mining of a taconite ore body within oxidized taconite could produce a cavern:
   a) up to up 140 feet high;
   b) with a holding capacity of 14 billion gallons;
   c) with a maximum head of 700 feet below the surface; and

   d) the site is near abundant upper reservoirs that are present in the form of water-filled abandoned mines and tailings basins;
2. Cliffs-Erie area = mining of metamorphosed high-grade taconite could produce one or two caverns (depending on unknown grades that will be acquired in the future):
   a) up to 150 to 90 feet high respectively;
   b) with a maximum head of 1,040 to 1,235 feet below the surface respectively; and
   c) the underground cavern would be in close proximity to several large water-filled abandoned taconite mines;
3. Northshore area = mining of metamorphosed high-grade taconite could produce a cavern:
   a) up to 150 feet high (based on crude data);
   b) with a holding capacity of 7.8 billion gallons (based on 150 foot high cavern);
   c) with a maximum head of 600 feet; and
   d) near a large water-filled abandoned taconite mine to the immediate north that could serve as the upper reservoir; and
4. Dunka Pit area = mining of metamorphosed high-grade taconite could produce one or two caverns, separated by a fault zone as follows:
   a) An upper underground cavern/ reservoir:
      - up to 110 feet high;
      - with a holding capacity of 1.5 billion gallons (with potential to expand to the south);
      - with a maximum head of 450 feet below the water-filled and abandoned Dunka Pit taconite mine;
   b) a lower underground reservoir:
      - up to 90 feet high;
      - with a holding capacity of 365 million gallons;
      - with a maximum head of 800 feet below the Dunka Pit taconite mine; and
   c) both reservoirs could be joined by a mine shaft/penstock to the adjacent abandoned Dunka Pit taconite mine.

While these four sites have sufficient drilling to make very preliminary estimates on water holding capacities, more drilling would be needed to fully assess their ore potential and to provide material for geotechnical tests.

In the event that any of the above four sites are eliminated due to conflicting land uses, any of the other six sites discussed in this report could be chosen for underground mining. These sites are classified as "lower priority" only because detailed drilling to define the full potential of an underground mine is lacking. Therefore, considerably more drilling would be required to make a more accurate assessment of their potential. Out of this lower priority group, the Eveleth area would be the best candidate due to the presence of a tailings basin that could be used as the upper reservoir, and the presence of several taconite ore zones at depth that are defined by two close-spaced drill holes. These drill holes indicate that mining of the thickest ore zone could produce a 245 foot high cavern, or series of caverns, with a maximum head of 1,831 feet below the surface. The lowest priority candidates would be the Two River Reservoir area and McKinley area due to a multitude of reasons.

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APPENDIX A

[A portion of an earlier]
Dunka Pit Underground and Open Pit Mining Proposal

TITLE: Determine the economic feasibility of the underground and open pit mining potential of high-grade, eastern Biwabik Iron-Formation ore (Dunka Pit area) as feedstock for the production of value-added products like DRI.

PRINCIPAL INVESTIGATORS: Larry Zanko and Steven Hauck - Economic Geology Group (EGG)

COOPERATORS: Mr. Thomas Gardner, Gardner Management Services, Inc., Saratoga Springs, NY; Mr. Ronald Graber, Chief Geologist, Cliffs Management Services, Ishpeming, MI.

PRINCIPLES: NRRI Economic Geology Group (EGG; Years 1-3) and Coleraine Minerals Research Laboratory (CMRL; Years 1-2)

BUDGET: Phase I/Year 1 - $120,000 (EGG); Phase II/Year 2 - $245,000 ($165,000 EGG; $80,000 (CMRL-high pressure rolls testing-process feasibility flow sheet); Phase II/Year 3 - $135,000.

PROJECT DURATION: 3 years - July 1, 2001 to June 3, 2004.

