QUATERNARY (SURFICIAL) GEOLOGIC MAPPING OF THE MESABI IRON RANGE
November 2005

Minnesota Geological Survey—University of Minnesota Project #523-6141
Funded September 2, 2003 through September 30, 2005

The published bedrock geologic map is referenced as follows:
Jennings, Carrie and Reynolds, Wade, 2005, Quaternary geology of the Mesabi Iron Range, Minnesota: Minnesota Geological Survey Miscellaneous Map M-164, scale 1:100,000.

An image of the map is provided as a PDF document--M164.pdf

All GIS shapefiles or coverages are NAD83, UTM Zone 15.

Files below and pictures linked from the ArcView project are in the zip file m164.zip

Index of GIS files:
1) buried_drumlins -- line shapefile showing buried, streamlined features interpreted as drumlins.

2) dnrhs.tif -- registered tiff formated, grey-scale image, showing hill-shade relief of the Mesabi region. Original gridded data from the Minnesota Department of Natural Resources, Minerals Division and published in 1999, as part of the Mesabi Elevation Project

3) dnrhs_sg.tif -- registered tiff formated, grey-scale image, showing hill-shade relief of the Mesabi region with a view of the surface geology shown as a transparent overlay. Source of hillshade same as above.

4) icemargins -- line shapefile showing approximate locations of mapped ice margins.

5) maparea -- polygon shapefile of study area.

6) pitlakes -- polygon shapefile showing locations and outlines of pitlakes, modified from the Dept. of Natural Resources file pitlakes98.

7) pot_aquifer_loc -- point file indicating sand and gravel features located in outcrops that could potentially be or become aquifers. Pictures of outcrop is indicated where available.

8) scarp_obscure -- line shapefile indicating area mapped as obscure scarp. Corresponding parallel line may indicate channel.

9) scarps -- line shapefile indicating area mapped as scarp.

10) sgpg -- polygon shapefile of the surface geology map units.

11) Tacmines.shp=Approximate outline of taconite mining; modified

locally from DNR Mine Lands Database using air photography.
12) waypoint_locations -- point shapefile of waypoints. Where noted the theme point is linked to a jpg image.

Additional files and folder:

legend.rtf --map unit legends from the printed map.

msb_fsa.img-- Imagine image format (Imagine extension is standard with ArcView). This image has been made smaller than the original county data files, but has not been clipped to the map area. It has not been included on the Quaternery cd, but can be obtained from the M-163 Bedrock geology CD.

Basemap datasets=Compiled and modified from 1990 TIGER/line digital files maintained by the U.S. Bureau of the Census. Subdivided into east and west halfs of the study area. East is in folder eastbase, West in folder westbase. Within the m164 folder.

InterpretedPhotos -- jpg images of outcrops with some added lines and text as geologic interpretations.

Photocatalogs -- Excel files containing information about photo locations.

Mesabi textures.xls -- Microsoft Excel file containing textural data from surficial samples collected for the project.

keyphotos Photographs are linked to the APR theme waypoint_locations so that users can select a location using the "Hotlink" icon and view the image. Image resolution is generally quite low—if higher resolution is needed, please contact the authors. Photos can also be viewed directly with the ifanviewer provided, although there will be no link to location other than the folder name indicating the mine.

Legends—folder containing ArcView legend files for shapefiles (.avl)
Iview—folder containing the jpeg viewer used for the hotlinks in the ArcView project.
Metadata--metadataMSB.doc. Word file of metadata about the map project. Also in the folder are metadata about standard MGS formats.

MesabiSurf.ppt--Powerpoint display that describes the project, explains the mapping methods and provides a summary interpretation of the results.

m164sg.apr—the ArcView project file.

For questions about the digital data contact Carrie Jennings (carrie@umn.edu) or Richard Lively (lively@umn.edu)

SUPPORTED IN PART BY THE MINERALS DIVERSIFICATION PROGRAM AS ADMINISTERED BY THE MINERALS COORDINATING COMMITTEE FOR THE MINNESOTA LEGISLATURE, AND BY THE EDMAP PROGRAM OF THE U.S. GEOLOGICAL SURVEY

