Regional Survey of Buried Glacial Drift Geochemistry over Archean Terrane in Northern Minnesota

1858

Minnesota Department of Natural Resources
Division of Minerals
Hibbing, Minnesota

Report 252
Part I (of II)

1988

Regional Survey of Buried Glacial Drift Geochemistry over Archean Terrane in Northern Minnesota

By

D.P.Martin, G.Meyer, T.L.Lawler, V.W.Chandler, and K.L.Malmquist

L.W.Gladen, Supervisor of Geoscience Section

E.H.Dahlberg, Acting Supervisor of Geoscience Section

A

Legislative Commission on Minnesota Resources Project

Minnesota Department of Natural Resources
Division of Minerals
Hibbing, Minnesota

Report 252
Part I (of II)

1988

This report is on file at various major libraries in Minnesota. It may be purchased at the Hibbing office, DNR Minerals Division. For further information contact Richard Ruhanen at (218) 262-6767.

Table of Contents

VIII. Appendices, continued

IX. Maps & Plates

IX. Maps & Plates, continued

X. List of Figures

XI. List of Tables

Regional Survey of Buried Glacial Drift Geochemistry Over Archean Terrane in Northern Minnesota

Abstract

A regional geochemical survey was conducted during 1985-1987 on drill samples of buried Rainy lobe glacial drift over two separate areas in the Precambrian shield of northern Minnesota. A primary objective was to test this method to search for large, mining-camp scale targets of base and precious metal mineralization or alteration. In order to thus evaluate the mineral potential and to foster further exploration, a framework of regionally-based data for glacial drift stratigraphy, glacial drift geochemistry, and limited geophysics was assembled.

The surveys were conducted over Superior Province Archean bedrock terrane in two areas: nine townships near Orr (in Koochiching and St. Louis counties) of typical Archean supracrustal layered bedrock and ten townships around Littlefork (in Koochiching county) over Vermilion Granitic Complex bedrock. The favorable glacial drift for geochemical exploration here is the Wisconsinan Rainy lobe (Labradorean provenance) which is lying on bedrock but buried beneath 50 to 100 feet of Des Moines lobe (Keewatin provenance) clayey till and/or lake sediments. In the 9 townships of the Orr area, 37 holes were drilled for an average of 4 holes per township. Similarly near Littlefork, 30 holes were drilled, or 3 holes per township. A total of 304 glacial drift samples of 5 to 10 foot composites were processed for heavy mineral concentration, and 383 similar composites were dry screened to obtain the silt plus clay fraction for analysis. Those two types of glacial drift plus 58 bedrock samples and 124 (out of the above 304) HMC magnetic fraction samples make up the regional geochemical database.

Three drilling methods, Rotasonic at $34.50/ft., air rotary at $20/ft., and mud rotary at $10/ft. were evaluated. The Rotasonic drilling produced excellent core samples of the glacial drift that enabled the stratigraphy to be well defined. The mud rotary drilling plus sampling produced low quality geochem samples, whereas the air rotary produced acceptable geochem samples.

A substantial amount of information about drilling and sampling, sample media, and regional geochemistry by stratigraphic unit is now available from the survey. The buried Rainy lobe till appears to be widespread and a good sample medium. The upper till of the Des Moines lobe, in contrast, contains an exotic regional geochemical signature that is significantly higher in As, Sb, Ba, Zn, Mo, Pb, Hf, and Th relative to the Rainy lobe. The Rainy lobe till contains an average from both areas combined of one gold grain (identifiable in an HMC) per 17 kg of till. Drill samples from four townships contained gold grain counts or delicate-shaped gold that encourages further evaluation. The most encouraging drill hole, in T62N-R20W contains 63 total counted gold particles, 33 of which were delicate, along with a high arsenopyrite content, and elevated Cu, Ni, Ag, Sn, Sb, Pb, W, and Bi that indicates a gold occurrence in the bedrock locally. The geochemical data was sorted and averaged by drift type, by region, and by drilling + sampling method for 19 elements.

Finally, to better understand the buried bedrock and its relation to drift geochemistry, two types of geophysics were run. Additional regional gravity stations were run to add to the existing network (seeking one mile spacing) and new gravity maps were produced. Secondly, seismics were tested, seeking the depth-to-bedrock, for planning drill site selection. VLF-EM was also run to help interpret the results in an area where faults and structures may be influencing the geochemistry.

In conclusion, a significant framework of regionally-based data was generated to evaluate this approach to mineral potential evaluation of state lands and to stimulate private exploration. Considerable information, such as core library reference samples of all products or a floppy disk of the geochem assay results, is available at the DNR Minerals Division Hibbing office.

INTRODUCTION

Funding and Objectives

This project was funded by the Legislative Commission on Minnesota Resources (LCMR) for the 1985-87 biennium at the rate of $100,000 each year. It was proposed and supervised by the DNR Minerals Division, with a significant contribution on glacial geology and geophysics by the Minnesota Geological Survey. Two people worked full time on the project, and many others contributed specific roles.

The project was designed to seek gold and other metal occurrences in an Archean Superior Province greenstone belt and a migmatite complex covered by 50 to 250 feet of glacial drift in two areas totalling approximately 700 square miles in northern Minnesota (see Map 10-1). This regional survey was designed based upon a specific set of objectives, economic criteria, geologic landscape conditions, and very limited information available about a relatively unexplored area. In summary, it required a survey unlike any previously reported.

There is very good potential for gold ore to occur in Minnesota within the Archean Superior Province, since 33 gold mines (each with production greater than 1 million ounces) exist in the same terrane in Canada (Hodgson and MacGeehan, 1982). It is fundamental to the design of this project that those gold deposits occur in clusters described by Colvine and Stewart (1984):

> "Concentrations of gold deposits occur along linear zones that . . . have been variously termed "breaks," "growth faults" or facies changes . . . . Felsic and alkalic stocks, often porphyritic, are more common along these zones . . . . Gold mineralization is not uniformly distributed along these zones, but is focused in individual mining camps up to tens of kilometers long and normally less than ten kilometers wide."

In Minnesota, these potential occurrences are buried by layers of glacial drift which commonly contain clay layers that hinder many exploration techniques. A goal of this project is to utilize the glacial till that is so detrimental to other exploration methods. Basically, as the advancing glacial ice overrode any exposed bedrock, the ice eroded, transported, and deposited that bedrock some distance down its path. Ore clasts can occur within discrete dispersal trains[1] within the glacial drift (see Fig. 1-1 and 1-2) which provide geochemical trace element "targets" that in two dimensions can be orders of magnitude larger in size than the actual bedrock ore zone being sought.

---

[1] Dispersal trains are so called since the dispersal of subglacial sediment down-ice from its bedrock source assumes the form of a negative exponential decay curve which can be quantified by its decay constant, half-distance, and total transport distance (Shilts, 1976; Clark, 1987).

In combination, a cluster of gold ore occurrences could be eroded and transported by the glacier and deposited as dispersal trains in till, thus providing the fundamental conceptual model for the widely spaced drilling of this reconnaissance survey (see example from literature in Fig. 1-3). That is, we sought large-scale targets of clustered dispersal trains of gold or pathfinder trace elements in the glacial drift. No intent was made to determine the nature of any specific gold occurrence; however, significant information is available for interpretation.

The project had many specific objectives which required contributions by different geoscience specialists. The objectives primarily were:

1. To test this regional method of evaluating large tracts of state mineral lands by looking for township-scale (mining camp size) occurrences of gold and other metals in glacial drift. The drill hole spacing, for example, was a big question.

2. To identify the buried glacial drift stratigraphy in order to interpret the directions and distance of glacial transport.

3. To test the necessary drilling methods and determine the costs of regional work. Each drilling method requires specialized sample collection and preparation methods.

4. To test which types of samples (i.e. heavy mineral concentrates vs. silt-clay screen fractions) would best serve this regional survey.

5. To identify whether, in fact, the glacial drift geochemistry could be correlated to local bedrock. The detail-, local-, and regional-scale correlations would be sought.

6. To help the MGS with their long-range goal of bedrock mapping by obtaining bedrock drill samples and with more gravity survey stations.

7. To create geochemical maps of the buried drift that try to identify areas of high mineral potential. In doing so, to provide samples in the DNR Core Library for geologists to learn firsthand, and to create a database of geochemistry upon which to compare results.

8. Finally, to identify the computer methods necessary to organize and manipulate the data.

The intent has been to present all the data so that it can be reviewed on a case-by-case basis, as well as a regional overview. The most important gold data is presented on Maps 10-7, 10-8, 11-4, and 11-5, Appendix 9-6, and Table 40-7. One of the authors (D.P.M.) presents an interpretation of the significant gold occurrences in "Discussion of Some Significant Individual Drill Hole Results."

Previous Work

The broad scope of the report precludes a lengthy review here of previous work of each topic covered within. Moreover, each section contains specific references to previous work. It is useful to review those key topics most essential to the central theme of this project, which was drilling to obtain buried glacial drift samples for geochemical evaluation.

Although the fundamental concepts of tracing boulder trains or till samples back to an ore-bearing bedrock source have been evolving for over a hundred years, the application of drilling to obtain buried drift samples is relatively new, having been reported in the 1970's (Gleeson & Cormier, 1971; Gleeson & Hornbrook, 1975). Shilts (1975) clearly defined the usefulness of glacial till as a prospecting medium. The recent development of such diverse topics as drilling methods, analytical methods, sample processing methods, glacial drift stratigraphy maps, infinitely complex geologic landscapes, exploration economics, and improved theories on glacial sediment dispersal has led to a bumpy, but successful, evolution of this exploration tool over the past two decades. The results include more than 150 dispersal trains reported in the literature as well as the discovery of a number of significant ore deposits (Salminen and Hartikainen, 1985; Averill, 1986).

The basic project design was outlined in the spring of 1985. Two important regional surveys were in progress at that time--the Ontario Geological Survey's Black River-Matheson (BRIM) project and the Nordkallot project in Scandinavia. The Nordkallot survey used primarily the -63 um fraction, since their extensive orientation surveys demonstrated that sample medium was most appropriate in their geologic landscape (Reijo Salminen, personal communication, 1987). The BRIM project introduced the use of the Rotasonic drilling method for a regional survey and focused on heavy mineral concentrates as the sample media since orientation surveys demonstrated the -63 um fraction to be inconsistent, at best, for gold (Cameron Baker, personal communication, 1985).

Numerous Geological Survey of Canada (GSC) projects on basic and applied research of geochemical dispersal trains have been reported (see Shilts, 1984, summary). And while the project was in progress, some significant basic research has been reported that better defines the current theories of glacial dispersal (Clark, 1987; Klassen, 1987; Strobel and Faure, 1987; Kaczicki, 1988). Furthermore, recent exploration economics relating to gold in Canada have encouraged the widespread use of overburden drilling as an early stage exploration tool for detailed, site specific evaluations.

Location

Two areas in northern Minnesota were surveyed in this project so that the results could be contrasted. The northernmost area (see Maps 10-1 and 11-1) covers approximately 10 townships centered around Littlefork in Koochiching County. This area is approximately 8 miles south of International Falls (U.S.-Canadian border) at its closest point. The second area is near Orr, (Map 10-2) approximately 53 miles south of International Falls along U.S. Highway 53. The area covers approximately 9 townships and straddles the St. Louis County and Koochiching County boundary. In total, the areas cover roughly 700 square miles. The areas are separated at the closest point by 3 tiers of townships, north to south, or 18 miles.

Physiography and Descriptive Geology

The dominant landforms in this region of the State include the lowland occupied by Wisconsinan glacial lake Agassiz (Eng, 1980), the upland of the core of the Vermilion Granitic Complex bedrock, and the upland end moraines of the Rainy lobe--the Vermilion moraine and an unnamed one (Hobbs and Goebel, 1982). The present surface continental divide is roughly 20 miles south of the Orr area and the river systems flow to the north, eventually into Hudson's Bay.

The Littlefork area is generally poorly-drained, black spruce forests or peatlands, which require winter access or special equipment for drilling. Aspen-birch forestlands exist primarily along the two major river systems that are deeply incised into the clay-rich glacial drift and drain the elevated peatlands.

The Orr area has some good access and even Rainy lobe at the surface of some uplands (see schematic Map 10-6) in the St. Louis County portion. Generally, to the west there is thicker clay-rich drift of the Des Moines lobe and poor access that limited our site selection.

The bedrock control in the total 700 square miles consists of a few dozen outcrops and a few bedrock drill cores and thus, for the most part, has been interpreted from state-sponsored geophysical surveys. It is relatively unexplored and poorly defined. The two geologic base maps, the 2° sheets for Hibbing and International Falls, are currently being revised by the Minnesota Geological Survey and the U.S. Geological Survey.

The Vermilion Granitic Complex (VGC), which is the dominant bedrock in the Littlefork survey area, is about 80 miles long by 35 miles wide. The VGC was named and described by Southwick and Sims (1979). In summary (Morey, 1981), it consists of a core of syntectonic granitic intrusions that grade outward into:

a.) granite containing numerous biotite-rich inclusions;

b.) then into a stromatoform migmatite with approximately equal proportions of schist and granite; and

c.) finally, into metamorphosed supracrustal rocks with primary textures changed to a metamorphic fabric, but still layered.

The VGC has a complex history of injection, anatexis, and metasomatism as indicated by fault-bounded linear blocks of biotite schist and amphibolite intercalated with igneous rocks that have been metamorphosed to the upper amphibolite facies (Southwick and Sims, 1979). The internal structure consists of gently plunging, large open folds that trend east-west (Southwick, 1972). The foliation and lineation is also east-west (op. cit.). Evidence for two periods of migmatite formation was cited in the Buyck area (op. cit.). Subsequent to folding, major faulting occurred. The southern boundary of the VGC is mainly defined by the Vermilion fault, which trends east-west and has a six mile wide cataclastic zone in some places (Southwick, 1979). The northern boundary is gradational and arbitrarily placed where the flanking biotite schist contains little or no granitic rocks of the complex (Southwick and Sims, 1979). In between, the VGC is described as heterogeneous granitic and migmatitic Archean rocks, consisting of subdivisions of: Lac La Croix granite, granite-rich migmatite, schist-rich migmatite, quartz-feldspar gneiss, hornblende quartz diorite and diorite, granodiorite and trondhjemite, amphibolite and amphibolite migmatite, older migmatite, biotite schist, and pegmatite.

Chemical analyses are presented by Southwick (1979 and 1972) and Ojakangas (1976). Alteration over wide areas and slight shearing were noted in the Lac La Croix granite by Southwick (1979).

The basement rocks in the Orr area have very little published about them. The Linden Pluton syenite and associated lamprophyres were briefly described by Sims and Mudrey (1972). Also, several diamond drill cores of the Linden Pluton are available at the Core Library. The interpretations must otherwise be based upon a few dozen scattered outcrops and geophysics. Generally, the supracrustal rocks strike east-west and were intruded by the Linden Pluton and associated lamprophyres. This greenstone belt is a westward extension of the Vermilion district, the most thoroughly studied Archean greenstone-granite complex in the State. Thus, a brief summary has been presented (see Appendix 9-1).

The Orr area, in conclusion, has Archean greenstone-granite terrain for which some generalizations can be made, but which is largely buried and unexplored even by Minnesota standards. The bedrock samples from this survey will significantly increase the overall bedrock database.

METHODOLOGY

Chronology of Events

The principles and procedures applied to this project were largely determined by its administrative framework. Time deadlines, available labor and funding, and the requirement to accept low bid contractors must be considered when discussing drilling methods, site selection, logging, sampling, and assaying. The chronology of events helps to illustrate this point (Table 30-1.)

The project was performed in stages, and due to time constraints, the planning was telescoped into each stage, at times without the benefit of results for review. Furthermore, some parts were written without the benefit of final data, such as Gary Meyer's 1986 report on glacial stratigraphy from the Rotasonic core logs. Subsequent drilling confirmed his interpretations.

The project was planned for completion June 30, 1987. However, an administrative policy that required us to accept the low bidder for the (intended, wintertime) reverse circulation drilling contract for the Littlefork Area resulted in a significant delay when the low bidder defaulted after 10 days. The driller and winter access were gone. The drilling was completed by an air rotary method in October 1987, and all assay results were received by March 1988, but the report competed with the start-up of new projects. Low bidders are not always the best choice.

Field Operations

The Orr and Littlefork areas contain favorable bedrock terranes which are obscured by glacial drift. Our survey criteria required: 1) visual examination of glacial drift samples from surface to bedrock; and 2) identification and geochemical sampling of the buried Rainy lobe drift. Drilling methods and the complimentary sampling system must provide: 1) consistently high recovery foot-to-foot, including recovery of silt sized gold flakes; 2) accurate stratigraphic information; and 3) large, representative samples of diverse glacial materials, from clay to boulders. Our survey tested three different drilling methods.

The Rotasonic drilling program of December, 1985, was the first stage of drilling in both the Orr and Littlefork areas. Stu Averill, president of Overburden Drilling Management, Ltd., was hired as a consultant for two days at the start of drilling to ensure proper methodology. The continuous core of overburden from surface into bedrock provided: 1) accurate logs of stratigraphy; 2) consistent recovery foot-to-foot of large, high quality samples for heavy mineral concentrate and -63 micron analyses; 3) a Core Library reference sample for visual examination of the types and textures of glacial drift present; 4) a clearer understanding of the local and regional glacial history; and 5) an excellent core of up to nine feet of bedrock. Overall, Rotasonic drilling provided the beginnings of an invaluable database of stratigraphic and geochemical information from which to design the next stages of drilling.

Rotasonic core drilling procedures are fully documented (Averill, et al., 1986). Basically, the procedures is to:

1. Resonate and rotate the core barrel 10 feet or more into the formation;
2. resonate, rotate, and water-flush the casing down to the bit face;
3. pull core barrel (and any extension rods);
4. resonate core from the barrel into plastic sleeves; and
5. repeat steps 1 through 4 into bedrock.

Two of the DNR-Minerals technical staff were assigned to the drilling rig to: 1) log bit penetration (and resistance) and stratigraphic information; and 2) receive, label, and box core. Rainy lobe till was often characterized by resistance to penetration (compact and stony material) and by not bearing water (angular, unsorted, and compact material).

Rotasonic cores were resonated from the core barrel into plastic sleeves and stored in four-foot, covered wooden boxes. Footages based on bit penetration and drift type were labelled on the sleeves and boxes. Core boxes remained covered and sleeves uncut until the sonic drilling was completed and all samples had been transported to the DNR-Minerals lab in Hibbing. This prevented excess drying of the core and, therefore, greatly facilitated logging and sampling to be done as personnel became available.

Sleeves were slit open just prior to logging, and the core was sliced along its length to expose the undisturbed center portion. Significant oxidation of the samples has occurred since the original logging.

The mud rotary drilling program in the Orr area followed and offered sharp contrast to the Rotasonic drilling program. At the drill site, the sample slurry, a combination of minus ½-inch overburden (or bedrock) chips, revert (drilling mud), and water was: 1) logged at the collar before mixing and homogenization of lithological units occurred; 2) screened to -10 mesh; 3) dewatered in a 10-foot settling trough; and 4) redirected back to the sump over a 4-foot sluice box with a removable carpet floor (Figure 3-5). Kevin Malmquist, Jay Niebuhr, and Tim Pastika made significant contributions during this phase of the project.

Mud rotary drilling procedures normally were as follows:

1. drive pit pipe (casing) down at least one foot to seal off surface;
2. drill out Des Moines lobe drift with a drag bit;
3. pull rods, change to tricone, button type, hard rock bit;
4. drill out Rainy lobe and bedrock, stopping the drill every ten feet to collect the sample from the trough.

Sampling began when the mud rotary drilling intersected the target Rainy lobe. This was marked by a transition from very calcareous Des Moines lobe clays to igneous and/or metamorphic pebbles and sand. Ten foot intervals were normally sampled but where the mud mix was very thick (i.e. in sand), intervals averaged up to 15 feet. As the mud mix usually thins after about 5 feet, sampling of these intervals of thick mud was (later) improved by first extracting a 5-foot sample and then returning to 10-foot intervals thereafter. The +10 mesh screen fraction and trough were thoroughly washed between each sample.

Drilling and sampling continued in this manner until one foot of boulder or bedrock was encountered. The sample in the screen and trough was then removed, and drilling ideally proceeded at least 4 more feet into bedrock. If five or more feet of rock was drilled, the assumption was that it was bedrock. Where drilling progressed through boulders larger than one foot, the driller's decision was often to continue to bedrock without stopping to avoid complete loss of circulation. In this case, only one composite sample from boulder to bedrock was taken. Drilling then continued slowly for one foot while the trough and screen were slid to the side and samples removed. The trough was replaced under the slurry, and five additional feet of bedrock were sampled. Although this basic sampling procedure was ready for the first drill hole, a few improvements were necessary during the first half of the drilling program to improve productivity.

The sluice carpet and sample were removed only after completion of each hole. This sample represents a heavy mineral concentrate composite of all Rainy lobe and bedrock drilled which overflowed the settling trough.

Conventional air rotary drilling in the Littlefork area offered a compromise in logging and sampling effectiveness between Rotasonic and mud rotary drilling. Logging took place at the collar as the sample ejected from the casing and before mixing and homogenization took place in buckets. Sampling for analysis began in the Rainy lobe, marked by a transition in drilling resistance and sample types between the calcareous Des Moines lobe lake clays or clay tills and the non-calcareous (to low carbonate content), often biotite-rich sands of the upper Rainy lobe.

Air rotary drilling procedures normally were as follows:

1. hammer and flush 20-foot lengths of casing to depth;
2. drill out encased material with a tricone bit (at times in the Rainy lobe, drilling had to preceed the casing);
3. weld on a new length of casing;
4. repeat steps 1 through 4 to bedrock; and
5. at bedrock pull the drill string to replace bit with a 4" down-the-hole hammer bit.

Site Selection

Several factors related to the project's design, funding, and framework largely determined drill site spacing and location. The expensive Rotasonic contract was limited to one hole per township with total coring footage of 2065 feet across both areas. The rotary contracts permitted an additional 3500 and 2220 total feet of drilling in the Orr and Littlefork areas, respectively, at lower cost. This totals 9 Rotasonic holes plus 28 mud rotary holes in approximately 9 townships near Orr (about 4 holes/ township) and 10 Rotasonic holes plus 20 air rotary holes in approximately 10 townships near Littlefork (3 holes/township). Since no accurate information existed on the glacial stratigraphy of the project areas, the Rotasonic coring holes were located in as many different glacial terraines as possible to obtain invaluable stratigraphic and geochemical data from which to design the subsequent rotary drilling programs.

Within these initial constraints, the objectives of site selection in each region were to:

1. distribute drill sites evenly;
2. locate sites down-ice from known faults and other bedrock unconformities;
3. avoid end moraines, eskers and major glaciofluvial and fluvial drainage systems;
4. locate sites on state-owned surface and mineral lands;
5. provide seasonal access for truck-mounted drill rigs and support vehicles;
6. resolve questions concerning buried glacial and bedrock features;
7. locate sites over bedrock lows and avoid sites down ice from bedrock highs to seek regional and local dispersal rather than only detailed dispersal;

8. drill one site with both sonic and rotary methods;
9. avoid excess site preparation work.

