NATIONAL UNDERGROUND SCIENCE AND ENGINEERING LABORATORY (NUSEL): GEOLOGICAL SITE INVESTIGATION FOR THE SOUDAN MINE, NORTHEASTERN MINNESOTA

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Executive Summary

On May 28, 2003, the National Science Foundation site panel report on developing a National Science and Engineering Laboratory (NUSEL) concluded that of the three submitted sites, the Homestake Mine in South Dakota is the most favorable. In addition, the panel considered the Soudan Mine near Tower, MN a possible back-up site for NUSEL, and that the San Jacinto site near Palm Springs, CA is not a viable NUSEL candidate. The evaluation criteria of each of the sites were partitioned into two broad categories: (1) geological suitability; and (2) relative costs. Geological suitability issues for the Soudan Mine included the uncertainty of the geology and rock mass conditions at depth. Given the present uncertainty around Homestake due to indemnification issues and flooding, which consequently jeopardizes most of the earth science initiatives, it is necessary to continue evaluating the favorability of the Soudan Mine for hosting NUSEL. Based on the recent detailed field mapping and interpretation described in this report, the geological and structural setting of the Soudan Mine is perfectly suited for hosting the NUSEL. In addition, a Soudan Mine NUSEL contains all the requirements outlined in the June 2003 publication "EarthLab, A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation".

This report presents the results of a detailed geological study of the Soudan Mine area, and outlines the geological suitability of the area for NUSEL and an integrated EarthLab. The five major themes addressed in this report include:

- **Bedrock Geology**
  The Neo-Archean bedrock geology of the Soudan Mine area is divided into five major lithostratigraphic units. These units include the: (1) *Fivemile Lake sequence*, moderate to shallow-water bimodal volcanic rocks; (2) *Central Basalt sequence*, deep-water tholeiitic basalts; (3) *Upper Sequence,* algoma-type iron formation, tuff, and epiclastic rocks; (4) *intrusive rocks,* felsic porphyries, granodiorite, diorite, gabbro, and lamprophyre; and (5) *sheared rocks*, distinct curvilinear zones of chlorite-sericite-ankerite-pyrite schists.

- **Structural Geology**
  The field area is divided into four main structural domains that include: (1) the Murray shear zone; (2) the Mine Trend shear zone; (3) the Linking Zone; and (4) the Collapsed Hinge Zone. These domains appear to be internally structurally coherent, and are separated from each other either by areas of relatively undeformed rocks or discrete sheared boundaries.

- **NUSEL Site Selection**
  The geological criteria deemed most important for NUSEL construction include: (1) definition of a competent rock mass for excavation of large caverns at depths of 1,450 m and 2,500 m; (2) minimizing the occurrence of major lithologic contacts that would be encountered during construction of shafts, drifts, and the helical decline; and (3) minimizing the occurrence of major structural features in the area proposed for construction of the helical decline. A large area in the competent pillowed basalts of the Central Basalt sequence appears to meet all of the criteria for construction of the helical decline, and large laboratories could probably be excavated out of a large, highly indurated dioritic sill.

- **Compatibility with EarthLab**

  One of the main requirements for EarthLab is a very large, instrumented rock volume and access to great depths. At Soudan, the volume of rock that can be reasonably be accessed for EarthLab research in a Soudan Mine NUSEL is approximately 30 km^3. The scientific themes of study proposed for EarthLab are: (1) microbial life at depth; (2) the hydrologic cycle; (3) rock fracture and fluid flow; (4) rock-water chemistry; (5) deep seismic studies; and (6) geophysical imaging. The compatibility of a Soudan Mine NUSEL with each of these themes is favorable. Although the conceptual design plans for the Soudan Mine NUSEL requires relatively high-cost new construction at depth, the pristine nature of this geological environment is highly desirable for EarthLab research. In addition, the close proximity of the Soudan Mine NUSEL to the four structural domains minimizes the cost of drilling and drifting into these structural settings for EarthLab research.

- **Outstanding Geological Research Opportunities**

  The geological and structural setting of the rocks within and adjacent to the proposed Soudan Mine NUSEL provides a unique opportunity for advances in several areas of earth science. Ideas on outstanding research opportunities include: (1) the structural control of lode-gold mineralization; (2) the hydrothermal alteration of subaqueous volcanic rocks and associated massive sulfide copper-zinc mineralization; (3) the origin of massive hematite ore bodies within Algoma-type iron-formation; (4) the genetic evolution and temporal development of a Neo-Archean volcanic arc; (5) the Neo-Archean tectonic architecture of the southern Laurentian margin; (6) the Pleistocene hydrogeology of the Superior Craton; and (7) the permeability of crystalline bedrock.

Table of Contents

List of Figures

List of Tables

List of Plates

Geologic Setting of the Soudan Mine Area

Introduction

The Soudan Mine, hosted by Archean rocks of the Canadian Shield and operated for over a century as a high-grade iron-ore deposit, is under consideration as the site for a new National Underground Science and Engineering Laboratory (NUSEL) (Calaprice et. al., 2001; Bahcall et al., 2001). For NUSEL, the University of Minnesota proposed a phased expansion of the mine's existing underground laboratory that would create new research space at depths of 1,450 and 2,500 m below the surface (Marshak et al., 2003). This laboratory would likely be built to the east of the existing labs, and would house not only subsurface physics labs, but also include the EarthLab concept (McPherson, 2003), which is intended to allow the study of geologic processes in ways not usually available from the surface.

Although there are published quadrangle-scale and regional-scale geologic maps of the area (Sims and Southwick, 1980, 1985; Peterson and Jirsa, 1999a), these works lack the detail required for engineering and designing the expansion of the Soudan Mine. The purpose of this project is to improve the geologic mapping coverage to the east of the existing Soudan Mine, where two subsurface physics laboratories currently are operating approximately 710m underground. The new geologic mapping covers about 5.7 sq. km (2.2 sq. miles) in sections 25, 26, 27, 34, 35, and 36 of Township 62 North, Range 15 West. Definition of a large number of new rock units and the existence of major east-west striking structural zones has been documented here, where previously published Minnesota and United States Geological Survey mapping shows essentially a single unit of Neo-Archean pillowed basalt. In the area tentatively proposed for the NUSEL, a large area of relatively undeformed rocks has been mapped. This area appears suitable for the proposed NUSEL caverns, and is both within and adjacent to rocks and major structural zones needed for EarthLab.

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Previous Geological Work

Archean rocks within the region surrounding the Soudan Mine have been investigated for well over a hundred years, with the first major publication by J. Morgan Clements on "The Vermilion Iron-Bearing District of Minnesota" (U. S. Geological Survey Monograph 45, 1903). Since that time, numerous workers have mapped portions of the immediate Soudan Mine area. Published geological maps include USGS maps by Sims and Southwick (1980, 1985), and Minnesota Geological Survey maps by Southwick (1993) and Peterson and Jirsa (1999a). Other sources of data include geologic maps from the terminated lease files at the Minnesota Department of Natural Resources, thesis maps, Oliver Mining Company outcrop maps of the Soudan Mine, and the first author's unpublished field mapping and interpretations. Details of the regional geologic framework can be found in numerous reports and publications in the geological literature. A short listing of these works include: The *Geology of Minnesota: A Centennial Volume* (edited by Sims and Morey, 1972), and articles, reports, and theses by Morey et al. (1970), Hooper and Ojakangas (1971), Hudleston (1976), Sims (1976), Schulz (1980), Bauer (1985), Hudleston et al. (1988), Jirsa et al. (1992), Southwick et al. (1998), and Peterson (2001).

Regional Geological Setting

The Soudan mine is located in the Neo-Archean (~2.7 Ga) Vermilion Greenstone Belt of the classic Vermilion district of northeastern Minnesota. Supracrustal rocks in the Vermilion district consist of volcanic-dominated stratigraphic sequences of the Wawa subprovince of the Superior Province of the Canadian Shield. Rocks of the Wawa subprovince in northern Minnesota are divided on the basis of stratigraphic and structural setting into: (1) the southern Soudan belt and (2) the northern Newton belt (Jirsa et al., 1992; Southwick et al., 1998). The boundary between these contrasting structural panels can be traced geophysically across the width of Minnesota, and was designated informally as the Leech Lake structural discontinuity (Jirsa et al., 1992). In the region west and north of the Soudan Mine, the Leech Lake structural discontinuity occurs along the Mud Creek shear zone (Hudleston et al., 1988), small segments of the Vermilion and Wolf Lake faults (Sims and Southwick, 1985), and the Bear River fault (Jirsa et al., 1992). The Soudan belt contains large, broad folds involving calc-alkalic and tholeiitic volcanic strata overlain by, and locally interdigitated with, turbiditic rocks. In contrast, the Newton belt consists of elongate, northeast-trending, and mostly northward-younging volcanic and volcaniclastic sequences. Volcanic rocks of the Newton belt differ from those of the Soudan belt in containing locally abundant komatiitic flows and peridotitic sills. The two belts are fault-bounded, and the relationship between stratigraphic units within each belt is largely conformable, although faults obscure contacts locally. In its eastern extension, the Soudan belt is continuous with the Saganagons assemblage in Ontario and terminates against the Saganaga pluton and Northern Light Gneiss. The Newton belt extends discontinuously eastward into the Shebandowan District of Ontario to form the Greenwater and Burchell assemblages. Intrusive rocks in both belts vary from gabbroic and felsic porphyries demonstrably related to volcanism, to large plutons emplaced post-tectonically. Both districts contain unconformable, Timiskaming-type sequences composed of calc-alkalic volcanic rocks, conglomerates, and finer grained sedimentary rocks. A simplified regional geological map of the Neo-Archean terranes of northeastern Minnesota and adjacent Ontario is presented in Figure 1.

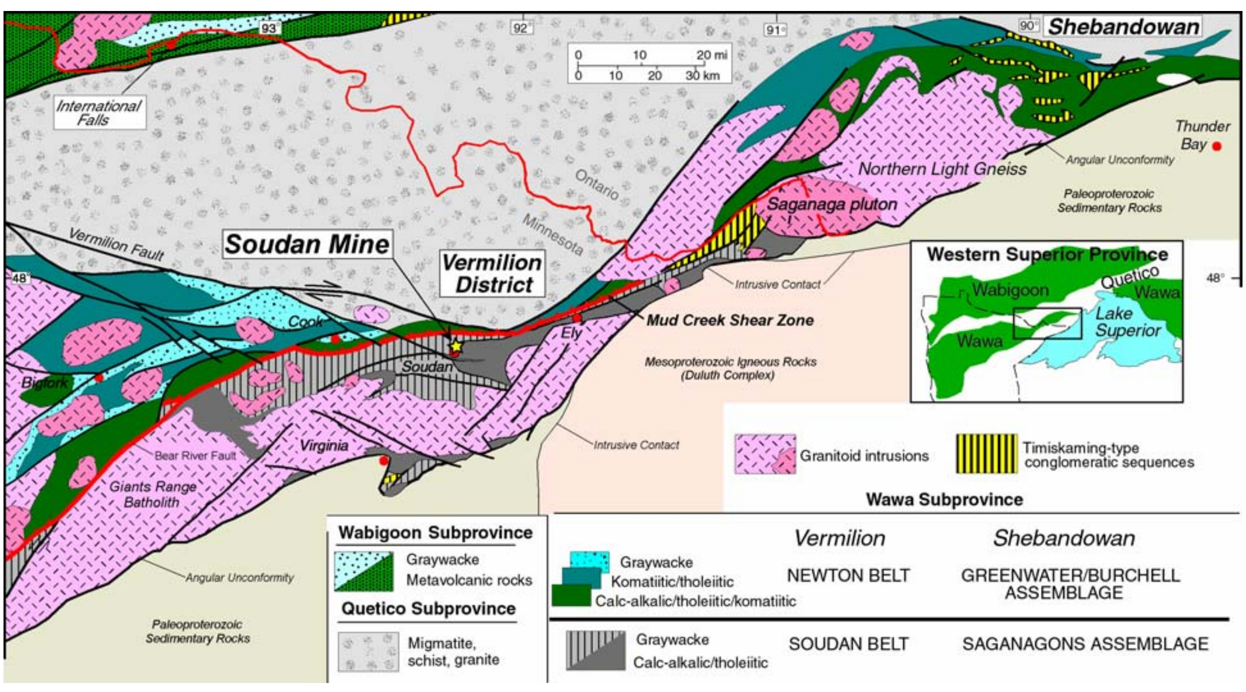

Figure 1. Simplified correlation map of Neo-Archean assemblages across the U.S. - Canadian border, modified from Peterson et al. (2001). Inset shows major subprovinces of the southwestern Superior Province.

Local Geologic Setting

Lithostratigraphic units in the Soudan Mine area include: (1) the Lower member, Soudan Iron Formation member, and Upper member of the Ely Greenstone, the Lake Vermilion Formation (including the informally named Britt and Gafvert Lake sequences), and the Knife Lake Group of the Soudan belt; (2) the Bass Lake sequence (Peterson and Jirsa, 1999a) of the Newton belt; and, (3) syn- to post-tectonic granitoid intrusions of the Giants Range batholith, and a suite of post-tectonic alkalic stocks and plutons (Fig. 2). Contacts between the different units are typically conformable, although considerable overlap in time and space is documented between volcanic and sedimentary sequences (Southwick, 1993). Rock types associated with the lithostratigraphic units in the area are presented in Table 1. The Lower and Soudan Iron Formation members of the Ely Greenstone (Morey et al., 1970) occur in the area of recent mapping, and are described in more detail below.

The Lower Member of the Ely Greenstone (Lower Ely) consists dominantly of pillowed and massive basalt and andesite flows of calc-alkalic and tholeiitic composition. Hypabyssal diabase, gabbro, and dioritic sills, isolated dacitic and rhyolitic lava flows and domes, and local fragmental units occur throughout the sequence. Pillows typically are irregularly shaped and well vesiculated, indicating moderate to shallow water depths of formation, and rare bedded scoria deposits may indicate local subaerial volcanism. The upper pillowed basaltic rocks of the Lower Ely typically are non-vesiculated and ovoid, suggesting a general subsidence of the volcanic pile to deep-water conditions.

Table 1. Lithostratigraphic units within Neo-Archean rocks of the Soudan Mine area.

Neo-Archean Intrusive Rocks	
Late Intrusions	Plutons & stocks of syenite, monzonite, diorite, and lamprophyre
Giants Range Batholith	Granite, granodiorite, monzodiorite, schist-rich migmatite
Neo-Archean Supracrustal Rocks	
Newton belt	
Bass Lake Sequence	Tholeiitic basalt lava flows, iron-formation, and felsic porphyries
Soudan belt	
Knife Lake Group	Greywacke, slate, conglomerate, and sheared equivalents
Lake Vermilion Formation	Greywacke, slate, dacitic tuff, and minor conglomerate
Gafvert Lake Sequence	Felsic to Intermediate lava flows, tuffs, and intrusions
Britt Sequence	Tholeiitic basalt lava flows
Upper Ely Greenstone	Tholeiitic basalt lava flows and iron-formation
Soudan Iron-Formation	Layered cherty iron-formation, epiclastic rocks, and tuff
Lower Ely Greenstone	Calc-alkalic and tholeiitic lava flows, tuffs, and epiclastic rocks

Stratigraphically overlying the volcanic rocks of the Lower Ely is the Soudan Iron Formation, which consists dominantly of laminated Algoma-type iron-formation, with lesser basalt lava flows and detrital rocks of basaltic to dacitic composition. In general, the exhalative nature of many of the rocks of the Soudan Iron Formation represents deep-water chemical deposition throughout a period of quiescence, which began during the latest stages of volcanism associated with the Lower Member of the Ely Greenstone. The stratigraphic thickness of the Soudan Iron Formation varies from 50 to 3,000 meters, and averages approximately 700 meters. The thickest sections occur in the nose of the Tower-Soudan anticline, and probably represent stratigraphy that is repeated by shearing and thickened by folding. The time period over which the Soudan Iron Formation was deposited is poorly constrained, as little detailed geochronological data exist for the Ely Greenstone. Nevertheless, the size (thickness and strike length) of the Soudan Iron Formation is much larger than typical Algoma-type iron-formations and probably represents a profound break in the volcanic history of the belt.