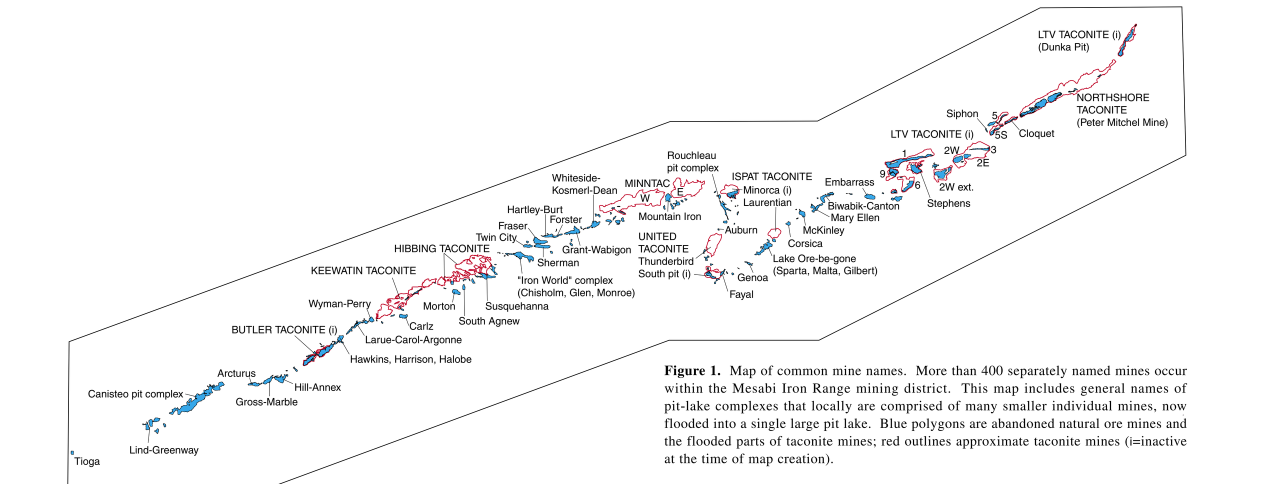


Figure 1. Map of common mine names. More than 400 separately named mines occur within the Mesabi Iron Range mining district. This map includes general names of pit-lake complexes that locally are comprised of many smaller individual mines, now flooded into a single large pit lake. Blue polygons are abandoned natural ore mines and the flooded parts of taconite mines; red outlines approximate taconite mines (i=inactive at the time of map creation).

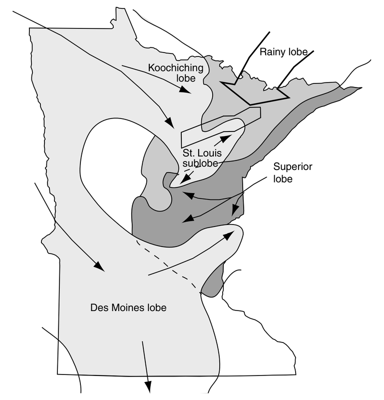


Figure 2. Ice lobes of the last glaciation in Minnesota. The area mapped for this project is at the confluence of northeast- and northwest-sourced ice lobes. All of the mapping area (boxed area on map) was affected by the northeast-sourced Rainy lobe. Subsequently, it was partly covered by ice issuing from the northwest. This later ice lobe was affected by the topography of the Giants Range as reflected by narrowing of the ice as it crossed the bedrock highland. North of the narrow area, the till is typical of Riding Mountain provenance and the ice is referred to as the Koochiching lobe. As the ice crossed the bedrock ridge and entered a Superior-sourced glacial lake basin southeast of the narrow zone, it spread to fill the basin and incorporated red, fine-grained sediment. This ice is known as the St. Louis sublobe. Modified from Meyer and others (2005).