Potential drill sites were then located on compilation maps with all pertinent glacial and bedrock geologic data (½" = 1 mile). Following legal review of surface and mineral ownership, all sites were field checked for off-road access, suitable ground conditions, and possible problems such as buried cables and overhead power lines. Finally, locations to be drilled were cleared of brush and trees, and winter sites were plowed and the ground allowed to freeze.

Comparison of Drilling Methods

Three drilling methods were evaluated in terms of their effectiveness in regional drift geochemical surveys. Table 30-2 summarizes drilling equipment, production, relative logging and sampling effectiveness, and total geochemical analyses.

In summary, Rotasonic drilling provides high quality samples for orientation to both geochemistry and stratigraphy. It is a fast, efficient, and successful drilling method, but it is costly. In contrast, the low cost mud rotary method we tried provided low quality samples of the drift and bedrock. Since no casing was used, it was difficult to maintain good drilling (or sampling) conditions, and the risk of losing the hole at any time is high. The air rotary with casing method can be viewed as a compromise, in terms of cost and sample quality, to the two methods above. Although our 20 holes had excessive downtime, the method holds promise. Finally, the air rotary holes were intended to be done by reverse circulation drilling, but the contractor defaulted. Reverse circulation is the most common method being used in Canada, but there are few, if any, rigs currently available in Minnesota.

Samples Types and Sample Processing

Four sample types obtained from drilling were analyzed: -63 um screen fraction of glacial drift, HMC nonmag fraction of glacial drift, HMC magnetic fraction of glacial drift, and bedrock samples. Sample processing flowsheets for the three drilling methods are shown in Figures 3-4, 3-6 and 3-7. Heavy mineral concentrate (HMC) processing and analysis of glacial drift samples follow a design by Stu Averill (Averill, et al., 1986). The results as reported by ODM include gold grain counts (see drill hole summary sheets). Basically, the HMC procedure: 1) allows large (8 kg minimum) representative samples to be analyzed to offset the heterogeneous nature of drift and provide reproducible results; 2) offsets glacial dilution (low physical concentrations of minerals) enabling detection of mineral dispersion farther from source; 3) provides a concentrate mineralogy which according to ODM can reflect the size and grade of source mineralization; 4) allows separation and description of gold grains to calculate their impact on assays and to estimate the distance to source mineralization; and 5) provides both a nonmagnetic HMC fraction, expected to contain the gold grains and also a magnetic fraction HMC that was analyzed in this survey.

The splits for -63 micron screening and analysis were dried and sent to the assay lab. The Rotasonic samples were screened at XRAL and the air rotary samples at Bondar-Clegg in Denver.

Sampling of the Rotasonic core was done within stratigraphic units. The objectives were to: 1) sample intervals up to 5 feet for -63 micron geochemical analyses; 2) sample intervals from 5 to 10 feet for heavy mineral concentration (HMC) analysis; and 3) preserve sufficient core for permanent storage in Hibbing's core library. First, the sample for -63 micron analysis was channeled from the center of the core. This sample averaged 6.5 cubic inches per linear foot of core (500-1000g, dry, per 5-foot interval). Large clasts were removed from the channel and returned to the core box. The remaining portion of the half split comprised the HMC analysis sample. A minimum of 8 kg of feed was necessary for HMC, so adjacent intervals were often composited.

For the mud rotary samples, the nonmag HMC and selected magnetic fraction HMC were produced and analyzed. No -63um fractions were produced, since the drilling method limits the recovery of that fraction of the sample.

For the air rotary samples, grab samples were collected from surface downward at 5-foot intervals, at stratigraphic changes, and of bedrock. These were put into one NX core box to represent a skeleton for each hole and are available in the Core Library. Minus 63 micron samples were taken in 5-foot intervals, HMC samples normally 10-foot intervals. Two 1/8 splits of each interval were dried for HMC processing and permanent storage. A 2" x 18" pipe sampler was used to collect a representative portion of the 3/4 split for -63 micron screening and analyses. This sample averaged 12.5 cubic inches per linear foot or about 2000 g per 5-foot interval.

Analytical Methods

Geochemical assays were performed on samples from the nonmagnetic HMC fraction, the -63 um fraction, the magnetic HMC fraction, and the bedrock. Standards with known assay values were also analyzed as a check for precision and accuracy. In general, the samples from Rotasonic and mud rotary drilling were analyzed by X-Ray Assay Labs, and the samples from air rotary drilling by Bondar-Clegg. The information, including sample numbers, analytical method, detection limit, subsample weight, and assay lab is summarized in Appendix 9-2.

Gold was analyzed in 3 of the 4 fractions: nonmagnetic HMC, -63 um, and the bedrock. The entire 3/4 split was analyzed for gold in the nonmagnetic HMC fraction by the neutron activation assay method. The -63 um fraction was analyzed from 20 gram subsamples. -63 um gold was assayed by neutron activation with fire-assay extraction. The bedrock samples analyzed for gold by Bondar-Clegg were 30 gram subsamples, and they were assayed by the neutron activation method. X-Ray Assay Labs analyzed 30 gram subsamples by neutron activation. The detection limit for gold in all fractions by the neutron activation assay method was 5 parts per billion.

Other elements were also assayed in each of the four fractions: up to 36 elements were analyzed in the nonmagnetic HMC fraction, up to 21 elements in the -63 um fraction, 10 elements in the magnetic HMC fraction, and up to 42 elements in the bedrock samples.

Sampling and Analytical Variability

The total variability can be described as the sum of the natural sample, drilling, splitting, processing, and analytical variabilities. It is expensive to try to isolate and define each, but an attempt was made to try to understand them by conducting the following tests.

Drilling variability was tested by drilling a mud rotary hole, 20200, approximately 50 feet from a previous Rotasonic hole, 202, which contained numerous gold grains. Similarly, an air rotary hole, 10700, was drilled approximately 10 feet from a previous Rotasonic hole, 107, that contained numerous gold grains (see Maps 10-7 and 11-5). A comparison can also be made from the average gold content per kilogram (see Table 40-7) from each drill method. Summarizing the results, the mud rotary and air rotary systems are interpreted to adequately get the gold-bearing drift sample to the surface; however, significant problems arise in the collection and subsequent splitting steps of the slurried sample that is produced. Some error is also introduced by drilling when the hole diameter, and thus sample volume, is not kept constant, especially in fine-grained water-bearing units. Since the samples are composited on five or ten foot intervals, varying hole diameters can overrepresent, for example, one or two feet out of a ten foot composite.

Splitting variability was tested on ten samples from mud rotary drilling (see Table 30-3). A separate split was submitted for heavy mineral concentration and gold counting. The results seem reasonable for seven samples but not for three samples--18602, 18612, and 18628. This test cannot differentiate variability by splitting, heavy mineral concentration, nor natural variation. Since none of our test samples contained 20 particles of gold per sample, which is suggested to be necessary by Clifton, et al.(1967) to test precision, the results must be viewed as equivocal. Merks (1988) suggests that splitting introduces the largest error in analyzing native gold-bearing samples.

The variability of HMC processing was not evaluated. Sopuk, et al. (1985) and Nicol and Shelp (1986) have been researching this question in detail. It was observed in our survey that 25 samples, however, had reported gold grain counts of zero but assays greater than 150 ppb, indicating gold in some form was present. Nor was the dry screening process for the -63 micron separation tested.

Analytical variability was tested for precision and accuracy for the -63 micron samples. A number of certified reference standards were submitted with the regular samples for analysis. For example, a standard, SO-1, was inserted for every twentieth sample. The analytical precision is presented in (Table 30-4). Another test, by repeating ten assays with new subsamples of the same sample, checks the sum of the natural and analytical variability of a (very low content) gold-bearing sample (see Table 30-5). Similarly, different splits of 19 Rotasonic samples were submitted to test the sum of natural, splitting, screening, and analytical variability. The results (see Table 30-6) show quite a range of variability by element.

RESULTS AND DISCUSSION

Glacial Geology Introduction

The following report by Gary Meyer (MGS) was written in 1986 after the 19 Rotasonic drill holes were completed, but before the mud or air rotary drilling. It is included here in its entirety, but note its separate internal outline and bibliography. Five illustrations were created for that section, but two of them (Plates 4 & 5) are very large and are available only upon request. Plates 1, 2, and 3 are included in the Maps Section of this report.

Subsequently, after the mud rotary drilling in 1987, Kevin Malmquist assembled all the data for the Orr area and composed a summary discussion. Kevin had worked on both Rotasonic and mud rotary drilling stages, and assisted Gary Meyer with the Rotasonic core logging.

QUATERNARY STRATIGRAPHY OF THE COOK AND LITTLEFORK EXPLORATION AREAS, NORTHERN MINNESOTA by Gary Meyer (4/30/86)

INTRODUCTION

This report summarizes and interprets data on subsurface Quaternary deposits in northern Minnesota based chiefly on visual examination of core obtained by a rotasonic drilling program funded by the Department of Natural Resources (DNR). Drilling was carried out in two areas selected by the DNR: (1) around Little Fork, in roughly nine townships (Plate 1) in northwest-central St. Louis and adjacent southeastern Koochiching Counties, and (2) west of Cook in roughly 10 townships in north-central Koochiching County (Plate 2). There were 19 holes, with 4"-diameter core, drilled in December 1985. Thus, this report is based on about one hole per township. The entire Quaternary sequence was core-drilled to Precambrian bedrock, with variable but generally good recovery. The objective of this project, which was very time constrained, was to develop the regional framework of the drift stratigraphy with the high-quality, nearly continuous rotasonic drill core samples. The project is part of a regional glacial drift geochemical survey being conducted by the DNR Minerals Division and funded by the Legislative Commission on Minnesota Resources.

Both areas were repeatedly overridden by Pleistocene ice advances of both northeastern (Labradorean) and northwestern (Keewatin) provenance. The bulk of the glacial deposits however, appears to have been laid down during the last (late Wisconsinan) major glaciation. This implies that the study areas were dominated by erosion during the Pleistocene, with each succeeding ice advance removing deposits left by the prior advance. Till that is possibly older than late Wisconsinan was encountered in only 2 of the 19 holes. Abundant striations and landforms indicate that the Rainy lobe advanced into the region from the northeast. Its deposits are overlain by deposits of the St. Louis sublobe, which advanced from the west (Fig. 1).

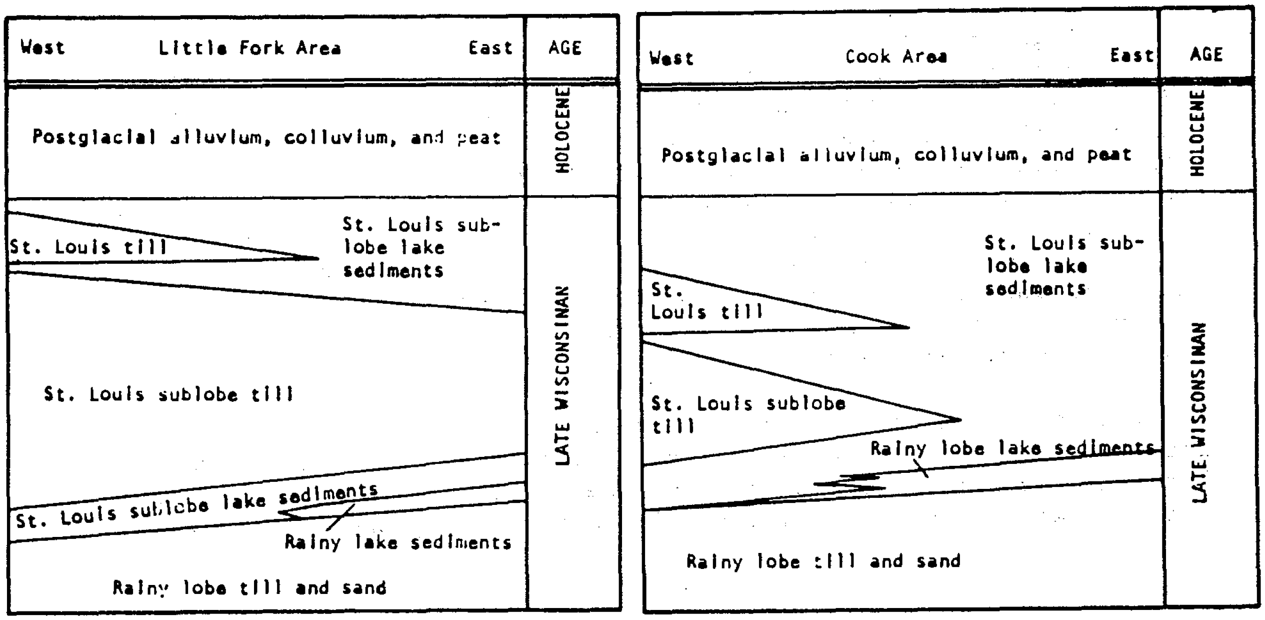

Figure 1. Time-distance diagrams showing relative timing and extent of glacial events in the study areas.

PREVIOUS WORK

Winter and others (1973) mapped and described the Quaternary geology of the Mesabi-Vermilion iron range area on the basis of extensive exposures in the mining district. The northern boundary of their map lies a few miles south of the Cook area. Matsch (1973) did a brief reconnaissance along part of Minnesota Highway 11, which parallels the Rainy River in northern Koochiching County, a few miles north of the Little Fork area. He informally named laminated lake sediment in the area the Little Fork formation, and the underlying clayey till the Indus formation. Eng (1980) mapped the surficial geology of Koochiching County at a scale of 1/2 inch = 1 mile, in support of the DNR Peat Program relying on interpretation of air photos and some field work. The glacial history of both study areas is treated broadly in Wright (1972), and relationships of the regional glacial geology to the rest of the state are shown on the Quaternary geologic map of Minnesota by Hobbs and Goebel (1982).

METHODS

No field work, sampling, or lab work was done by the Minnesota Geological Survey for this study, nor was any geochemistry available. Core was logged in the DNR Minerals Division facility in Hibbing. All locations of water-well, USBM Minnesota clay project, and MNDOT bridge-boring subsurface data on file at the Minnesota Geological Survey are shown on Plates 1 and 2, as are measurements of glacial striation directions. Driller's water-well locations were not checked, and may be imprecise or incorrect. Quaternary stratigraphy and bedrock topography between rotasonic drill holes as portrayed in the cross sections (Plate 3) are largely interpreted from this unconfirmed well information. The cross sections, therefore, should be viewed as only a generalized representation of the Quaternary stratigraphy in each area with the reliable data points being miles apart.

Characteristics noted during logging of the core include texture; Munsell color; reaction to hydrochloric acid; pebble abundance and type; and sedimentary structure. Descriptive logs are given in the Appendix; graphic logs are presented on Plates 4 and 5. Oxidation state and carbonate content were described using terminology adapted from Hallberg and others (1978). Oxidation occurs where the oxygen supply is high and exceeds biological demand. Iron is the element most commonly oxidized, although manganese also readily weathers to an oxidized form and may contribute to the color of the sedimentary matrix. Reduction of oxidized material occurs where oxygen is limited or the biological demand is high, i.e. in zones of saturation or near saturation in the presence of organic materials and micro-organisms. Segments of core were designated as unoxidized if the sediment matrix apparently had never been exposed to oxygen or oxygenated waters.

The terms leached, unleached, and noncalcareous were used on Plates 4 and 5 to describe carbonate content of the core. No reaction to hydrochloric acid indicates the absence of calcium and magnesium carbonate. Such segments were termed leached if they probably once did contain carbonate, and noncalcareous if they probably did not. Segments designated as unleached probably still contain most or all of the original carbonate. The categories are somewhat arbitrary, due both to the complexity of the leaching process and to assumptions made about the original chemical composition of the sediment.

During logging, depths recorded on individual samples were checked against the on-site drill log provided by the DNR to determine actual thicknesses of the various units encountered. Recovery was not always good due to a variety of factors, and cores were sometimes distorted during drilling or following extraction from the core barrel. For example, clay strata tended to expand upon removal from the barrel, and sand lost structure during the vibration drilling and tended to flow following extraction. The true depths of some lithologic contacts may be 1 or 2 feet away from their apparent depth, despite efforts to maintain accuracy.

QUATERNARY UNITS

The Quaternary section in both the Little Fork and Cook exploration areas is dominated by clayey calcareous sediments deposited during the advance and retreat of the northwest-provenance St. Louis sublobe of the Des Moines lobe (Wright, 1972). Sandy noncalcareous sediments of the northeast-provenance Rainy lobe, however, are generally present as the basal unit across both areas (Table 1), and they predominate in the northeastern and southeastern parts of the Cook area. The drift section in the Little Fork area (Fig. 1; Plate 4) is chiefly clayey till directly laid down by ice of the St. Louis sublobe; in the Cook area (Fig. 1; Plate 5) it is chiefly stratified clay and silt deposited in a proglacial lake created by the sublobe. New evidence derived from the DNR rotasonic drilling program indicates that the St. Louis sublobe advanced at least twice into both areas, but did not reach as far southeast into St. Louis County as previously mapped (Winter and others, 1973; Hobbs and Goebel, 1982).

Pre-Late Wisconsinan Till

Only 2 of the 19 holes drilled, both in the Cook area, encountered till units which may be older than the latest advance of the Rainy lobe into the area. About 4 feet (1.2 m) of olive-brown, noncalcareous, loamy, gravelly till was encountered above weathered bedrock in hole OB-212 (Appendix). Both texture and color seemed transitional with the overlying sandy till, and pebble lithology seemed similar, with local rock fragments increasing with depth. The apparent oxidized color of the basal till may simply be due to extensive incorporation of the underlying weathered bedrock.

The basal till in OB-208 also seems to contain much incorporated weathered bedrock. Only about 1 foot (0.3 m) of dark-gray, noncalcareous, loamy till was recovered from a 5-foot (1.5 m) interval above bedrock. This till is overlain by cobbly gravel and sandy till of the Rainy lobe. Its dark color and loamy texture may result from incorporation of a soil layer formed on bedrock prior to late Wisconsinan glaciation. At any rate, both loamy tills were probably laid down by ice moving southwestward across the Cook area. A deposit of oxidized "Keewatin" till was found beneath

Table 1. Summary of drill holes by Quaternary unit
[Intervals in feet below surface; bedrock below lowest interval]

	Post-glacial	St. Louis Sublobe			Rainy Lobe		
OB#		Lake sediments	Sand and gravel	Till	Lake sediments	Sand and gravel	Till
101	0-2.5	29-31 107.5-123	-	2.5-29 31-107.5 123-125	-	-	125-126
102	0-0.5	31-32 157-159	-	0.5-31 32-157	-	176-182.5	159-176 182.5-183.5
103	No core recovery before 65 -	91-119.5	-	65-91	-	-	119.5-122
104	-	25.5-34 77.5-81	-	0-25.5 34-77.5	-	-	81-89
105	0-1	-	10-14.5	1-10 14.5-18	-	18-56	-
106	-	0-13 23-24 82-98.5	13-19.5	19.5-23 24-82	-	-	98.5-108
107	-	0-3 9.5-13.5 48.5-63.5	-	3-9.5 13.5-48.5	-	63.5-142	-
108	0-1	1-12 90.5-93	76-84	12-76 84-90.5	93-96 99-100.5	96-99 126-131.5	100.5-126
109	-	-	-	0-45	-	-	-
110	0-1	1-3 33-37.5	-	3-33	37.5-42	-	42-52
202	-	0-0.5 12.5-14	-	0.5-12.5 14-69.5	-	-	69.5-122.5
204	0-1	1-11 27.5-65	-	11-27.5 65-80	-	-	80-95
206	0-0.5	0.5-32.5 37-75 82.5-94.5	-	32.5-37 75-82.5	94.5-107.5	-	107.5-108
207	-	0-70.5	-	-	70.5-91.5	93.5-97.5	91.5-93.5 97.5-108
208	0-0.5	-	-	-	0.5-12.5 30-97	12.5-30 103-108	97-103 108-113*
209	-	0-39.5	-	-	39.5-52	52-74 75-82 95-99.5	74-75 82-95 99.5-105
210	-	10-21.5	-	0-10	21.5-30	36-47	30-36 47-48
211	0-0.5	0.5-25	-	-	25-36	-	36-56
212	-	0-73.5	-	-	73.5-80	-	80-104†

* Interval from 108' to 113' in OB-208 may be pre-late Wisconsinan.
† Interval from 100' to 104' in OB-212 may be pre-late Wisconsinan.

Rainy till in the Rainy River area (Johnston, 1915), but none was noted in this study.

Rainy Lobe Till

Till laid down by Rainy lobe ice, especially in northeastern Minnesota, is commonly so granular that it meets gravel specifications and is difficult to distinguish from sand and gravel deposits sorted by meltwater. This is due to the till's general paucity of fines, especially in the clay fraction (Zoltai, 1961). The till is essentially unweathered rock debris, and most fines consist of "rock flour." Rainy till is generally hard and compact, and is commonly described by water well drillers as "hardpan." It is unsorted and cobbles and boulders are commonly abundant. Clast content is almost exclusively Precambrian rock fragments, and the sandy till matrix ranges from slightly to noncalcareous. It typically lacks the carbonate and shale characteristics of the St. Louis sublobe till.

Areas of Rainy till, at least between major recessional moraines, were inundated by proglacial lake water and buried beneath lake sediments as the ice lobe retreated. For this reason, all of the Rainy till sections encountered in drilling were unoxidized at the top, and some were thought to have been wave-washed following deposition (OB-102, 209; Appendix). Relatively little water action would be required to remove most fines from the till matrix and create lenses of sand or gravel.

A few Paleozoic carbonate and chert pebbles were noted in cores of Rainy lobe sediment. A rugose coral, typical of the Silurian, was found within a sand sequence between beds of Rainy till in OB-102. Zoltai (1961) found similar fossils in Rainy lobe sediment in northwestern Ontario. It is believed these fossils were eroded from Silurian bedrock in the Hudson Bay lowland rather than from the Winnipeg lowland, on the basis of probable ice-flow direction. Ice of northwestern provenance flowed parallel to the strike of Ordovician bedrock in Manitoba (McRitchie, 1980) and directly into northern Minnesota, whereas ice of northeastern provenance flowed out of the Hudson Bay lowland across the strike of predominantly Silurian bedrock (Ayres and others, 1970 a,b), and thence across the entire breadth of the Canadian Shield. Far-traveled Paleozoic detritus was therefore greatly diluted in drift of northeastern provenance.

Some of the Paleozoic content of the Rainy drift may have been derived through incorporation of older northwest-provenance drift. Some fine carbonate may have been derived as a leachate via ground-water movement from the overlying thick calcareous St. Louis sublobe sediment. This may have occurred in OB-202 where the top portion of the thick Rainy till section is slightly calcareous.