A gradational contact over several tens to hundreds of meters occurs between the underlying Lower Ely and the overlying Soudan Iron Formation. The upper contact of the Soudan Iron Formation member is more diverse; overlying stratigraphic units along strike include the Upper member of the Ely Greenstone, the Gafvert Lake sequence, and the Lake Vermilion Formation. Two aspects of the regional structural framework dominate the local structural setting of the Soudan Mine area: (1) the steeply west-plunging, overturned D_1 Tower-Soudan anticline, and (2) the steep D_2 shear fabrics associated with the Murray shear zone. In addition, localized NE and NW trending D_3 faults occur throughout the area (Fig. 2).

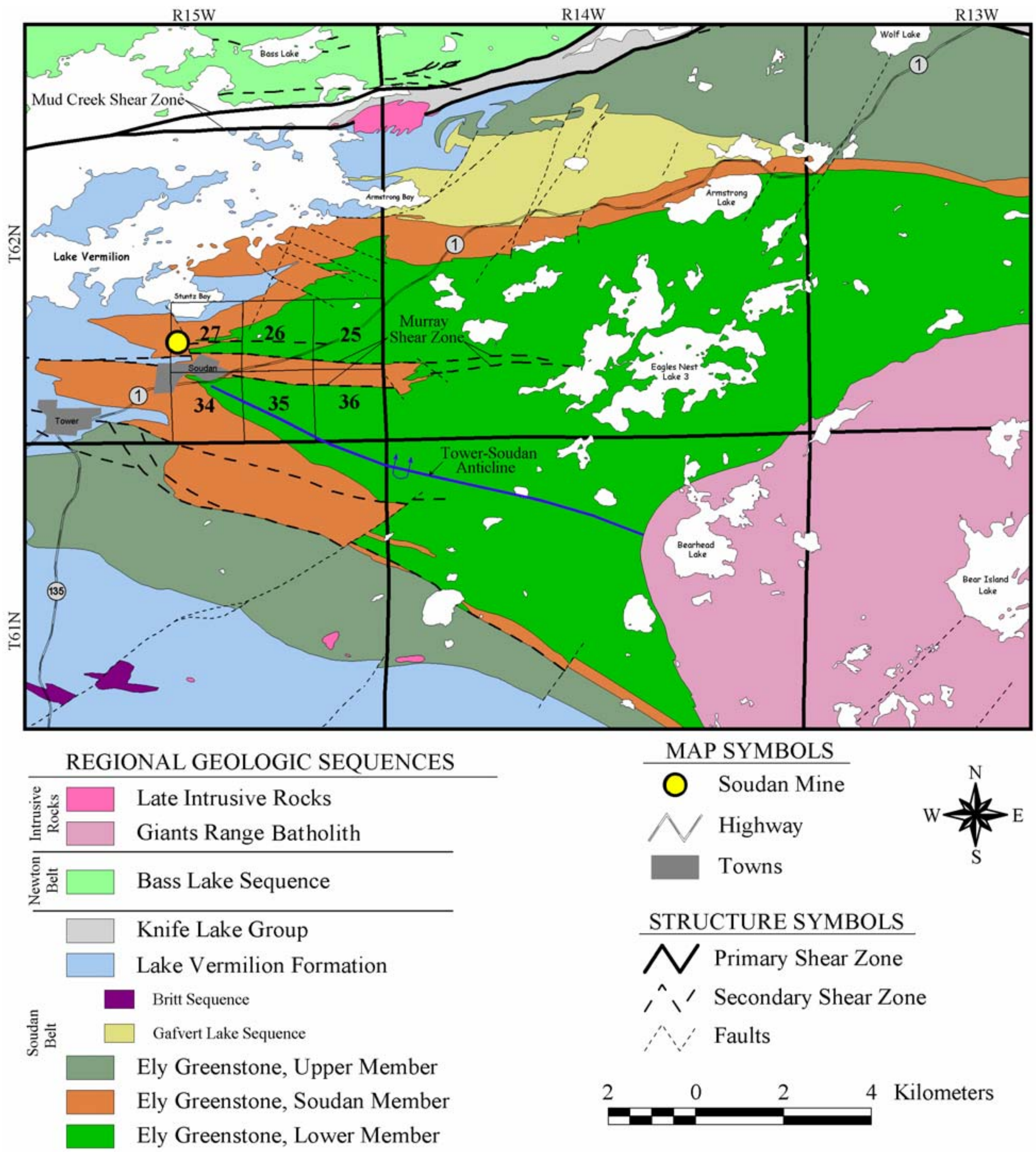

Figure 2. Simplified lithostratigraphic map of the Soudan Mine area. Modified from Peterson (2001).

Structural Geology

Periods of generally N-S directed compression resulted in three major regional deformation events in the Neo-Archean terranes of northern Minnesota. The earliest deformation event (D_1) produced broad, locally recumbent folds within the Soudan belt and major fault zones throughout the region. In the Newton belt, D_1 was accommodated by thrust imbrication of large crustal blocks, resulting in mainly northward stratigraphic facing. Field relationships indicate that uplift, faulting, and the deposition of Timiskaming-type clastic sequences in local fault-bounded basins occurred late in D_1 deformation (Jirsa, 2000). A large, map-scale structure related to D_1 deformation in the Soudan Mine area is the Tower-Soudan Anticline, which is a west-plunging anticline within which the axis and plunge changes orientation along strike from nearly vertical in basalts to shallow NE plunging in the western sedimentary rocks. Axial-planar cleavage associated with this early fold typically is lacking, although Bauer (1985), Hooper and Ojakangas (1971), Hudleston (1976), and Jirsa et al. (1992) have described early cleavage (S_1) locally.

A second deformation event (D_2) associated with synchronous regional metamorphism resulted in foliation development and structures having largely dextral asymmetry. D_2 is constrained in the Vermilion district to the time period 2674 to 2685 Ma (Boerboom and Zartman, 1993), and between about 2680 and 2685 Ma in the Shebandowan (Corfu and Stott, 1998). Because D_2 deformation affected all of the supracrustal rocks in the area and is reasonably constrained by geochronology, the regional foliation (S_2) can be used in the field to relate other structural, intrusive, and deformation events. The relationship between S_2 fabric and shear structures indicates that most shearing occurred relatively late in the D_2 event. Major shearing that produced the Mud Creek (Fig. 1) and related shear zones, e.g., the Murray shear zone in the Soudan Mine area, is attributed to the late stages of D_2 dextral transpression.

Structures related to the third deformation event (D_3) include abundant NE- and NW-trending faults that dissect the stratigraphic assemblages. Named structures related to D_3 include the NE-trending Waasa and Camp Rivard faults east of the Soudan Mine area, and the WNW-trending, crustal-scale Vermilion and related faults that form the Wawa-Quetico Subprovince boundary north of the Soudan Mine (Fig. 1).

Economic Geology

Massive hematitic ores (> 60% iron) of the Soudan Mine were continually mined from 1883 to 1962. The ore zones were irregular-shaped bodies of massive hematite derived from the lower grade iron-formation by uncertain geologic processes. The most likely origin was by contemporaneous leaching of silica and precipitation of hematite by hydrothermal solutions active during D_2 shear-dominated deformation. Mining usually started in open pits and progressed underground as safety concerns from the steep walls of the pits outweighed mining economics. Extensive test pit programs and dip-needle surveys in the first half of the 1900s by the Oliver Iron Mining Company, a division of United States Steel, suggest that other near surface massive hematite bodies are unlikely to be present in the immediate project area.

Four volcanogenic massive sulfide (VMS) and two lode gold prospects have been identified in the Lower Member of the Ely Greenstone. The VMS prospects include the Skeleton Lake prospect on the south limb of the Tower-Soudan Anticline (drilled by Exxon, 1972), the Eagles Nest (drilled by Newmont, 1988), Purvis Road (drilled by Rendrag, 1999), and the Fivemile Lake (drilled by Teck, 1994) prospects on the north of the Tower-Soudan Anticline. Peterson (2001) described the regional VMS-style alteration and mineralization associated with most of these prospects, which includes a zone of semi-conformable quartz-epidote alteration greater than 19 km in strike length. All of these prospects occur along felsic volcanic horizons in the Lower Ely, and are still viable exploration targets for VMS mineralization.

Newmont Exploration Limited completed lode gold mineral exploration in the Lower Member of the Ely Greenstone in the mid- to late-1980s, and discovered gold mineralization at the Murray and Eagles Nest prospects. Geologists from Newmont first discovered gold mineralization along the Murray shear zone during the initial reconnaissance mapping and sampling of rocks, seeps, and stream sediments in the area. Encouraging results from the reconnaissance work led subsequently to the completion of a 101 line-kilometer grid and an extensive exploration program across the area. Gold mineralization in this area is associated with quartz-carbonate-pyrite-galena-tetrahedrite veins in strongly sheared and carbonatized rocks of presumed basaltic protolith. The shearing is associated with the north edge of the east-west trending Murray shear zone, which horizontally displaces a narrow sliver of the Soudan and Lower Members of the Ely Greenstone 3-5 km to the east. The location of lode-gold and VMS prospect areas east of the Soudan Mine area are shown in Figure 3.

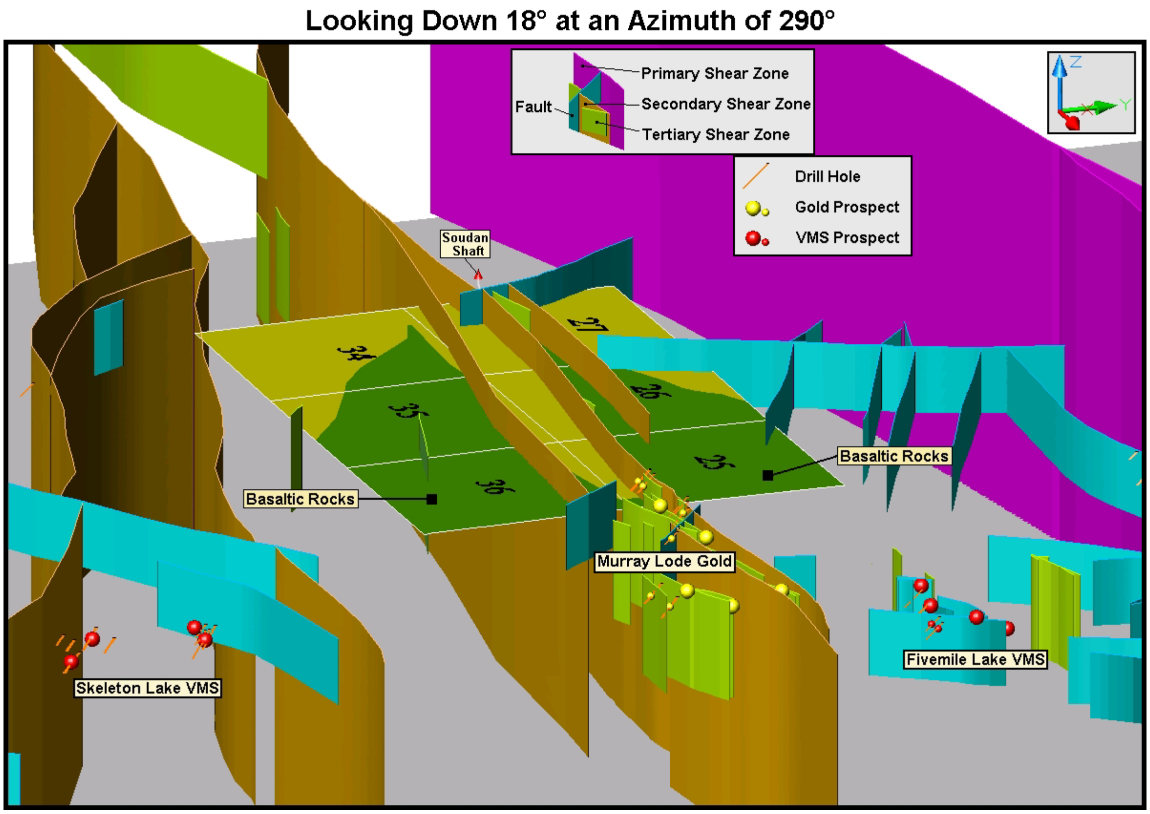

Figure 3. Simplified 3D view of previously mapped regional structures with superimposed locations of anomalous drill hole intersections from known gold and VMS prospects. Detailed mapping has been completed in portions of the six sections (25,26,27,34,35,36 of Township 62 North, Range 15 West) depicted. Structural features (shear zones and faults) are projected vertically downward, taken from Peterson and Jirsa (1999a).

Pleistocene and Holocene Deposits

Late Pleistocene glacial deposits (Late-Wisconsin glaciation) in the region around the Soudan Mine are associated with the stepwise retreat of the Rainy Lobe of the Laurentide Ice Sheet, approximately 14,000 to 12,000 years ago. The repeated glaciations of the Pleistocene epoch modified the pre-existing topography of northeastern Minnesota, i.e. the surface was scoured by glacial ice, exposing fresh bedrock, and new surficial materials were deposited following the retreat of the glaciers. During the retreat of the glacier, the margin of the ice-sheet blocked the natural drainage to the north, and pro-glacial lakes formed in front of this barrier (glacial lakes Norwood, Koochiching, and Agassiz). Subglacial streams left sinuous ridges of sorted sand and gravel (eskers), and delta/fan complexes formed where these streams exited the ice margin and entered the pro-glacial lakes. A simplified history of the Late Wisconsin glacial events and related landforms is given in Table 2, and regional and detailed digital elevation maps of the area are presented in Figure 4.

Surficial deposits covering much of the bedrock in the immediate field area include glacial deposits related to the ~12,500 year old margin of the Laurentide ice sheet (ice margin defined by the location of the Vermilion Moraine), and the recent Holocene (<10,000 year old) soils and forested peat bogs. Glacial deposits include: 1) a thin veneer of basal till, erratics, melt-out boulder lag deposits, and steep sided ridges of subglacial fluvial deposits (eskers) on the scoured bedrock uplands north of the moraine; 2) a boulder-rich end moraine (the Vermilion Moraine); and 3) an outwash plain/delta and older undifferentiated glacial deposits (tills overlain by glacial lake deposits) south of the Vermilion Moraine. Photographs of glacial features and landforms seen in the immediate field area are presented in Figures 5 and 6.

Table 2. Simplified timing of Late Pleistocene glacial events and associated landforms for the region around the Soudan Mine, modified from Lehr and Hobbs (1992). Landforms depicted on Figure 4.

Age	Glacial Landforms and Features Developed
Advancing Ice of the Rainy Lobe of the Laurentide Ice Sheet	
30 – 14 ka	Regional bedrock scouring of weathered surface
Retreating Ice of the Rainy Lobe of the Laurentide Ice Sheet	
13.5 ka	Big Rice and Wampus Lake Moraines, Glacial Lake Norwood ponded at ice margin at 1,470 ft. elevation. Lake Norwood drains south through the Embarrass Gap.
13.0 ka	Wahlsten Moraine, Glacial Lake Norwood ponded at ice margin at 1,450 ft. elevation, and merges with Lake Koochiching. Lake waters drain south through the Embarrass Gap.
12.5 ka	Vermilion Moraine, Glacial Lake Koochiching/Norwood ponded at ice margin at 1,450 ft. elevation. Melt water streams and jökulhlaups deposit deltas along the shore of glacial lakes.
12.0 ka	Glacial Lake Koochiching/Agassiz dammed by Vermilion Moraine. Prairie River outlet develops to the west and lake level drops to 1,350 ft. elevation.
10.5 ka	Final melt out of stagnant ice throughout the area.