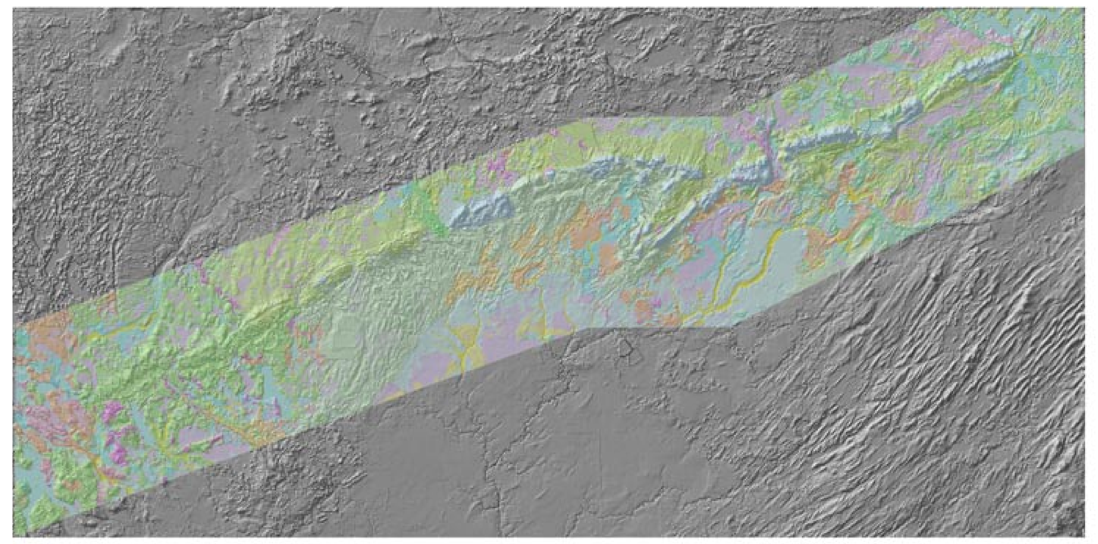
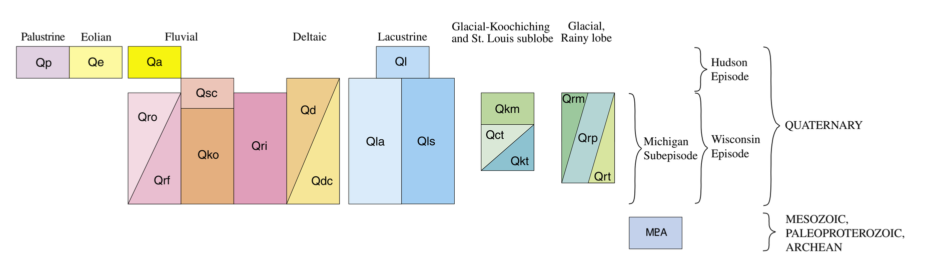
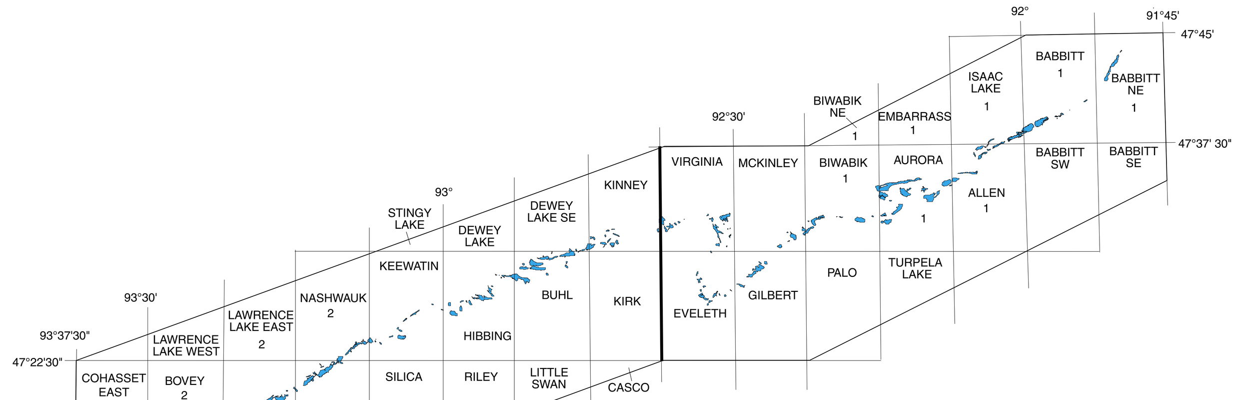


Figure 3. Surficial geologic map draped over a digital elevation model of the land surface topography. Elevations were drawn from the 1999 Minnesota Department of Natural Resources Mesabi Elevation Project. The total range of elevation on this figure is 1,183 to 1,948 feet above mean sea level. False illumination is from the northwest.