Rainy Lobe Sand and Gravel Deposits

Most of the coarse sand and gravel related to the Rainy lobe advance was probably laid down in deltas near the edge of the glacier (Zoltai, 1961), as drainage to the north would have been blocked by ice. Somewhat finer deposits are thought to have been laid down as turbidity currents in the ice-walled lake, as indicated by fining-upward sequences such as those in OB-102 and 202. The thick sections of sand encountered in OB-107 and 209 appear to partially fill bedrock valleys, but these too may have been laid down by lake currents and may not represent true outwash deposits.

Rainy Lobe Lake Sediment

Slightly to noncalcareous lake sediment believed to be related to the Rainy Lobe was encountered in two holes in the eastern part of the Little Fork area, and in all but the two westernmost holes in the Cook area. Rainy lobe lake sediment may have been removed by glacial ice in the western part of the Cook area where St. Louis sublobe till lies directly on Rainy till. The lake sediment was probably laid down in the same ice-walled lake as the overlying calcareous lake sediment, which was present in most holes drilled in both areas. When the St. Louis sublobe advanced into the lake, it contributed much more clay and silt to the basin than the Rainy lobe ice, which typically had very little fines. The great difference in relative loads of fine sediment in the two ice lobes is probably responsible for the much greater thickness of calcareous over noncalcareous lake sediment in the Cook area.

Slightly calcareous clay and silt beds interbedded with more calcareous beds in the easternmost holes in the Cook area (OB-209, 211, 212), and at the lowest elevations in the Little Fork area, (OB-103, 106) suggest intermittent contributions of eastern-source sediment during the advance of the St. Louis sublobe. A moderately calcareous, dark-gray, laminated clay layer, containing more clay-size particles than clay layers above it overlies Rainy lobe lake sediments in holes OB-206, 207 and 210; it represents the first sediment distinctly related to the St. Louis sublobe in the area. The Rainy lobe lake sediment in these three holes is a fining-upward sequence from fine sand to clay, easily correlated from hole to hole despite elevation differences. Despite a separation of more than 9 miles (14.5 km), correlation is evident between OB-207 and 210, the only sequences noted to include what may be true varves.

A unique band of noncalcareous red clay interbeds was noted toward the top of the Rainy lobe lake sediment section in holes OB-206, 207, and 212. A similar band of red clay was noted by Zoltai (1961) and earlier workers over a very large area in northwestern Ontario, trending northwest-southeast, southwest of and parallel to the Hartmann moraine of the Rainy lobe. The band thins from about 24 to 3 inches (61 to 8 cm), and becomes discontinuous to the southwest. It was not encountered in the 10 holes drilled in the Little Fork area, but Zoltai noted its scattered presence along the Rainy River west of Fort Frances, Ontario. Matsch (1973) also noted reddish-brown clay beds in an exposure near the mouth of the Little Fork River, but it is uncertain if these occurrences along the Rainy River are Rainy lobe lake sediment. The red beds in the Cook area probably were derived from water displaced by an advance of the St. Louis sublobe into the glacial lakes south of the Mesabi range (Wright, 1972).

St. Louis Sublobe Till

Till laid down by the St. Louis sublobe in the two study areas, although easily distinguished from the noncalcareous and very sandy Rainy till, is commonly quite similar to clayey lake sediment found above, below, and within it. The sublobe's clay content was originally derived through erosion and incorporation of Cretaceous shale to the west. Clay content increased at the margins of the ice sheet as it advanced over and incorporated proglacial lake sediment. Depositional environments at the margin of the St. Louis sublobe were analogous to those described for the Rainy lobe, with much sloughing of unsorted material off the ice margin into the lake and rafting of material by floating icebergs. Therefore clayey lake sediment commonly contains abundant dropstones and lenses of loamy till-like sediment, whereas clayey till in places includes beds and lenses of both clay and more sandy, but very poorly sorted sediment.

Where sandy, as in holes OB-104 and 202, St. Louis sublobe till can be distinguished from Rainy till by its carbonate-rich pebble content, and the calcareous nature of its matrix. Cretaceous shale grains, decreasing in abundance to the east in both study areas, occur in the St. Louis till, but not in the Rainy till. In general, the clayey till was distinguished from lake sediments by its lack of sedimentary structure and greater abundance of sand, pebbles, and cobbles. Lake clay also tended to exhibit a sheen on freshly broken surfaces in core. In places the contact between till and lacustrine deposits is interbedded and gradational (OB-102, 107, 110, 204, 206).

In the Cook area, the St. Louis sublobe advanced as a tongue of ice between the Vermilion moraine to the northeast and older recessional moraines of the Rainy lobe to the southwest. However, evidence from the core drilling indicates that the sublobe advanced only several miles into St. Louis County, Rainy lobe sediments to the east being generally buried by thick calcareous proglacial lake sediment.

The St. Louis till was also found to have been laid down in at least two phases in both the Little Fork and Cook study areas. The initial advance was apparently longer lived, as the lower till is much thicker than the upper. Clayey lake sediment separates the two tills in all but OB-105, 109 and 110. Two thin clayey tills are separated by what appears to be coarse ice-contact sand in OB-105. OB-109 and 110 are the easternmost holes in the Little Fork area, and may be beyond the margin of the second advance of St. Louis sublobe ice. The intervening lake clay layer is quite thin especially in the northern part of the Little Fork area. It thickens to the southeast, and in the Cook area it is thicker than either the upper or lower till in OB-204 and 206 (Plate 3).

Evidence of an earlier advance is found in the northwesternmost hole drilled, OB-101, where 2 feet (0.6 m) of calcareous clay till interbedded with lake clay lies below lake sediment and till from two later phases. This thin deposit may have been laid down by an early surge in St. Louis sublobe ice, or may be a far-traveled flow deposit in the proglacial lake. Tills from the two or three phases appear quite similar in a broad sense, but may be distinguishable through detailed texture and grain analysis.

St. Louis Sublobe Sand and Gravel

Thin beds of silty, pebbly, medium to coarse sand within St. Louis till in OB-104 and 108 were laid down underwater at the edge of the ice sheet.

Pebbly coarse sand between two clayey tills in OB-105 is apparently related to an ice-contact deposit mapped by Eng (1980) about 2 miles (3 km) to the northwest. This sand too was probably deposited underwater, but on a topographic high. Thin, clayey till beneath the sand overlies thick sections of slightly to noncalcareous sand that probably was laid down during a still-stand of the Rainy lobe on a bedrock high.

St. Louis Sublobe Lake Sediment

Calcareous lake sediment was encountered in all but 3 of the 19 holes drilled in the two study areas, below, between, and above St. Louis sublobe tills. The lake sediment is primarily clay, but significant silt beds were noted in OB-211 and between the two St. Louis tills in OB-104, 107, and 206. Varved clay and silt occurs toward the top of OB-206 and 209. Very fine sand forms the base of the calcareous lacustrine section in OB-101 and 210. The calcareous lake clay is very thick and massive in OB-207, 212, and 103.

Postglacial Sediments

Four fining-upward sequences encountered at the top of the drift section in OB-106 were included on the cross section with the upper lake sediment. They may represent alluvium laid down in the waning stages of Glacial Lake Agassiz. The hole was drilled near the recognizable floodplain of the Little Fork River, but outside and above it. Pebbly coarse sand is at the base of the three lower sequences.

Thick postglacial alluvium is known from a number of bridge borings near Little Fork to be present beneath the floodplain of the Little Fork River. Similar deposits are inferred to be present along the Big Fork River as well. Forested peatlands and bog deposits cover extensive portions of the low-lying lake plain between major streams in the area (Eng, 1980).

PROSPECTING APPLICATIONS

The primary target in the drift section for prospecting purposes within the Little Fork and Cook areas is the till of the Rainy lobe, which occurs at or near the base of the section in all but 3 of the 19 holes drilled, although it is quite thin in several holes. Rainy till commonly contains abundant locally derived clasts, as opposed to St. Louis sublobe till which contains primarily far-travelled clasts. The high percentage of locally derived material, the sandy gravelly texture of the Rainy till, and the lack of older, underlying drift indicate intense local glacial scouring of the bedrock surface. Thus it is an attractive sampling medium for exploration purposes (Sauerbrei and others, 1985). Rainy lobe-related sand deposits, as in OB-105 and 107, and especially lacustrine deposits, are composed primarily of more far-travelled material and thus are not as useful for property-scale prospecting.

Rainy lobe till and its closely related ice-contact sand and gravel are easily distinguished from St. Louis sublobe sediments by their generally much coarser texture and scarcity of carbonate pebbles. Most St. Louis till in both areas is separated from Rainy lobe sediment by a layer of calcareous, proglacial lake sediment, indicating little incorporation of underlying northeast-provenance drift, and even less incorporation of local bedrock. The lake clay is not continuous across either area, however, as St. Louis till lies directly on bedrock in OB-109 and directly on Rainy till in OB-101, 202, and 204. Till in all of these holes contained indications of probable incorporation of Rainy till. Incorporated sandy material near the base of St. Louis till in OB-106 implies probable overriding of Rainy till. If anomalous heavy mineral or geochemical values are noted in St. Louis till samples, it will be necessary to determine whether the values are primary, derived from local bedrock, or secondary, derived from Rainy till, as ice flow directions for the two advances were nearly perpendicular (Plates 1 and 2).

Glacial Striations

Measurements of abundant glacial striations (Plates 1 and 2) indicate a southwestward to south-southwestward flow for the Rainy lobe (Ojakangas and others, 1977; Southwick, oral communication). The same flow direction is indicated by the trend of Rainy lobe recessional moraines, which were laid down at the ice margin, perpendicular to flow. Seemingly anomalous striation measurements can be shown to correspond to local deviations in the general trend of an individual moraine. For example, striations near Nett Lake (Plate 2) trend nearly due south (azimuth of 188° and 195°), corresponding to an east-west segment of the Vermilion moraine (Hobbs and Goebel, 1982). A striation trending 175° found on an outcrop west of the Cook area corresponds to a segment of an older Rainy lobe moraine to the south which trends slightly northeast from due east.

The above examples of local flow deviation must be considered when working in areas without nearby directional indicators, such as striations and moraines. During exploratory work using till deposits in Saskatchewan, Averill and Zimmerman (1984) found outcrop striations to differ by a 15-degree angle from a gold dispersion train in the till. They concluded that striations record direction of erosion, but not necessarily transport. This provides more reason to consider the trends of local geomorphology, as well as striations, in determining transport direction.

The establishment of prominent moraines by the Rainy lobe, some of which can be traced below the Lake Agassiz plain because beaches tended to form on them (Hobbs and Goebel, 1982), is another factor in favor of using Rainy drift for prospecting purposes. By contrast, the lack of recognizable moraines and the scarcity of striation measurements related to the St. Louis sublobe in the study areas further reduce the attractiveness of its till as a tool for exploration.

Three striation measurements taken from outcrops west of the Cook area and south of the Little Fork area correspond to the expected eastward to east-southeastward flow direction for the St. Louis sublobe in that region. Eleven measurements in the Birchdale-Indus area, about 12 miles northwest of the Little Fork study area, have an azimuthal trend of 85° (Ojakangas and others, 1977) indicating a slight deflection toward the northeast as the sublobe fanned out. St. Louis till in the Little Fork area was therefore probably laid down by ice flowing more or less due east, whereas St. Louis till in the Cook area was deposited by ice flowing more toward the southeast.

RECOMMENDATIONS

Rainy till should continue to be the primary target of future exploration programs exploiting the glacial overburden in northern Minnesota. Most positive topographic features in northwestern St. Louis and in Koochiching Counties can be presumed to be cored by Rainy lobe till or ice-contact deposits, or by bedrock. In a regional program, especially east of the limit of glaciation by the St. Louis sublobe (Plate 2), these features should be investigated by shallow core drilling and by trenching. In the two study areas, Rainy till was more likely to have been eroded by St. Louis ice on topographic highs than on topographic lows. However St. Louis till on topographic highs would have a greater tendency to contain locally incorporated Rainy till and bedrock than elsewhere.

Bedrock topography below the Lake Agassiz plain is apparently as complex and rugged as it is to the east where bedrock forms the surface. A detailed bedrock topographic map--based on bedrock and surficial geologic maps and possibly on electromagnetic and aeromagnetic data--would be necessary for efficient drill-hole siting. Sampling of drift units exposed in cuts along major streams may also prove useful.

ACKNOWLEDGMENTS

Howard Hobbs of the Minnesota Geological Survey and Kevin Malmquist of the DNR Minerals Division assisted in logging core. Dennis Martin and Morris Eng of the DNR Minerals Division reviewed the manuscript. Howard Hobbs also made many useful suggestions.

REFERENCES CITED

Averill, S.A., and Zimmerman, J.R., 1984, The riddle resolved: The discovery of the Partridge gold zone using sonic drilling in glacial overburden at Waddy Lake, Saskatchewan: A paper presented at the 1984 CIM Annual General Meeting, Ottawa, Ontario.

Ayres, L.D., Lumbers, S.B., Milne, V.G., and Robeson, D.W., 1970a, Ontario geological map, west central sheet: Ontario Department of Mines and Northern Affairs Map 2199, scale 1:1,013,760.

__________, 1970b, Ontario geological map, northwest sheet: Ontario Department of Mines and Northern Affairs Map 2201, scale 1:1,013,760.

Eng, M.T., 1980, Surficial geology, Koochiching County, Minnesota: Minnesota Department of Natural Resources, Division of Minerals, Minnesota Peat Inventory Project, scale 1:126,720.

Hallberg, G.R., Fenton, T.E., and Miller, G.A., 1978, Standard weathering zone terminology for the description of Quaternary sediments in Iowa, in Hallberg, G.R., ed., Standard procedures for evaluation of Quaternary materials in Iowa: Iowa Geological Survey Technical Information Series 8, p. 75-109.

Hobbs, H.C., and Goebel, J.E., 1982, Geologic map of Minnesota, Quaternary geology: Minnesota Geological Survey State Map Series S-1, scale 1:500,000.

Johnston, W.A., 1915, Rainy River District, Ontario. Surficial geology and soils: Geological Survey of Canada Memoir 82.

Matsch, C.L., 1973, Quaternary geology of northern Koochiching County: Unpublished report, Minnesota Department of Natural Resources, Division of Minerals, Project no. 36-2, 11 p.

McRitchie, W.D., 1980, Mineral map of Manitoba: Manitoba Department of Energy and Mines, Mineral Resources Division Map 80-1, scale 1:1,000,000.

Ojakangas, R.W., Meineke, D.G., and Listerud, W.H., 1977, Geology, sulfide mineralization and geochemistry of the Birchdale-Indus area, Koochiching County, northwestern Minnesota: Minnesota Geological Survey Report of Investigations 17, 78 p.

Sauerbrei, J.A., Pattison, E.F., and Averill, S.A., 1985, Till sampling in the Casa-Berardi area, Quebec, a case history in orientation and discovery: A paper presented at the 11th International Geochemical Exploration Symposium, Toronto, Ontario.

Winter, T.C., Cotter, R.D., and Young, H.L., 1973, Petrography and stratigraphy of glacial drift, Mesabi-Vermilion iron range area, northeastern, Minnesota: U.S. Geological Survey Bulletin 1331-C, 41 p.

Wright, H.E., Jr., 1972, Quaternary history of Minnesota, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 515-547.

Zoltai, S.C., 1961, Glacial history of part of northwestern Ontario: Proceedings of the Geological Association of Canada, v. 13, p. 61-83.

1987 Discussion of Orr Area Buried Stratigraphy by Kevin Malmquist

Introduction and Previous Work

This project is the first attempt at detailing the poorly exposed stratigraphy of the area. The purpose of this section is to describe the sediments and define the framework within which the geochemical samples must be interpreted. A series of cross-sections correlating the Quaternary units between drill holes and surface exposures were drawn and are available for inspection. Lithologic logs are displayed with analytical data in Appendix 8. Quaternary sediments are subdivided into three groups; Pre-Rainy lobe, Rainy lobe, and Des Moines lobe (St. Louis sublobe). The area is underlain mainly by Archean supracrustal rocks which are folded, faulted, and intruded. Bedrock composition and topography influenced the direction of ice movement and till deposition.

In addition to the previous work cited by Meyer (preceeding section), Norvitch (1962) mapped portions of the Vermilion moraine including its associated outwash fans and beach deposits in the northeastern portion of the Orr area. Wright and Ruhe (1965) presented a generalized regional glacial history of the area. Lehr (in progress) and Lehr and Matsch (1987) mapped portions of the Vermilion moraine and presented depositional models explaining the origin of this ice-marginal feature. Friedman (1981) presents grain-size distribution of Rainy lobe deposits in Lake County for the following: (1) glaciofluvial gravels; (2) ice-margin deposits; (3) outwash; and (4) till. He used that and geomorphic expression, field observations, stratigraphic position, and other data to map his area, but we are limited by the nature of our drill samples.

Discussion of Quaternary History

Glacial sediments representing the advance and melting of three major ice lobes are present in recent DNR drilling in the Orr area (Meyer, this report, 1986).

The earliest advance, probably pre-late Wisconsinan in age, is evidenced by oxidized till (Meyer, this report, 1986) in Rotasonic drill cores OB-208 and OB-212. The exact age and glacial origin of these units is not fully understood.

The second major advance in the Orr area was that of the late Wisconsinan Rainy lobe. This lobe advanced from the northeast to the southwest across the area and terminated in central Minnesota at the St. Croix moraine (Wright and Ruhe, 1965). As this lobe retreated, it formed two end moraines within the Orr area, one occurring in the western portion of the area (hereafter referred to as end moraine #1) and the other, the Vermilion moraine, in the northeast portion of the area. Between these two end moraines, Rainy lobe ground moraine is common. With the Rainy lobe terminus at the Vermilion moraine, a glacial lake formed south of it in the St. Louis County portion of our Orr area (Lehr & Matsch, 1987). Rainy lobe silt, clay, and well sorted fine- to medium-grained sand was deposited within the glacial lake basin. The well sorted sand is probably outwash from the Vermilion moraine and/or the underlying Rainy lobe ground moraine locally reworked by glacial lake wave action (see Map 10-6). Reworking of these sediments probably occurred at several different elevations (Norvitch, 1962).

The third and last major ice advance was that of the St. Louis sublobe of the Des Moines lobe. This advance was from the northwest and is first indicated in the Rotasonic cores by an interbedding of Rainy and St. Louis sublobe glacial lake clays (Meyer, this report, 1986). St. Louis sublobe clays overlap Rainy lobe clays. Two advances of the St. Louis sublobe ice into the lake basin are suggested by two St. Louis sublobe tills separated by thick lake sediments. A third earlier advance of the St. Louis sublobe was recognized in the rotary drill cuttings from OB-20103. Each advance of the St. Louis sublobe deposited a dark gray clayey till containing abundant dolomite and shale pebbles.

The Littlefork River and its tributaries are deeply incised into the glacial sediments, creating exposures as much as 100 feet high. In places, these rivers have cut down to and even through Rainy lobe sediments; however, it appears that the top of this unit is commonly resistant to erosion by the rivers. The formation of these channels was probably initiated by drainage from the glacial lake and enhanced by isostatic rebound. Drainage of these rivers is to the northwest.

Although most of the area is covered by glacial drift, some outcrops are present in the eastern townships. Many of the topographic highs in T64N-R20W, T63N-R20W, and T62N-R20W are interpreted to be bedrock highs covered by a thin blanket of glacial drift. Examples of bedrock knobs covered by a thin veneer of glacial drift have been excavated along U.S. Highway 53 between Orr and Virginia. Although commonly not exposed at surface, the bedrock knobs associated with the Linden pluton are recognizable on topographic maps (T62N-R21W; T62N-R20W; T63N-R21W).

Rainy Lobe Deposits

Advancing from the northeast (Wright, 1965) Rainy lobe ice eroded igneous and metamorphic rock types from the Archean basement and deposited them as a variety of sediments resulting in a variety of landforms. During retreat of the Rainy lobe, two large, bouldery end moraines and intervening ground moraine were deposited within the Orr area.

The oldest end moraine, #1, occurs in the western part of the Orr area and has some surface exposures. End moraine #1 is slightly concave to the north and trends northwest-southeast. It is recognizable along a line from Sec. 15, T63N-R24W to Sec. 17, T62N-R21W. It has been mapped by Hobbs and Goebel (1982) and Eng (1980) and can be readily identified on 7.5 minute topographic maps by its linear shape and relief of 80 to 100 feet. It can be traced for approximately 20 miles across the area and is composed of ice-contact deposits.

Rainy tills consisting of sandy gravel, gravel and gravelly sand, occur between end moraine #1 and the Vermilion moraine. These sediments lie on bedrock and are generally 10 to 25 feet thick. They are recognized in Rotasonic cores and rotary drill cuttings by an abundance of subangular igneous and metamorphic clasts, a paucity of silt and clay, and a poorly to unsorted texture (Meyer, this report, 1986).

The Vermilion moraine occurs in the northeast part of the Orr area. This feature is a northwest-southeast trending linear ridge which commonly extends 100 to 150 feet above the surrounding area and continues for 75 miles (Hobbs and Goebel, 1982).

The majority of the DNR drill holes are located within the area described as Rainy lobe ground moraine. A variety of lithologies and thicknesses were encountered in test holes within the area termed Rainy lobe ground moraine. Seven Rotasonic and 27 mud rotary holes were drilled to delineate this unit. For comparison, two additional Rotasonic holes and one mud-rotary hole were located on features associated with the end moraines. Meyer (1986, this report) identified Rainy lobe tills lying directly on bedrock in all nine of the Rotasonic holes. He described these units as being an unoxidized, sandy, gravelly till which commonly contained pebbles and cobbles of a lithology similar to the underlying bedrock.

Mixing and removal of silt and clay by drilling fluids made genetic interpretation of mud-rotary samples difficult. However, an increase in the amount of +10 mesh cuttings within the basal section of the Rainy lobe unit may suggest that till was present in the mud-rotary holes. Appendix 9-3 contains weight/foot calculations for the +10 mesh drill cuttings from the Rotasonic and mud-rotary drill holes for comparisons.

Lacustrine Sediments of Rainy Lobe

Leverett (1932) cited a glacial lake level at an elevation of 1360 feet in the area near the Vermilion moraine. A survey of gravel pits posted on topographic maps throughout the eastern one-half of the Orr area suggests that many pits commonly occur at or close to this elevation. The impact of this glacial lake on the sedimentological record is recognized as a fining upward sequence of well sorted coarse-to-fine sand and silt within the uppermost Rainy lobe sediments. Six of the Rotasonic cores contain this fining upward sequence of sands overlying till. The thickness of this sequence varies and may relate to the distance from the drill hole to the location of sediment erosion. For example, OB-206 is located within the central part of the lake basin at some distance from the nearest sediment source and contains a relatively thin (less than 3 ft.) sequence of sand and silt. Drill holes OB-210 and OB-209 are located within one-half mile of the Vermilion moraine and contain sand sequences of 20 and 35 feet, respectively. In addition, a silt layer, approximately 15 feet thick, also occurs within the overlying lake clays in OB-209. Drill hole OB-208 contains a massive section (greater than 90 ft.) of well sorted sands. There were numerous islands of Rainy lobe till within the lake. Located in the downwind portion of the lake, these islands may have been situated in a favorable location for the removal of large amounts of sand and silt.