Analysis of pollen from lake sediment cores taken over the last forty years in northeastern Minnesota documents the vegetation history of the area since the retreat of glacial ice from the state. These studies include the works of Fries (1962), Cushing (1967), Wright and Watts (1969), and Huber (1987). Huber (1992) summarized the data from these works (and many others) into a simplified history of the Holocene climate and vegetation of northeastern Minnesota (Table 3). The demise in local trapping over the last twenty years has brought about an increase in the beaver population of northern Minnesota. In the field area, beavers have dammed many streams and quite large areas of cedar and black spruce forest have been flooded. Photographs of Holocene features noted in the field area are presented in Figure 7.

Table 3. Simplified Holocene pollen assemblages and vegetation history for northeastern Minnesota (Huber, 1992).

Age	Named Pollen Assemblage	Interpretation
13.5 – 10.5 ka	Compositae-Cyperaceae Zone	Tundra developed in deglaciated areas (grass, herbs, shrubs)
10.5 ka	Betula-Picea Zone	Shrub parkland (birch-spruce)
9.5 – 8.3 ka	Picea-Pinus Zone	Conifer Forest (spruce-pine)
8.3 ka	Pinus-Betula-Alnus Zone	Mixed conifer-hardwood forest (pine-birch-alder)
6.8 ka	Upper Zone 1	Mid-Holocene warming, increase in White Pine, prairie to west
3 ka	Upper Zone 2	Cooling of climate, increase in Spruce
Since 1890	Ambrosia	Deforestation and land clearing by pioneer settlement (ragweed)

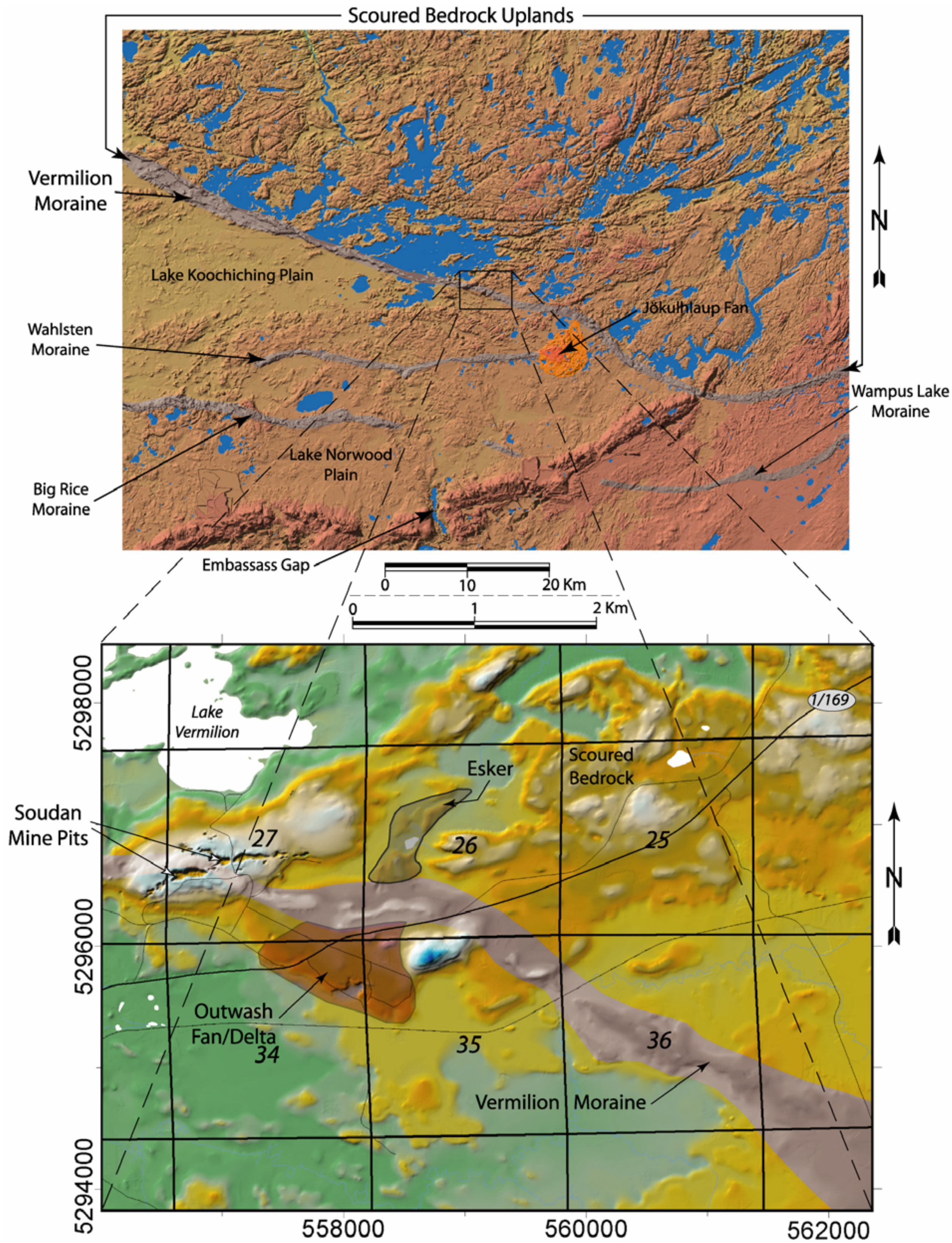

Figure 4. Regional (top) and local (bottom) digital elevation maps depicting superimposed glacial landforms. Grid values in the detailed map are UTM coordinates, in meters.

Figure 5. Photographs of Quaternary features and landforms in the field area: A) glacially striated and polished bedrock surface, ice flow parallel to hammer handle; B) unsorted basal till with angular pebbles and cobbles; C) coarsening upwards sequence of sands and gravels in the outwash fan/delta complex (~30 ft. vertical face in gravel pit); D) close up of cross-bedded sands in the outwash fan/delta complex (hammer 68 cm long); E) partial cross-section through the boulder-rich Vermilion Moraine (30 ft. high exposure of glacial materials on top of the north margin of the open-pit directly north of the No. 8 shaft of the Soudan Mine); and F) logging road across esker sand and gravel beds.

Figure 6. Photographs of Quaternary features and landforms in the field area: A) boulder lag deposit (field of view 10 m); and B) large granite erratic, probably derived from the Quetico Subprovince to the north, on an outcrop of pillowed andesite of the Fivemile Lake sequence (boulder ~2 m high).

Figure 7. Photographs of Holocene features: A) marsh/peat bog filling a small basin in the scoured bedrock terrain; and B) a six-foot high beaver dam that blocks drainage and forms a 35 acre pond in the west-central portion of the field area.

Detailed Geologic Studies

Field Work Completed

Bedrock geological mapping was confined to an area of about 5.7 sq. km (1,400 acres) in Sections 23, 24, 25, 26, 27, 34, 35, and 36 in Township 62 North, Range 15 West, and Section 30 in Township 62 North, Range 14 West. This fieldwork was completed between April 22 and June 17, 2003. Fieldwork for this map was completed by the authors, the professional geological staff of the NRRI (John Heine, Peter Jongewaard, Mark Severson, and Steve Hovis), all with experience mapping in Neo-Archean greenstone terranes, and Adam Hoffman, a graduate student from the Department of Geological Sciences, University of Minnesota Duluth. Approximately 175 kilometers of mapping traverses were walked, ~1,300 outcrop polygons mapped, ~2,000 structural elements measured, ~600 rock samples collected, and ~600 photographs taken in the map area. Figure 8 shows the coverage of this recent field mapping.

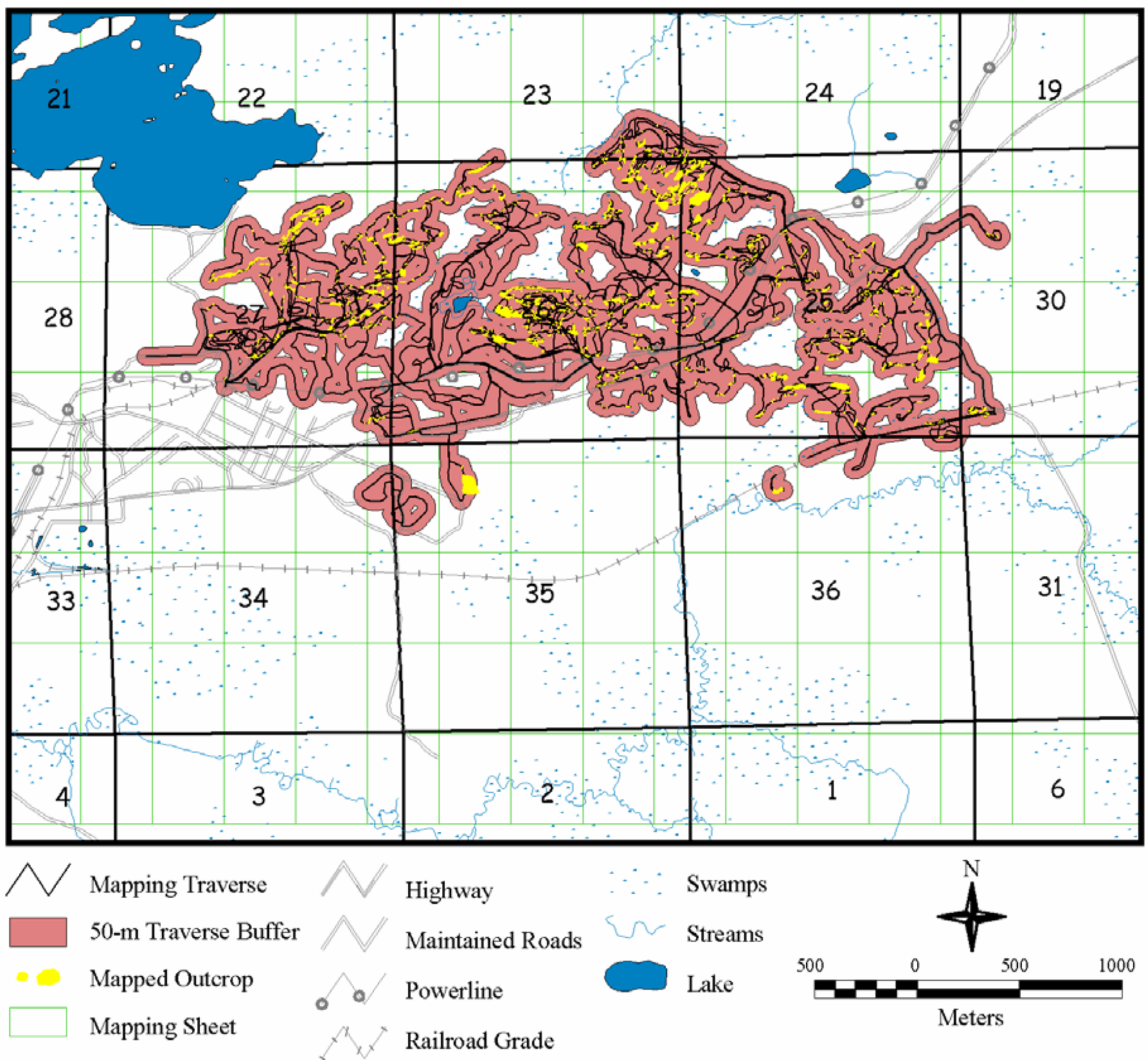

Figure 8. Location of traverses and outcrops mapped for this project.

Outcrop Mapping Technique

Bedrock geological mapping was completed at a scale of 1:2,000 on 8 ½" x 11" mapping sheets (Fig. 8) with topography (10-foot contour interval) and a pre-printed grid (100-meter spaced) of Universal Transverse Mercator (UTM) coordinate lines. All data obtained and generated for this project is georeferenced into Zone 15 of the UTM projection using the North American Datum of 1983 (Nad83). Each sheet covered about 0.2 km^2. For the base map, topography was digitized on screen in AutoCAD™ from digital copies of the United States Geological Survey 7.5' Soudan and Tower quadrangles and converted to ArcView shapefile format. The information recorded on the field sheets included outcrop polygon shape, outcrop number, sample number, outcrop rock type, some fault and lithological contact data, miscellaneous geologic information, and traverse route. Appendix 1contains descriptions of the GIS databases included on the accompanying CD-ROM with this report.

Outcrops were located along traverses that followed the surficial terrain to locations where bedrock exposure were likely, e.g., knobs, ridges, and steep slopes. Exact outcrop location and shape was obtained using handheld Global Positioning System (GPS) units. Although the GPS units used in this project were not survey-grade, their accuracy is similar to the topography on the USGS topographic maps. The high points of knobs coincide with the GPS generated coordinate, and the roads and trail intersections as digitized from georeferenced air photos appear to coincide with the GPS generated coordinate at our mapping scale of 1:2,000. Estimated position error-ellipses given on the GPS units averaged approximately 12 feet.

Outcrops were described on pre-printed, individually numbered outcrop sheets sized to fit into field notebooks. The outcrop sheets contain space for geologic data (tabular, such as structural measurements, and descriptive, such as an outcrop sketch and a short description of the salient points about the particular outcrop). The sheets also included records for non-geologic information such as date, geologist, UTM coordinate of a central location on the outcrop, map sheet number, sample number cross reference, Public Land Survey location, and outcrop condition. Information about glacial features and pillow morphology were also recorded. Further geologic comments were kept on extra pages if warranted. The outcrop sheets proved particularly useful during the cartographic generation of the final map, since essentially all of the information gathered in the field could be sorted and reviewed in a timely manner. These sheets will prove to be a valuable archive of geological information for future studies. In addition, digital photography was done for both general outcrop morphology and specific geologic features. An example of digital photographs and the data gathered on an outcrop sheet are presented in Figure 9. Rock samples collected were assigned sample numbers from pre-numbered sheets, which also recorded date, geologist, outcrop number, mapping sheet, UTM location, rock type, mineralization, and alteration.

Depending on the size of the outcrop, and the apparent complexity of the geology, the outcrop polygons on the map sheets, the published map, and the GIS database may represent individual outcrops or multiple similar outcrops where a single description is appropriate. As much as practical during fieldwork, effort was made to have other geologists on the team look at individual outcrops and comment on and/or verify an interpretation. At the end of each day of fieldwork, all geologists working on the project entered the data they had collected into ArcView GIS databases. The data entered included: 1) outcrop polygons; 2) rock sample location points; 3) structural measurement points; and 4) mapping traverse lines. Cleaned and labeled slabs of all collected rock samples were boxed for easy access and reference. Heels from the samples were set aside for future thin section work (Adam Hoffman of UMD will be doing a masters thesis in the area), geotechnical testing, or geochemical analysis. At the termination of fieldwork, all geologists reconciled the digital data for the outcrops they had mapped as best as possible with the project-wide geological picture. Some rock descriptions were modified because of the availability of cut samples. This final reconciled geology was combined with the input of the geologists to define the geologic units and the overall structural setting of the area. The structural and stratigraphic concepts were then merged through a set of iterations by the primary author to create the final geology map of the area.