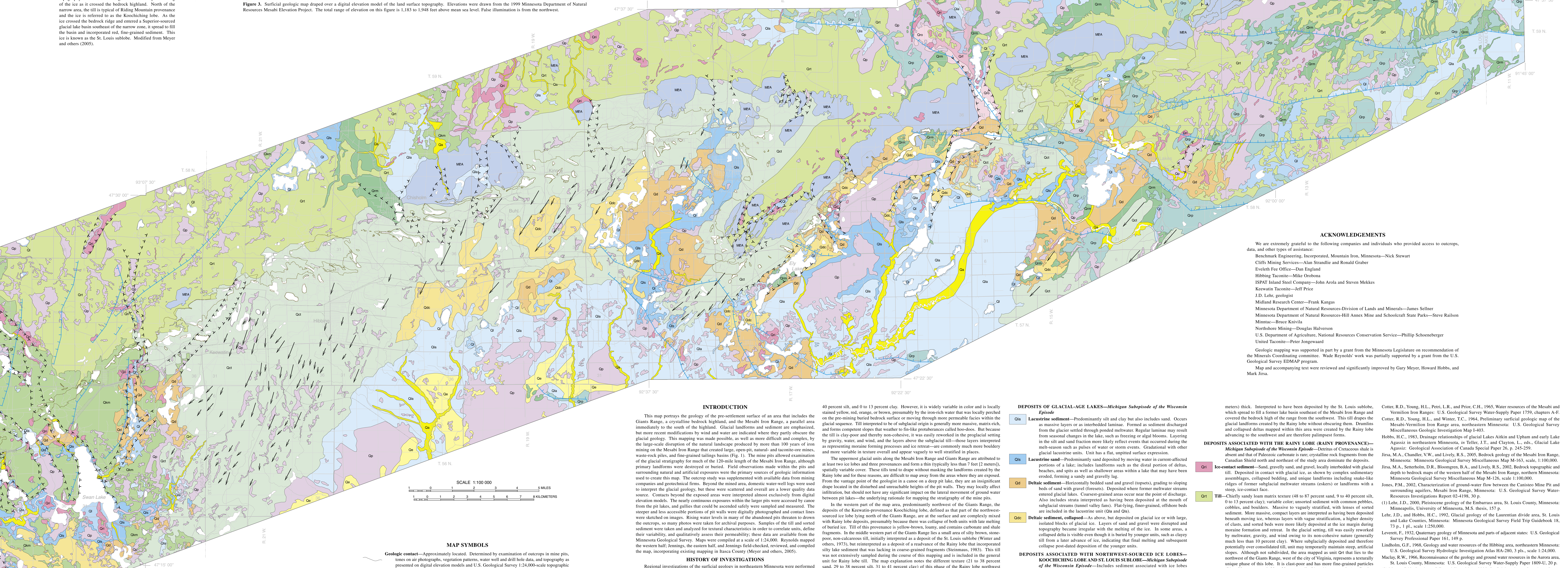
CORRELATION OF MAP UNITS





MAP COMPILATION INDEX

Index of 7.5-minute quadrangles in the map area. Numbers correspond to sources of previous surficial mapping, as listed (in parentheses) in the references. Winter (1973) and Winter and others (1973) mapped the entire area. Reynolds mapped the area west of the heavy black line; Jennings mapped the area east of the heavy black line. Jennings compiled the map. Blue polygons represent mine pit lakes.



SCALE 1:100 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 6 7 8 KILOMETERS

MAP SYMBOLS

Geologic contact—Approximately located. Determined by examination of outcrops in mine pits, tones on air photographs, vegetation patterns, water well and drill hole data, and topography as presented on digital elevation models and U.S. Geological Survey 1:24,000-scale topographic maps. Gradational as indicated in the descriptions of map units.

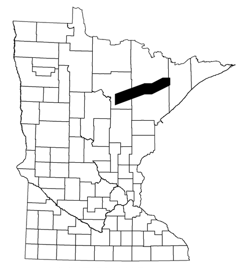
Ice margin—Inferred former position of glacial ice margins, multiple ice fronts, and events. Barbs are on the up-ice side. Interpreted from the position of linear ridges and ridge segments aligned with heads of outwash and ice collapse topography.

Sharp scarp—Linear break in elevation interpreted as the erosional margin of a channel. Typically paired to represent a channel form.

Obscure scarp—Interrupted linear break in elevation, interpreted as a former channel that has been somewhat masked by later sediment or disrupted by the melting of buried or supporting ice. Where paired, interpreted as broad, subglacial tunnel valleys. Small eskers are preferentially located within these channels and represent a later depositional phase of subglacial water flow.

Drumlin, buried—Streamlined hills appearing in coherent swarms and aligned with ice-flow direction to the southwest. Interpreted as the product of subglacial shaping by moving ice of the Rainy lobe. The hills were subsequently buried by the St. Louis sublobe, which advanced from the southwest.

Mine outline—Approximate boundary of an active or inactive mine or mine pit lake.



LOCATION MAP

GIS compilation by R.S. Lively
Edited by Lori Robinson

Digital base modified from 1990 Census TIGER/line files of the U.S. Bureau of the Census (source scale 1:100,000); digital base annotated by the Minnesota Geological Survey.
Universal Transverse Mercator grid, zone 15
1983 North American Datum

SURFICIAL GEOLOGY OF THE MESABI IRON RANGE, MINNESOTA

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2005

INTRODUCTION

This map portrays the geology of the pre-settlement surface of an area that includes the Giants Range, a crystalline bedrock highland, and the Mesabi Iron Range, a parallel area immediately to the south of the highland. Glacial landforms and sediment are emphasized, but more recent modifications by wind and water are indicated where they partly obscure the glacial geology. This mapping was made possible, as well as more difficult and complex, by the large-scale disruption of the natural landscape produced by more than 100 years of iron mining on the Mesabi Iron Range that created large, open-pit, natural- and taconite-ore mines, waste-rock piles, and fine-grained tailings basins (Fig. 1). The mine pits allowed examination of the glacial stratigraphy for much of the 120-mile length of the Mesabi Iron Range, although primary landforms were destroyed or buried. Field observations made within the pits and surrounding natural and artificial exposures were the primary sources of geologic information used to create this map. The outcrop study was supplemented with available data from mining companies and geotechnical firms. Beyond the mined area, domestic water-well logs were used to interpret the glacial geology, but these were scattered and overall are a lower quality data source. Contacts beyond the exposed areas were interpreted almost exclusively from digital elevation models. The nearly continuous exposures within the larger pits were accessed by canoe from the pit lakes, and gullies that could be ascended safely were sampled and measured. The steeper and less accessible portions of pit walls were digitally photographed and contact lines were sketched on images. Rising water levels in many of the abandoned pits threaten to drown the outcrops, so many photos were taken for archival purposes. Samples of the till and sorted sediment were taken and analyzed for textural characteristics in order to correlate units, define their variability, and qualitatively assess their permeability; these data are available from the Minnesota Geological Survey. Maps were compiled at a scale of 1:24,000. Reynolds mapped the western half; Jennings, the eastern half, and Jennings field-checked, reviewed, and compiled the map, incorporating existing mapping in Itasca County (Meyer and others, 2005).