Two drill holes, OB-202 and OB-204, located in the western portion of the study area, contain clayey till (St. Louis sublobe) lying directly on

Rainy lobe till, suggesting the St. Louis sublobe was present in T63N-R22W at the time of this lacustrine deposition in T63N-R20W. Transitional zones of 1 to 5 feet are noted between the Rainy lobe and St. Louis sublobe tills. The remaining Rotasonic drill hole, OB-212, was located directly between two end moraines but did not contain the fining upward sequence of sand and silt. It appears that this hole may be located on a saddle in the bedrock or Rainy lobe till and sediments may have been washed away from the drill hole location.

Although not as evident as in the Rotasonic cores, the fining upward sequence was recognized within the mud-rotary holes as a gradual shift from Des Moines Lobe clay to Rainy Lobe silt and eventually fine sand (see Appendix 9-3, +10 mesh wt/ft graphs).

Rainy lobe lacustrine sediments including very fine silt and clay commonly cap the reworked Rainy lobe sands. Meyer (1986, this report) noted that the noncalcareous Rainy lobe lacustrine sediments are interbedded with the calcareous lacustrine sediments of the St. Louis sublobe.

Des Moines Lobe Deposits

Calcareous lacustrine clays and clayey tills of the St. Louis sublobe were recognized in almost all of the DNR drill holes. Two St. Louis sublobe advances represented by clayey tills were identified within the Rotasonic cores. A third, earlier, advance was identified during the follow-up mud-rotary drilling. These clayey tills are separated by thick sequences of lake clays. Several surficial, calcareous sand deposits within St. Louis sublobe sediments were drilled. In these instances (OB-20201, OB-20104, OB-20303 and OB-20204), the sand deposits were separated from the underlying Rainy lobe till by thick, clayey tills and lacustrine sediment.

Conclusion

Pre-St. Croix phase Rainy lobe, Rainy lobe, and St. Louis sublobe deposits are identified within the area. The average percent thickness of these units, based upon 4500 feet of drilling in 37 holes, is as follows: less than 1% pre-St. Croix phase Rainy lobe, 28% Rainy lobe, and 71% St. Louis sublobe. Dominant cobble and pebble lithologies vary with location and are interpreted to commonly reflect the underlying bedrock. Field investigations of surface exposures and examination of the +10 mesh drill cuttings support this. Rainy lobe sediments can be easily correlated between drill holes, contain the greatest proportion of local bedrock clasts, and have the greatest potential for interpreting the bedrock geochemistry. St. Louis sublobe deposits do not contain large amounts of local bedrock. The percentage of local bedrock lithologies present in glacial sediments is variable and depends upon such factors as bedrock lithology, topography, regolith, degree of fracturing within the bedrock, and variations in basal glacial dynamics (see Table 43-4).

RESULTS AND DISCUSSION

Glacial Drift Geochemistry: Introduction

The raw geochemical data is presented in four ways in the Appendix: (1) the summary information by drill hole sheets; (2) the graphic lithology logs by drill hole; (3) the complete sample information and analysis sheet by drill hole; and (4) total listings by sample fraction.

The gold grain counts, measurements, and descriptions as reported by Overburden Drilling Management (ODM) lab are on the summary information sheet. Also listed on the summary sheets are elements that have elevated values in each drill hole. Time did not permit those to be rigorous statistical values, rather they are intended only as a guide through the large database. Each value, for example, can be easily compared to the regional arithmetic mean value (Table 40-7) for interpretation.

Gary Meyer (MGS) logged, described and compared the Des Moines lobe and Rainy lobe tills in the Rotasonic core samples from both regions (see previous section). In summary, the lower stratigraphic package of the Rainy lobe drift is concluded to be the better sample medium for this regional drift survey. Thus, the emphasis of the discussion shall be the Rainy lobe drift.

The Rainy lobe till is generally sandy but appears to vary if there was an older till, regolith, or other material in its path. It appears to reflect the regional Precambrian bedrock in geochemistry and often the local bedrock. Based upon the geochem sample processing of 120 till samples from both regions, the Rainy lobe till has on average: 6 wt.% silt + clay, from dry screening; 29 wt.% pebbles, from +10M of shaker table; 65 wt.% sand, by difference of above. The till is heterogeneous, however, so the above values can vary considerably.

Regional Summary Statistical Data: Gold Grains in Nonmagnetic HMC

The data has been set up so that it can be sorted to contrast and compare drilling methods, Orr vs. Littlefork areas, and drift types. The Rainy Lobe drift types have been lumped into three subgroups to present the data: 1) "till" includes here samples logged as till and, especially for the mud rotary drilling, gravelly sand; (2) "sand" includes samples logged as vfgr-mgr sand, silt and a couple clay-rich samples; and (3) "gravel" includes samples logged as gravel or vcgr-cgr sand.

The gold data is presented in Table 40-7, where average counted gold grains/10kg and weights and gold assays are compared. Comparing the gold grain counts, the average Rainy lobe till sample of both areas combined requires about 17 kg of till to get one gold grain counted in the nonmag HMC. The till (arithmetic average) has a HMC nonmag gold assay of approximately 163 ppb and a -63 um fraction assay of 3 ppb Au (see discussion of -63 um fraction in later section). There were 304 total samples submitted for gold grain counts, and 89 samples had one or more grains counted by ODM. It is interesting, however, that 25 more samples had 0 gold grains counted but more than 150 ppb Au (often much more) in the HMC assay. No attempt was made here to identify the nature of the gold in those additional 25 samples, yet if the gold is very fine-grained or locked in sulfides or other heavy minerals, then it could be significant. Note, however, that the nonmag HMC gold assay is also imperfect since only a 3/4 split of it is assayed. With that in mind, the 30 highest assays for Au, As, Ni, Cu, and Zn from the HMC nonmag samples are listed in Appendix 9-6.

Comparing the drilling methods, there appears to be little difference between Rotasonic and air rotary methods. The mud rotary samples appear to contain more gold grains, but there are many considerations to the data. Two important notes for the mud rotary samples are that the +10 mesh was scalped off at the drill site, and hole 20801 had 20 gold grains both of which increase the mud rotary samples <u>average</u> gold count. Appendix 9-3 contains graphs of +10 mesh content of mud rotary and Rotasonic samples for comparison. Appendix 9-4 is a discussion of gold grain losses in the mud rotary sampling phase.

Comparing the Rainy Lobe drift sample types, there appears to be some contrast between till and the other two types. For example, the "sand" group has significantly fewer gold grains counted, yet the HMC and -63 micron gold assay averages are not significantly different. In contrast, the "gravel" group has a higher average weight of HMC indicating minor placer-type concentrating processes, yet lower average HMC gold assay, perhaps from dilution.

Comparing the two areas, there was no significant difference in the average values except in -63 micron gold assays. More detailed results are presented for additional elements in Table 40-7B. The average assay for HMC nonmag of Rainy till for Au, As, Fe, Mn, and Co are higher in the Littlefork area. Only Cu, Pb, and Cr are higher in the Orr area. Note also the Des Moines lobe (exotic) till has great contrast in HMC chemistry and weight (g/10kg) compared to the Rainy lobe. The Des Moines lobe has significantly elevated HMC nonmag values of Zn, As, Mo, Pb, Sb, Ba, Hf, and Th and low values of Co and Cu (see hole 102 assays for example). The -63 um sample assay results are complicated by a change in assay lab (feed weight, screening and analysis) for the Littlefork air rotary samples and also by no -63 um samples from the mud rotary drilling.

With that in mind, the Littlefork area Rainy till samples have higher averages for Au, Mn, Cu, As, Se, Sn, Sb, and Pb. Only -63um fraction Cr, Zn, and Mo average higher for Orr area Rainy till samples (from the Rotasonic drilling there).

In conclusion, some background information is now available for glacial drift geochemical samples in these terranes. The Rainy lobe till samples can be contrasted to the Des Moines lobe till samples by number of gold grains, weights of nonmag and magnetic HMC, and analyses. The Des Moines lobe till nonmag HMC carries an exotic regional signature of elevated values of As, Zn, Ba, Cr, Mo, Sb, and Hf. Thus, based upon those analyses, G. Meyer's descriptions of the drift, and the fact that the Rainy lobe generally lies upon bedrock, the Rainy lobe is the obvious choice for geochemical sampling. Variations in the data by region, drilling method, drift type, and sample fraction have been presented. The interpretation of anomalous dispersal trains, whether on the detailed, local, or regional scale, should be less ambiguous because of this information.

Gold Particle Size Data

Gold particle size distributions were determined for the total 218 gold particles found in the Orr and Littlefork areas. The data are presented in Figure 4-8. The summary statistics of gold grains per 10 kilograms of sample feed is presented in Table 40-7. Sixty-seven percent of these particles were in the range of medium sand to very fine sand (largest dimension greater than 63 um and less than or equal to 250 um). Thirty-three percent of the particles were silt size (largest dimension less than or equal to 63 um). One particle had a dimension greater than 250 um. The gold particle data has been sorted and graphed to compare drilling methods and area (Orr vs. Littlefork), with the assumption that the total variability involves more than just these two factors. No significant contrasts are interpreted from the graphs for either drilling method or area. The sluice box/mud rotary/Orr area subgroup, however, was skewed to the finer particle sizes.

These results are good estimates but are imperfect in many ways. They are based upon the Overburden Drilling Management lab reports (see right hand page of each drill hole summary sheet). For example, gold particles less than 25 microns in greatest dimension are not counted. Also, the assays show that 25 of the samples reported with zero gold grains have assays greater than 150 ppb gold, thus they do, in fact, contain gold in some form. In general, trying to replicate gold grain numbers is a topic of its own, whoever performs the work.

Bedrock Samples

Each drilling method produced a different type of bedrock sample:

1. Rotasonic: 3½ inch core, 5 to 10 feet;
2. Mud Rotary: Chips to sand from a tricone bit, 1 to 9 feet;
3. Air Rotary: Sand and some chips from a down-the-hole hammer, 4 to 6 feet.

The bedrock lighologies are reported on the individual logs and on the region maps. The low quality mud rotary bedrock samples were sent to Stu Averill's ODM lab, since they have experience differentiating bedrock from glacial drift (see Stu Averill' report, Appendix 9-5).The bedrock chemistry is reported on the individual drill hole analysis sheets. Time constraints did not permit detailed review of the bedrock samples.

The U.S.G.S. is currently conducting the CUSMAP project in Koochiching County, including the Littlefork Area. The M.G.S. is currently conducting a drilling program adjacent to the western part of the Orr Area, and thus will improve the regional geology map. No attempt was made within this project to improve the regional bedrock geology map with the newly acquired bedrock samples, since the MGS is actively performing that role in an adjacent region.

The regional gravity results and the bedrock samples indicate a previously unreported belt of volcanic rocks striking in a northerly direction through township T63N-R23W. There is an occurrence of gold in the glacial drift in hole 202 in this belt.

All the bedrock cores and chip/sand samples are available in the DNR Core Library for inspection or further analysis. Thin sections are also available for inspection for the Rotasonic and mud rotary samples (see drill hole summary sheets). The M.G.S. provided thin section descriptions for all the Rotasonic core thin sections available.

Till Data Correlation with Bedrock: Nonmagnetic HMC Chemistry and Mineralogy

A few observations should be made concerning the attempt to relate Rainy lobe till composition as reflected in HMC mineralogy, clast composition, and geochemistry to the local bedrock. First, the till at any given site may contain material from detailed, local, or regional dispersal (see discussion in following section). Moreover, studies in Finland of the -63 um fraction of specific ore-bearing dispersal trains at the bedrock source indicate rapid dilution to background or elevated background levels usually within two kilometers (Salminen and Hartikainen, 1985). Finally, there are very few "truth points" on the ground within our survey area upon which to point without hesitation. The bedrock, in fact, is often interpreted from geophysics. In summary, within the larger target area of the tail of any dispersal train (see Fig. 1-2), subtle differences in composition (of any sample fraction selected) must be sought.

Visual observations of the heavy mineral concentrates indicated obvious differences in some of the heavy mineral suites from hole to hole. The data is summarized in as quantitative a way as was feasible (see Table 43-1.) The visual observations are far more striking than the table implies. One probable example of a correlation to local bedrock is the very high sulfide content as well as mica, chlorite, and some delicate gold in sample 18612, hole 20801. Mafic metavolcanic rocks are interpreted to occur for approximately 3 kilometers in the up-ice direction and probably contain the source. Another example is the high pyroxene and amphibole content in sample 17032, hole 207, in the Linden Pluton syenite. This is the best truth point, with the source rocks interpreted to occur for approximately 5 kilometers in the up-ice direction. In short, the mineralogy of at least some of the HMC's appear to relate to local bedrock.

The +10 mesh clasts in Rainy till in holes in the eastern part of the Orr area contain a significant percentage of metasediments. Since the migmatite terrane boundary occurs in the area of the Haley-Vermilion fault system, the metasediments are of local origin. No attempt was made to quantify the amount of metasediments.

Geochemical data in a hole may relate to local bedrock such as the multi-element anomaly in hole 20801. By observing the bedrock samples or interpreting geophysical data, it is possible to group together, for example, all the graywacke holes. Then by averaging the analyses of till samples from those graywacke holes, one can try to fingerprint the bedrock-till associations. Such data is presented in Table 43-2. It appears that the 9 holes interpreted to be on metavolcanics in the Orr area contain higher background values of gold, chromium, arsenic, selenium, antimony, and lead. The Linden Pluton samples have significantly more weight of nonmag HMC, reflecting the high amphibole and pyroxene content.

That high weight appears to have lowered the gold content by dilution. The 8 holes of quartz-biotite-schists of the Littlefork area have the highest gold content. The Littlefork area holes in general contain higher background arsenic contents and lower lead contents.

In review, although there are few "truth points" to confirm the observations, there appears to be a number of correlations between the local bedrock and the Rainy lobe till samples.

Discussion of Some Significant Individual Drill Hole Results

The number of gold particles and the relative abrasion of each gold particle is more important than the HMC nonmagnetic gold assay (Averill, 1986, see Fig. 1-4). The drill holes which had multiple gold particles in Rainy Lobe samples are 107, 202, 209, 20801, 20906, 20804 (see drill logs and gold grain maps). Hole 10303 has an unusual suite of anomalous elements, but no gold grains were counted. Furthermore, many samples contained gold above background in the -63 micron screen fraction (see discussion in next section).

The most significant gold occurrence identified is in hole 20801 in T62N-R20W. It contains 33 particles of delicate gold, much arsenopyrite and pyrite, and elevated values of Se, Ag, Sb, W, Pb, Bi, Sn, Cu & Ni in the HMC which indicates relatively short transport (on the "detailed scale" of Klassen, 1987). Holes 20804 and 20906, with less significant gold occurrences are within 2.5 miles of 20801. It is difficult to assess the details of 20801, because it was drilled by the mud-rotary method, which was lower cost, but provided low quality samples and some loss of gold (see Appendix 9-4).

Another significant gold occurrence is in hole 202 in T63N-R23W (see drill log). The gold occurs at the top of a thick Rainy Lobe till package, indicating a relatively longer transport (on the detailed or local scale). The bipartite distribution (see sample analysis sheet) of the MgO, TiO_2, Mo, and Pb content of the HMC magnetic fraction is interpreted to show the different provenance of the gold-bearing upper part (70-94 ft. interval) of this thick till from the lower part. Elevated values of W and Pb are also present in the HMC at 70-94 feet.

The third significant gold occurrence in the Orr Area is in hole 209, near the bottom of Rainy lobe gravels and till. The source of the high (120 ppm Au in HMC nonmag.) assay was not identified on the gold grain count report. Discussions with Stu Averill, however, lead to the conclusion that one nugget could account for all the gold present. The presence of three gold grains in gravelly sand at 85-95 feet lends support to the interpretation of a potential occurrence in the local bedrock (on a local scale of Klassen, 1987). Elevated values of Pb, W, Se, Cu, and Ni in HMC nonmagnetic and Pb in HMC magnetics are present.

The fourth significant gold occurrence is in the Littlefork Area in hole 107 and surface sample #17557 in T68N-R24W. There are 24 very small gold particles present in a thick sand sequence in hole 107. The weight of the heavy mineral concentrates indicates that some placer-type concentration may have occurred. No elements in the HMC nonmag have elevated values. In the -63 micron screen fraction, however, gold is present in significant amounts (estimated more than 30 gold flakes in sample #16981) and zinc is elevated in two samples. It is very difficult to assess this occurrence.

Downice less than two miles from hole 107, a surface sample of Rainy lobe till(?) was taken in the valley of the Littlefork River in S31 during early reconnaissance work. That sample contains six particles of gold and one is delicate. Again, because of its location near the river, deposition by glacial ice is not certain. In combination, these occurrences in T68N-R24W remain an enigma that cannot be completely discounted at this time.

Finally, in township T69N-R26W, hole 10303 had only two feet of Rainy Lobe till above bedrock, but all sample fractions had multi-element anomalies. The significant elements include Cu, Ni, Co, La, Th, U, Pb, Mo, Au, Ag, and As.

Discussion of Sample Fractions

The concept of this survey is to use only a few drill holes in a township to try to identify the bedrock mineral potential. All four sample fractions (HMC nonmag, HMC mag, -63 micron, and bedrock, see Fig. 3-4, 3-6, and 3-7) in combination yield the most information for base and precious metals to accomplish that. The objective of choosing between the HMC nonmag or the -63 micron fraction as the primary medium remains unresolved due to the ambiguous -63 micron data. A statistical review of that data will continue in an attempt to unravel it.

The HMC nonmag fraction appears to be the most valuable within the typical Rainy Lobe till found in these two regions, since the till for the most part "is essentially unweathered rock debris" (see G. Meyer, Section III). Numerous reports have been written in Canada about detailed surveys, but not regional surveys, using this sample media. Listed in Table 43-3 are general statements about HMC and -63 micron sample fractions.

In comparison, it appears that the -63 micron fraction would be most valuable in townships where gold occurs as primary -25 micron particles, or secondary in regolith, older oxidized tills, or weathered caps of ore zones. Since these are unknown factors, the use of both sample fractions are appropriate in the regional survey.

The Rotasonic drilling -63 um samples (i.e. 3 digit hole numbers, 101, 202, etc.) are not directly comparable to the air rotary drilling -63 um samples (drill number sequence 10102, 10303, etc.). The dry, plastic screening was done at XRAL labs, which took 8 months, on less than or equal to 1 kilogram of Rotasonic sample, and often not enough -63 um was obtained for the 20g gold assay. Thus, for the air rotary program two to three kilograms of feed was used and the screening and analysis done at the Bondar-Clegg lab. Compare the results of hole 107 to 10700 as shown on the Littlefork map 11-5. The larger feed weight of 2 to 3 kg apparently was more effective at concentrating native gold particles. In the section on measured gold grain sizes, a graph is presented that shows 33% of the total gold grains are smaller than 63 microns (largest dimension). Thus, screening is effectively concentrating the gold grains with 33% of the gold particles able to pass into 6 wt. % in the average -63 um Rainy till. A similar case is postulated for Rainy sands, such as hole 107, where the effective concentration appears to be even higher.

The HMC magnetic fraction contributed in many ways to understanding the mineral potential, as cited below. Magnetite is a member of the solid-solution series of the spinel mineral family, thus its major element content (Fe, Cr, Ti, Al, Mg, Mn) varies considerably. Magnetite also may contain a suite of trace elements (Cu, Ni, Pb, Zn, Sn, V, Co, As, Se, Ag, Mo), or inclusions of other minerals such as sulfides which appear to be a potential pathfinder for differing processes of ore deposition (Mather, 1977).

Since magnetite is ubiquitous and easily separated, it is useful in till prospecting. In Sweden, Granath (1982) reported the identification of sulfide-bearing skarns from their distinctive trace element content of magnetites separated from till samples 1-5 kms down-ice from their source.

Drill steel will be collected in the magnetic fraction and may have skewed some of the results due to a communications error with the assay lab. Drill steel, which is malleable, can be significantly eliminated by fine grinding and fine screening (150M to 230M) of the magnetic fraction. The majority of drill steel will remain on the screen.

Five examples of distinctive HMC magnetic fraction composition can be cited from our work. In drill hole 20801, the distincitve trace content of Cr, Ni, Cu, Se, Mo, Ag, Pb, and especially As adds to the significance of the occurrence. According to Macdonald and Fyon (1986), during the sulfidation of banded iron formation, arsenic is the only cation added in significant quantities (up to the percent level). It appears the magnetite found in hole 20801 may reflect such a sulfidation process.

In hole 202, there is a gold occurrence (in the HMC non-mag. fraction) in the upper part of a thick till sequence. According to the simple model of dispersal trains (see Averill, 1986), this implies longer transport (still local or detailed scale). The content of Mg, Ti, Pb, Mo, and Ag of the HMC magnetic fraction seems to confirm this by indicating a different source for the upper part of the till (70-94 ft.) than the lower part.

Thirdly, the Des Moines lobe till appears to have a different magnetite composition and weight than the Rainy lobe till (see Table 40-7). For example, in drill hole 102, the content of Mg, Ti, Cr, Cu, and Pb seems to contrast the two tills.

The fourth example is the high silver content of a limited number, 12 out of a total 124, of HMC magnetic samples (Appendix 9-7). Eleven of these anomalous samples occur 2½ to 8 miles from gold-bearing hole 20801. The twelfth anomalous sample occurs in gold-bearing hole 202. The anomalous samples occur in holes 20801 (5 samples), 20901, 20902, 20906, 20803, 20702, 20704, and 202. Does this reflect a local-scale mineralization event near 20801, since it appears to cover tens of square miles? In contrast to gold or sulfides, the resistant nature of magnetite may permit it to persist in subglacial dispersion in larger, more recoverable sizes over longer distances. Lee (1963) mapped the occurrence of Ag-bearing magnetites in till down-ice from Au mineralization along the Destor-Porcupine Fault in the Kirkland Lake camp.

The fifth example is the expectation for pyrrhotite to report to the magnetics. One unconfirmed example may be in hole 10303, with 1210 ppm Ni in the HMC magnetic fraction.