OBJECTIVE: The project will assess the economic feasibility of mining and processing the currently unexploited high grade magnetic taconite resources on the easternmost Mesabi Iron Range. Both open pit and underground mining methods will be evaluated, but the project will focus on the latter, given the potential environmental difficulties posed by the necessary stripping and stockpiling of sulfide-bearing rocks if open pit mining were to continue in this area. To meet this objective, a full-blown feasibility study will be conducted. The study will take place in two major phases, and will be completed in three years, depending on the outcome of the first year's (Phase I) work, i.e., are sufficient resources available to support long-term (>10 years) mining?

BACKGROUND: The most eastern end of the Biwabik Iron-Formation was metamorphosed by the intrusion of the Duluth Complex 1.1 billion years ago. This metamorphism enhanced both the grade and physical properties of the magnetic taconite resources in this area, so much so they represent some of the highest grade material on the Mesabi Iron Range. For example, the higher grade ores of the Dunka Pit area on the easternmost Mesabi Iron Range, mined by LTV Steel Mining Company until 1995, typically returned 40% to 42% weight recovery values (Graber, pers. com., 2000). Furthermore, the coarse-grained nature of these ores made it possible to achieve a 100% liberation grind in the 150 to 200 mesh range, with a total gangue (silica, etc.) of about 2 percent, which is very close to what is desired for producing a DRI-equivalent concentrate. Low gangue concentrations are important because during DRI melting in an electric arc furnace, gangue materials form slag, decrease metallic yield, and increase consumption of electricity, electrodes and refractories, and increase heat time (Poveromo and Swanson, 1999).

A significant magnetic taconite resource remains within the Upper Cherty member of the Biwabik Iron-Formation (100 to 150 feet thick), with the highest grade portion measuring 75 to 100 feet in thickness (Graber, pers. com., 2000). Graber estimates 50 to 100 million tons of ore;

70% of this ore occurs over the 5,000 ft. strike-length with a 100 ft. ore thickness and down-dip mining extent of 1,500 ft, based on the projection of existing drill hole data. Additional down-dip resources are possible, but drilling data are lacking. However, the down-dip portion of the eastern end of the Biwabik Iron-Formation in the Dunka Pit area is overlain by sulfide-bearing rocks of both the Duluth Complex and the Virginia Formation, which is one reason that the underground mining option needs to be explored.

Pfleider and Yardley (1963) examined the economic feasibility of underground mining in the central portions of the Mesabi Iron Range where the Lower Cherty member would provide a better mining thickness and more magnetite. This conclusion was based upon the work of Gundersen and Schwartz (1962), who suggested that the contact metamorphism of the eastern BIF by the Duluth Complex and later hydrothermal activity would produce more non-magnetic iron mineral, e.g., iron-silicates, and therefore, reduce the amount of magnetite. However, this conclusion was proved invalid by subsequent mining in Dunka Pit, which had higher magnetite and lower silica than typical Mesabi Iron Range ores (Graber, pers. com., 2000). Pfleider and Yardley (1963) further concluded that the economic feasibility of underground mining was attainable for the central Mesabi Iron Range, based on certain assumptions and critical factors, i.e., roof control and rock breakage techniques. Their assumptions were: 1) improvement in grade of ore (30% magnetic Fe); and 2) better productivity rates, or lower amortization or shipping charges.

Because sulfide-bearing rocks overlie most of the high grade taconite resources in the Dunka Pit area, potential environmental problems (acid mine drainage and heavy metals) associated with the removal and stockpiling of these materials presently rules out the continuation of mining by open pit methods, at least in the vicinity of the current limits of Dunka Pit. However, if these hanging wall rocks - a significant portion of which contain low grade Cu-Ni values - could be processed by a future non-ferrous facility operating in the vicinity, the possibility of continuing to mine the taconite resources by open pit methods might be reasonable. Additional, potentially open pitable, reserves remain between Dunka Pit and the eastern extent of Northshore Mining Company's Peter Mitchell mine, but it is unclear whether similar environmental issues would apply.

In light of the potential environmental concerns, underground mining of these easternmost Mesabi Range ores may be the only viable mining option, but much of the data in this area remains in paper form only. These data need to be converted to digital form, and the economic feasibility of underground mining and subsequent production of a DRI material needs to be comprehensively revisited.