HISTORY OF INVESTIGATIONS

Regional investigations of the surficial geology in northeastern Minnesota were performed by Leverett (1932), Wright (1955, 1956), and Wright and Ruhe (1965). There have been many local studies (Cotter and Rogers, 1961; Cotter and others, 1964, 1965; Oakes, 1964; Maclay, 1966; Lindholm, 1968; Winter 1971, 1973; Lehr and Hobbs, 1992; Lehr, 2000). Studies of glacial lakes that fringed the area and drained through the Mesabi range are also relevant to unraveling the late-glacial history of the area (for example Winchell, 1901; Hobbs, 1983). The most thorough studies to date, and those most often referenced for the surficial geology in the Mesabi range, are Winter (1971, 1973) and Winter and others (1973), which includes a surficial map of the Mesabi Iron Range at a scale of 1:250,000. Since the time of Winter's work, the emphasis has been on geologic mapping with a hydrogeologic component or purpose. The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, conducted a study (1998-2001) to characterize ground-water flow conditions in the vicinity of the Canisteo Mine Pit near Bovey following mine abandonment (Jones, 2002). The Legislative Commission on Minnesota Resources funded a project proposed by the Minnesota Geological Survey to produce a bedrock topography map of the Mesabi Iron Range (Jirsa and others, 2002).

LOCATION AND GEOLOGIC SETTING

The advances of ice lobes and the routing of meltwater in the vicinity of the Giants Range were profoundly affected by the bedrock relief. Areas where the bedrock was topographically high diverted thin ice lobes, delayed them from crossing the highland until the ice had thickened substantially, created the proglacial stress environment that allowed for glaciotectonic thrusting of Cretaceous sedimentary rock, and locally dammed and controlled the flow of glacial meltwater. Subglacial and subaerial water was channeled through gaps in the range.

Although the area was glaciated repeatedly during the Pleistocene epoch, the late Wisconsin sediments of the Rainy lobe dominate the glacial section (Fig. 2). Winter (1971) interpreted the lowermost unit as till of the earliest advance (Pre-Hewitt phase) of the Wadena lobe (Fig. 2). He called this the basal till but was not using this term to necessarily indicate subglacial deposition, as the word is used today. He was using it to refer to this stratigraphically lowermost till. It is dark gray to dark greenish- and brownish-gray, calcareous, and during this mapping exercise was only observed in a few locations where it was restricted to bedrock lows. The matrix texture of this lowermost unit ranged from loam to clay loam to silty clay loam, suggesting either a variable nature or the presence of more than one till in this stratigraphic position.

The deposits of the Rainy lobe (Fig. 2) form the bulk of the glacial sediment, and even where buried, control the surficial glacial landforms (Fig. 3). The till of the Rainy lobe is typically gray to pinkish-gray, non-calcareous, with a matrix texture ranging from 48 to 87 percent sand, 9 to 40 percent silt, and 0 to 13 percent clay. However, it is widely variable in color and is locally stained yellow, red, orange, or brown, presumably by the iron-rich water that was locally perched on the pre-mining buried bedrock surface or moving through more permeable facies within the glacial sequence. Till interpreted to be of subglacial origin is generally more massive, matrix-rich, and forms competent slopes that weather to fin-like protuberances called hoo-doos. But because the till is clay-poor and thereby non-cohesive, it was easily reworked in the proglacial setting by gravity, water, and wind, and the layers above the subglacial till—those layers interpreted as representing moraine forming processes and ice retreat—are commonly much more bouldery and more variable in texture overall and appear vaguely to well stratified in places.

The uppermost glacial units along the Mesabi Iron Range and Giants Range are attributed to at least two ice lobes and three provenances and form a thin (typically less than 7 feet [2 meters]), spatially variable cover. These tills tend to drape without masking the landforms created by the Rainy lobe and for these reasons, are difficult to map away from the areas where they are exposed. From the vantage point of the geologist in a canoe on a deep pit lake, they are an insignificant drape located in the disturbed and unreachable heights of the pit walls. They may locally affect infiltration, but should not have any significant impact on the lateral movement of ground water between pit lakes—the underlying rationale for mapping the stratigraphy of the mine pits.