The lack of information on the HMC magnetic fraction compositions of specific Archean bedrock types, ore deposits, and metamorphic events is a hindrance to understanding the data. Studies are available from other geologic ages (Hamil and Nackowski, 1971; Fleischer, 1965; Tacker and Candela, 1987; de Grys, 1970). Some maximum values (ppm) of certain elements in magnetite were reported by Mather (1977, as reported in Watters and Sagala, 1979, p. 32): 400 Cu, 5000 Ni, 500 Pb, 500 Sn, and 4000 Zn. Saccocia (1987) presented photomicrographs of sulfidized magnetite from Precambrian rocks of east-central Minnesota. Hattori (1987) reports on the theory that magnetite-rich felsic intrusions are favorable mining camp scale targets for Archean Superior Province gold deposits. In conclusion, although questions remain, the HMC magnetic fraction has provided useful clues cited in the above 5 examples to the provenance of till and to different types of mineralization processes.

Detailed, Local, and Regional Dispersal

Theories on the quantification of erosion, transport, and deposition of glacial drift are currently evolving (Shilts, 1976; Clark, 1987; Strobel and Faure, 1987; Salminen and Hartikainen, 1985). To estimate the transport of till at any given site requires the review of many factors, summarized in Table 43-4. In general, till may contain components transported on the regional scale (100's of kms), local scale (10's of kms), and detailed scale (100's of meters to kms) as presented by Klassen (1987). Identification of these components is difficult but can sometimes be accomplished by:

a) regional scale: overall drift particle size distribution, or specific pebble lithology, or a geochemical signature;
b) local scale: clasts of local bedrock types, or specific local mineralogy in heavy minerals, or a geochemical signature; and
c) detailed scale: specific local mineralogy or local geochemistry of various fractions.

The focus of this report is on the results of geochemistry. Samples are available, however, and geologists are encouraged to check the other means (above) of interpreting transport distance. Although it could be helpful, the intent of the project was not to evaluate the specific sites by returning with follow-up drilling, but to try to understand the local and regional geochemistry.

Examples of each transport scale are suggested by the geochemistry and HMC mineralogy. The delicate nature of numerous gold grains in samples of hole 20801 and the extremely high sulfide content of the HMC are indicative of detailed-scale transport. In contrast, the gold grain summary data (less than 1 gold grain/10 kg average Rainy Till) is indicative of metasediments predominating on the local scale. Also, the mineralogy of nonmag HMC presented in Table 43-1 is interpreted to indicate some examples of local-scale transport. Finally, the most obvious example of regional-scale transport is found in the Des Moines Lobe till by any method listed above. That till is extremely clayey, contains limestone, dolomite, chert, ± shale, and has an unusually high content of Zn, Mo, Se, Pb, As, Sb, Ba, Hf, and Th in the nonmagnetic HMC (see hole 102 for example).

GEOPHYSICS

Introduction

Three different types of geophysical investigations were performed: gravity work, seismics depth-to-bedrock work, and VLF-EM and magnetic traverses. Each played a role to better understand the glacial drift geochemistry by providing information about bedrock lithologies and structures.

The following report on the regional gravity work by Dr. Val Chandler of the MGS improved the available data on buried bedrock features. For example, he identifies a previously unmapped metavolcanic belt striking northwest through T63N-R23W. There is an occurrence of gold in the glacial drift in hole 202 over that belt.

The report by Tom Lawler (DNR) describes the seismics and VLF-EM plus magnetics. The seismics tests to determine depth to bedrock provide important information for the regional drilling program. For example, three holes of 100-foot depth each are far more valuable than one hole that is 300 feet deep.

The VLF-EM and magnetics were conducted to locate major fault zones. Where possible, drill holes were sited down-ice (of the Rainy lobe) at varying distances from fault zones (see Maps 10-2, 10-7, and 55-4). Thus, to interpret the geochemistry, fault zone locations relative to drill hole locations are important. For example, there appears to be gold in the glacial drift down-ice from the Haley fault in holes 209 and 20901. In contrast, there is less evidence of gold down-ice from the Silverdale fault (only in hole 20603). The most prominent gold occurrences (holes 20801, 20804, 20906) do not seem to be related to a mapped fault zone. The available evidence at this time, however, is meager, and thus equivocal.

GRAVITY STUDIES IN THE LITTLEFORK AND COOK EXPLORATION AREAS, NORTH-CENTRAL MINNESOTA

by Val W. Chandler, Minnesota Geological Survey

INTRODUCTION

This report summarizes gravity work that was conducted in two areas of north-central Minnesota as part of the Minnesota Department of Natural Resources (DNR) basal till sampling program. New gravity data were gathered in the two regions defined by DNR as the Littlefork and Cook exploration areas (Fig. 1) and the new data were merged with previously existing Minnesota Geological Survey (MGS) data. Because of poor outcrop control, the use of geophysical data is critical to investigating the bedrock geology of both exploration areas. The main objective of this study was to investigate bedrock structure with particular emphasis on the configuration of metavolcanic belts and the location of faults. The Archean supracrustal and granitic belts of northern Minnesota are known to be associated with significant density contrasts, and the gravity method thus provides a useful supplement to geologic interpretation.

The gravity data were acquired by various individuals using different instruments (Fig. 1) and consist of areal coverage using a minimum station interval of 1 mile and detailed coverage using a station spacing of 660 feet along two short profiles. All data were tied into the MGS gravity base network and reduced with the 1930 International Gravity Formula using a sea level datum and a Bouguer density of 2.67 gm/cc. Owing to flat topography in the exploration areas, no terrane corrections were necessary.

Gravity stations for the areal coverage were located at points of known elevation as posted on existing 7.5-minute topographic sheets. In the more remote parts of the exploration areas some elevations were estimated from topographic contours at carefully located stations. The areal gravity data are believed to be accurate to within a few tenths of a milligal. The gravity control for the Littlefork and Cook exploration areas is shown on (Figs. 2-5).

Two detailed gravity profiles were taken in the Cook exploration area (Fig. 1 and 4-7) to investigate details of bedrock structure and to assess the magnitude of ledge effect (bedrock topography buried by glacial till). Gravity stations were taken at 660-foot intervals at points leveled to within a few tenths of a foot and each profile was about 2 miles long. All readings were rechecked and base ties were made every 1 to 1.5 hours. The precision of each station is believed to be better than 0.05 of a milligal. Two Bouguer anomalies were originally calculated, one using a sea level datum and reduction density of 2.67 gm/cc and one using a local datum and reduction density of 2.00 gm/cc. The latter approach is sometimes more appropriate when the local topography and its substrate both consist of glacial overburden; however, both approaches yielded essentially identical anomaly curves and only the 2.67 reduced curves are discussed here. The detailed lines are named "Deer Lake NE" and "Gheen NW" after the names of their respective topographic sheets.

The gravity data were enhanced by calculation of the second vertical derivative (SVD). This procedure tends to eliminate the regional anomaly effect due to broad and deep-seated crustal sources and enhances the anomalies arising from near-surface geology (Nettleton, 1976). Gravity studies over similar rocks in northwestern Ontario (Gupta and Wadge, 1986) reveal strikingly close and consistent relationships between SVD variations and rock type. In areas of vertical structures the zero contour of the SVD gravity approximately traces out contacts, although the highly variable station control in the exploration areas dictate that this correlation be applied with caution. The SVD data used in this study were slightly smoothed by upward continuation of the data to a level of 1.24 miles (2.0 km). The programs used here to derive the SVD data were developed at Purdue University (Reed, 1980).

DISCUSSION OF GRAVITY DATA

Littlefork Exploration Area

The areal gravity expression of the Littlefork exploration area is dominated by an east-striking anomaly gradient between a regional high to the south and a regional low to the north, combining for a total anomaly relief of about 20 milligals (Fig. 2). The present geological interpretation of the region (Southwick and Ojakangas, 1979) indicates metasedimentary rocks that to the south become progressively more invaded and migmatized by granitic rocks. Density determinations from the vicinity indicate that the metasedimentary rocks average around 2.75, whereas most granitic rocks average around 2.70 (MGS open-file data) and, therefore, the gravity signature is in the opposite sense to the density distribution expected from the present bedrock interpretation. Furthermore, the persistence of more negative SVD gravity values in the northern part of the area than to the south (Fig. 3) implies that the paradoxical gravity signature probably arises from near-surface geology.

It is possible that the northern part of the metasedimentary rocks is more felsic and/or the southern part is more mafic than the poor outcrop control shows. Felsic schists are known to occur somewhat sparingly in this metasedimentary sequence to the east in the vicinity of Kabetogama Lake (Ojakangas and others, 1982) and an abundance of these rocks could possibly cause the negative expression over the northern part of the area. This proposed felsic sequence may then grade to a denser composition to the south. Southwick and Ojakangas (1979) reported scattered occurrences of amphibolitic and hornblende-gneissic paleosomes in the migmatitic sequence. The distribution and lithology of the granitic rocks may also in part account for the positive gravity expression over the migmatitic rocks to the south. It is believed that the granitic fraction in the migmatitic rocks generally decreases to the west (Southwick, 1972) and thus relatively little granitic component may actually exist in the western part of the International Falls Sheet. Furthermore, the granitic neosome of the the migmatitic sequence is known to include some earlier phases of tonalitic and granodioritic composition (Southwick, 1972; Ojakangas and others, 1982), which are generally believed to be slightly denser than most granitic rocks.

The SVD gravity data on (Fig. 3) isolate several minor anomalies in the Littlefork exploration area that appear to reflect local geology. Two northwest-striking positive anomalies in T69N, R26W and between R23 and

R24 of T69N, appear to lie along the trend of diabase dikes, although not all dikes known in the general region are associated with such anomalies. The presence of a positive anomaly along some dikes may reflect thick or deep-seated nature not common to all.

In detail the second vertical derivative expression is choppy, perhaps reflecting somewhat chaotic lithic variations in the metasedimentary and migmatitic rocks. Many of these choppy anomalies lie roughly along east-west strikes, parallel to the foliation trends in the area (Southwick and Ojakangas, 1979). There is little evidence in the gravity or SVD gravity data for any major fault zones crossing the Littlefork exploration area.

Cook Exploration Area

The northernmost extension of the Cook exploration area includes the Archean Vermilion Granitic Complex (Southwick and Ojakangas, 1979), whereas the bulk of the area lies south of the Vermilion fault and is underlain by deformed belts of Archean supracrustal rocks (Sims and others, 1970). The gravity and SVD gravity data (Figs. 4 and 5) over the Vermilion Granitic Complex are associated with subtle highs and lows that appear to reflect the ratio of schistose to relatively less dense granitic components in the migmatized terrane. Weak lows outlined by the SVD gravity data in T64N, R20W, correlate with granite-rich migmatites and a low in T64N, R21W, correlates in part with a biotite-hornblende granodiorite body. In contrast, weak highs in the SVD data in T64N, R19W and T64N, R22W correlate with large masses of schist-rich migmatite. The southern margin of the Cook exploration area is dominated by a strong east-striking gravity high (Figs. 4 and 5) reflecting a belt of mafic metavolcanic rocks that are sparingly exposed in T62 and T63N, R22W. A northwest-striking gravity high extending from the main belt through T63N, R23W (Figs. 4 and 5) probably represents a limb of the main metavolcanic belt. A second major volcanic belt along the southern margin of T62N, R21-24W is indicated by a positive east-striking gravity high and scattered outcrops (Sims and others, 1970). Prominent gravity lows in T63N, R24W and in R22-24W of T62N, correlate with what Sims and others (1970) infer to be metasedimentary belts. However, similar negative SVD signatures in northwestern Ontario (Gupta and Wadge, 1986) were found to correlate most commonly with either felsic volcanic or granitic belts. Subdued SVD expression characterizes the east-central part of the area, which is apparently underlain by metasedimentary rocks.

In T62N, R21W and surrounding areas the Archean supracrustal rocks discussed above are intruded by the Late Archean Linden pluton. The pluton is very poorly exposed and is best defined by aeromagnetic data (Chandler, 1983). Exposures include only syenitic rocks near the contact, but a narrow gravity high extending along the axis of the pluton (Figs. 4 and 5) implies a core of mafic intrusive rocks. A minor gravity high projecting a short distance east-northeastward of the Linden pluton near the center of T.63N., R.21W. is tentatively interpreted to reflect mafic metavolcanic rocks. A series of linear northeast-striking magnetic highs with amplitudes of 100-500 gammas lie immediately southeast of the Linden pluton (Chandler, 1983) and are interpreted to reflect other syenitic intrusions. Test hole OB-212, which is drilled on one of these linear magnetic anomalies, encountered syenitic rocks.

The gravity data yield no conclusive evidence of faulting in the area, although existing magnetic data constrain interpretaion in some areas. Aeromagnetic data (Chandler, 1983; Zietz and Kirby, 1970) clearly demark the Vermilion fault, which strikes east-southeast across the northern prong of the Cook exploration area. The subsidiary Haley fault strikes parallel to the Vermilion fault about 3 miles to the south. The area betweeen the Haley and the Vermilion faults correlates with a linear negative gravity anomaly in the NE corner of T64N, R20W, perhaps reflecting a sliver of felsic rocks caught up between the two faults. The Silverdale fault, as mapped by Sims and others (1970), does not appear to have any pronounced gravity effect, nor does it offset northeast-striking magnetic highs revealed by the high-resolution aeromagnetic data (Chandler, 1983) southeast of the Linden pluton. Thus, if the Silverdale fault exists in the exploration areas, it is not associated with any significant lateral offset. The Dark River fault of Sims and others (1970) crosses the western part of the exploration area, where it may correlate subtly with some minor inflections and gradients in the gravity data. However, any definitive statements on the nature of the Dark River fault will have to await the release of high-resolution aeromagnetic data currently in preparation by the U.S. Geological Survey.

DISCUSSION OF DETAILED GRAVITY PROFILES IN THE COOK EXPLORATION AREA

The Deer Lake NE data (Fig. 6) shows a general low near the center of the line, corresponding to the dacitic volcanic rocks encountered in drill hole OB-202. Anomaly values increase toward either end of the line and probably indicate proximity to mafic metavolcanic rocks. The only possible ledge anomaly exists between 0 and 1320 South, although an intrabasement source cannot be discounted. Assuming reasonable density contrast for the ledge-overburden contact, this 1-milligal gravity high would equate to a buried hill around 100 feet in height, and drill hole OB-202 would lie about halfway up its flank. A magnetic high of about 200 gammas amplitude lies along the southern margin of the anomaly (T. Lawler, personal communication). One possible explanation for the hypothetical bedrock ridge might be a diabase dike of the Early Proterozoic Kenora-Kabetogama swarm. Dikes of this swarm are commonly associated with bedrock ridges and the aeromagnetic data indicate a dike may be in the vicinity of our gravity line. However, additional geophysical data and drilling are needed to test the dike hypothesis.

Nowhere on the Gheen NW line (Fig. 7) were prominent anomalies observed that could be easily attributed to ledge effects. A slight rise at the west end of the profile may reflect a bedrock rise to nearby outcrop. The most prominent anomaly is a 3-milligal high centered near 2640 East, which is believed to represent an intrabasement source. The amplitude of this anomaly is simply too high to represent a bedrock ledge rising from a 104-foot depth (drill hole OB-212) to the surface, assuming reasonable ledge and overburden densities. A coincident magnetic high of about 800 gammas amplitude (T. Lawler, personal communication) also argues in favor of an intrabasement origin. This gravity high may reflect a mafic offshoot of the Linden pluton or a mafic source within the metavolcanic country rock.

CONCLUSIONS

The gravity method has been a useful supplement for interpreting the geology of DNR's Littlefork and Cook exploration areas. Existing areal coverage was supplemented by 30 new gravity stations, yielding an average station interval of 1 to 3 miles over most of both areas. The areal coverage was significantly enhanced by calculation of the second vertical derivative (SVD) of gravity, which amplifies the anomaly effect of near-surface geology. In addition to the areal coverage, a total of 34 stations were taken along two detailed profiles in the Cook exploration area in order to investigate some detailed aspects of bedrock geology and to assess the ledge effect in the area.

Gravity and SVD gravity data in the Littlefork exploration area indicates a generally negative expression to the north and a generally positive expression to the south. The anomaly pattern somewhat contradicts the existing geologic interpretation of the area that implies a fairly uniform terrane of moderate density, metasedimentary rocks that become progressively invaded and migmatized to the south by low-density granite. The southward increase in density, as implied by the gravity data, may reflect a stratigraphic transition in the metasedimentary sequence toward denser rocks to the south. Furthermore, the granitic neosome of the southern migmatitic terrane may actually by dominated by intermediate phases. In detail, SVD data in the southern part of the Littlefork area reveal a somewhat choppy signature with generally eastward strikes, consistent with the character and structure of the migmatitic terrane. There are also a few minor, northwest-striking maxima cross cutting the anomaly grain that probably reflect concentrations of mafic rocks along large diabase dikes.

The Cook exploration area includes the Vermilion fault which separates migmatitic terrane to the north from a supracrustal terrane to the south. The migmatitic rocks are characterized by subtle lows over granite-rich zones and highs over schist-rich zones. The Vermilion fault and the sub-parallel Haley fault correlate with minor gravity lows, possibly reflecting felsic rocks caught up between the two faults. A prominent gravity high along the southern margin of the area reflects an east-striking metavolcanic belt and indicates that a branch of this belt extends northwest through T63N, R23W. Prominent negative anomalies flanking the metavolcanic rocks may reflect metasedimentary or felsic metavolcanic rocks. A narrow gravity high along the axis of the Linden pluton may reflect a mafic core. There is little evidence in the gravity data of the Silverdale fault, as mapped by Sims and others (1970), and linear aeromagnetic anomalies southeast of the Linden pluton show no evidence of offset along its proposed trace. The Dark River fault appears to correlate with minor inflections in the gravity anomaly data.

The detailed gravity profiles in the Cook exploration area revealed further detail on the geology of the area. The Deer Lake NE line reveals a central low, possibly reflecting dacitic rocks surrounded by more mafic volcanic rocks. A minor 1-milligal gravity high on this line may reflect a buried topographic high along a diabase dike. Otherwise, bedrock topography appears to be rather smooth along the Deer Lake NE line. The Gheen NW line revealed a 3-milligal high east of the Linden pluton, perhaps reflecting a related mafic intrusion or a sliver of mafic metavolcanic rocks. The otherwise flat expression along the Gheen NW line indicates a rather flat, buried bedrock surface.

ACKNOWLEDGMENTS

The author wishes to thank Bob Horton of the U.S. Geological Survey and Kevin Malmquist of the Department of Natural Resources for their superb efforts in getting off-road gravity data. Bob Tipping and Tim Wahl of the Minnesota Geological Survey assisted in computer compilations. This project was entirely funded by the Minerals Division, Minnesota Department of Natural Resources, as a part of the basal till sampling program.

REFERENCES CITED

Chandler, V.W., 1983, Aeromagnetic map of Minnesota, St. Louis County: Minnesota Geological Survey Aeromagnetic Map Series A-2, scale 1:250,000, 2 pls.

Gupta, V.K., and Wadge, D.R., 1986, Gravity study of the Birch, Uchi, and Red Lakes Area, District of Kenora (Patricia Portion): Ontario Geological Survey Report 252, 98 p.

Nettleton, L.L., 1976, Gravity and magnetics in oil prospecting: McGraw Hill, 464 p.

Ojakangas, R.W., Day, W.C., and Southwick, D.L., 1982, Field Trip 2, Archean Geology of the International Falls - Kabetogama Area, Minnesota: Institute on Lake Superior Geology, 28th Annual Meeting, International Falls, Minnesota, 1982, Proceedings: Sponsored by the Minnesota Geological Survey, p. 89-139.

Reed, J.E., 1980, Enhancement isolation wave number filtering of potential field data: Unpublished M.S. thesis, Purdue University, 88 p.

Sims, P.K., Morey, G.B., Ojakangas, R.W., and Viswanathan, S., 1970, Geologic map of Minnesota, Hibbing Sheet: Minnesota Geological Survey, scale 1:250,000.

Southwick, D.L., 1972, Vermilion granite-migmatite massif, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 108-119.

Southwick, D.L., and Ojakangas, R.W., 1979, Geologic map of Minnesota, International Falls Sheet: Minnesota Geological Survey, scale 1:250,000.

Zietz, I., and Kirby, J.R., 1970, Aeromagnetic map of Minnesota: U.S. Geological Survey Map GP-725, scale 1:1,000,000.

BASAL TILL SAMPLING PROJECT 252 GEOPHYSICS

By T. L. Lawler

INTRODUCTION

Project 252 basal till sampling geophysical survey work had three separate objectives. These were: (1) To test and/or devise a method for cheap, accurate, bedrock depth determinations, with information on glacial stratigraphic units where possible. (2) To locate structures which might be gold bearing and display their relationship to basal till sampling drill holes. (3) To devise and/or test geophysical methods for gathering data, on characteristic geologic features commonly associated with epigenetic, hydrothermal, Archaean greenstone lode gold deposits.

The success of the project depends on sampling basal tills which contain the primary indication of gold mineralization, although there may be some secondary dispersion of gold grains in later glacial sediments. In most places these basal tills will conform to bedrock topography with the deepest deposits in preexisting valleys. Bedrock hills may have been above basal till deposits or have had these deposits removed during periods of inter-glacial erosion.

To achieve objective number one, several geophysical methods were investigated. The method chosen had to work under rigorous physical conditions. Most of the drill sites are on woods roads in heavy timber or swamp. Any method requiring a large loop of wire, laid on the ground, would have a high cost to put out and recover the loop. Bedrock topography is seldom flat, and depth determination accuracy is directly related to the required amount of instrument offset from the drill site. There is also not a large contrast in the physical characteristics of the units to be defined. The stratigraphy of glacial units can be very complex with interfingering lobes and deposit types which change in a short distance.

Electromagnetic or resistivity methods provide an inexpensive estimate of bedrock depths and might give some indication of stratigraphy but they are inaccurate. Seismic methods are more accurate at a large percentage of hole sites but can fail and they are more expensive. In the winter of 1985-1986 the D.N.R. tried some refraction seismic profiles but found that accuracy required placing the geophones well below frozen ground which increased cost. In the early summer of 1986 reflection depth determinations were made at a number of previously drilled sites. These are shown as a black dot with an OB number on figures 55-2 and 3. They were done with a method used by the D. N. R. Division of Waters, described by Stoner and Streitz, 1987. It was found that these depths usually had less than ten percent error when compared with depths from the drill holes, (see table 55-1). At some sites a reflection could be obtained from an acoustic interface between glacial stratigraphic units, although this might not define the stratigraphic units significant for basal till sampling. The depths of these interfaces are shown on the tables under the glacial heading.

After this test reflection seismic methods were chosen as the best compromise between cost and accuracy. In some places glacial deposits are not thick enough for the reflection method and refraction profiles were used. Twenty-six seismic vertical profiles were completed at sites proposed for project 252 drill sites. These are shown on figures 55-2 and 3 as a black dot with a S-number. Those that were drilled are shown with a hexagon around the black dot and the number is underlined.

The second objective was to locate structures which might be gold bearing and display their relationship to basal till sampling holes. In the Little Fork Area there was leasing on known structures where glacial deposits are shallow. In other areas of the Little Fork part of the project, glacial deposits are too deep for the equipment we have on hand. In the Cook-Orr area there were no leases and the east one-half of the area, has shallow glacial deposits, with some outcrop.