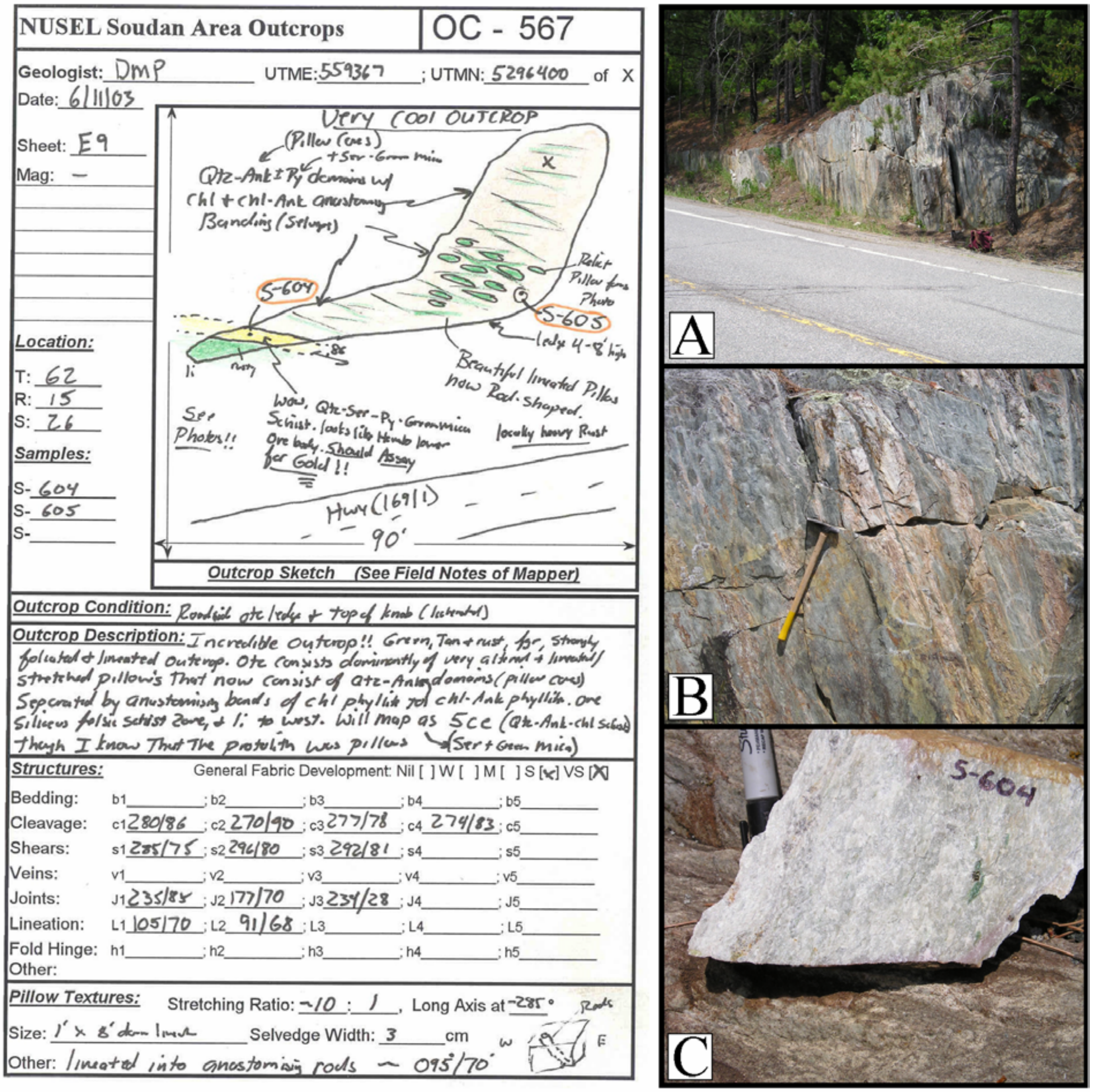

Figure 9. Scanned image of the field sheet used to map outcrop OC-567. On the right are digital photographs of outcrop OC-567: A) the overall outcrop view looking WNW; B) view to the north of steeply east plunging, lineated and rod-shaped pillowed andesite (rock hammer 68cm for scale); and C) close-up view of rock sample S-604, taken from the west side of the outcrop (bright zone on the left side of picture A). The combination of field sheets and digital photographs documents geology and geologic structures not described in regional maps, e.g., Sims and Southwick (1980).

Nomenclature and Map Unit Codes

The categorization of the various volcanic and sedimentary rocks of the field area into distinct facies is not a trivial matter. For this study, the naming of the volcanic and sedimentary rock units follows the nomenclature of Fisher (1961, 1966) and Dott (1964). The coding of lithologic units depicted on the bedrock geology map (Plate 1) is a compromise between the formats typical of maps produced by the Minnesota

Geological Survey (lithostratigraphic subdivision of map units with coding by letters) and the Canadian Geological Survey (based strictly on dominant rock type with coding by numbers and letters). For this study, the Neo-Archean bedrock geology has been divided into five distinct lithologic suites: 1) Sheared rocks; 2) Intrusive rocks; 3) the Upper Sequence; 4) the Central Basalt Sequence; and 5) the Fivemile Lake Sequence. The coding of map units for each of these suites is unique, and consists of either combinations of letters and numbers or strictly letters. The map unit code nomenclature used in this report is presented in Table 4.

Table 4. Coding scheme of bedrock geology map units.

1 – MAFIC VOLCANIC ROCKS (Basalt and Andesite)	
1a - Massive Lava Flows	1h - Bedded Scoria deposits
1b - Pillowed Lava Flows	1i - Foliated Basaltic Rocks
1e - Tuff and Resedimented Hyaloclastite	1u - Undifferentiated
2 - FELSIC VOLCANIC ROCKS (Dacite and Rhyolite)	
2a - Massive Lava Flows	2d - Monolithic Breccia Deposits
2b - Tuff Breccia Deposits	2e - Tuff and lapilli Tuff Deposits
2c - Heterolithic Breccia and Conglomeratic Rocks	2f - Epiclastic Deposits
3 - CLASTIC SEDIMENTARY ROCKS	
3a - Greywacke and Argillite	3c - Conglomerate
4 - CHEMICAL SEDIMENTARY ROCKS	
4a – Oxide Facies Iron Formation	4f - Chert
5 - SHEARED ROCKS (Mineralogical Codes Below)	
b - sericite	i - green mica
c - ankerite	p - pyrite
e - chlorite	
INTRUSIVE ROCKS	
L - Lamprophyre	Gd - Granodiorite
Qfp - Quartz-Feldspar Porphyry	Db - Diabase
Fp - Feldspar Porphyry	Gb - Gabbro
D - Diorite	

SUPRACRUSTAL SEQUENCES	*MAP CODE EXAMPLES*
5xxx – Sheared Rocks	5ecp – chlorite-ankerite-pyrite schist
Xy – Intrusive Rocks	Fp – Feldspar Porphyry
USxx – Upper Sequence Rocks	US1b – Mafic pillowed lava flows
CBxx – Central Basalt Sequence Rocks	CB1a – Mafic massive lava flows
FMxx – Fivemile Lake Sequence Rocks	FM2d – Felsic monolithic breccia deposits

Bedrock Stratigraphy

Outcrops in the region are characteristically overgrown with vegetation. Most exposed rock has a fine growth of lichen obscuring the finer surface textures. Many (most) outcrops were exposed by peeling back moss layers and sweeping up the remaining soil with wisk brooms. Further cleaning and treatment of "lichenated" areas with dilute household bleach would greatly improve the outcrop surface for more detailed mapping in the future. Therefore, the rock units (and their descriptions) depicted within the "Limits of Recent Mapping" line (Plate 1) are based on these man-made exposures, natural exposures, subsequent examination of broken rock faces, re-examination of the rocks after slabbing, and prior knowledge and experience in the region. Petrographic and geochemical analyses were not available for compiling these descriptions.

Geological context was very critical during the course of the field investigation, in that our assumptions and prior knowledge about the terrane have an effect on our interpretation of what we see in the field. Observations of color, texture, fabric, and estimates of mineralogy imply a certain genesis and are constantly tested against the other outcrops in the immediate area prior to determining the shape of a mappable unit. In the strictest sense, all of the rock units are metamorphosed to greenschist facies, and thus the prefix meta- has been omitted for brevity. Virtually all units have a weak D_2 fabric, and have been altered to some degree. Silicification, and in some cases carbonitization, are not always visually recognizable in the field, and are estimated from surface staining and the level of difficulty encountered in breaking the rocks. With the exception of one gabbro sill, and one area of pillow basalt where selvages are composed of magnetite, no rocks other than the iron-formation were magnetic. No oxide mineral concentrations were seen elsewhere in the field area. However, iron-rich soils derived from the glacial drift in area have stained almost all the lighter colored rock units red to orange.

Schistose units are the result of both large-scale tectonic movements and small-scale localized compression and/or shear where adjacent units of differing competency have moved relative to one another. Therefore, a "patchy foliation" is common in the area, where otherwise massive units will locally show weak to moderate foliation over small areas. This "patchy foliation" may not be traceable from outcrop to outcrop.

Stratigraphic units have been classified into five lithostratigraphic divisions based on their textures and composition. These divisions, each individually described below, include: (1) sheared rocks; (2) intrusive rocks; (3) the Upper sequence; (4) the Central Basalt sequence; and (5) the Fivemile Lake sequence (Fig. 10). Rock units that lie outside the "Limit of Recent Mapping" line (Plate 1, Fig. 10) were not investigated during the course of this project, and the description of these rocks are taken from the previous maps and studies by Sims and Southwick (1980, 1985), Southwick (1993), Peterson and Jirsa (1999a), and Peterson (2001).

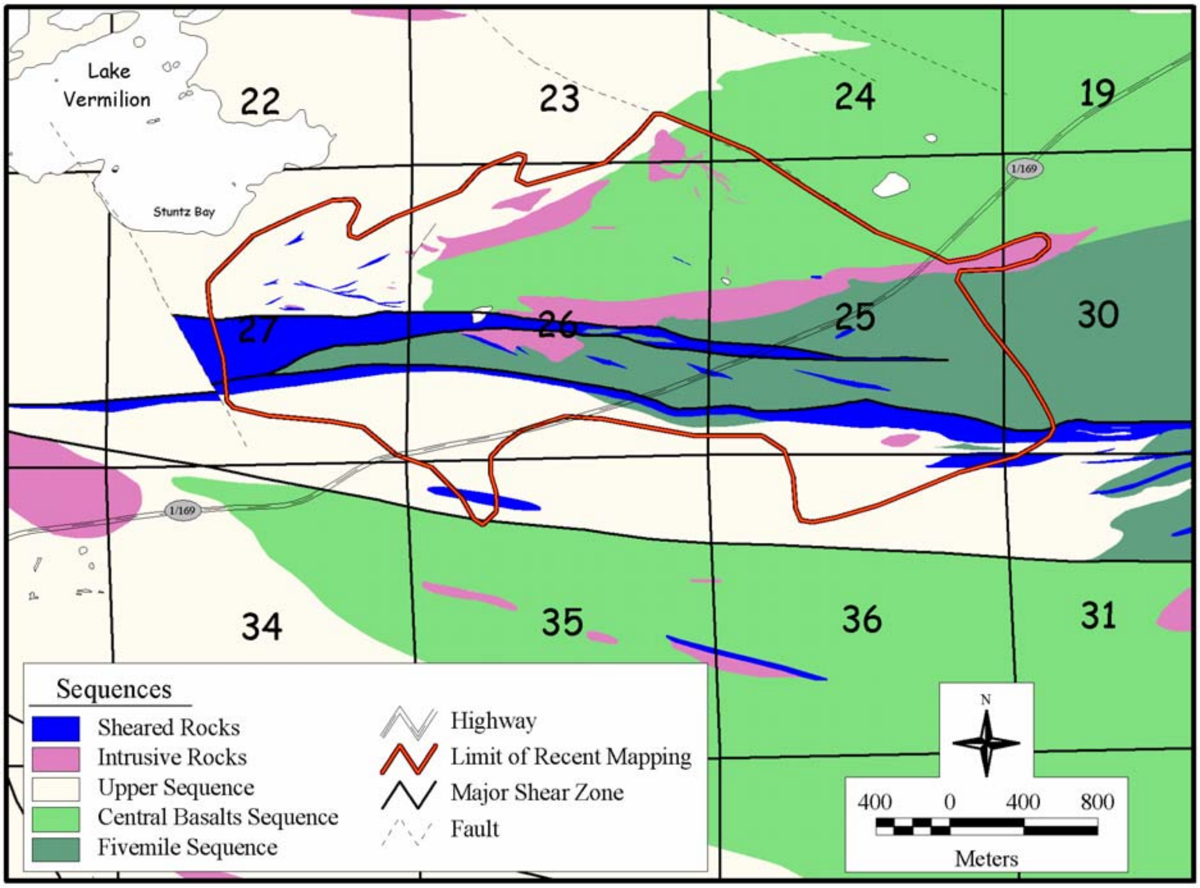

Figure 10. Location map of sheared rocks, intrusive rocks, and the Fivemile Lake, Central Basalt, and Upper sequences.

Sheared Rocks - [5xxx Series Map Units]

Sheared rocks comprise a diverse series of units that occur dominantly as east west-trending, curvilinear bands of schistose rocks (Fig. 10). Based on the orientation of the foliation in these strata, the units are inferred to have formed largely during the late-stages of D_2 deformation, with individual rock units occurring along discrete ductile to brittle-ductile structures. Sheared rock unit domains include: 1) S-tectonites, with anastomizing fabric composed of discrete flattened sigmoidal domains with wrapping foliations and shear bands (S-C structures); 2) L-tectonites, with pervasive lineation and localized foliation; and 3) LS-tectonites, with both strong foliation and lineation. The latter LS tectonite fabrics are most common. Individual domains occur at seemingly all scales, from mm to tens of meters. Distinct map units are defined by mineral assemblages noted in outcrop, and are coded by letters from dominant to minor components. Mineralogical coding includes: b = sericite; c = ankerite; e = chlorite; i = green mica; and p = pyrite. Ankerite commonly occurs as 2-3 mm porphyroblasts and pyrite as either finely disseminated grains or semi-massive zones in siliceous domains. The four discrete groups of sheared rocks depicted on the map (Plate 1) are described below.

5,4 Schist 'n' BIF

Schist 'n' BIF is a complex series of schistose rocks composed of interlayered and fragmental-textured, chloritic and sericitic schists with iron-formation bands and fragments (Fig. 11). The unit occurs only within the Mine Trend shear zone east of the Soudan Mine, and commonly contains domains of strongly pyritic schist. Protoliths prior to shearing probably include Upper Series map units US2e (felsic lapilli tuff and fragmental rocks) and US1,4 (interbedded basaltic rocks and iron-formation). The unit is generally poorly exposed due to extensive open-pit mines (which are fenced and were not mapped), and coverage by mine dumps. However, the unit is known from historic drilling, recent mapping, recent and previous examination of the 17th and 27th levels of the Soudan Mine, and historic surface mapping by Oliver Mining Division of United States Steel Corp. Definition and subdivision of the unit into chlorite and/or sericite-dominant schists was controlled by outcrop density.

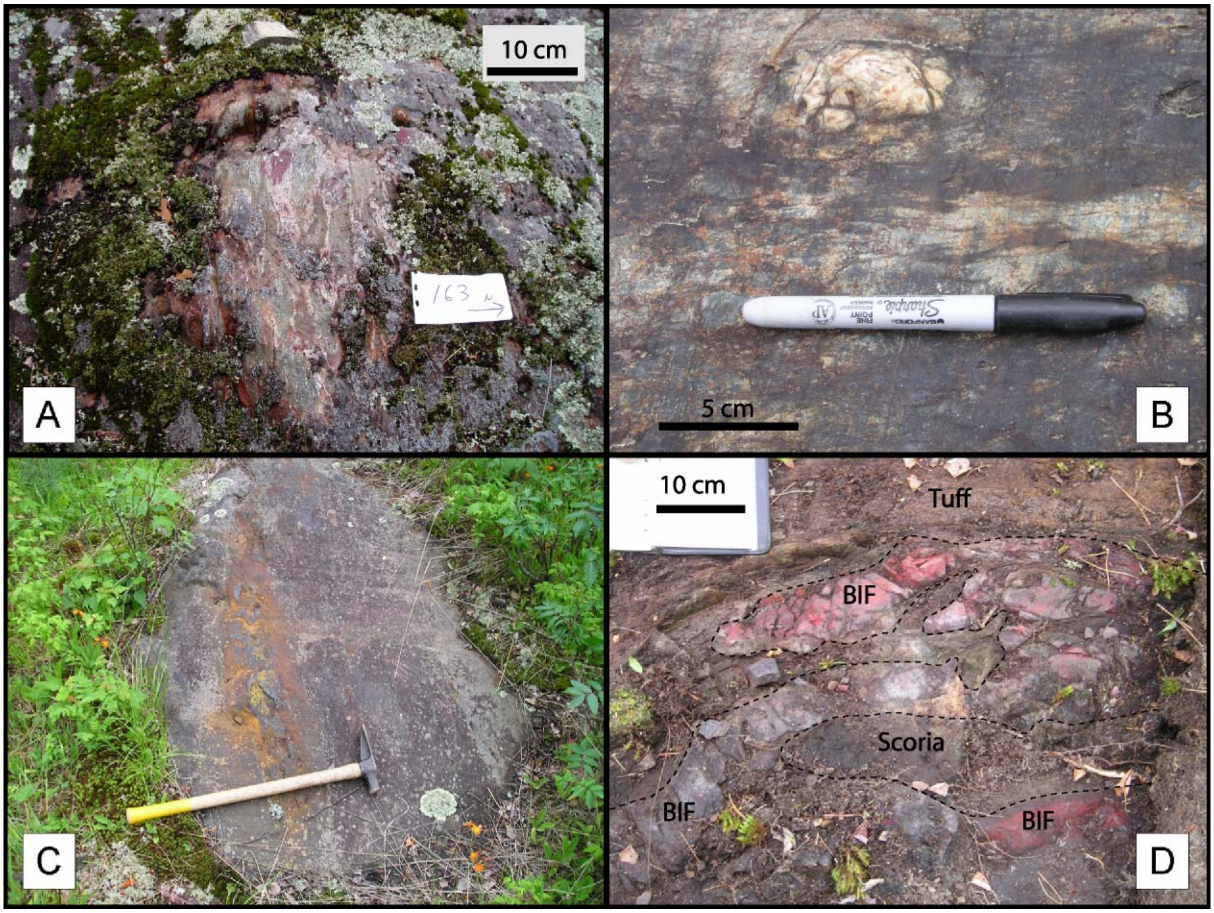

Figure 11. Outcrop photographs of map unit 5,4: A) typical exposure with abundant moss and lichen; B) white cherty clasts in sericitic schist; C) a 1 Ft. x 4 Ft. pyrite-rich domain; and D) probable protolith, felsic lapilli tuff with iron-formation (BIF) and basaltic scoria fragments.