In the western part of the map area, predominantly northwest of the Giants Range, the deposits of the Keewatin-provenance Koochiching lobe, defined as that part of the northwest-sourced ice lobe lying north of the Giants Range, are at the surface and are complexly mixed with Rainy lobe deposits, presumably because there was collapse of both units with late melting of buried ice. Till of this provenance is yellow-brown, loamy, and contains carbonate and shale fragments. In the middle western part of the Giants Range lies a small area of silty brown, stone-poor, non-calcareous till, initially interpreted as a deposit of the St. Louis sublobe (Winter and others, 1973), but reinterpreted as a deposit of a readvance of the Rainy lobe that incorporated silty lake sediment that was lacking in coarse-grained fragments (Steinmaus, 1983). This till was not extensively sampled during the course of this mapping and is included in the general unit for Rainy lobe till. The map explanation notes the different texture (21 to 38 percent sand, 29 to 38 percent silt, 31 to 41 percent clay) of this phase of the Rainy lobe northwest of the Giants Range. In the central portion of the Giants and Mesabi ranges, red, clayey (2 to 26 percent sand, 23 to 49 percent silt, 47 to 66 percent clay), stone-poor till is typically 3 to 7 feet (1 to 2 meters) thick, but double that thickness according to drill records in a few spots south of Chisholm and Virginia (Meyer, unpub. data, 2005). However, it is thin enough to allow drumlins formed during an earlier phase of the Rainy lobe to be identified. Although red, thereby suggesting a Superior provenance, this till is attributed to the St. Louis sublobe (Keewatin Provenance), which incorporated Superior-sourced red clay that also diluted the more typical shale and carbonate grains during the crossing of the basin of Glacial Lake Upham I (Wright, 1956; Wright and Ruhe, 1965). This ice of the St. Louis sublobe then flowed onto the Mesabi range from the southwest as it spread out in the low of the former lakebed. No evidence to either support or refute this scenario was found during the course of this mapping.

DESCRIPTION OF MAP UNITS

QUATERNARY

POSTGLACIAL DEPOSITS—*Hudson Episode*

Qe **Eolian sand**—Fine-grained sand generally more than 3 feet (1 meter) thick, forming low-lying barchan dunes or a sand sheet. In places, a northeast-trending linear ridge of sand is apparent on the southeast side of the sand sheet and the northwest side of a wetland. Interpreted as windblown sand with wind from the northwest; the linear ridge is interpreted as an advancing dune front.

Qa **Alluvium**—Interbedded fine-grained sand, fine-grained sandy loam, and silt loam. Varies in grain size with substrate and with the gradient of the reach of the river. Streams incising till tend to have more gravel as a lag deposit. Shells, wood, and other organic debris are typically present in low-gradient, slack-water areas. Interpreted as the deposits of modern rivers during high-water stages.

Qp **Peat**—Organic material in various stages of decomposition. Some deposits include small bodies of open water. Interpreted as palustrine deposits that form as fresh-water lakes and shallow depressions of glacial origin fill with vegetation.

Ql **Lake sediment**—Predominantly silt, clay, and organic material that have settled to the bottom of modern lakes. Clay is most common in the deep, still portions of the basins. Sandier sediment is more common in nearshore and shallow areas where waves and wind keep finer-grained particles suspended.

DEPOSITS OF GLACIAL-AGE LAKES—*Michigan Subepisode of the Wisconsin Episode*

Qla **Lacustrine sediment**—Predominantly silt and clay but also includes sand. Occurs as massive layers or as interbedded laminae. Formed as sediment discharged from the glacier settled through ponded meltwater. Regular laminae may result from seasonal changes in the lake, such as freezing or algal blooms. Layering in the silt and sand fraction more likely reflect events that occurred during the melt-season such as pulses of water or storm events. Gradational with other glacial lacustrine units. Unit has a flat, unpitted surface expression.

Qls **Lacustrine sand**—Predominantly sand deposited by moving water in current-affected portions of a lake; includes landforms such as the distal portion of deltas, beaches, and spits as well as shallower areas within a lake that may have been eroded, forming a sandy and gravelly lag.

Qd **Deltaic sediment**—Horizontally bedded sand and gravel (topsets), grading to sloping beds of sand with gravel (foresets). Deposited where former meltwater streams entered glacial lakes. Coarsest-grained areas occur near the point of discharge. Also includes strata interpreted as having been deposited at the mouth of subglacial streams (tunnel valley fans). Flat-lying, finer-grained, offshore beds are included in the lacustrine unit (Qla and Qls).

Qdc **Deltaic sediment, collapsed**—As above, but deposited on glacial ice or with large, isolated blocks of glacial ice. Layers of sand and gravel were disrupted and topography became irregular with the melting of the ice. In some areas, a collapsed delta is visible even though it is buried by younger units, such as clayey till from a later advance of ice, indicating that final melting and subsequent collapse post-dated deposition of the younger units.

DEPOSITS ASSOCIATED WITH NORTHWEST-SOURCED ICE LOBES—KOOCHICHING LOBE AND ST. LOUIS SUBLOBE—*Michigan Subepisode of the Wisconsin Episode*—Includes sediment associated with ice lobes originating from the northwest, where the detritus of Cretaceous shale and Paleozoic carbonate were incorporated (Riding Mountain and Winnipeg provenance). These fragments are used to distinguish northwest-sourced deposits from those of other ice lobes. These two ice lobes are really a continuum of ice; the Koochiching lobe lies to the north of the Giants Range and the St. Louis sublobe to the south. The till of the St. Louis sublobe changes considerably from the original composition because it incorporated local, red, fine-grained lake sediment that diluted the material being imported by the ice.