Objective two work started with studies of the GEOLOGIC MAP OF MINNESOTA, HIBBING SHEET, Sims, et al., SIMPLE BOUGUER GRAVITY MAP OF MINNESOTA, HIBBING SHEET, Chandler et al., and airborne magnetic surveys. Geologic units and known structures were then plotted on a county map used as a work sheet with land divisions, cultural features, lakes, rivers and overburden drill holes. During late summer and early fall of 1986, over twenty- six miles of magnetic and very low frequency electromagnetic surveys were completed. These traverses are shown on figures 55-2 as double dashed lines numbered from east to west. In two areas structural features were evaluated and then profiles of bedrock depths were surveyed using refraction and reflection seismic methods. If more basal till sampling sites are sought in these areas the profiles will help select them. Profiles are shown on figure 55-2 as solid lines covering parts of the traverses.

Objective number three was to devise and test geophysical methods for gathering data from beneath glacial deposits, on characteristic geologic features commonly associated with epigenetic, hydrothermal, Archaean greenstone lode gold deposits. Epigenetic hydrothermal gold deposits are defined as those formed later than the enclosing rocks, from magmatic emanations high in water content. There is also evidence that metamorphic events contribute to genetic processes, Roberts, 1983. Characteristic geologic features are listed as follows: (1) Common host rocks for this type of deposit are mafic volcanics, of tholeiitic composition, iron formations, and other sediments associated with the volcanics. (2) Most of these host rocks contain ferromagnetic minerals. (3) They are found in structurally prepared sites or permeable units which formed conduits for solution movement. (4) Along the conduit there is an early, pervasive, high temperature and high pressure infusion of quartz and carbonates. (5) Common wall-rock alteration consists of; hydration, loss of silica, and pyritization. (6) At intermediate temperatures, quartz, carbonates, sulfides and gold are deposited in late fractures or areas where earlier quartz has undergone cataclasis. (7) At this stage the quartz-carbonate alteration is more intense. (8) Temperatures of these hydrothermal systems approach 600° centigrade near the heat source and range down less than 100° C. in some epithermal precious metal deposits. Documentation for this information is found in Berger and Eimon, 1983, Boyle, 1979, Boyle, 1980, Boyle, 1987, Cameron, 1988, Cathles, 1981, Edwards and Atkinson, 1986, Hodgson, et al., 1982, Macdonald, 1986, Roberts, 1983, White, 1981, and Woodall, 1979.

Geophysical methods will not detect gold. In the highest grade mines there is an insufficient quantity of gold to change the physical properties of the host rock. However, some of the listed characteristic geologic features of epigenetic, hydrothermal, gold deposits will change the physical properties of the host rock. Compared to host rock minerals, quartz and carbonates are resistant to electrical energy and quartz is resistant to erosion. Wall-rock alteration mineral assemblages and hydration would be more conductive than host rocks, Heiland, 1940 and Keller, 1982. The characteristic conductivity features of a deformed zone invaded by quartz-carbonate can be modeled as a tabular unit of very resistant rock separated from moderately resistant rock by two weak conductors. The very low frequency electromagnetic method (VLF-EM) is sensitive to weak conductors and displays a distinctive response profile when comparing units with a strong conductivity contrast, see figure 55-1A. VLF-EM has limited depth penetration and many of the conductors observed on a normal traverse are from surficial deposits.

Many of the host rocks contain ferromagnetic minerals including; titanomagnetite, pyrrhotite and magnetite. If these minerals are oxidized by ascending hydrothermal solutions or descending surface water and/or they are converted to pyrite by the addition of sulfer the magnetic susceptibility will be reduced. The magnetic susceptibility will also be reduced by dilution of the ferromagnetic mineral content when quartz and carbonates are infused into the fault zone. This would be observed as a smooth, negative, dish shaped feature on a magnetic susceptibility response profile, see figure 55-1B.

When an igneous rock containing ferromagnetic minerals cools through the Curie points of those minerals, their magnetic poles are fixed in the orientation of the earths' field. This also occurs when sedimentary rocks are consolidated. A magnetic susceptibility observation is the vector product of two magnetic moments. These are: (1) The induced magnetic moment from the earths' present field. (2) The paleomagnetic moment from the field when the rock cooled or became consolidated, Dobrin, 1960. The earths pole positions have changed because of continental drift, Telford, et. al., 1978. This changes the orientation of the paleomagnetic moment and reduces the observed magnetic susceptibility. Rotation of a rock unit by structural deformation will produce the same result. If minerals from parts of the rock unit are then reheated through their respective Curie points the paleomagnetic moment will be reestablished. If this happens at a time when the earths pole positions are closer to their present position there will be positive anomalies over the reheated rock, figure 55-1B. Curie points for titanomagnetite are 210° C., pyrrhotite 348° and magnetite 525° to 580° C., Heiland, 1940 and Carmichael, 1984. For most deposits at least some of the ferromagnetic minerals will be heated through their Curie points and the paleomagnetic moment will be reset.

On a sensitive magnetic susceptibility traverse over an epigenetic hydrothermal vein system, two small positive peaks will be observed over reheated wall-rocks. These will be separated by a negative dish shaped feature over the zone of deformation subjected to alteration. The positive peaks will usually have amplitudes from fifty to five hundred gammas and half widths less than 200 feet. The negative feature will usually be about 50 gammas below a local background, figure 55-1B. The described characteristic features can coincide in width with the VLF-EM response defining the pervasive quartz-carbonate alteration or it can be a relatively small part of the profile. It will be found within the limits or at the edges of the quartz-carbonate alteration. Sometimes because of depth of burial, surface deposits, mineral assemblages or an unknown condition within the system only part of the characteristic magnetic susceptibility or VLF-EM features will be observed. These partial features can still provide useful information if tested further by refraction seismic profiles.

Combined VLF-EM and magnetic susceptibility surveys are very economical, refraction seismic profiles are more expensive but confirm the structure and contribute valuable information on the type of alteration, depth of burial and degree of structural deformation. For this project refraction seismic surveys were done at sites targeted by the other two methods. Structural deformation related to epigenetic hydrothermal gold deposits interrupts a relatively horizontal seismic acoustic interface such as the bedrock surface. Seismic energy is propagated down through overlaying deposits and refracted along relatively horizontal interfaces, then back to the surface. Sometimes the first significant interface is bedrock and there is a simple two layer condition to work with. Most often the first significant interface is the water table and the second is bedrock. This is a more complicated three layer condition and the calculations are more complex, but accurate results can still be obtained. Changes in signal propagation velocity caused by physical changes in the rock can be observed in both cases. Structural deformation particularly faulting, or shearing will reduce velocities relative to host rock velocities. Massive sulfides will increase velocities but oxidized gossan will decrease them below that found in the unoxidized structurally deformed zone. The profile will also define bedrock topography. Depressions or bedrock topographic highs related to alteration of structurally deformed areas will be observed as will vertical displacement across faults. Silicification having a low sulfides to quartz ratio forms bedrock ridges, sulfidation with a high sulfides to quartz ratio forms bedrock depressions. Figure 55-1C displays a characteristic refraction seismic profile. For this project four areas targeted by magnetic susceptibility and VLF-EM were tested with refraction seismic profiles.

PREVIOUS WORK

The geophysical methods described in this report have been used for many years. For example seismic methods are a primary exploration tool of the oil industry. Before recent developments in equipment and energy sources reduced the cost and improved data quality, they were too expensive to consider for the objectives of this project. Now we are in the process of trying to modify these methods to obtain useful, high quality, information. This must be obtained working under different physical conditions than those where the methods have previously been successful. The data must also be obtained at a cost that makes the method practical to meet project objectives.

One of the big problems in reflection seismic work is the development of an accurate velocity model of the geologic units surveyed. In oil work they use refraction surveys and down hole velocity measurements to develop a velocity model of sedimentary lithologic units. These units persist for long distances. Oil explorationists have extensive records of velocity measurements in areas where there is a history of oil exploration and spend large amounts of money to develop velocity data in new exploration areas. In the glaciated terrains of northern Minnesota, there is no velocity data available, and glacial units or various types of near surface material have limited areal extent. For example dry peat is a very low velocity unit. There is a complex pattern of peat distribution. Also the water table will rise and fall seasonally, or with the quantity of precipitation. If the velocity model is in error because of a few feet of dry peat, the error will be small when investigating a deep reflector at several thousand feet, but large when investigating a reflector at 100 feet.

The D. N. R. Division of Waters use a rather complex method for shallow reflection depth determinations. They obtain the velocities of near surface unsaturated and saturated deposits using a short refraction profile. Then the velocity of the saturated sediments is projected to the reflector. There is a more complete description in the section on GEOPHYSICAL METHODS, Mooney, 1980 also Stoner and Streitz, 1987. This method worked reasonably well for most of the depth determinations done for this project. A few of the errors observed were caused by small differences in site locations of the seismic profile and the drill hole. Others were caused by dipping bedrock surfaces. We are currently trying to overcome these errors by using a normal-move-out correction in our calculations.

There are several magnetic susceptibility response profiles that indicate faulting, Breiner, 1980. There are also refraction seismic profiles that define structure and measure profile depths to bedrock, Crice, 1980 and Redpath, 1973. Klein and Lajoie, 1980, described electromagnetic response profiles over a conductive vertical sheet. There have also been some case histories of how geophysical methods have been used to help define gold deposits. Sauerbrei, et. al., 1985, presented a detailed description of how electromagnetic , magnetic and induced polarization surveys combined with basal till sampling led to gold deposit discoveries in the Casa-Berardi area of Quebec. Butler, et. al., 1987, describe how induced polarization and electromagnetic methods have contributed to the discovery of several deposits. Stephenson, 1989, describes how aeromagnetics was used to trace an iron formation and map structural deformation of the formation, in the Meen-Dempster area of Ontario. Then he goes on to describe how electromagnetic and magnetic surveys contribute to discoveries in the Muskeg Lake Project by St. Joe Canada. The drilled targets referred to in these papers were: (1) Mostly electromagnetic conductors, indicating a sulfides rich target. (2) Induced polarization anomalies, indicating disseminated sulfides at a shallow enough depth to detect the mineralization. (3) Structures defined by spatial relationships of anomalies rather than characteristic profile features. As <u>used</u> these techniques exclude detection of gold deposits that are: (1) Quartz rich and sulfide poor. (2) Are deeply buried for their size and sulfide content. (3) Do not display spatial relationships of structural deformation. We found no reference to the use of refraction seismic methods for structure definition or depth of burial, which would help evaluate the effectiveness of the other methods. To supplement these references the writer presents in figure 55-1, three idealized geophysical profiles over characteristic geologic features described in the introduction.

GEOPHYSICAL SURVEYS

Seismic surveys have recently become an important addition to geophysical methods used by the mining industry. While their use is not widespread there is increasing acceptance and confidence in survey results. The development of multi-channel, signal enhancement equipment, available at a reasonable cost has made the method more feasible. Data storage and handling by computer techniques have contributed to low cost, high quality, surveys.

For surveys done in conjunction with the basal till sampling program both reflection and refraction methods were used. With the exception of a few sites where glacial deposits are not deep enough for reflection surveys, bedrock depth determinations were done with the reflection method. This applied to both proposed sample sites, objective one vertical seismic depth profiles and objective two profiles for a target evaluation mode of basal till sampling where depth determinations were made at 500 foot intervals. Refraction surveys were used in conjunction with other geophysical methods for objective three target evaluation, and for bedrock depth determinations at sites where drift is too shallow for reflection surveys.

Our surveys were done with a Bison GeoPro, model 8012A, twelve channel instrument which belongs to the D.N.R. Division of Waters. Note: the use of equipment brand names in this report is for identification purposes only and does not constitute endorsement by the Minnesota Department of Natural Resources. Reflection surveys used forty hertz marsh case geophones or eight hertz surface geophones, with a ten foot geophone spacing and varying shot-point offsets to test for reflectors at different depths. A twelve gauge pipe gun, Bison "elastic wave generator" or one third pound charge of Kinepak binary explosive with a zero delay electric blasting cap was used as an energy source. The pipe gun seemed to have a higher frequency and the capability of picking up subtle reflectors which no doubt represent acoustic velocity interfaces within the drift but not necessarily those of interest for basal till sampling. Bedrock reflections are stronger and more easily defined.

Normal reflection survey field procedure located the proposed sample site in a place that would be accessible to a drill rig and had level topography. After flagging the site and laying out the geophone array, shot points would be put in moving away from the array. At most sites several shots were fired to develop a good reflection pattern using the signal enhancement features of the equipment. Seismic records were further enhanced using digital filtering. Long enough offsets were used to obtain refraction data for the determination of the velocities of unsaturated and saturated glacial deposits, and the depth to the top of the water table. These were calculated using the theory and formulas presented by Dobrin, 1960, for a two layer case. This information is then used to develop a two layer velocity model for the drift above the water table and the drift from the water table to bedrock. The velocity model is used to compute a root-mean-squared velocity (Vrms) for N layers to the reflector. The reflector depth is calculated using the Vrms, arrival time of the reflected signal and source to geophone distance, Mooney, 1980, The Vrms is found by using formula (1), and the reflector depth by using formula (2).

$$(1) \quad Vrms = \left[\frac{\sum_{i=1}^{N} divi}{\sum_{i=1}^{N} di/vi} \right]^{1/2}$$

where di = thickness of layer i, and
vi = velocity of layer i.

$$(2) \quad D(\text{reflector}) = \frac{(T^2 Vrms^2 - X^2)^{1/2}}{4}$$

where T = arrival time of reflection signal and
X = source to geophone distance

The algorithm for calculating Vrms requires an unknown value for the depth which is the thickness of the saturated glacial sediments above the reflector. In an iterative approach an estimated depth is used to compute a Vrms which is used in equation (2) to compute a depth. The comparison of the estimated and computed depths determines accuracy. If there is good agreement the depth is accurate, if they do not agree the algorithm is repeated until the difference between estimated and calculated reflector depths meets a suitable error criteria. If done by hand these calculations become cumbersome. A. R. Streitz of the D.N.R. Waters Division has worked out a computer program to perform these calculations and we devised a program for the Hewlett Packard, HP41CX programmable calculator. This program is presented as Appendix 8-3. The procedure is repeated going away from both ends of the array, until accurate depths have been determined for all reflectors. Significant field data is stored on a digital cassette recorder for later computer processing, also site location, shot distance, and field calculated depths are recorded in a field book. Stoner and Streitz, 1987, presented a report at the 21st Annual Meeting of the North-Central Section of the Geological Society of America which describes in detail how this method has been used for locating confined aquifers in glacial drift.

For refraction surveys we use the same equipment and seismic sources except that geophone station spacing is ten meters and we obtain station elevations with a hand level and rod. For target evaluation several spreads may be arrayed end to end and to obtain continuous data the last station of one spread becomes the first station of the next spread. To overcome near surface conditions, geophones are often put in at two or three foot depths with a small hand held, power driven auger. If an explosive source is used, the charge is always augered in to the maximum depth possible and stemmed with whatever is available to get good energy coupling and for the safety of the workers. Shots are always fired at the center of the spread and usually at ten and 100 foot offsets from the last geophone on each end. A time-distance plot with first arrival times noted is prepared at the survey site and layer velocities calculated. From this plot we determine additional shot requirements. In the field book, elevation surveys and location data are recorded as well as first arrival times from each shot location. For the most significant shots data is recoded on the digital recorder and/or a hard copy printed by the instrument.

Refraction seismic profiles are computed using the time delay method as described by Redpath, 1973. If done by hand these computations are very time consuming, cumbersome and subject to mistakes. To overcome these problems we wrote a program for the Hewlett Packard HP-41CX calculator which will work out depths and velocities for either a two layer or three layer case. This program is presented as Appendix B. We had a student worker versed in writing programs in turbo-pascal and he rewrote the program so that it could be used in a computer but encountered a problem because turbo-pascal apparently cannot handle an arc-sine computation which is required. The program is available and works, but arc-sines must be put in when requested. We use a HP 82162A printer with the HP-41CX calculator which provides a hard copy of completed calculations. A rough draft of the profile is usually drawn on the time-distance plot, very soon after the field work is completed.

The survey used a Scintrex IGS-2 combined proton magnetometer and a VLF-4, very low frequency electromagnetic sensor. The magnetometer reads total field and the VLF-EM was set to read the NLK station at Seattle, Washington, tuned to 24.8 KHz. When the NLK station was off the air we used the 24.0 KHz. NAA station at Cutler, Maine or the 24.4 KHz. NSS station at Annapolis, Maryland. The survey used a fifty foot station interval with the 500 foot stations being flagged.

RESULTS OBJECTIVE ONE: VERTICAL DEPTH PROFILES

Cook Area Glacial Till Profiles

The first objective results of trying to determine bedrock depths and information on glacial drift stratigraphic units are shown on tables 55-2 and 3, with locations shown on figures 55-2 and 3. Figure 55-2 is a location map for the geophysical methods used in the Cook-Orr Area. Previously drilled sites used to test the seismic method are designated with hole number, for example OB-209. These results are displayed on table 55-1. Seismic glacial till profile sites are lettered S and numbered one through ten. These were done in September 1986 in preparation for basal till sampling drill holes to be put in during the 1986-1987 drilling program. Of the ten sites surveyed, three were used for drill sites. These are shown on figure 55-2 with a hexagon around the black dot and the number underlined. Of these three one was not completed to bedrock, but the bottom of the hole was at 146 feet and bedrock depth as indicated by the seismic profile is 155 feet. Comparison calculations for the seismic and drilled bedrock depths show a 6.6 percent difference at one site and 1.7 percent difference at the other. Both estimate errors are well below acceptable limits and need no explanation. These results are shown in table 55-2.

In this area the basal till is the St. Croix phase of the Rainy Lobe which moved southwest across the area, Wright and Frey, 1965. Gary N. Meyer, 1986, examined glacial deposit samples taken in the 1985-1986 basal till sampling program. He has a section showing basal Rainy Lobe till and sand covered by Rainy Lobe and St. Louis Sublobe lake sediments. In the eastern part of the Cook Area a reflector from within the glacial stratigraphic units above the bedrock would most likely come from this interface.

In the western part of the area there are interfingering units of St. Louis Sublobe till encroaching from the west. Here it would be almost impossible to determine if a reflector represented the basal till overlain by the lake sediment interface or till-lake sediment interfaces from the fingers of St. Louis Lobe tills. Possibly a continuous profile from a hole where stratigraphic units have been defined could trace some units with a significant reflector.

Little Fork Area Glacial Till Profiles

Figure 55-3 shows the location of geophysical surveys in the Little Fork Area. Tests of the reflection seismic method at previously drilled holes are marked with a black dot and the hole number, for example, • OB-110. The sixteen sites where seismic reflection depth determinations were done for planned basal till sampling holes are also marked with dots and numbered S-11 to S-26. The results at previously drilled holes, those shown as OB-number of figure 55-3 are reported in table 55-1 and the results for planned holes are presented on table 55-3.

Of the sixteen sites where seismic profiles were completed, ten were drilled and nine reached bedrock, drilled holes are shown on figure 55-3 with a hexagon around the black dot and the number underlined. These had estimate errors ranging from two percent to forty-seven percent and averaging 15.7 percent. In a review of the survey and drill data we found several reasons for the errors, some are fairly simple to correct others more complex. At two sites, S-15 and S-18, (OB-10603 and OB-10404) respectively, the drill sites are far enough from the seismic sites to account for the error with less than a 20 degree bedrock slope. At one site, S-22, (OB-10102), the deepest reflector at 203 feet was taken for bedrock, with the top of the Rainy Lobe at 137 feet. Drilling hit bedrock at 136.5 feet with the top of the Rainy Lobe at 119 feet. A normal-move-out correction reduced this 14 percent error to 5.8 percent. At hole (10901), S-11 and hole (10105), S-20, the velocity profile (Vrms) may not be accurate. Using a normal-move-out correction reduced the errors on these two holes from 9 percent and 15 percent to 7.3 percent and 3.6 percent. We think that by using this correction we can reduce estimate errors below 10 percent.

The results on correctly identifying interfaces within the glacial deposits were not as good. A frequency analysis of seismic data and unit thickness showed that with a dominant signal frequency less than 100 hertz we were better able to define thick units. If we can increase the frequency we should be able to define a larger percentage of these stratigraphic units. With the 1988-1989 program we will use fast burning primer cord as a seismic source to develop a higher frequency energy source, and we will use 100 hertz geophones to increase the received strength of higher frequency signals. We anticipate this will improve definition of these interfaces.

RESULTS OBJECTIVE TWO: BEDROCK STRUCTURES

The second objective was to locate structures which might be hydrothermal conduits and sources for gold found in basal till sampling holes. This work was restricted to the southern (Cook-Orr) area. In that part of the Little Fork area where glacial deposits are shallow enough for available equipment to be effective there are State leases. In the Cook-Orr area west of T-7 on figure 55-2, glacial deposits were proven too deep for the methods used. These methods were most effective from T-7 east, the eastern half of the area.

Available geologic and geophysical publications were studied and a work map drafted which we show as figure 55-4. Known faults including: The Vermilion Fault; The Haley Fault and the Siverdale Fault are shown as heavy black lines trending from west-northwest to northwest. Geologic units are also displayed as are the locations of basal till sampling holes. These are described in the section of the report on basal till sampling.

Twenty-six miles of combined VLF-EM and magnetic susceptibility traverse were completed to meet this objective. Shown as T-1 through T-11 on figure 55-2. Printouts of these traverses are available on an open-file basis at the Hibbing Office of the Department of Natural Resources. The equipment and survey procedures for this work are described under geophysical surveys. On figure 55-4, structures located by these methods are shown as short hatchered lines or parallel diagonal lines. The direction is oriented parallel to the closest mapped fault. More work would be required to connect the lines between profiles.

From the limited work completed it appears there is another major fault southwest of the Haley Fault and possibly converging with it to the northwest. The faulting becomes more intense toward this convergence. This fault system is very likely the source of the gold found in hole OB-209, other anomalies are less certain. There is a strong indication of faulting south of hole (OB-20402), S-1, in the SW1/4 of section 36, T.63N., R.22W. This fault was not tested with basal till samples and thus far it is only defined on the single traverse. There is also a weak suggestion of a fault on the magnetic susceptibility response profile just south of hole OB-206 in the southwest corner of section 22, T.63N., R.21W.

At the P-1 profile, hole OB-209, refraction profiles for target evaluation were combined with reflection depth determinations at 500 foot intervals, to produce the depth to bed-rock profile shown in figure 55-5. Note the vertical scale is exaggerated by about 20:1 compared with the horizontal scale. OB-209 was located, by chance, in a perfect place to test the bed-rock high at station 3500N. It probably would not test the target indicated by a VLF-EM crossover at 1500N. The bed-rock depression at 5000N would be a better place to test the target indicated by the VLF-EM crossover at 6750N.