5bxx Sericite Dominant Schists

Sericite dominant schists are pale yellow-green to gray, very fine- to fine-grained, sericitic schists that are commonly highly lineated, siliceous, and iron-stained. A felsic volcanic or porphyritic felsic intrusive protolith for some zones of sericitic schist can be locally interpreted, whereas in other areas, the genesis of the mineralogy is believed to have formed by alteration associated with syn-deformational potassic hydrothermal fluids (Fig. 12). Includes individual map units [5b] Sericite Schist; [5bcep] Sericite-Ankerite-Chlorite-Pyrite Schist; [5bcip] Sericite-Ankerite-Green Mica-Pyrite Schist; [5bcp] Sericite-Ankerite-Pyrite Schist; [5be] Sericite-Chlorite Schist; [5bec] Sericite-Chlorite-Ankerite Schist; [5bep] Sericite-Chlorite-Pyrite Schist; [5bip] Sericite-Green Mica-Pyrite Schist; and [5bp] Sericite-Pyrite Schist.

Figure 12. Outcrop photographs of sericite-dominant schists: A) lineated sericite-chlorite-pyrite schist in the Mine Trend shear zone south of the Soudan Mine open pits (rock hammer 68 cm long); B) sericite-quartz schist from the eastern extension of the Mine Trend shear zone; C) sericite schist derived from rhyolitic fragmental rocks; D) a 1.5 m wide sericite-quartz-green mica-pyrite schist from the Murray shear zone; E) close-up view of sample from picture D; and F) the 0.3 – 0.5 m wide gold-bearing quartz vein in sericitic and chloritic schists of the Murray prospect (see Fig. 3). Note inset picture of hand sample of the quartz vein.

5cxx Ankerite Dominant Schists

Ankerite dominant schists consist of strongly foliated and carbonatized rock units that contain an abundance of Fe-bearing carbonate (mapped as ankerite in the field). These rocks dominantly occur in discrete highly foliated zones containing ankerite porphyroblasts in chlorite phyllite, and quartz-vein bearing brittle domains of nearly massive ankerite replacement of previously sheared schist (Fig. 13). The ankeritic schists and carbonatized zones are believed to have been formed from deep crustal, CO_2-rich hydrothermal fluids that were channeled up from depth along the Murray shear zone, and are analogous to carbonate alteration zones associated with mesothermal lode gold deposits. Individual map units include [5cbep] - Ankerite-Sericite-Chlorite Schist; [5cebip] - Ankerite-Chlorite-Sericite-Green Mica-Pyrite Schist; and [5cp] - Ankerite-Pyrite Schist.

Figure 13. Outcrop photographs of ankeritic-dominant schists: A) typical occurrence of ankerite-chlorite schist; B) close up view of iron-stained ankerite porphyroblasts and a thin quartz vein in a schistose chloritic matrix; C) essentially massive ankerite replacement of chlorite schist; and D) ankerite-chlorite-pyrite schist with quartz and ankerite veins.

5exx Chlorite Dominant Schists

Chlorite dominant schists are green to dark-green, very fine- to fine-grained, chloritic schists that are generally composed of fine-grained chlorite folia anastomizing around small (1 mm x 6 mm) domains of more massive grains, but locally can consist entirely of chlorite phyllite with 2-4 mm sugary-textured quartz domains. Dominant protolith for the chloritic schists is undoubtedly pillowed basalt and andesite lava flows (Fig. 14). Weathered surfaces are commonly pock-marked with elongate pits aligned along the dominant foliation trend. Includes map units [5e] - Chlorite Schist; [5eb] - Chlorite-Sericite Schist; [5ec] - Chlorite-Ankerite Schist; [5ecp] - Chlorite-Ankerite-Pyrite Schist; and [5ep] - Chlorite-Pyrite Schist.

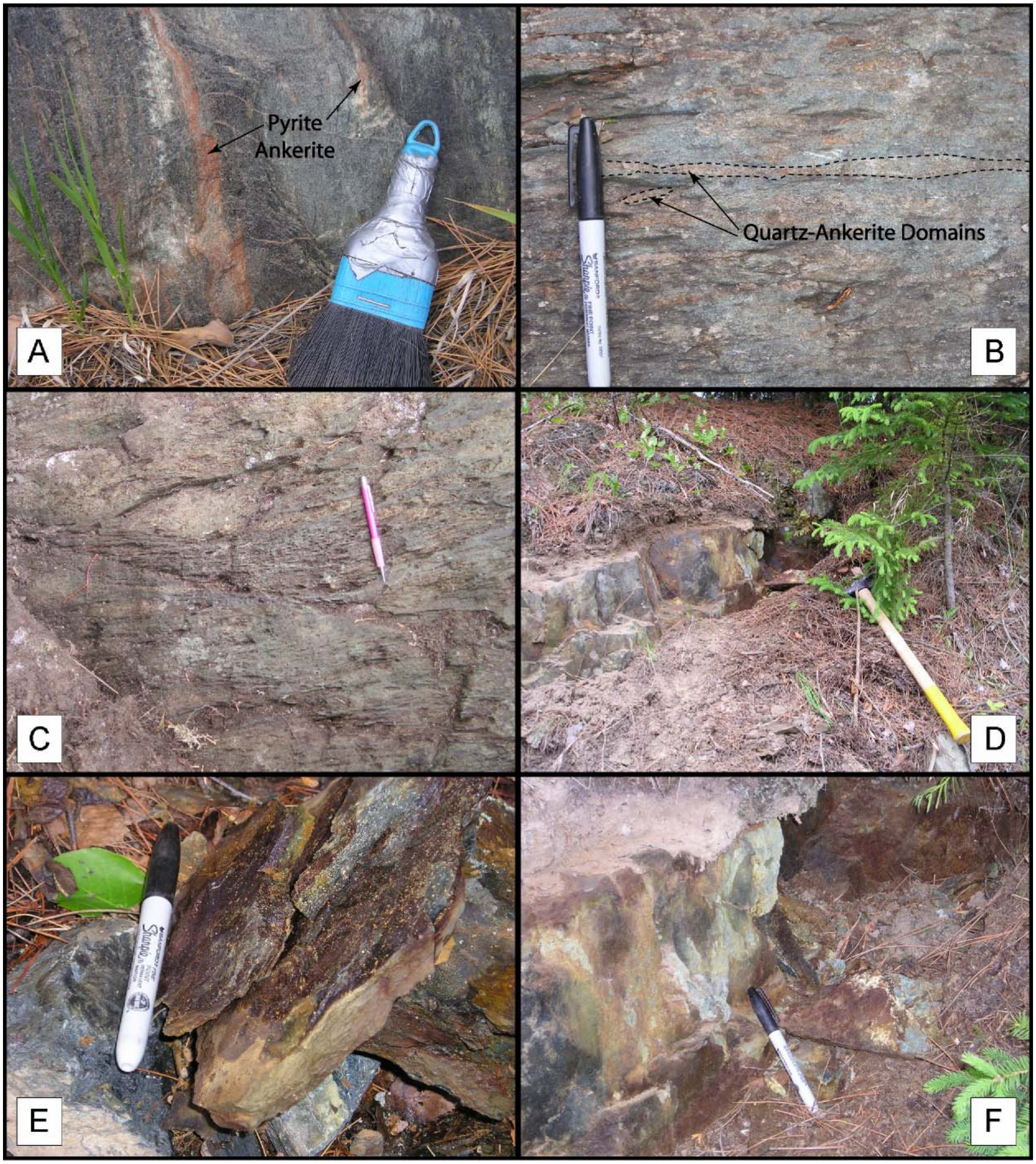

Figure 14. Outcrop photographs of chlorite-dominant schists: A) banded siliceous chlorite schist with 1-2 cm wide rusty pyrite-ankerite zones; B) typical chlorite phyllite with elongate domains of slightly rusty quartz-ankerite (marker 14 cm); C) highly deformed pillowed andesite/chlorite schist from the Fivemile Lake sequence (pencil 14.5 cm); D) chlorite-sericite-ankerite-pyrite schist (hammer 68 cm); E) close-up view of chlorite-pyrite schist shear band separating chlorite schist and sericite-chlorite schist in the Mine Trend shear zone (marker 14 cm); and F) strongly sulfide mineralized chlorite-sericite-ankerite-pyrite schist from the north margin of the Murray shear zone (marker 14 cm).

Intrusive Rocks

Intrusive rocks in the map area span the Neo-Archean geologic history of the region from syn-volcanic (hypabyssal dikes and sills of mafic to felsic composition), to syn-tectonic (felsic porphyry dikes), to post-tectonic (enigmatic lamprophyric bodies) timing. The timing of the intrusive rocks is based strictly on field observations of the D_2 fabric. The location of intrusive rocks of the map area are given in Figure 10, and described in the following sections.

L Lamprophyre

Two outcrop areas of enigmatic rocks of truly unknown affinity, which are similar in characteristics to lamprophyre described by Sims and Southwick (1980), were mapped in the field area. The map unit includes an outcrop of massive grey-green fragmental intrusive rocks (clasts of scoria, chert, and granite) composed of >85% acicular amphibole set in a pinkish matrix (Fig. 15). The map unit also includes an outcrop of black, fine-grained, massive, hornblende-feldspar intrusive rock that contains 10-15% fine hornblende needles in a gray-black and red matrix. This phase is notable for containing large (>25 cm) rounded zones of granite, as well as inclusions of foliated supracrustal rocks. The granitic portions of these two enigmatic outcrops may have originally been a comagmatic felsic phase of the intrusions. The massive and unfoliated nature of these units implies intrusion into surrounding rocks after D_2 deformation.

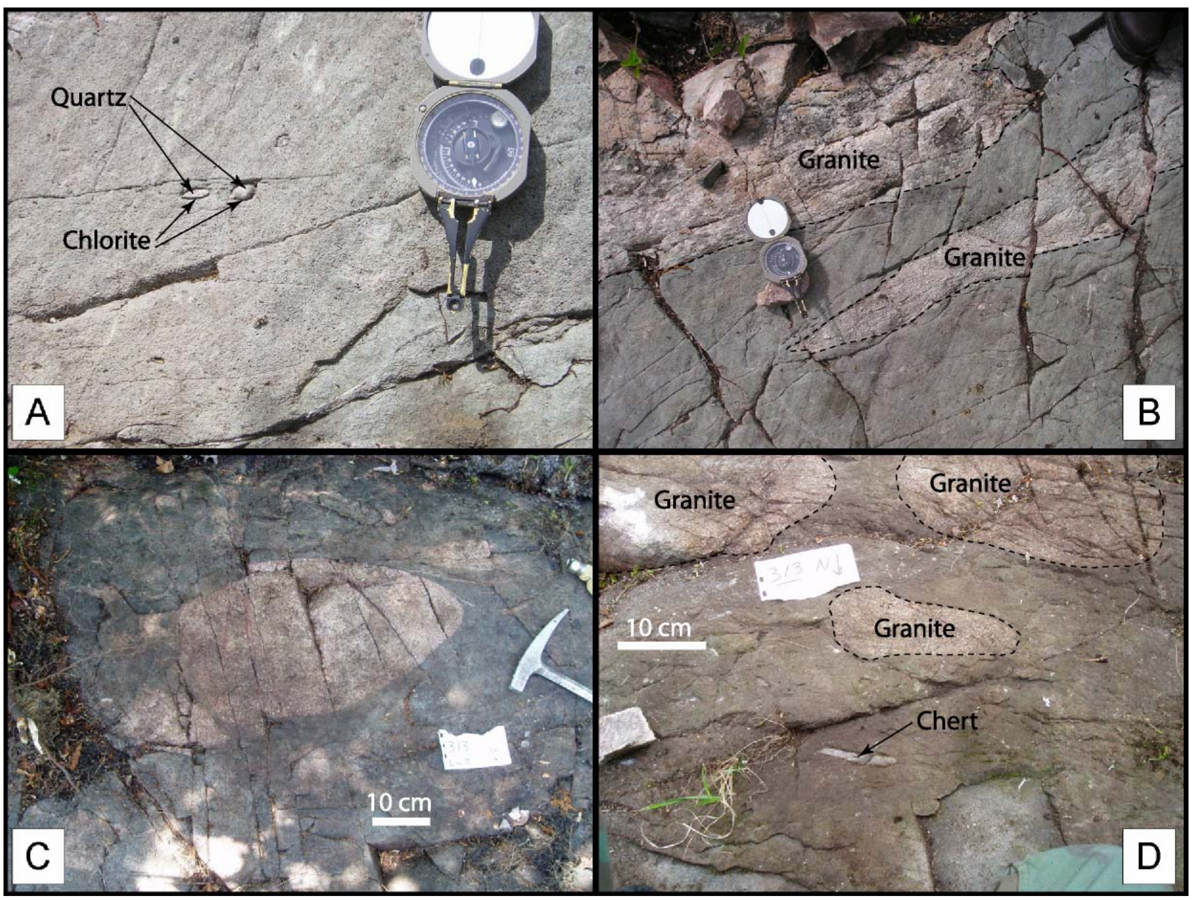

Figure 15. Outcrop photographs of lamprophyric rocks: A) small quartz-chlorite knots in massive acicular amphibole of OC-049 (Brunton for scale); B) elongate granite dikes/clasts in OC-049 (Brunton for scale); C) rounded granite clasts in outcrop OC-313; and D) chert and granite clasts in outcrop OC-313.

Qfp *Quartz-Feldspar Porphyry*

Quartz-feldspar porphyry intrusions are white to whitish-pink, medium-grained intrusive rocks with sub-rounded white feldspar and clear to white quartz phenocrysts in a fine-grained quartzofeldspathic + mafic groundmass. The original mafic component (5 to 15 %) appears to be (or was) hornblende, which is typically pseudomorphed by chlorite and/or epidote. Traces of disseminated pyrite are common. Typically well-jointed outcrops that commonly occur as areas of frost-heaved angular blocks. Individual Qfp map units are interpreted as both syn-deformational dike-like bodies associated with shear zones, and as local felsic intrusions associated with syn-volcanic diorite sills (Fig.16).