Qko **Fluvial sediment**—Sand, gravelly sand, and gravel deposited within broad, planar channels. Bedding is generally flat-lying. Interpreted as having been deposited by braided streams flowing from melting ice.

Qsc **Scoured landscape**—Erosional channel scar. Includes gravel bars and sand within channels, but is predominantly a lag of boulders to gravel lying on till. Interpreted as the result of discharge of lake water stored to the north in a proglacial lake of the retreating Koochiching lobe (Glacial Lake Koochiching). Channels merge into deposits of a former lake to the southeast (Glacial Lake Upham/Aitkin II). Channels terminate in sandy deltas. Interpreted as the scoured landscape resulting from lake outbursts.

Qkm **Mixed deposits, predominantly till**—Unsorted yellow-brown to gray clay to loam-textured sediment with incorporated pebbles, cobbles, and boulders juxtaposed chaotically with a variety of other glacial and ice-proximal units. Mapped in areas where till may be complexly mixed with lake sediment, stream sediment, and till from other ice lobes, owing to rapidly shifting depositional environments common to ice-proximal glacial settings. The confluence of the northwest-sourced ice lobe (Koochiching lobe) with a northeast-sourced ice lobe (Rainy lobe) and subsequent collapse of stagnant ice have made the confluence of these two ice lobes difficult to interpret.

Qkt **Till**—Chiefly clay to clay loam matrix texture; yellow-brown to gray unsorted sediment with pebbles, rare cobbles, and uncommon boulders. Massive, with few lenses of bedded sediment. Interpreted as having been deposited directly by northwest-sourced ice with little subsequent modification.

Qct **Clayey till**—Matrix dominated red clayey till (2 to 26 percent sand, 23 to 49 percent silt, 47 to 66 percent clay) with rare clasts. Generally less than 10 feet (3 meters) thick. Interpreted to have been deposited by the St. Louis sublobe, which spread to fill a former lake basin southeast of the Mesabi Iron Range and covered the bedrock high of the range from the southwest. This till drapes the glacial landforms created by the Rainy lobe without obscuring them. Drumlins and collapsed deltas mapped within this area were created by the Rainy lobe advancing to the southwest and are therefore palimpsest forms.

DEPOSITS ASSOCIATED WITH THE RAINY LOBE (RAINY PROVENANCE)—*Michigan Subepisode of the Wisconsin Episode*—Detritus of Cretaceous shale is absent and that of Paleozoic carbonate is rare; crystalline rock fragments from the Canadian Shield north and northeast of the study area dominate the deposits.

Qri **Ice-contact sediment**—Sand, gravelly sand, and gravel, locally interbedded with glacial till. Deposited in contact with glacial ice, as shown by complex sedimentary assemblages, collapsed bedding, and unique landforms including snake-like ridges of former subglacial meltwater streams (eskers) or landforms with a steep, ice-contact face.

Qrt **Till**—Chiefly sandy loam matrix texture (48 to 87 percent sand, 9 to 40 percent silt, 0 to 13 percent clay); variable color; unsorted sediment with common pebbles, cobbles, and boulders. Massive to vaguely stratified, with lenses of sorted sediment. More massive, compact layers are interpreted as having been deposited beneath moving ice, whereas layers with vague stratification, a higher density of clasts, and sorted beds were more likely deposited at the ice margin during moraine formation and retreat. In the glacial setting, till was easily reworked by meltwater, gravity, and wind owing to its non-cohesive nature (generally much less than 10 percent clay). Where subglacially deposited and therefore potentially over consolidated till, unit may temporarily maintain steep, artificial slopes. Although not subdivided, the area mapped as unit Qrt that lies to the northwest of the Giants Range, west of the city of Virginia, represents a texturally unique phase of this lobe. It is clast-poor and has more fine-grained particles (21 to 38 percent sand, 29 to 38 percent silt, 31 to 41 percent clay), reflecting the local incorporation of lake sediment from water ponded on the north side of the Giants Range. This till is most likely buried by clayey till (unit Qct) south of the bedrock highland and is the drumlin-forming till in this area.

Qrm **Till**—As above, but eroded by water, producing a less rugged surface expression and possibly concentrating coarse-grained clasts as a lag at the surface.

Qrp **Till, re-sedimented till, and sorted sediment**—Forms distinct but discontinuous highlands aligned with other features that mark the transition from a glacial to a proglacial setting (for example ice-contact delta fronts). Recognized mainly by topographic expression. Interpreted as created by deposition of basal Rainy lobe till at the ice front (unit Qrt), followed by resedimentation by gravity and slope processes down a steep moraine front. The result is a poorly sorted diamicton to a sand and gravel. Facies are not laterally continuous. Where the ice fronted a proglacial lake, unit grades into deltaic landforms.

Qro **Fluvial sediment**—Sand, gravelly sand, and gravel deposited within broad, planar channels. Bedding is generally flat-lying. Interpreted as having been deposited by braided streams flowing from melting ice.

Qrf **Fluvial sediment**—As above, but deposited on glacial ice or with isolated blocks of glacial ice. Layers of sand and gravel were disrupted and topography became irregular upon the melting of the ice.