Using the same procedure a similar profile, figure 55-6, was constructed for P-2. OB-210 is in a clearing some distance west of the road. Here there are a number of targets with two indicated by VLF-EM crossovers at 4500N and 10400N. The southern crossover could be tested with a basal till sampling hole at 2500N and the northern one at 7000N or 9500N.

RESULTS OBJECTIVE THREE: TARGETS WITH GOLD DEPOSIT CHARACTERISTICS

Targets displaying geologic characteristics of epigenetic hydrothermal gold deposits as described in the introduction, would have a much higher priority for further evaluation than simple fault zones. As already explained there were limitations on this objective imposed by leases to private industry and depth of glacial deposits. There are no doubt other targets that could have been defined using electromagnetic methods, these methods are being used by private industry. On figure 55-4 fault zones with these characteristics are shown in a crosshatch pattern for those measured with three geophysical methods. A pattern of parallel lines is used where the geophysical data is less definitive. Question marks are added where faults are not well established. In the objective three part of this report the first areas described are those where VLF-EM, magnetic susceptibility and refraction seismic response profiles correlate to define encouraging indications of structural deformation with geologic features characteristic of epigenetic hydrothermal alteration. Then a second group of targets are described which have encouraging VLF-EM and magnetic susceptibility response profiles that correlate to define good target areas. Finally a group of targets are described which have either encouraging magnetic susceptibility response profiles or VLF-EM response profiles but the two methods do not correlate to indicate strong targets.

Traverse 7 Profile 3

Traverse 7, (T-7), shown on figure 55-2, was run north and south from a point +-400 feet north of the southeast corner of section 35, T63N, R22W. This point was station 0 on the profile. Station 1175 north was the midpoint of reflection seismic spread S-1, where eighty feet of glacial deposits were recorded. Metavolcanic rocks outcrop near the south line of section 35. This area is close to the contact with the Linden Pluton which is to the southeast as shown on the Hibbing Sheet of the Bedrock Geology, of Minnesota, Sims, et. al., 1970.

Figure 55-7 shows a characteristic VLF-EM response profile for a very resistive unit in contact with moderately resistive units to the north and south. That is, strong back to back positive and negative swings or half cycles across conductors from weak positive and negative swings or half cycles.

On this profile the north contact is a single weak positive swing and a strong negative swing or half cycle. It can be argued that this is the result of moderately conductive overburden against a steeply sloping bedrock profile rather than a fault contact or alteration conductor. If this is true the shape of the negative half cycle indicates a very steep bedrock slope which at least suggests a fault contact or alteration conductor. The magnetic susceptibility response profile shows no indication of a fault on the north side.

The south side, from station 900S to 1600S appears more broken with four conductors in this interval. Figure 55-8 displays the magnetic susceptibility response profile for this area stacked above the VLF-EM response profile and the refraction seismic profile. Note that the refraction seismic profile has an exaggerated vertical scale compared with it's horizontal scale. Also to clarify detail the seismic profile horizontal scale is expanded in relation to the magnetic susceptibility and VLF-EM response profiles. The center of the fault zone at 1150S is lined up on the three profiles.

The magnetic response profile has the characteristic features of a deformed zone where wall-rock minerals have been heated by a hydrothermal system through their Curie points to reset the paleomagnetic moment. The positive feature from 850S to 1000S defines the north side reheated wall-rocks. The negative feature from 1000S to 1250S is typical of reduced magnetic susceptibility in a zone where ferromagnetic minerals have been silicified, sulfidized and oxidized. This feature is about fifty gammas below a local background. A part of this negative feature is caused by the dipolar nature of magnetism which produces a negative anomaly on the north side of a positive high in these latitudes. That part of the anomaly related to this affect can be judged by the small negative swing between stations 750S and 850S. The positive feature from 1250S to 1550S is wider than would be expected from wall-rock reheating emanating from a single vertical structure. There is a break in the magnetic susceptibility profile at 1450S. Likely heat was introduced along a smaller fault or shear in this area.

In detail there are four VLF-EM crossovers, indicating conductors on the south side of the characteristic VLF-EM response profile shown in figure 55-8. The crossover between 900S and 950S is coincident with the north wall-rock positive magnetic feature. This suggests sulfidation which is common in many Archaean gold deposits. The crossover between 1100S and 1150S is related to deformation, and the third conductor between 1250S and 1300S could be related to either deformation or wall-rock sulfides.

The refraction seismic profile shows bedrock sloping gently to the south with a valley at the north end of the profile. There may be some saturated sediments in the valley indicated by the V_2 velocity of 8,500 feet per second. V_1 velocities over the ridge are consistent with those expected for unsaturated sediments. The gentle bedrock slope to the south is interrupted by a steeply dipping zone of deformation, about 250 feet in width. Within the zone V_2 velocities are reduced from those of undeformed bedrock. V_3 velocities are normal for unaltered Precambrian metamorphic rocks except for the 29,854 feet per second in the north wall-rock area. This is a high velocity and supports the concept of conductive sulfides. There is a slight bedrock topographic high above the deformed zone, indicating a quartz rich alteration with more resistant rock than the host lithologies. Of the profiles examined the P-3 group are most like the idealized response profiles described in the PREVIOUS WORK section.

Years ago there was some prospecting done in this area and a Ms. Violet Hall of Gheen, Minnesota gave us samples of quartz veins bearing chalcopyrite that were taken by her grandfather in the S1/2 of the NW1/4 of section 2, T62N, R22W. Some of this rock was analyzed by the Minnesota Geologic Survey under their Minnesota Public Geologic sample program with the following results, as reported by Morey and McDonald, 1987: The sample number is GSP43 and it contained anomalous indicator minerals of gold deposits including: 15 ppb gold; 181 ppm arsenic; 28 ppm lead; and 215 ppm antimony.

We discussed the sample with Robin Nelson, who, with his brothers, owns the property. We then visited it and were shown outcrop and a test pit about four cubic feet in size with a six inch quartz vein along the west side. The pit is located +-fifty feet north of the farm house, just south of the center of the NW1/4 of section 2, T62N, R22W. Float around the pit and a small rock fragment from the quartz vein all display copper mineralization. More extensive copper mineralization was observed in one part of the vein about 2.5 by 3 inches in area. From a visual inspection we have no doubt the sample submitted by Ms. Violet Hall is a "grab" sample of parts of the vein containing high quantities of chalcopyrite.

Traverse 2 Profile 1

In the 1985-1986 basal till program hole OB-209 was drilled on the west side of the road in the NE1/4 of the SE1/4 of section 16, T63N, R20W, figure 55-2. The hole contained some encouraging samples and P1 was put in to further investigate the results. The traverse started south of the southeast corner of section 16 and ran north along the road between sections 15 and 16, then continued along a trail and brushed section line between section 9 and 10 to the Willow River, figure 55-2.

On the traverse there are two VLF-EM crossovers. Detailed geophysical response profiles from the southern crossover are displayed on figure 55-9. The VLF-EM, magnetic susceptibility and refraction seismic responses display many of the features which would define geologic characteristics of epigenetic hydrothermal gold deposits. Although some features are displaced or incomplete.

The refraction seismic profile provides much of the basic information needed to interpret the geophysics. There is a distinctive bedrock ridge from 1050N to 2000N. It has an abrupt slope to the south and a more moderate, longer slope to the north. The ridge has a lower bedrock velocity, 17494 ft./sec., then the bedrock to the north, 24244 ft./sec.. We interpret this as an early, pervasive, resistant silica-carbonate alteration of a structurally deformed host. The north slope has been eroded deeper and is more modified by erosion. On the slopes three layers are defined including unsaturated surface, saturated surface and bedrock. Over the ridge this is reduced to two layers of somewhat saturated surface and bedrock. These features could result in part from down slope drainage.

The magnetic susceptibility response profile has two fairly distinctive positive anomalies peaking at 1000N and 1900N. The southern one is just over 100 gammas amplitude and the northern one about 60 gammas. These are the right amplitude, but are somewhat wider than would be expected from reheating of wall-rock mineral assemblages through their Curie points by heat from the silicified zone mapped on the seismic profile. There could be thin vertical faults not observed at the scale of these surveys. On the profile there is a small negative feature peaking at 1250N which would indicate intensive silicification, with dilution of ferromagnetic minerals, there might also be oxidation and sulfidation of these minerals but no increase of conductivity is indicated. The lower amplitude of the north positive anomaly would be consistent with deeper wall-rock burial.

The VLF-EM profile displays one half of the features expected from a resistant unit of pervasive silica-carbonate alteration, with wall-rock alteration conductors in a moderately conductive host rock. There is a negative swing or half cycle peaking with -14 at 1300N-1350N, then a positive swing or half-cycle peaking with a +91 at 1800N. The crossover, (conductor), is between 1450N and 1500N. If it were measuring a wall-rock alteration conductor of the pervasive silica-carbonate phase of the hydrothermal system, the conductor should coincide with the north edge of the southern magnetic susceptibility anomaly. Also the south edge of the ridge defined by the refraction seismic profile.

It appears the magnetic susceptibility profile and the refraction seismic profile are measuring the affects of early high temperature pervasive alteration. The VLF-EM is responding to a late, moderate temperature event. The north half of the characteristic VLF-EM response profile has been eliminated by deeper erosion and glacial deposits too deep for the method to penetrate.

On traverse 2 profile P-1, figure 55-10, the second VLF-EM crossover is at station 6750N on the section line between sections 9 and 10 of T63N, R20W. This is on a ridge which has a thin soil covering. Just to the east there is outcrop with some silicification. This would be a good target area for the gold found in hole OB-209 to the south. The VLF-EM does not have the distinctive response profile of a very resistive unit in fault contact with a unit of normal resistivity. Rather it marks a fault near the center of a unit resistant to erosion as shown by the seismic profile on figure 55-10.

The magnetics are generally irregular with nothing distinctive in the immediate area of the VLF-EM crossover. There is a distinctive positive peak at 6150N which is probably the south edge of the silicified fault zone. The feature has sharp negative anomalies on both sides of the 100 gamma positive anomaly. This suggests an oxidized zone at the fault contact with some late additions of a mineral with modest magnetic susceptibility. There is a second smaller positive peak at 7550N. which could mark the north edge of the zone. Note that both the south and north positive peaks are coincident with the edges of the ridge defined by the refraction seismic profile.

The seismic profile is the real basis for the interpretation of this area. The VLF-EM features and magnetic anomalies are not coincident and without the seismic work would be interpreted as being unrelated with little economic interest. On the seismic profile the bedrock ridge with shallow soil cover is immediately apparent. This means the VLF-EM conductor is a bedrock feature not a surficial conductor. The steep slopes at the edges of the high indicate a resistant geologic unit forming the ridge. This is consistent with the silicified volcanics observed in outcrop, east of the traverse. The VLF-EM crossover is on the south edge of distinct late faulting defined by three acoustic layers with lower velocities near the center of the ridge. With the shallow surface and encouraging structural and alteration features a phase induced polarization survey might prove very valuable for selection of bedrock drill sites. Dr. Philip G. Hallof and Mitsuru Yamashita, 1984, of Phoenix Geophysics Limited have presented several papers describing the use of induced polarization to locate gold bearing sulfide mineralization with survey results from a number of properties. These papers are listed in the bibliography and can be obtained from the company. Magnetic, VLF-EM and seismic traverses and profiles profiles which haven't been fully used for this report are on open file at the D. N. R. office in Hibbing, MN and copies can be obtained upon request.

Traverse 4 Profile 2

Hole OB-210 is located in the SW1/4 of the SE1/4 of section 25, T64N, R21W, it contained some gold although not as much as OB-209. Traverse number four (T4) was put in and then part of it profiled with refraction and reflection seismic methods, (P-2), to define gold potential target areas.

There are a number of targets indicated by seismic work but only one area where all three methods combine to define a potential gold area. This area will be reviewed in detail.

This target is between 10000N and 10800N on the east side of section 24, T64N, R21W as shown on figure 55-11. The magnetic susceptibility response profile is typical of late hydrothermal resetting of a fault zone wall-rock paleomagnetic moment. The slightly stronger magnetic susceptibility on the south side of the fault suggests a steep dip to the south. The shape of the VLF-EM profile in the immediate area of the crossover appears to confirm this but the refraction seismic survey indicates a nearly vertical feature. The fault zone is clearly defined by the refraction seismic profile with a reduced velocity in the zone and development of a third layer. The fault is directly coincident with the oxidized zone indicated on the magnetic response profile. The VLF-EM conductor correlates with the magnetic wall-rock peak on the north side of the fault which suggests a response to conductive sulfides in the wall rock rather than the fault zone. The three methods have combined to define a target with gold potential. This could be further tested with a basal till sampling hole in the bedrock depression at station 9500N as shown on figure 55-6 or by more geophysical work. A phase induced polarization survey would be a good way to define these targets.

The wider fault zone to the north, (11100N. to 11750N.), figure 55-11, is also an excellent target as defined by the refraction seismic profile. The bedrock ridge indicates a rather wide silicified zone which in turn has been broken by more recent faulting. The magnetic profile indicates high temperature resetting of wall-rock paleomagnetic moments on some of these late faults. There is a relatively strong peak at 11600N., another more moderate peak at 11350N. and a weak anomaly at 11050N. The curves between the peaks are reasonably smooth dish shaped features suggesting some oxidation. There is no VLF-EM support for the faulting within this zone. The openings may have been healed with silica so that the whole unit is resistive. Target evaluation basal till samples at 10950N. would evaluate this target.

Traverse 3

This zone has not been surveyed with the refraction seismic method and therefore is shown on figure 55-4 with parallel lines bracketed by question marks. Traverse 3, (T-3), started at the center of section 21, T64N, R20W and ran south along county road 119 to the southeast corner of section 5, T63N, R20W. Near the south end of the traverse are some granite outcrops and associated with these outcrops are two crossovers; a modest conductor at 16950S and a much stronger conductor at 18000S.

This VLF-EM response profile is shown on figure 55-12 below the magnetic response profile. Both suggest a fault zone, or possibly parallel faults. The very strong positive in phase VLF-EM observations between 17200S and 17900S are caused by a very resistive unit which is probably the granite intrusive or silicification. The positive magnetic features having an amplitude of 50 to 100 gammas could be mapping a late infusion of minerals with a modest magnetic susceptibility in fault openings, or resetting of wall-rock paleomagnetic moments by a 200°C.-600°C event, although the anomaly to the north has a wide half width for simple resetting of the paleomagnetic moment. This area should be evaluated with refraction seismic profiles then tested for gold mineralization, it would be a good target for skarn type mineralization.

Traverse 1

Traverse number 1, (T-1), starts at the southwest corner of section 35, T63N, R20W and runs northeasterly along state highway 73 for 15,550 feet ending at the junction with county road 481. On the magnetic susceptibility traverses there are a number of very sharp one or two station anomalies related to man made fabrications, mostly culverts. Removing these there are some very broad low amplitude, (150 gamma) features related to deep geologic sources and one interesting feature between stations 9400N and 11400N.

This feature, shown on figure 55-13 has a modest anomaly of 150 gammas amplitude and a half width of 400 feet. On the north side there appears to be three fault zones with hydrothermal reset of wall-rock paleomagnetic moment and oxidation in the center of the zones. The reset of the paleomagnetic moment in the fault on the north side of the positive anomaly results in a sharp two station positive spike of about 170 gammas peaking at 10000N. This is most likely a major fault with lesser faults to the north indicated by small positive anomalies peaking at 10350N, 10850N and 11350N. Between the northern peaks are dish shaped curves suggesting oxidation.

Traverse number 1 also displays some VLF-EM features which should be further evaluated, although they do not have support from magnetic susceptibility responses. These are displayed on figure 55-14. On the profile between stations 2600N. and 3600N. there is one crossover with a strong positive half cycle to the north and a very weak negative swing to the south. This suggests a contact between a resistive unit and a unit with very moderate resistance. There could be a fault contact but it is questionable.

North of this, between stations 11800N. and 13100N, is a good example of a response resulting from a very resistive unit between moderately resistive units. The shape of the curve on the south side suggests a steep contact, probably a fault, but the lack of a good crossover indicates a tight nonconductive contact. Since this could result from silicification in a fault zone this area should be further evaluated.

Outcrops were observed in the area between 13600N. and 15400N. This crossover also suggests a fault contact between a very resistive rock unit and a moderately resistive rock unit, although it is likely a steeply dipping bedrock profile. The crossover on the south side and some of the erratic swings of the vertical in phase component should be further evaluated particularly the area of 15150N..

Traverse 4 VLF-EM and Mag. Sus. Anomalies

In addition to the mineral potential targets described which have seismic support under traverse 4, profile 2, there are four other areas of interest on traverse 4, (T-4). Three of these are VLF-EM response profiles shown on figure 55-15. All three indicate good near surface conductors which should be further evaluated.

On T-4 there is also a magnetic susceptibility response profile that has a shape resulting from faulting with the north side down thrown, figure 55-16. Because there is no positive peak on the north side the fault zone appears to dip to the south. The positive anomaly on the south side indicates the paleomagnetic moment has been reset to increase magnetic susceptibility. This area should be further evaluated for gold potential.

West of S-1 glacial deposits become deeper, greater than 100 feet, as indicated by these surveys. VLF-EM surveys do not penetrate deep enough to map bedrock features. Magnetic susceptibility surveys are still effective for defining larger geologic units and gross structural features but lack the sensitivity to define subtle features such as those described from the traverses to the east.

RECOMMENDATIONS AND CONCLUSIONS

The objective one determination of bedrock depths and profiles at planned basal till sample sites are very important for an effective basal till sampling program. The stratigraphy of glacial deposits is less important but would help in planning and obtaining good basal till samples. Project 252 geophysical surveys show this can be done at reasonable cost with less than fifteen percent average error on bedrock depth determinations. We believe the accuracy can be improved. It is more difficult to define stratigraphic units within glacial deposits and those defined might not always be an interface important to the sampling program. The D. N. R. should continue making depth determinations at all basal till sample sites.

In areas where glacial deposits are less than fifty feet deep, detailed very low frequency electromagnetic and magnetic susceptibility surveys can effectively define lithologic units, structure, indications of alteration and hydrothermal events often associated with gold mineralization. With other methods they can be used to complete objectives two and three. Targets developed with VLF-EM and magnetic susceptibility methods can be further evaluated with refraction seismic profiles. Following target definition bedrock profiles can be surveyed using both refraction and reflection seismic methods to locate optimum basal till sample sites for target screening prior to an expensive core drilling program. This completes the second part of objective two.

In the eastern half of the Cook-Orr area these methods worked very well to complete objectives two and three, that is to define targets having characteristic features of epigenetic, hydrothermal gold deposits and map a bedrock profile to select optimum sites for basal till sampling holes. In areas of deeper glacial deposits as defined by seismic work, the D. N. R. should consider using a method such as magnetotellurics in combination with magnetic susceptibility to meet these objectives.

ACKNOWLEDGEMENTS

The seismic gear used for this project belongs to the D. N. R. Division of Waters. Their cooperation and help is appreciated. Particularly helpful were Andrew Streitz and Pat Bloomgren.

In the field Jay Niebuhr and Kevin Malmquist provided valuable assistance with geophysical surveys including equipment repair and operation. Jay's expertise in repair, design and construction of needed equipment was appreciated. Kevin also helped resolve survey problems with a good understanding of local Quaternary geology.

REFERENCES

Berger, Byron R. and Eimon, Paul I., 1983, Conceptual models of epithermal precious metal deposits: in Shanks, W. C. ed., Cameron volume on unconventional mineral deposits: Am. Inst. Mining Metall. and Petroleum Engineers, Inc. p. 191-205.

Boyle, R. W., 1979, The geochemistry of gold and its deposits: Canada Geol. Survey, Bull. 280, 584 p.

--- 1980, Gold deposits: A review of their geological and geochemical setting: in Hodder, R. W. and Petruk, William, eds., Geology of Canadian gold deposits: The Canadian Inst. of Mining and Metall., Special Vol. 24, p. 1-5.

--- 1987, Gold history and genesis of deposits: Canada Geol. Survey, New York, Van Nostrand Reinhold Co., 676 p.

Breiner, Sheldon, 1980, Chapter 5 magnetics, applications for portable magnetometers: in Richard Van Blaricom, comp., Practical geophysics for the exploration geologist: Spokan, WA., Northwest Mining Assoc., p. 205-237.

Butler, H. R., MacGibbon, A. T. and Church, J. F., 1987, New approaches detailed for gold exploration in the Canadian shield: Mining Engineering, Feb. p. 103-106.

Cameron, Eion, M., 1988, Archean gold: Relation to granulite formation and redox zoning in the crust: GEOLOGY, Vol. 16, p. 109-112.

Carmichael, Robert S., 1984, Magnetic properties of minerals and rocks: in Carmichael, Robert S., ed., Handbook of physical properties of rocks: Florida CRC Press Inc., Vol. II, p. 229-287.

Cathles, L. M., 1981, Fluid flow and genesis of hydrothermal ore deposits: ECON. GEOL. 75TH ANNIV. VOL. p. 424-457.

Chandler, V. W., Jirsa, M. A. and Ikola, R. J., 1985, Simple bouguer gravity map of Minnesota, Hibbing sheet: Minnesota Geological Survey, Misc. Map Series, Map M-56, Univ. of MN.

Crice, Douglas B., 1980, Chapter 4 seismic, applications for shallow exploration seismographs: in Richard Van Blaricom, comp. Practical geophysics for the exploration geologist: Spokan, WA., Northwest Mining Assoc., P. 165-203.

Dobrin, Milton, B., 1960, Introduction to geophysical prospecting: New York, McGraw-Hill, Inc., 2nd. Ed., 446 p.

Edwards, Richard and Atkinson, Keith, 1986, Ore deposit geology and its influence on mineral exploration: New York, Chapman and Hall Ltd., 446 p.

Hallof, Philip G., and Yamashita, Mitsuru, 1984, The use of the induced polarization method to locate gold-bearing sulfide mineralization: PHOENIX Geophysics Ltd. Markham, Ontario, Canada, 19 p.

-----, Phase ip results known gold orezones eastern Canada: PHOENIX Geophysics Ltd. Markham, Ontario, Canada, 5 p.

-----, Gold-bearing sulphide zones northwestern Quebec detected by phase ip surveys: PHOENIX Geophysics Ltd. Markham, Ontario, Canada, 9 p.

-----, Phase ip results known gold orezones: PHOENIX Geophysics Limited, Markham, Ontario, Canada, 3 p.

Hansen, D.A., Hallof, Philip G., Guion, D.J., Crice, D.B., Breiner, Sheldon, Klein, J., and Lajoie, J.J., Compiled by Van Blaricom, Richard, 1980, Practical geophysics for the exploration geologist, Northwest Mining Association, Spokan, WA. 303 p.

Heiland, C. A., 1940, Geophysical exploration: New York, Prentice-Hall Inc. 1013 p.