RATIONALE: The long-term health of iron ore mining on the Mesabi Range will depend more and more on the production of value-added products (like DRI), cost-savings through technological advances in mining (robotics and automation) and processing (like high-pressure roller presses), and the ability to adapt to changing markets and competition more quickly and efficiently. The announced closure of LTV Steel Mining Company in Hoyt Lakes and the loss of 1,400 jobs underscore the importance of keeping Minnesota's iron mining industry competitive. All of these issues, coupled with the presence of high grade magnetic taconite resources on the eastern end of the Mesabi Range that may be best (or *only*) developed by underground mining methods, makes an up-to-date assessment of underground mining feasibility an important and timely task.

In almost all but the most technically challenging cases, large-scale open pit mining will beat the per ton cost of large-scale underground mining. However, given the potential environmental hurdles associated with continued open pit mining, and the presence of some of the highest-grade magnetic taconite resources on the Mesabi Range, an underground mining scenario for the Dunka Pit area may be prudent. For example, Pfleider and Yardley (1963), proposed a "lane and pillar" method for extracting higher grade intervals of the iron-formation where the magnetic Fe content approached 30%. Later work by Pfleider and Scofield (1967) used an underground model averaging 27.4% magnetic Fe for an 85 ft. mining thickness. The lane and pillar method is a modified form of room-and-pillar mining, and would appear to be a reasonable mining option, given the anticipated mining thickness, formation geometry, and rock characteristics. Various caving and stoping methods are probably not appropriate, because they work best in situations where the rock is already highly fractured and/or weak (caving methods), or in deposits that are relatively narrow, more steeply dipping, and with a greater vertical extent (caving and/or stoping methods; Hamrin, 1982). Furthermore, room and pillar-type mining lends itself well to a higher degree of mechanization, and tends to be one of the lowest cost underground mining options available.

Underground mining would also leave the sulfide-bearing Virginia Formation and South Kawishiwi intrusion of the Duluth Complex as unmined hanging wall; thus, mitigating most environmental problems associated with potential sulfide-bearing waste. Depending on faulting and the contact relationships between the iron-formation and the South Kawishiwi intrusion, there may be small tonnages of prospective sulfide-bearing material that may have to be removed to mine the iron-formation. Also, if the open pit reserves have sulfide-bearing South Kawishiwi intrusion above the iron ore, then these wastes will have to mitigated with constructed wetlands, and/or water treatment plant to catch and clean run-off, and/or other environmentally sound practices, e.g., capping the waste piles with topsoil and vegetation.

Mining operations like those at Kiruna in Sweden, Pea Ridge and the New Lead Belt (Viburnum Trend) in Missouri, and Brunswick Mining and Smelting in Canada show that underground mining can be done at competitive costs (Hustrulid, pers. com., 2000). For underground mining to be an economically viable option on the easternmost Mesabi Range, however, combined mining and processing costs will need to be kept below $20 per long ton of concentrate (Bleifuss, pers. com., 2000). For example, *Mining Cost Service* (Schumacher, 2000), shows that operating costs for room and pillar mining can range from about $11 per long ton for an 8,000 long tons per day operation, to under $9 per long ton for a 14,000 long tons per day operation; the latter mining rate approaches what would likely be required to supply a DRI facility (Graber, pers. com., 2000). In addition, new mine automation technology may reduce mining costs (operating and capital).

Processing costs as low as $5 per long ton of concentrate might be achievable when coupled with advances in crushing technology, i.e., a high pressure roller presses (HPR) plant. Fischer-Helwig and Oberheuser (1994) indicate that energy savings using HPR can be in the range of 20-50% over conventional ball mills. Bleifuss et al., (1996) demonstrated that HPR, based on generalized data and broad assumptions, could save $2.4-$2.8 MM per year in a conventional taconite facility. The potential cost savings would leave about $15 per long ton of concentrate to cover mining costs. Assuming weight recovery values in the 45% range, e.g., for a 30% Mag. Fe ore, the actual underground mining cost would need to be kept at or below $7 per long ton of crude ore. A difficult proposition, to be sure, especially when coupled with development costs associated with underground mining (which can be substantial), but certainly not out of the question. Other important economic factors like royalties and taxes will also have an impact.