MESOZOIC, PALEOPROTEROZOIC, AND ARCHEAN

BEDROCK FORMING THE GIANTS RANGE AND MESABI IRON RANGE, UNDIVIDED

MEA **Bedrock at or near the surface**—Where buried, generally by till, the expression of the surface is controlled by the underlying bedrock. See the depth to bedrock and bedrock geology maps (Jirsa and others, 2002, 2005) for outcrop locations and types.

REFERENCES

Cotter, R.D., and Rogers, J.E., 1961, Exploratory drilling for ground water in the Mountain Iron-Virginia area, St. Louis County, Minnesota: U.S. Geological Survey Water-Supply Paper 1539-A, 13 p.

Cotter, R.D., Young, H.L., Petri, L.R., and Prior, C.H., 1965, Water resources of the Mesabi and Vermilion Iron Ranges: U.S. Geological Survey Water-Supply Paper 1759, chapters A-F.

Cotter, R.D., Young, H.L., and Winter, T.C., 1964, Preliminary surficial geologic map of the Mesabi-Vermilion Iron Range area, northeastern Minnesota: U.S. Geological Survey Miscellaneous Geologic Investigation Map I-403.

Hobbs, H.C., 1983, Drainage relationships of glacial Lakes Aitkin and Upham and early Lake Agassiz in northeastern Minnesota, *in* Teller, J.T., and Clayton, L., eds., Glacial Lake Agassiz: Geological Association of Canada Special Paper 26, p. 245-259.

Jirsa, M.A., Chandler, V.W., and Lively, R.S., 2005, Bedrock geology of the Mesabi Iron Range, Minnesota: Minnesota Geological Survey Miscellaneous Map M-163, scale, 1:100,000.

Jirsa, M.A., Setterholm, D.R., Bloomgren, B.A., and Lively, R.S., 2002, Bedrock topographic and depth to bedrock maps of the western half of the Mesabi Iron Range, northern Minnesota: Minnesota Geological Survey Miscellaneous Map M-126, scale 1:100,000.

Jones, P.M., 2002, Characterization of ground-water flow between the Canisteo Mine Pit and surrounding aquifers, Mesabi Iron Range, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 02-4198, 30 p.

(1) Lehr, J.D., 2000, Pleistocene geology of the Embarrass area, St. Louis County, Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 157 p.

Lehr, J.D., and Hobbs, H.C., 1992, Glacial geology of the Laurentian divide area, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Field Trip Guidebook 18, 73 p., 1 pl., scale 1:250,000.

Leverett, F., 1932, Quaternary geology of Minnesota and parts of adjacent states: U.S. Geological Survey Professional Paper 161, 149 p.

Lindholm, G.F., 1968, Geology and water resources of the Hibbing area, northeastern Minnesota: U.S. Geological Survey Hydrologic Investigation Atlas HA-280, 3 pls., scale 1:24,000.

Maclay, R.W., 1966, Reconnaissance of the geology and ground water resources in the Aurora area, St. Louis County, Minnesota: U.S. Geological Survey Water-Supply Paper 1809-U, 20 p.

(2) Meyer, G.N., Jennings, C.E., and Jirsa, M.A., 2005, Surficial geology of southeast Itasca County, pl. 5 *of* Meyer, G.N., Jennings, C.E., and Jirsa, M.A., Aggregate resource potential of Itasca County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-131, 6 pls., scale 1:100,000.

Oakes, E.L., 1964, Bedrock topography of the eastern and central Mesabi Range, northeastern Minnesota: U.S. Geological Survey Miscellaneous Geologic Investigation Map I-389.

Patterson, C.J., and Wright, H.E., Jr., eds., 1998, Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, 208 p.

Steinmaus, K., 1983, Geology and exploration geochemistry of the glacial deposits of northeastern Itasca County, Minnesota: Duluth, Minn., University of Minnesota Duluth, M.S. thesis, 131 p.

Winchell, N.H., 1901, Glacial lakes of Minnesota: Geological Society of America Bulletin, v. 12, p. 109-128.

Winter, T.C., 1971, Sequence of glaciation in the Mesabi-Vermilion Iron Range area, northeastern Minnesota, *in* Geological survey research: U.S. Geological Survey Professional Paper 750-C, p. 82-88.

———1973, Hydrogeology of glacial drift, Mesabi Iron Range, northeastern Minnesota: U.S. Geological Survey Water-Supply Paper 2029-A, 23 p.

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., 1955, Valders drift in Minnesota: Journal of Geology, v. 63, p. 403-411.

———1956, Sequence of glaciation in eastern Minnesota: Geological Society of America Guidebook Series, Minneapolis Meeting, pt. 3, p. 1-24.

Wright, H.E., Jr., and Ruhe, R., 1965, Glaciation of Minnesota and Iowa, *in* Wright, H.E., Jr., and Frey, D.G., eds., The Quaternary of the United States: Princeton, Princeton University Press, p. 29-41.

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