Figure 16. Outcrop photographs of quartz-feldspar porphyry: A) foliated, weakly pyritic quartz-feldspar porphyry dike intruding foliated basalts of the Fivemile Lake sequence in OC-037; and B) irregularly shaped quartz-feldspar porphyry sill intruded along a pillowed basalt-massive basalt contact in the Central Basalt sequence in OC-344. Note wrapping of foliation around the edges of the porphyry body.

Fp *Feldspar Porphyry*

Feldspar porphyry intrusions occur as white to whitish-pink, medium-grained, felsic intrusive rocks with 2-4 mm feldspar phenocrysts set in a very fine-grained quartzofeldspathic + mafic groundmass. The original mafic component (5 to 15 %) appears to be (or was) hornblende, which is typically pseudomorphed by chlorite and/or epidote. Traces of disseminated pyrite are common. Individual map units occur dominantly as thin (<1 to 25 ft. wide) north- to northwest-trending dikes in the Central Basalt sequence that are interpreted to be apophyses of the "Sugar Mountain Diorite". Unit is typically siliceous, and forms massive outcrops. Outcrops are generally quite strongly jointed (commonly occur as areas of frost heaved angular blocks), and the dikes locally appear to have intruded along early cooling joints in basaltic rocks (Fig. 17).

Gd-Qfp *Granodiorite to Quartz-Feldspar Porphyry*

This complex composite rock unit is exposed in the NE corner of Section 26 and the SE corner of Section 23. Outcrops typically occur as whitish-pink to green-gray, medium-grained, inclusion-rich, felsic intrusive rocks. The unit includes hornblende granodiorite and quartz-feldspar porphyry (both foliated and massive) with inclusions of iron-formation (both cherty and magnetite-rich), felsic epiclastic rocks, and basaltic rocks (Fig. 18). As currently mapped (Plate 1), the unit is a moderate-sized intrusive body (~ 10 acres on the surface) fed from the ESE by feldspar porphyry dikes. The unit is interpreted to have intruded into the lowermost iron-formation horizon of the Upper Sequence with country rock xenoliths being incorporated into an upper-level magma chamber.

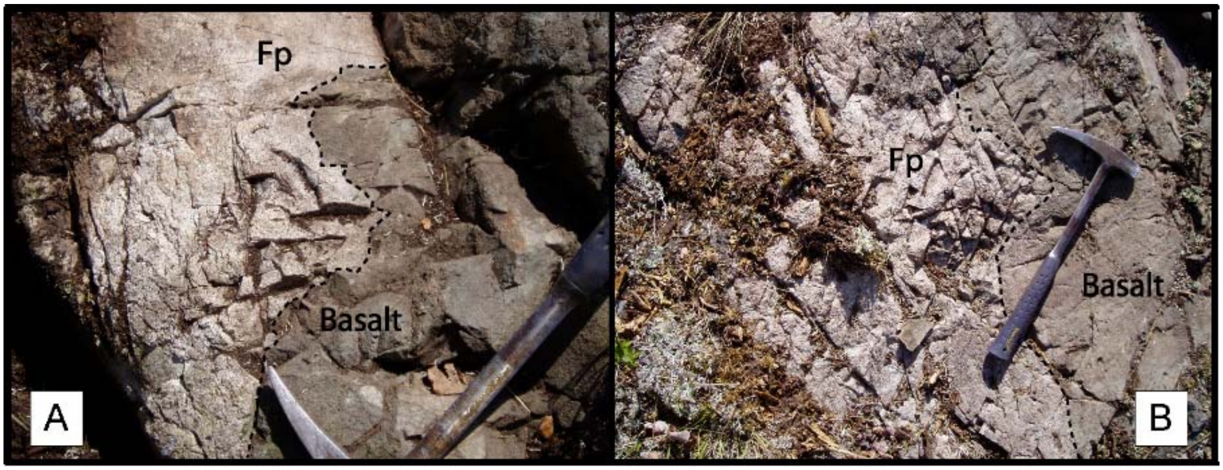

Figure 17. Photographs of feldspar porphyry in OC-113 (rock hammer 42 cm): A) close-up of a white-weathered feldspar porphyry intrusive contact along early joint planes in pillow basalt; and B) outcrop view of the irregular contact between feldspar porphyry and pillow basalt of the Central Basalt sequence.

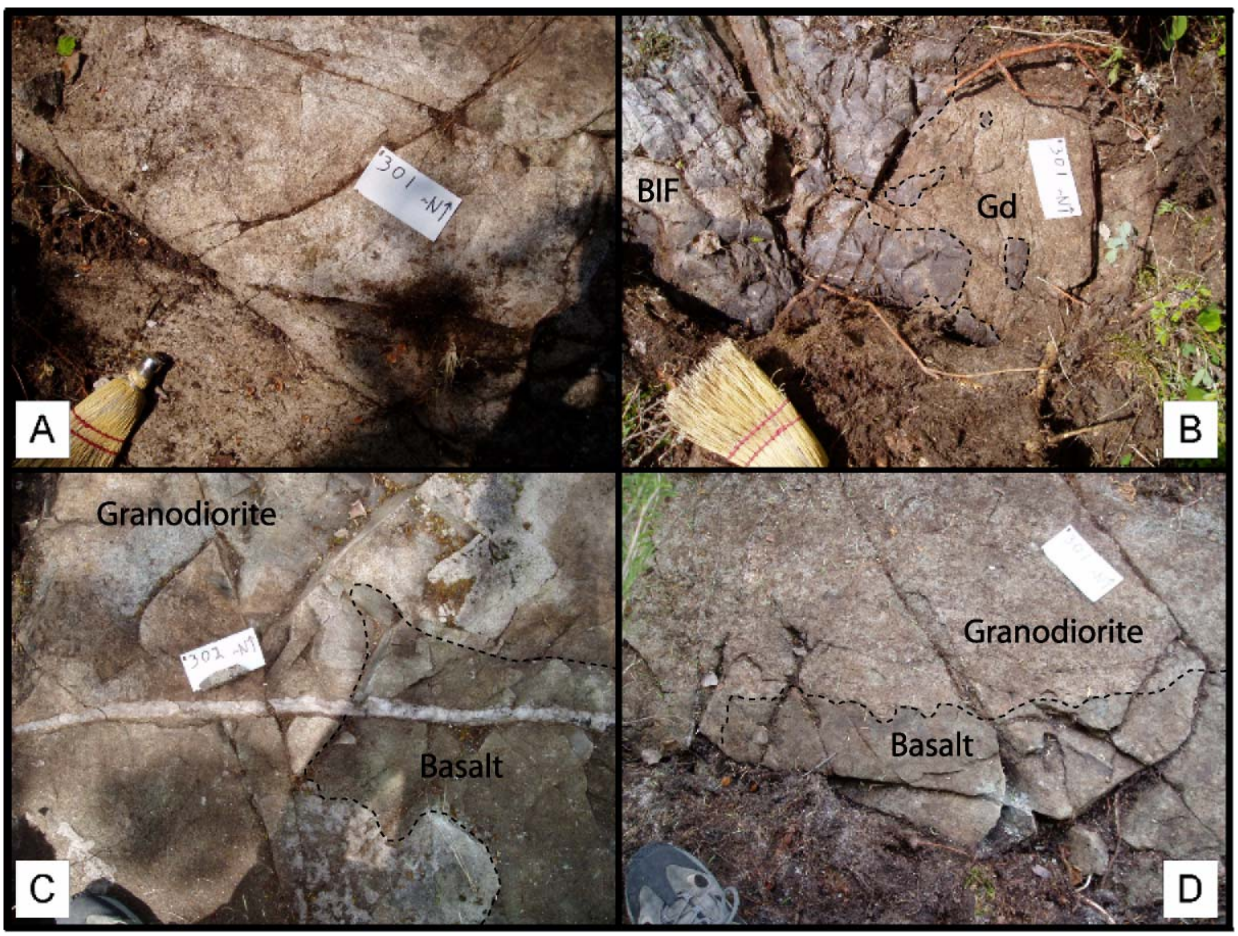

Figure 18. Outcrop photographs of map unit Gd-Qfp (notebook paper 11.5cm wide for scale): A) typical weathered surface texture of granodiorite, OC-301; B) iron-formation xenoliths in granodiorite, OC-301; C) thin quartz vein cutting across a contact between granodiorite and a basalt xenolith, OC-302; and D) irregular contact of a basaltic inclusion in granodiorite, OC-301.

D Diorite

Diorite consists of grey to grey-green, fine- to medium-grained, equigranular felsic to intermediate composition intrusive rocks. Map units typically occur parallel to the volcanic stratigraphy, with the largest mass along the contact between the Fivemile Lake and Central Basalt sequences, herein termed the "Sugar Mountain Diorite" (SMD). The SMD extends from the center of Section 26 and through Section 25 of Township 62 North, Range 15 West, to the limits of recent mapping in Section 30, Township 62 North, Range 14 West. It may extend an additional 2.5 miles to the ENE to the northeast shore of Needleboy Lake (Hudak et al., in prep). Dioritic intrusive rocks also include smaller sill-like bodies intruded into pillow basalts of the Fivemile Lake and Central Basalts sequences. The SMD is notable in outcrop for being very massive, indurated and featureless, with very few veins, large-scale joints, or changes in grain size. Pillow basalt inclusions are scattered within the SMD, and pseudo-pillow alteration forms (Fig. 19) are present locally. The northwestern portion of the SMD is a grey to grey-green, very fine-grained to medium-grained, diorite composed of plagioclase with hornblende (now chlorite pseudomorphs) with traces of very fine-grained pyrite. Where the SMD is slightly coarser in grain size, red biotite is locally present. The eastern part of the SMD is light grey-green, fine- to medium-grained, siliceous diorite with ubiquitous finely disseminated pyrite and thin quartz-pyrite veins, and local acicular amphibole and pyroxene. South of the Mine Trend shear zone, the SMD is grey to grey-green, fine- to medium-grained, siliceous and very hard massive diorite to granodiorite with sigmoidal veins of quartz and crystalline chlorite. Outcrop photographs of dioritic intrusive rocks are presented in Figures 19 and 20.

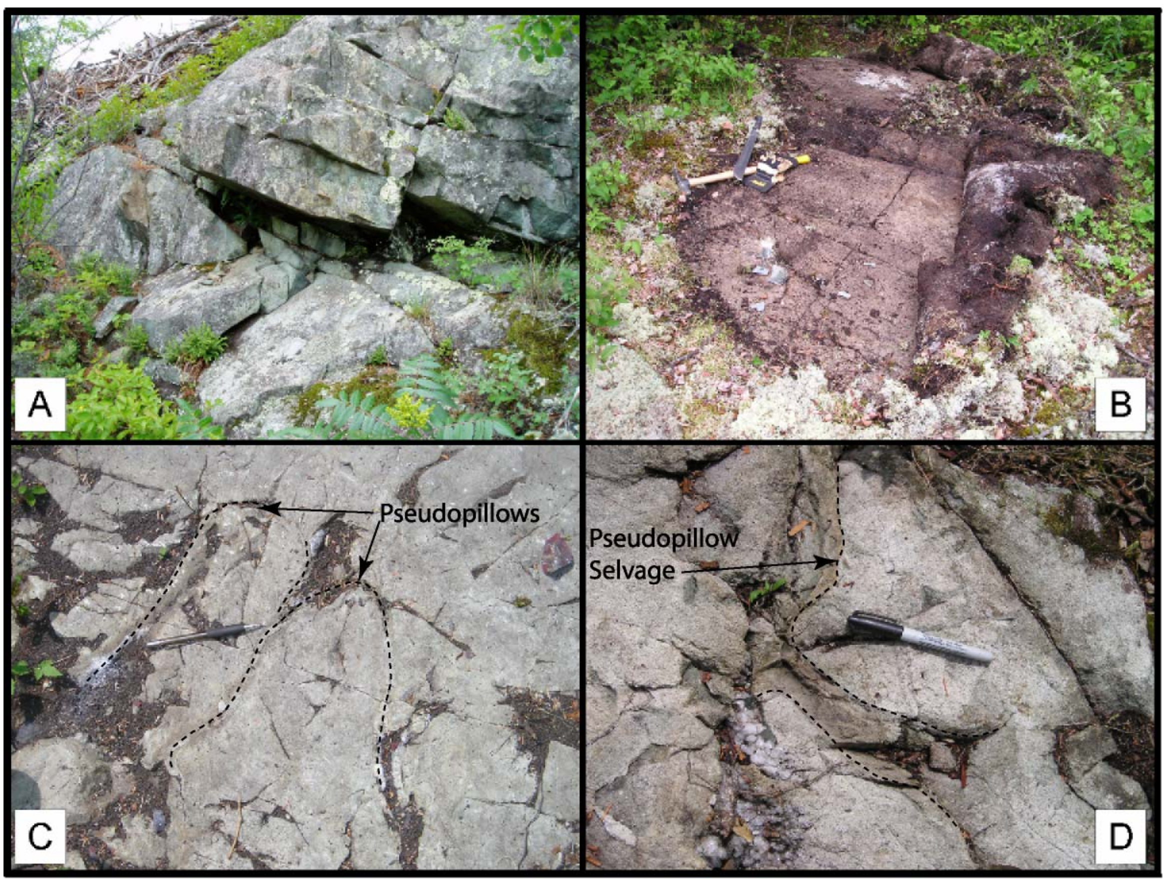

Figure 19. Outcrop photographs of dioritic intrusive rocks: A) 4 m high hillside exposure (OC-069) of massive diorite; B) glacially polished exposure of a dioritic sill (OC-559) in the Fivemile Lake sequence (yellow handle rock hammer is 68 cm long); C) pseudo-pillow form (OC-041) in massive diorite (mechanical pencil 14.5 cm for scale); and D) pseudo-pillow selvage form in massive granodiorite outcrop OC-057 (marker 14 cm for scale).

The dioritic rocks intruded into the volcanic pile prior to D_2 deformation and are interpreted to be synvolcanic sills based on field relationships. These relationships include their shape (elongate sill-like bodies lying parallel to the volcanic stratigraphy) and the lack of contact metamorphism in the surrounding rocks (heat dissipated by trapped seawater in the volcanic rocks). Local zones of north-trending, healed and rusty hydrothermal breccias in the interior of the SMD may indicate that high-temperature hydrothermal fluids emanated out of the intrusion up section into pillow basalts of the Central Basalt sequence. In addition, the SMD may also have been the heat engine that caused the formation of the extensive sub-seafloor hydrothermal fluid circulation in the Central Basalt sequence. Local brecciated zones with foliated matrix occur at the base (south edge) of the SMD, and may represent the strong competency of the unit that either deformed as the strong component in a cuspate-lobate style pattern during the D_2 deformation or blocked subsidiary D_2 shear zone development associated with the Mine Trend shear zone.

Figure 20. Outcrop photographs of dioritic intrusive rocks: A) typical weathered surface of massive diorite in OC-041 (silva compass for scale); B) close-up of weathered surface of granodiorite exposed in OC-057 (marker tip for scale); C) outcrop view of OC-057. Note sigmoidal quartz-chlorite veins probably formed during shearing along the Mine Trend shear zone directly north of this exposure (yellow handle rock hammer 68 cm for scale); and D) close-up view of a sigmoidal quartz-chlorite vein in OC-057 (marker for scale).

Db Diabase

Diabase occurs as dark green to black, fine-grained, plagioclase-phyric dikes that are interpreted as feeders to overlying mafic volcanic rocks. Though scale precludes their depiction on the map (Plate 1), scattered outcrops with thin (1-3 ft. wide), deformed diabasic dikes occur in the rocks within the Mine Trend shear zone.

Diabase is distinguished from massive basalt lava flows only where there is clear evidence of its intrusive nature (Fig. 21).