Hodgson, C. Jay, Chapman, R. S. G. and MacGeehan, P. J., 1982, Application of exploration criteria for gold deposits in the Superior Province of the Canadian Shield to gold exploration in the Cordillera: in Levinson, A.A., ed., Precious metals in the northern Cordillera: Assoc. of Expl. Geochemists, Proc. of a Symposium Held Apr. 13-15, 1981 in Vancouver, British Columbia, Canada. p. 173-206.

Keller, George V., 1982, Electrical properties of rocks and minerals: in Robert S. Carmichael, ed., Handbook of physical properties of rocks: Florida, CRC Press Inc., Vol. I, p. 217-293.

Klein, Jan and Lajoie, Jules J., 1980, Chapter 6 electromagnetic, electromagnetic prospecting for minerals: in Richard Van Blaricom, comp., Practical geophysics for the exploration geologist: Spokan, WA., Northwest Mining Assoc., P. 239-293.

Macdonald, A. James, ed., 1986, Gold 86: An international symposium on the geology of gold deposits: Toronto, Canada, GAC, SEG, MNDM, OGS, TGDG, Proceedings Vol., 517 p.

Meyer, Gary N., 1986, Open File Report, Quaternary stratigraphy of the Cook and Little Fork exploration areas, northern Minnesota: Report Submitted to the D.N.R. Minerals Division, April 30, 1986.

Mooney, Harold M., 1980, Handbook of engineering geophysics, Vol. 1: seismic: Bison Instruments Inc.

Morey, G. B. and McDonald, L. L., 1987, Analytical results of the public geologic sample program, 1985-1987 biennium: Information Circular 25, Minnesota Geological Survey, Univ. of MN., St. Paul.

Redpath, Bruce B., 1973, Technical Report E-73-4 seismic refraction exploration for engineering site investigations: Livermore, California, U. S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory, 51 p.

Roberts, R. Gwilym, 1983, Ore deposit models #11. Archean lode gold deposits: Geoscience Canada, Vol. 14, Number 1., p. 37-52.

Sauerbrei, J. A., Pattison, E. F. and Averill, S. A., 1985, Till sampling in the Casa-Berardi area, Quebec a case history in orientation and discovery: A Paper presented at the 11th. Inter. Geochem. Expl. Symp., Toronto, Canada, Apr. 30, 15 p.

Sims, P. K., Morey, G. B., Ojakangas, R. W. and Viswanathan, S., 1970, Geologic map of Minnesota, Hibbing sheet, bedrock geology: State of Minnesota Geol. Survey, Univ. of Minnesota.

Stephenson, John, 1989, Grassroots gold: The Northern Miner Mag., Sept., 5 p.

Stoner, Jeffrey D. and Streitz, Andrew R., 1987, Locating confined aquifers in glacial drift with seismic-reflection methods, western Minnesota: A Paper Presented at the 21st Annual Meeting, North-Central Section of the Geological Society of America, St. Paul, Minnesota, 49 pp.

Telford, W. M., Geldart, L. P., Sheriff, R. E. and Keys, D. A., 1978, Applied geophysics: New York, Cambridge University Press, 860 p.

White, Donald E., 1981, Active geothermal systems and hydrothermal ore deposits: ECON. GEOL., 75TH ANNIV. VOL., p. 392-423.

Woodall, R., 1979, Gold-Australia and the world: in GOLD MINERALIZATION, Issued Jointly by the Geology Department and the Extension Service, The University of Western Australia, Publication No. 3. p. 1-34.

Wright, H.E., Jr., and Frey, D.G., Eds., 1965, The Quaternary of the United States: Princeton University Press, Princeton, N.J., 870 p.

CONCLUSIONS

Cazalet (1973) aptly summarized the broad requirements of a successful exploration survey as he tested the application of (surficial) glacial drift prospecting for base metals in Europe. Two of his criteria are especially pertinent, namely, that the method should reduce the area to be further explored and to provide further assessment of the expectations of occurrences found. This DNR regional survey achieved both of those requirements by designating townships with occurrences and providing samples and a database from which to assess each occurrence. It is difficult to further rate this regional survey because it is based upon a new, unproven conceptual model described in the Introduction, there are many variables to be tested, and there were no good "truth points" (gold mining camps) in the survey areas or Minnesota on which to test it. Moreover, all the primary objectives listed in the Introduction were completed.

The results confirm that this method is an appropriate means to survey the regional mineral potential where Rainy lobe till occurs above bedrock. Selection of the most cost effective drilling, sampling, processing and analytical methods depends upon the objectives of each survey and specific landscape factors. The methods used in this survey have been fully explained, in the event the reader chooses to design a similar survey. Based upon our results and numerous successful site-specific case histories in Canada, reverse circulation (air plus water) drilling with heavy mineral concentration of large samples (+8 kg.) should be an effective method in most of the of 700 square miles surveyed. An opportunity exists for innovative drillers to develop a cost-effective overburden drilling method for the difficult conditions encountered.

From the summary data, one gold grain can be expected in 17 kg of typical Rainy lobe till. The Rainy lobe till appears to reflect bedrock, at least on the local scale of dispersal of Klassen (1987). Many other geochemical parameters were defined (see summary Table 40-7) and the framework of the regional glacial drift was well defined. Thus, for example, very high background values (As, Sb, Ba, etc.) for gold mineralization pathfinders in the Des Moines lobe exotic till have been identified, so no future expenditures will be made to chase them. Furthermore, we were lucky enough to find one very encouraging (and a few other) gold occurrence in Linden Grove township, T62N-R20W, in St. Louis County. The delicate gold grains and numerous pathfinder elements present in hole 20801 are good indications of gold mineralization in the Precambrian bedrock of the area. (See Map 10-7 and nearby holes 20804 and 20906.) At least two additional anomalous gold occurrences (holes 202 and 209) in the Orr Area and one gold occurrence (hole 107) and one base metal occurrence (hole 10303) in the Littlefork Area were found (see Discussion of Some Significant Individual Drill Hole Results, Maps 10-7 and 11-4, Appendices 8-59, 8-31, 8-36, 8-7, 8-14 and Table 40-7).

One of the overall goals was to try to quantify the information, some of which is subjective in nature. The final results, such as the geochemical sample database, reflect this conformation process in a new style of data reporting.

Available Samples and Database

A large range of library samples are available for examination at the Hibbing office from the Rotasonic, mud rotary, and air rotary drilling.

The Rotasonic core was composited into 5 or 10 foot lengths for heavy mineral concentration. Available samples include: 1/2 split of the sonic core and bedrock core in boxes and the bedrock assay pulps and rejects, the -63 um fraction assay pulp, approximately 250 grams of HMC feed and the HMC light fraction after heavy liquid concentration, the HMC magnetic fraction assay pulp, the 1/4 split nonmagnetic HMC fraction.

Mud rotary samples represent 5 to 10 feet of tricone bit cuttings in buckets and range from 50 to 100 lbs. Available samples include: a split of the +10M and -10M Rainy lobe and bedrock, bedrock assay pulps and rejects, thin sections are also available from the +10M bedrock chips, 1/2 split of the -10M fraction, approximately 250 grams of HMC feed along with the HMC light fraction after heavy liquid concentration, the HMC magnetic fraction assay pulp, 1/4 split HMC nonmagnetic fraction.

The available air rotary samples include 5 to 10 feet of tricone bit cuttings of Rainy lobe and weigh from 50 to 100 lbs. The samples available from the 4 foot bedrock interval are the 7/8 split plus the assay pulps and rejects from the remaining 1/8 split. Other samples include: a grab sample of each stratigraphic unit put into a cardboard core box and the -63 um assay pulps, about 250 grams of the HMC feed, HMC light fraction after heavy liquid concentration, the HMC magnetic fraction assay pulp, 1/4 split nonmagnetic HMC fraction.

Also available are photomicrographs from a scanning electron microscope of 12 gold particles found in replicate sample #18612 in hole 20801.

The database consists of a master file of sample data and individual files of nonmagnetic fraction assays, -63 um fraction assays, magnetic fraction assays, and brief stratigraphic logs. The database for Project 252 is available on an IBM formatted, 5½-inch flexible standard or high density diskette. A number of other formats are available (please inquire).

The master file is a list of 700 sample numbers with their related information. The list includes: sample number, sample interval, drill hole number, sample thickness, drilling method, drill hole location, sample drift type, heavy mineral concentrate assayed interval, number of gold particles, heavy mineral concentrate feed weight, +10 mesh fraction feed weight, nonmagnetic HMC fraction weight, magnetic HMC fraction weight, -63 um fraction weight, weight of the -63 um fraction feed, -63 um fraction weight percent, +10 mesh fraction weight percent, and the sand fraction weight percent.

The geochemical assays are available for the four sample fractions along with the assay weight and the weight of each fraction divided by the weight of the feed. There are 311 samples of nonmagnetic data, 383 of -63 um data, 124 of magnetic data, and 63 of the bedrock.

Stratigraphic logs were created with a program called "Logger" and are available for each drill hole in the Orr and Littlefork areas. Each log consists of: 1) graphic presentation of the geologic units with emphasis on the glacial stratigraphy and unit descriptions; 2) heavy mineral concentrate sample interval, -63 um fraction sample interval, gold particle counts, and indicator minerals; 3) designation of Des Moines lobe and Rainy lobe strata; and 4) histogram with a graphic presentation of the geochemical assays based on a relative scale according to high and low assay values. The scale bar high value (ppm, Au = ppb, Fe = %, g/kg) is listed at the top of the column. Assays include: 5 elements assayed for the nonmagnetic HMC fraction, 7 elements for the -63 um fraction, 3 elements assayed for the magnetic HMC fraction, nonmagnetic HMC fraction gold, and -63 um fraction gold. The histogram also graphically shows the weights of each fraction divided by the feed in grams per kilograms. The intent of the graphic presentation is to show geochemical trends (vertically) down the hole and interrelationships between sample fractions (horizontally). The stratigraphic logs are only available in text form as an ASCII file. The text is compatible with the Logger program from Rock Ware Inc., 1985.

Some items were not included in the final report but are available at the Hibbing office. These include such diverse information as the detailed drill hole site maps, Rotasonic and air rotary field logs with some drilling times on them, the large-size Plates 1 and 2 of Gary Meyer's report, cross sections of interpreted stratigraphy in the Orr area, and color slides of drilling and sampling.

Acknowledgements

Stu Averill - Overburden Drilling Management
Dan Beckwith
Erv Berglund
Terry Boerboom - Minnesota Geological Survey
Richard Buchheit
John Bushey
Dale Cartwright
Val Chandler - Minnesota Geological Survey
Morris Eng
Leon Gladen
Gene Karel
Coleen Keppel
Helen Koslucher
Tom Lawler
Kevin Malmquist
Gary Meyer - Minnesota Geological Survey
Jay Niebuhr
Tim Pastika
Darold Riihiluoma
Rick Ruhanen
Sue Saban
Ed Spawn and the MCC
Theresa Stilinovich
Andrew Streitz
Marty Vadis
Greg Walsh

This project would not have been possible without the previous experience and helpful guidance of Morris Eng who has recently retired. Nor would it have been as productive without the helpful support, design input, and funding levels provided by Marty Vadis. Tim Pastika, and Dale Cartwright have made significant contributions and improvements during their helpful assistance in completing this big project. Everyone of the people listed has provided a significant contribution at some point in the project and is thanked for their help.

References Cited *

Averill, S. A., 1978, Overburden Exploration and the New Glacial History of Northern Canada. Can. Mining J., V. 99, No. 4, pp. 58-64.

Averill, S. A., 1986, Heavy Mineral Anomaly Interpretation - The Importance of Minerology and Quaternary Stratigraphy. Presented to Prospectors and Developers Association, Toronto, March, 1986.

Averill, S. A., MacNeil, K. A., Huneault, R. G., and Baker, C. M., 1986, Rotasonic Drilling Operations (1984) and Overburden Heavy Mineral Studies, Matheson Area, District of Cochrane. Ontario Geological Survey, Open File Report 5569, 61 pages.

Cazalet, P. C. D., 1973, Notes on the Interpretation of Geochemical Data in Glaciated Areas. Inst. of Min. & Met., Prospecting in Areas of Glacial Terrain, pp. 25-30.

Clark, P. U., 1987, Subglacial Sediment Dispersal and Till Composition. Jour. of Geol., Vol. 95, No. 4, pp. 527-541.

Clifton, H. E., Hubert, A., and Phillips, R. L., 1967, Marine Sediment Sample Preparation for Analysis for Low Concentrations of Fine Detrital Gold. U.S. Dept. of the Interior, Geol. Surv. Circular, Prof. Paper 625-C.

Colvine, A. C. and Stewart, James W., 1984, Precambrian Shield Gold Exploration Trends Detailed. Mining Engineering, pp. 1642-1645.

de Grys, A., 1970, Copper and Zinc in Alluvial Magnetites from Central Ecuador. Economic Geol., Vol. 65, No. 6, pp. 714-717.

Eng, M. T., 1980, An Evaluation of the Surficial Geology and Bog Patterns of the Red Lake Peatlands, Beltrami and Lake of the Woods Counties, Minnesota. Minnesota Department of Natural Resources, St. Paul, Minnesota, 1 plate.

Fleischer, M., 1965, Composition of Magnetites as Related to Type of Occurrence. U.S.G.S., Prof. Paper No. 525D, pp. 82-84.

Friedman, Albert L., 1981, Surficial Geology of the Isabella Quadrangle, Northeastern Minnesota. U. of M., Thesis (unpublished), March, 66 pages.

Garret, R. G., 1969, The Determination of Sampling and Analytical Errors in Exploration Geochemistry. Econ. Geol., Vol. 64, pp. 568-569.

Garrett, Robert G., 1973, The Determination of Sampling and Analytical Errors In Exploration Geochemistry - A Reply. Econ. Geol., Vol. 68, March-April, p. 282.

Gleeson, C. F. & Cormier, R., 1971, Evaluation by Geochemistry of Geophysical Anomlies and Geological Targets Using Overburden Sampling at Depth. CIMB, Special Vol. 11, pp. 159-165.

---

* The sections by G. Meyer, V. Chandler, and T. Lawler have separate lists of references cited, at the end of each section.

Gleeson, C. F. and Hornbrook, E. H. W., 1975, Semi-Regional Geochemical Studies Demonstrating the Effectiveness of Till Sampling at Depth. Elsevier Scientific, Geochem. Explor., pp. 611-630.

Granath, G., 1982, Trace Elements in Magnetites as Pathfinders for Base-Metal Deposits in Dalecarlia, Sweden. Canadian Inst. of Mining & Met., in Prospecting in Areas of Glaciated Terrain - 1982, August, p. 338.

Green, J. C., 1982, Two Harbors Sheet, Bedrock Geology: Minnesota Geological Survey, Geologic Map Atlas, Scal 1:250,000.

Green, J. C. and Schulz, K. J., 1982, Geologic Map of Ely Quadrangle, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey, Open-File Map, Scale 1:24,000.

Hamil, B. M., and Nackowski, M. P., 1971, Trace Element Distribution in Accessory Magnetite from Quartz Monzonite Intrusives and its Relation to Sulfide Mineralization in the Basin and Range Province of Utah and Nevada. Preliminary Report in CIM Special Volume No. 11, Geochemical Exploration, pp. 331-334.

Hattori, K., 1987, Magnetic Felsic Intrusions Associated with Canadian Archean Gold Deposits. Geology, Vol. 15, No. 12, December, 1987, pp. 1107-1111.

Hobbs, H. C. and Goebel, J. E., 1982, Geologic Map of Minnesota. Quaternary Geology; Scale 1:500,000, Minn. Geol. Survey.

Hodgson, C. J. and MacGeehan, P. J., 1982, A Review of the Geological Characteristics of "Gold Only" Deposits in the Superior Province of the Canadian Shield. Hodder, R. W., Eds., Geology of Canadian Gold Deposits, C.I.M.M., Spec. Volume 24, pp. 211-228.

Kaczicki, C. A., 1988, Till Composition and Glacial Dispersal; Influence on the Resolution of Geochemical Anomalies. Presentation at Prospectors and Developer's Convention, Toronto March 6-March 9, 1988.

Klassen, R. A., 1987, Relationship Between Glacial History and Drift Composition. Jour. of Geochem. Explor., Vol. 29, No. 1-3, Special Issue 13, pp. 421-422.

Lee, H. A., 1965, Investigation of Eskers for Mineral Exploration and Buried Valley near Kirkland Lake, Ontario. Geological Survey of Canada, Paper 65-14, 20 pages.

Lee, Hulbert A., 1963, Glacial Fans in Till from the Kirkland Lake Fault: A Method of Gold Exploration. GSC, Paper 63-45, 36 pages.

Lehr, J. D. and Matsch, C. L., 1987, The Late Wisconsin Vermilion Moraine in Northeastern Minnesota; An Ice-Marginal Complex of Multiple Origin. Presented at Quaternary Paleoecology and Glacial Geology of the North American Midcontinent Symposium, St. Paul, MN, April 30-May 1, 1987.

Leverett, Frank, 1932, Quaternary Geology of Minnesota and Parts of Adjacent States. U.S.G.S. Prof. Paper 161, 149 pages.

Macdonald, A. J. and Fyon, J. A., 1986, Sulfidation - The Key to Gold Mineralization in Banded Iron Formation. Abstract, Gold 86 Conference, Toronto, G.A.C., Poster Paper Abstracts, pp. 98-99, ed. by A.M. Chater.

Mather, A. L., 1977, Analytical Statistics. Assn. Explor. Geochem. Newsletter, No. 21, Ontario, Report from 6th I.G.E.S., Syndey, 1976.

Merks, Jan, 1988, Sampling and Assaying. Presentation at Prospectors and Developer's Convention, Toronto, March 6-March 9, 1988.

Morey, G. B., 1978, Metamorphism in the Lake Superior Region, U.S.A., and Its Relation to Crustal Evolution. G.S.C., Paper 78-10, pp. 283-314.

Morey, G. B., 1980, A Brief Review of the Geology of the Western Vermilion District, Northeastern Minnesota. Precambrian Research, Vol. 11, 1980, PP. 247-265.

Morey, G. B., 1981, Geologic Terranes of Minnesota and Their Uranium Potential. MGS, IC 19, 40 pages.

Nichol, Ian and Shelp, Gene S., 1985, Geochemical Exploration for Gold. O.G.S Misc. Paper 127, Grant 192, pp. 124-135.

Norvitch, Ralph F., 1962, Geology of the Vermilion End Moraine, Nett Lake Indian Reservation, Minnesota. U.S.G.S., Prof. Paper 450-D, pp. D130-D132.

Ojakangas, R. W., 1976, Uranium Potential in Precambrian Rocks of Minnesota. U.S. Energy Research and Development Administration, Contract AT (05-1) - 1652, 259 pages.

Ojakangas, R. W., Sims, P. K., and Hooper, P.R., 1978, Geologic Map of the Tower Quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey, Map GQ-1457, Scale 1:24,000.

Saccocia, P. J., 1987, Sulfidation of Oxide Facies Iron Formation: Implications for Gold Mineralization in the Glen Township Formation, Aitkin County, East-Central Minnesota. Univ. of Minn., Thesis, April, 1987, 93 pages.

Salminen, R. and Hartikainen, A., 1985, Glacial Transport of Till and Its Influence on Interpretation of Geochemical Results in North Karelia, Finland. Geol. Surv. of Finland, Bulletin 335, 48 pages.

Schulz, Klaus J., 1980, The Magmatic Evolution of the Vermilion Greenstone Belt, NE Minnesota, Precambrian Research, Vol. 11, 1980, pp. 215-245.

Shilts, W. W., 1975, Principles of Geochemical Exploration for Sulphide Deposits Using Shallow Samples of Glacial Drift. CIMB, Vol. 68, No. 757, May, 1975, pp. 73-80.

Shilts, W. W., 1976, Mineral Exploration and Till; in Glacial Till. Edited by R. F. Legget, Royal Society of Canada, Special Publication 12, pp. 205-224.

Shilts, W. W., 1984, Till Geochemistry in Finland and Canada. Journal of Geochemical Exploration, 21, pp. 95-117.

Sims, P. K., and Mudrey, M. G., Jr., 1972, Syenitic Plutons and Associated Lamprophyres. Geology of Minnesota: A Centennial Volume. Minn. Geol. Survey, General, Chp. III, pp. 140-152

Sims, Paul K., 1976, Early Precambrian Tectonic-Igneous Evolution in the Vermilion District, Northeastern Minnesota. G.S.A. Bul., V.87, March, 1976, pp. 379-389.

Sims, Paul and Southwick, David, 1979, New Evidence on the Stratigraphy and Structure of the Soudan area, Western Vermilion District, Minnesota. Inst. Lake Sup. Geol., 1979.

Sopuck, V., Schreiner, B. T., and Averill, S. A., 1985, Drift Prospecting for Gold in the Southeastern Shield of Saskatchewan, Canada. Gold in Western Sheild Symposium, Saskatchewan, September, 1985.

Southwick, D. L., 1972, Vermilion Granite-Migmatite Massif. Geology of Minnesota: A Centennial Volume. Minn. Geol. Survey, General, Chp. III, pp. 108-119.

Southwick, D. L., 1979, The Vermilion Grantic Complex, Northern Minnesota. Field Trip Guidebook for the Western Vermilion District, Northeastern Minnesota, M.G.S., Guidebook Series No. 10, 65 pages.

Southwick, D. L. and Sims, P. K., 1980, Shorter Contributions to Mineralogy and Petrology, 1979. U.S.G.S., Prof. Paper 1124-A-F, 43 pages.

Strobel, M. L. and Faure, G., 1987, Transport of Indicator Clasts by Ice Sheets and the Transport Half-Distance: A Contribution to Prospecting for Ore Deposits. J. of Geology, Vol. 95, pp. 687-697.

Tacker, R. C. and Candela, P. A., 1987, Partitioning of Molybdenum between Magnetite and Melt: A Preliminary Experimental Study of Partitioning of Ore Metals between Silicic Magmas and Crystalline Phases. Econ. Geol., Vol. 82, No. 7, Nov., 1987, pp. 1827-1838.

Tourtelot, Harry A., 1968, Hydraulic Equivalence of Grains of Quartz and Heavier Minerals and Implications for the Study of Placers. U.S.G.S., Prof. Paper 594-F, 13 pages.

Winter, R. C., Cotter, R. D., and Young, H. L., 1973, Petrography and Stratigraphy of Glacial Drift, Mesabi-Vermilion Iron Range Area, Northeastern Minnesota. U.S.G.S., Bulletin 1331-C, 41 pages.

Wright, H. E., Jr., 1965, Wisconsinan Glaciation of Minnesota: Midwest Friends of the Pleistocene. 15th Annual Field Conference, Eastern Minnesota, Minnesota Geological Survey.

Wright, H. E., Jr. and Ruhe, R. V., 1965, Glaciation of Minnesota and Iowa. H. E. Wright, Jr. and D. G. Frey, eds., The Quaternary of the United States, Princeton, Princeton Univ. Press, pp. 29-41.