In the end, the proposed research would provide any party interested in future development on this end of the Mesabi Range with a significant head-start that identifies the potential operating and capital costs, the ore grade and ore reserves, a mine plan and related costs, production costs, and environmental costs and considerations.

RESEARCH APPROACH:

As outlined below, the research program will be a two phased program. In Phase I/Year 1, after: a) the paper data are compiled and made digital; b) the geology and assay data have been well-defined, perhaps including supplemental Davis Tube analyses; and c) an initial assembly of cost and economic data has been completed, a geologic block model of the taconite resources will be built. If the determined ore grade and tonnage (at the end of Year 1) is not sufficient to support a reasonable (10+ years) mine life, then the project will not continue, and a final report will be written.

However, given a favorable grade and tonnage picture, the project will continue to the second phase, with Phase II beginning in Year 2. Davis Tube and HPR testing of a representative bulk sample and other samples, if necessary, will be performed at CMRL to provide a reasonable processing cost estimate. Large-scale underground mining operations will be visited in Year 2, and this experience will assist in choosing the most efficient underground mine design for this project. Year 2 work will focus on refining mine development costs, and the operating and capital costs related to mining and processing. Also included will be an assessment of operating and capital costs for transporting the finished product to market, environmental costs, and taxes and royalties. At this point in the project (mid to late Year 2), an accurate determination of project costs and economics will be needed so that an economic block model can be built for both underground and open pit mining options. The economic block model for the open pit option will allow for the ultimate pit limits to be determined. Knowing the potential down-dip extent of an open pit operation will influence the design of an underground mine. From Year 2 into Year 3, a DRI process flowsheet will be determined, along with related capital and operating costs. The final feasibility study will be completed in Year 3, and a final report produced.

Phase I/Year 1

This phase will begin with the assembly of all pertinent project data, and converting all non-digital data (geology, assay, land ownership, hydrology, etc.) into digital form. At the same time, a preliminary assessment of potential project-related costs, e.g., mine and mill development costs, environmental costs, permitting, transportation costs, royalties, capital costs, operating costs, etc., and other economic data will be made, which will allow for an order-of-magnitude economic analysis to be performed. Supplemental geological and assay work, e.g., core logging and Davis Tube analyses of available drill core and/or cuttings, will be performed, and used in the construction of a digital geological block model. The block model will provide estimates of grade and tonnage for the area's remaining taconite resources. If the block model shows that insufficient resources are available for continued mining, by either open pit or underground methods, the study will end with Phase I. Phase I's products will be a complete digital representation of the area's taconite resources (geology, grade, etc.) and a summary of preliminary economics. If the block model confirms that a sufficiently large geologic resource is available, the project will continue to Phase II, which covers years 2 and 3.

Phase II/Year 2

This phase will include high pressure rolls testing of a bulk sample that best represents the type of ore present on the easternmost end of the Mesabi Range. Testing would take place at CMRL, so that a process feasibility flow sheet and a reasonable estimate of the potential cost savings are available for subsequent economic modeling. A much more detailed fleshing out of development, mine, mill, etc. costs, and economic data assembled during Phase I will occur. The detailed economic data are needed so that an economic block model can be built that defines the ultimate pit limits for an open pit mining option. While underground mining will be the study's focus, an open pit mine model will be needed for comparative purposes, not only to address the potential environmental costs associated with pursuing an open pit mining option, but to show where an open pit to underground mining transition could occur, if that scenario plays out. Site visits to large scale underground mining operations will also take place during this phase of the project. The practical knowledge gained from those visits will be used to guide the choice of the best underground mining method to digitally model.

Phase II/Year 3

This phase will culminate with the completion of the feasibility study and presentation of representative mine models and project economics. By the end of the third year, the project will have continued through the mine and mill development stage (taking into account the production of a DRI-type product) all the way to mine and plant closure. State-of-the-art geological, mining, simulation, and economic modeling software will be used in the feasibility study that considers the latest mining and processing technologies, and the most realistic economic assumptions.

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