Gb Gabbro

Gabbroic rocks characteristically occur as dark-green to black, medium-grained, locally magnetic, massive intrusive bodies. The gabbros occur as sill-like bodies and locally contain preserved patches of ophitic texture. The gabbro bodies are interpreted to represent high-level magma chambers that fed basaltic volcanism up-section. Thick massive units (such as those in the northern portion of Section 26, Plate 1) commonly contain inclusions of the local country rock and were competent during D_2 deformation. Thin gabbroic sills generally have a moderately well developed east-west fabric, but are not strongly foliated (Fig. 21). There are rare concentrations of fine-grained pyrite, and very fine-grained leucoxene alteration is commonly visible on cut and broken faces. White quartz veins filling brittle fracture arrays are locally common.

Figure 21. Outcrop photographs of mafic intrusive rocks: A) contact of a north-trending diabase dike (left) cutting and disrupting vesicular pillows of the Fivemile Lake sequence in OC-561 (field of view approximately 3 m); and B) massive gabbro sill with quartz-veins filling brittle fractures in OC-037 (field of view approximately 6 m).

Upper Sequence - [USxx Series Map Units]

The Upper Sequence map units are a diverse series of north-facing and steeply (75°- 85°) north-dipping rocks. The sequence represents stratigraphy associated with the transition from basaltic volcanism of the Lower Ely Greenstone, through chemical sedimentation of the Soudan Iron Formation, and finally to felsic volcanism and clastic sedimentation of the lower portion of the Lake Vermilion Formation. In the mapping area, the Upper Sequence dominantly consists of tuffaceous and epiclastic rocks of dacitic composition associated with the Gafvert Lake sequence of the Lake Vermilion Formation (Peterson and Jirsa, 1999a) and thick zones of banded iron-formation. The lowermost units include intercalated basaltic rocks and iron-formation, and the whole sequence is overlain by greywacke-argillite typical of the Lake Vermilion Formation. Upper Sequence rocks mapped during the course of this study trend WSW from the SE corner of Section 23, through the NW quarter of Section 26, and into the north half of Section 27 (Fig. 10).

US3a Greywacke

This unit correlates with the "Avgc" unit of Sims and Southwick (1980), which is described as "dacite-derived chloritic volcanic greywacke, greenish-grey, thin to medium bedded, bedding commonly graded". The greywacke occurs as two west trending rock units west of the Soudan Fault along the western edge of the map (Plate 1).

US2c Dacitic Conglomerate

This unit correlates with the "Avc" unit of Sims and Southwick (1980), which is described as "grey to greenish-grey, massive or thick bedded conglomerate with rounded clasts of dacite and lesser iron-formation". These deposits occur as west-trending units in Sections 21, 22, and 23 in the NE corner of the map (Plate 1).

US2b Felsic Tuff Breccia

This unit consists of grey to tan, moderately to strongly foliated, felsic tuff breccia composed of 2-20 cm highly vesicular dacite clasts set in a foliated sericite-chlorite (recrystallized ash) matrix. The unit was mapped in one area of the NW quarter of Section 36 within the panel of rocks bounded by the northern and southern edges of the Murray shear zone, and occurs in drill holes that penetrated south of the northern edge of the Murray shear zone near the eastern edge of the map (Plate 1). The felsic lapilli tuff and tuff breccias correlate with the “Aest and Aesf” map units of Sims and Southwick (1980) and locally, unit “Lft” from Southwick (1993). Outcrop photographs of unit US2b and its sheared equivalents mapped during this study are presented in Figure 22.

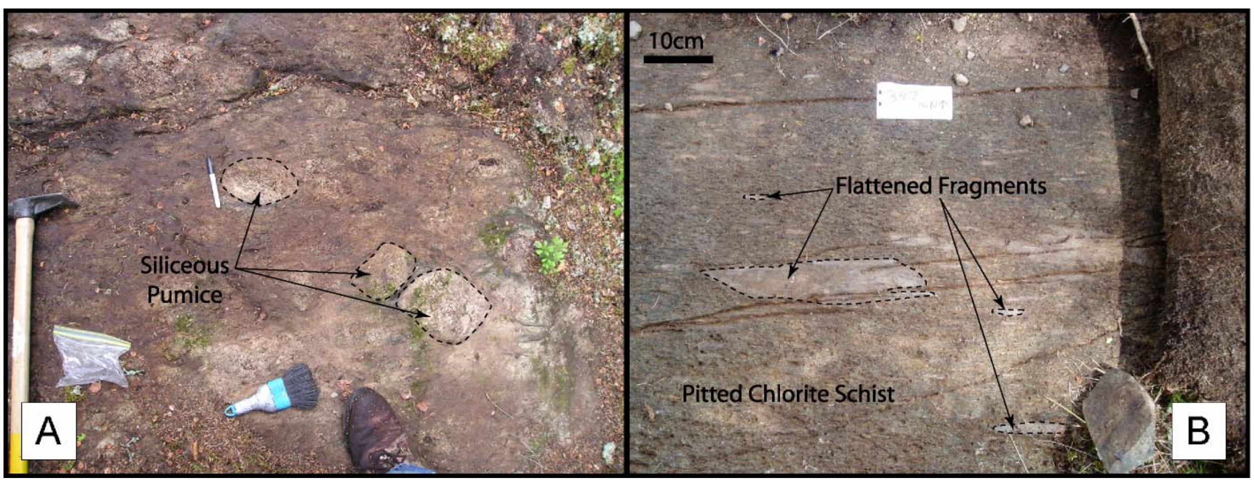

Figure 22. Outcrop photographs of map unit US2b: A) felsic tuff breccia (OC-547) with silicified pumice clasts set in a foliated chloritic matrix (yellow handle rock hammer 68 cm for scale); and B) fragmental textured sericite-chlorite schist in OC-347, interpreted to be a sheared felsic tuff breccia (map unit US2b protolith).

US2e Felsic Tuffs and Lapilli Tuffs

Felsic tuffs and lapilli tuffs are a diverse series of rocks which are lumped into a single stratigraphic package in the NE quarter of Section 27 and NW quarter of Section 26 (Plate 1). The unit correlates with map unit "Avft" of Sims and Southwick (1980) outside of the recently mapped area. Mapped outcrops of unit US2e range from virtually pristine (Fig. 23) to highly schistose rocks (Fig. 24). Pristine portions of the unit include light grey to tan, well bedded, dacitic crystal-lithic tuff and interbedded coarser-grained dacitic tuffs and lapilli tuffs. Accidental fragments include jaspery iron-formation and basaltic scoria. North and east of the Soudan Mine in Section 27, the unit consists of 1 x 3 cm domains of recrystallized cherty tuff (+/- sericite) in, and separated by, a coarse anastomizing sericite-chlorite foliation with pyrite clots. In this area, local massive beds now lie parallel to foliation, which are interpreted to have formed during D_1 deformation. Immediately north of the historic workings of the Soudan Mine, the unit is virtually a sericite-quartz schist with foliation wrapping around 2 to 5 cm, angular to subrounded, cherty tuff clasts. In the north half of Section 27, the unit overlies epiclastic felsic rocks (map unit US2f) and defines the shape of interpreted D_1 folds.

Figure 23. Outcrop photographs (OC-009) of pristine end-members of map unit US2e: A) thin-bedded crystal-lithic tuff with rare dacitic lapilli fragments; and B) unsorted lapilli tuff with dacitic lava clasts set in a quartz-phyric tuffaceous matrix. Rock unit unconformably overlies bedded dacitic tuff on the left.

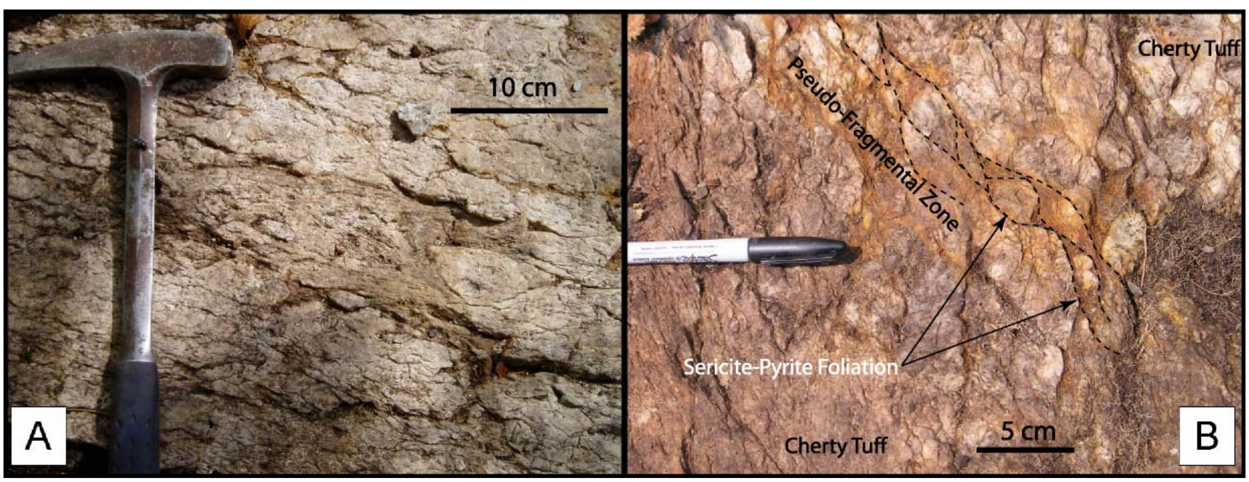

Figure 24. Outcrop photographs of fragmental dacitic rocks of map unit US2e: A) dacitic lapilli tuff exposed in OC-191; and B) pseudofragmental texture formed by a series of rusty sericite-pyrite foliation planes cutting a highly siliceous dacitic tuff deposit in OC-505.

US2f Felsic Epiclastic Deposits

Felsic epiclastic deposits are pale green to medium green, fine- to medium-grained, massive or thickly bedded epiclastic rocks. Common constituents include rounded quartz eyes (both sugary and clear), chlorite clots (which can be locally rounded), rare hornblende crystals, and pyrite (up to 1 mm). The unit is generally very massive and indurated in outcrop. Few volcanic or sedimentary features were clearly recognized in outcrop (though one outcrop does contain a single 25-35 cm thick bed) indicating the deposits are massive or thickly bedded. The deposits are interpreted as metamorphosed and recrystallized dacitic to andesitic volcanic wackes or arenites, though somewhat enigmatic in appearance (Fig. 25). The unit correlates with map unit "Avc" of Sims and Southwick (1980) outside of the recently mapped area. In the north half of Section 27, the unit is stratigraphically overlain by felsic tuffaceous rocks (map unit US2e), and forms the core of two interpreted D_1 folds.

Figure 25. Outcrop photographs of map unit US2f (ripped notebook paper 11.5 cm wide for scale): A) typical massive and indurated outcrop (OC-196); and B) hand sample of felsic epiclastic rocks from outcrop OC-220.

US4a Banded Iron-Formation

Grey-red, laminated to thin-bedded, iron-formation of the formally named Soudan Iron Formation (Morey et al., 1970). The iron-formation dominantly consists of interbedded jasper and hematite with lesser beds of magnetite and chert (Fig. 26). The rock is generally weakly to moderately magnetic. Bedding (<1 mm to 2 cm) varies from laminar to highly convoluted, and locally is brecciated with abundant quartz veining. The convolute bedding is presumed to largely be a pre-lithification soft-sediment deformation phenomenon, and generally few measurements were taken in the iron-formation units because the magnetism and convoluted bedding make these measurements relatively variable and inconsistent in relation to others in the area. Banded iron-formation deposits are locally interlayered with chlorite schist and lesser amounts of sericite schist. Large massive hematite bodies (not seen in surface mapping) have been mined in the past as iron ore.

US1,4 Basalt and Iron-Formation

Massive and foliated basaltic protolith rocks with lenses of chert and iron-formation. The unit occurs as distinctive stratigraphic horizons at or near the base of the Upper Sequence in the formally defined Soudan Iron Formation (Morey et al., 1970). This unit correlates with map unit "Aesb" of Sims and Southwick (1980), and generally occurs as foliated chloritic rocks (locally with fragments of scoria) with iron-formation horizons (jasper, black chert, white chert, and hematite) disaggregated and strung out along the fabric in the rock (Fig. 27). The basaltic matrix is commonly pitted chlorite schist, with the iron-formation fragments not rotated completely into the fabric of the rock. The unit is believed to be composed of an original interbedding of iron-formation and basalt or basalt-derived mudstones. The fabric in the unit is interpreted to have formed largely by layer-parallel slip during D_1 deformation. This unit is interpreted to be a protolith for the sheared map unit 5,4 Schist 'n' Bif.

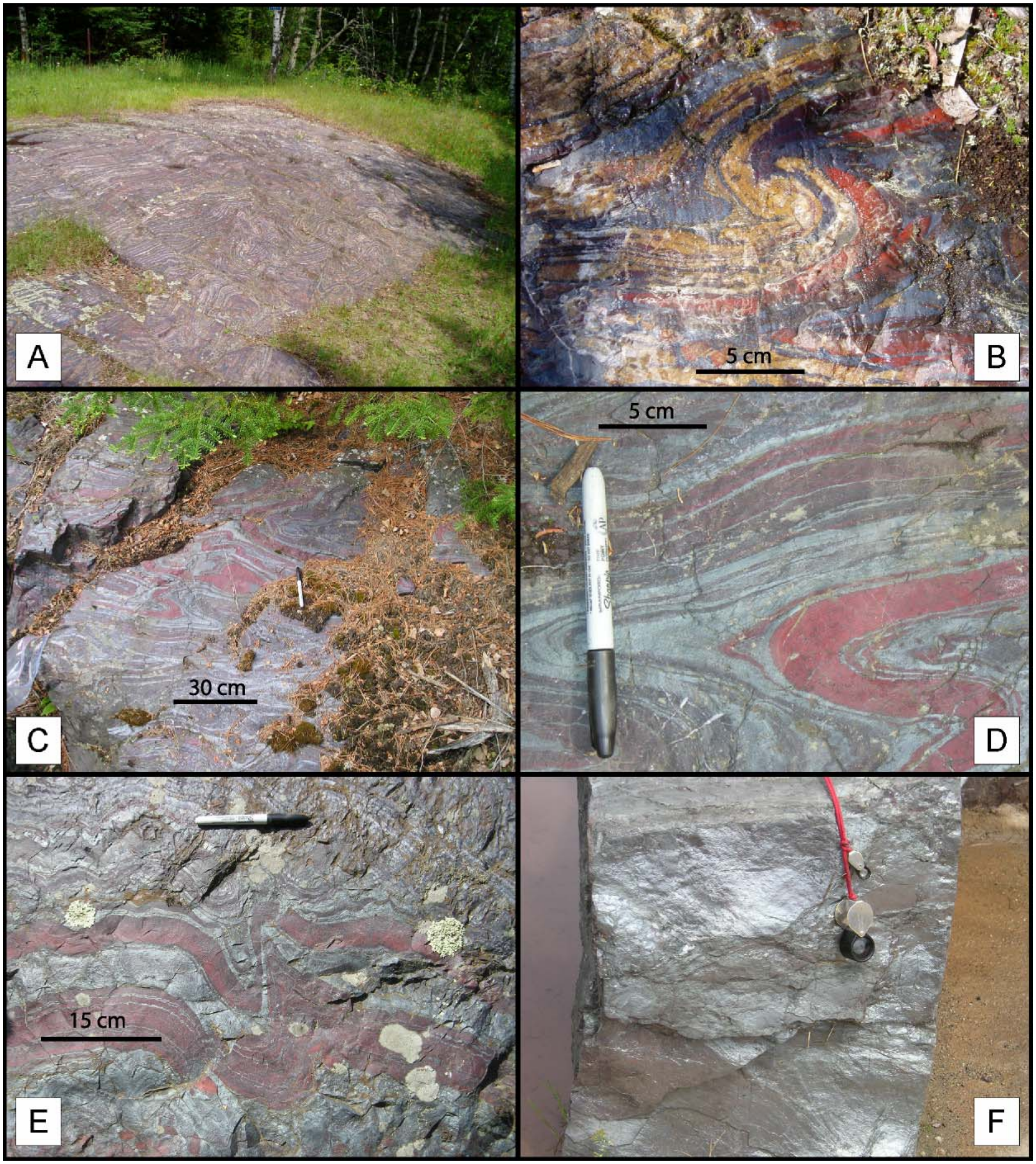

Figure 26. Outcrop photographs of Map unit US4a: A) contorted bedding in iron-formation in outcrop OC-501 (field of view ~50 ft.); B) interlayered jasper-chert-hematite-magnetite in outcrop OC-159; C) outcrop view (OC-532) of interbedded hematite and jasper; D) close-up view of outcrop OC-532; E) convoluted hematite-jasper bedding in outcrop OC-524; and F) high-grade massive hematite ore from the Soudan Mine (10x hand lens for scale).

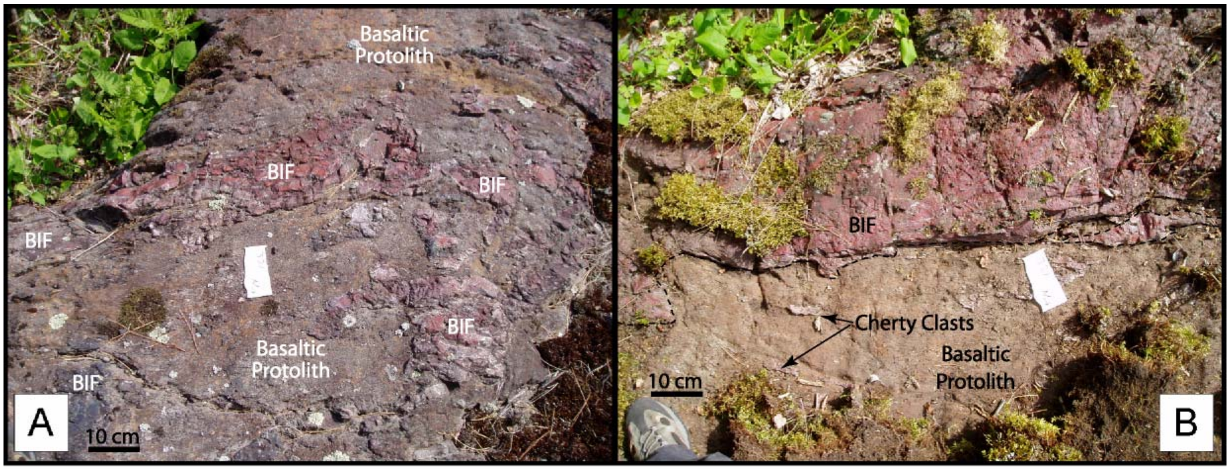

Figure 27. Outcrop photographs of map unit US1,4: A) disaggregated, jasper-rich iron-formation (BIF) in a chloritic matrix, outcrop OC-321; and B) outcrop scale contact between jasper-rich iron-formation (BIF) and cherty-fragment-bearing chlorite-rich basaltic rocks of outcrop OC-320.

Central Basalt Sequence - [CBxx Series Map Units]

The Central Basalt sequence (CBS) is a north facing and steeply (75°- 85°) north-dipping, presumably deep-water volcanic sequence of pillowed and lesser massive lava flows of basaltic composition. The sequence probably correlates with the tholeiitic Armstrong Lake volcanic sequence mapped to the east by Jirsa et al. (2001) in the Eagles Nest quadrangle (their map unit "ab"). The sequence occurs between the Sugar Mountain dioritic sill on the south and rocks of the Upper Sequence on the north (Fig. 10). All map units are typically strongly hydrothermally altered to a variable mineral assemblage of quartz±epidote±clinozoisite±garnet. The general style of alteration is dependant on original lithological permeability. Alteration in massive lava flows occurs as thin veins healing early-formed cooling joints, whereas the alteration in permeable pillowed lava flows ranges from coarse-grained replacement of interpillow hyaloclastite to local total replacement of the rock by quartz±epidote±clinozoisite±garnet. The alteration is interpreted to be synvolcanic (affected by D_2 deformation), and is the western extension of a very large (>20 km long), sub-seafloor, semi-conformable alteration zoned mapped to the east by Peterson (2001) and Hudak et al. (2002, 2003). The unit is exposed in very large outcrops in the NE quarter of Section 26 and NW quarter of Section 25. In the map area, the volcanic sequence is relatively undeformed, with original small-scale volcanic textures (glassy-hyaloclastite fragments and flow top breccias with angular recrystallized vitric fragments) well preserved. The lack of deformation is attributed to early alteration and subsequent strain partitioning to the south.

CB1a Massive Basalt

Massive basalts in the CBS are generally green to gray-green, fine-grained, massive units largely comprised of subaqueous sheet flows, though may also include high-level diabasic intrusive rocks (Fig. 28). Individual lava flows locally have original basal breccia preserved, and are locally interlayered with pillowed lava flows. Ubiquitous quartz-epidote alteration occurs as thin, interconnecting north-trending veins.

CB1b Pillow Basalt

Green to white, fine-grained, pillowed basalt generally occur as small (<0.75 m) ovoid and non-vesiculated pillows with thin (1-2 cm) interpillow hyaloclastite in the CBS (Fig. 23). Selvages and interpillow hyaloclastite deposits may be green and chloritic, rusty hematite-stained, or composed of coarse-grained epidote-garnet or fine-grained quartz. The unit is commonly strongly silicified and/or epidote altered with pale-brown hydrothermal garnet (andradite) locally associated with epidote patches. The unit is relatively undeformed with flow top breccia and recrystallized vitric hyaloclastite fragments locally present.

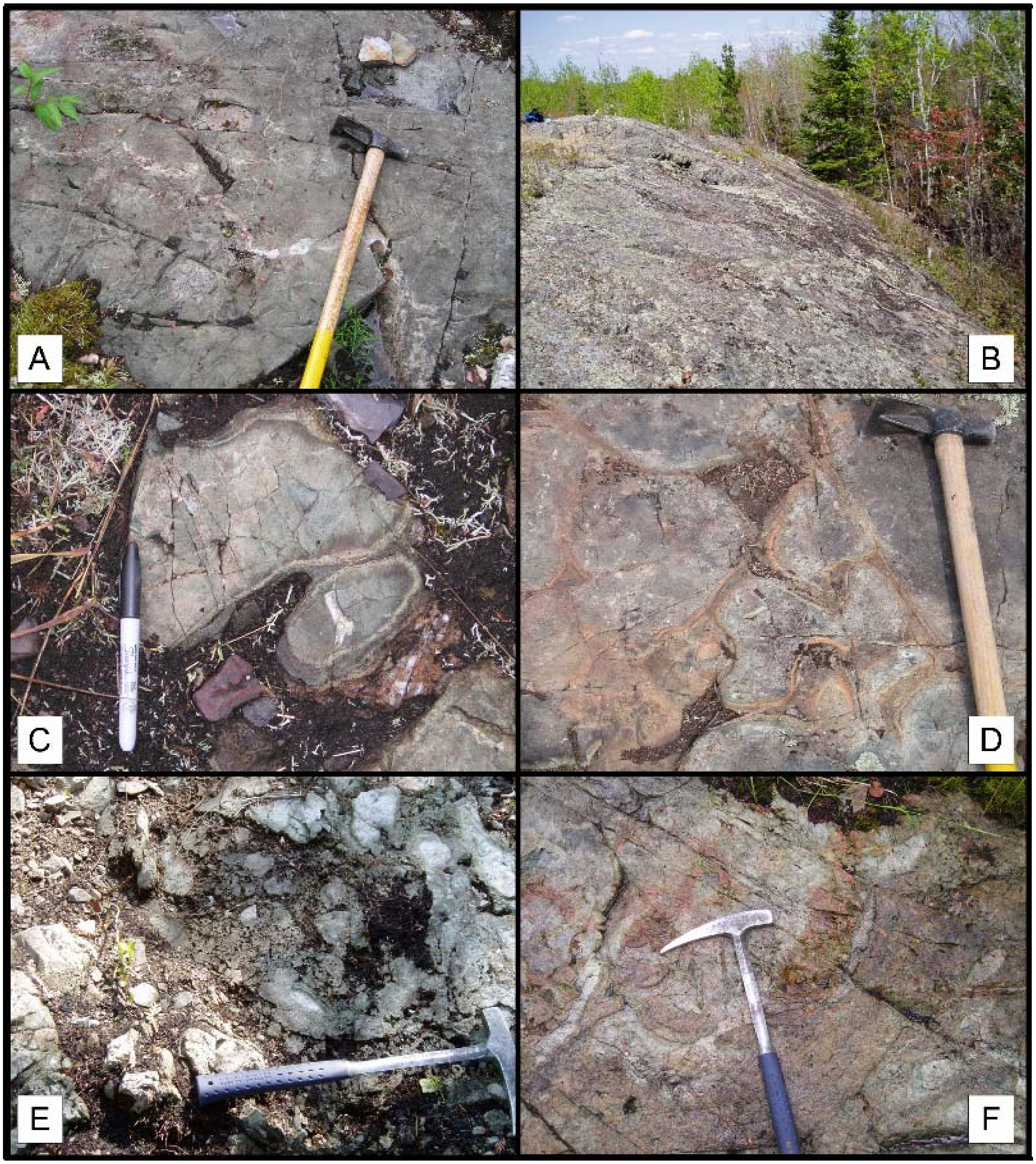

Figure 28. Outcrop photographs of basaltic rocks of the Central Basalt sequence: A) massive basalt flow (OC-001) with quartz-epidote alteration veinlets (hammer 68 cm for scale); B) typical very large exposure of pillowed basalt (outcrop OC-175); C) small, ovoid and non-vesiculated pillows with quartz-rich selvages from outcrop OC-333 (marker 14 cm for scale); D) pillowed basalt with rusty, hematite-stained selvages in outcrop OC-006 (hammer 68 cm for scale); E) silicified flow top breccia at the contact between pillowed and massive basalt lava flows in outcrop OC-048 (hammer 42 cm for scale); and F) intense quartz±epidote±garnet alteration of pillowed basalt in outcrop OC-435 (hammer 4 2cm for scale).

CB1e Mafic Tuff

Green, fine-grained, mafic tuff occurs locally as thin horizons (<3 m thick) at the top of the massive basalt flow in the southern half of the SW quarter of Section 25. These tuffaceous horizons probably represent the metamorphic equivalent of basalt-derived mudstone or very fine-grained resedimented basaltic hyaloclastite.

CB1i Foliated Basalt

Green, fine-grained, moderately to strongly foliated basaltic rocks that are characterized by anastomizing bands of chloritic phyllite separating elongate domains of less deformed basalt. Relict pillow forms (cores and selvages) locally preserved (especially silicified pillow cores) although commonly highly attenuated along foliation. The unit occurs in a series of small WNW-trending outcrops along the eastern edge of Section 26, although the east-west trending foliated basalt map unit located between the Mine Trend and Murray shear zones at the Section 27-26 boundary may be part of the Central Basalt sequence (Plate 1).

CB1u Basalt Undivided

Undivided basaltic rocks, presumed to be dominantly pillowed flows, which correlate with the "Aelb" unit of Sims and Southwick (1980) outside of the limits of the recent mapped area. Large areas of map unit CB1u located south of the southern boundary of the Murray shear zone may be Fivemile Lake sequence rocks.

CB4a Banded Iron-Formation

Banded iron-formation occurs as black and white, laminated to finely bedded, banded chert-magnetite iron-formation. The iron-formation generally occurs as rare, thin lenses (<3m) interbedded with pillowed lava flows.

Fivemile Lake Sequence - [FMxx Series Map Units]

The Fivemile Lake sequence (FLS) is a north facing and steeply (75°- 85°) north-dipping, bimodal (basalt/andesite and rhyolite), shallow-water (Peterson, 2001; Hudak et al., 2003) volcanic sequence dominated by highly vesiculated pillowed andesite with thick (4-25 cm) chloritic zones of interpillow hyaloclastite. The sequence is named after the similar volcanic rocks found in the well-studied Fivemile Lake area (Hudak and Morton, 1999; Peterson, 2001; Hudak et al., 2002, 2003) located three kilometers east of the map area. The sequence correlates with andesite/basalt lava flows in the Fivemile Lake and Needleboy Lake areas mapped by Hudak et al. (in press) and Hudak et al. (in prep), and probably correlates with calc-alkalic basalt and andesite lava flows of the Eagles Nest volcanic sequence mapped further to the east in the Eagles Nest quadrangle by Jirsa et al. (2001) (their map unit “ev”). Basaltic tuffs (bedded scoria lapilli tuff deposits) and massive flows and fragmental rocks of rhyolite to rhyodacite composition occur locally. Early sub-seafloor, quartz±albite±epidote alteration of pillow cores is ubiquitous, though patchy in nature, and moderate to strong ankerite alteration of volcanic rocks is common around sheared and foliated zones associated with D_2 deformation. The sequence occurs between the northern margin of the Murray shear zone and the “Sugar Mountain Diorite” sill, and also includes minor weakly to moderately deformed mafic domains intercalated with the schists in the Murray shear zone (Fig. 10).

FM1a Massive Basalt Flows

Green to gray-green, fine-grained, massive basalt lava flows of the FLS sequence are composed of subaqueous sheet flows. However, due to the lack of good outcrop control in some areas, massive lava flow map units may also include hypabyssal diabasic sills, or massive basal portions of large pillowed flow units. As mapped in the field, individual flows locally have original basal flow breccia preserved, and are locally interlayered with pillowed lava flows (Fig. 29).

FM1b Pillow Andesite and Basalt Flows

Pillowed lava flows consist of light bluish-green to green, highly vesiculated (amygdaloidal) pillowed andesite and basalt. Pillows are generally large (>1 m on average), mattress shaped to amoeboid in shape, and have wide (2-25 cm) zones of interpillow hyaloclastite largely composed of chlorite±actinolite. The pillowed flows are very distinctive in outcrop due to deep weathering of carbonate-filled amygdules and local quartz±albite alteration of pillow cores. Amygdule fillings include calcite (weathered out on the surface of outcrops), chlorite, actinolite, and epidote (Fig. 29). Individual pillowed flow units are commonly interbedded with bedded scoria lapilli tuff deposits.

FM1e Mafic Tuff

Green, fine-grained, mafic tuff that occurs as thin zones stratigraphically above pillowed andesite flow units (Fig. 29). This unit probably represent the metamorphosed and recrystallized equivalent of mafic-derived mudstones or very fine-grained, resedimented hyaloclastite.

FM1h Bedded Scoriaceous Deposits

Scoriaceous deposits consist of green, well-bedded, scoria tuff, lapilli tuff, and tuff breccia deposits. Scoria fragments range in size from <1 to 20 cm, are commonly ovoid to subangular in shape, highly vesicular (to 75%), may be silicified, and are set in a chloritic matrix (Fig. 29). Individual units generally have a strong fabric that mimics the regional east-west D_2 foliation, and is believed to be caused by the competency contrast between competent scoria clasts and the less-competent fine-grained matrix.

FM1i Foliated Basalt

Green, fine-grained, moderately to strongly foliated basaltic rock units that are characterized by anastomizing bands of chloritic phyllite separating elongate domains of less deformed basalt. Relict pillow forms (cores, selvages, and interpillow hyaloclastite) are locally preserved, though commonly highly attenuated along foliation. Local "pock-marked" appearance is interpreted to represent highly deformed vesicular/amygdaloidal pillowed lava flows. Units are most commonly found adjacent to chloritic shear zones, and are distinguished as separate map units (from pillow basalt, i.e., FM1b) by the strong deformation and tenuous correlation of volcanic stratigraphy across the mapped units.

FM2a Felsic Lava Flows

Felsic lava flows of the FLS are composed of light grey to greenish-grey, fine-grained, massive, aphyric to quartz-phyric rhyolite to rhyodacite. In outcrop, curvilinear cooling cracks and possible flow banding indicate that the lava was originally highly viscous. Breccia zones on the top of individual flow units are locally preserved (Fig. 30). When adjacent to shear zones, the felsic lava flows are deformed in a brittle manner, and are cross-cut by numerous quartz veins. A quartz-phyric rhyolite lava flow in similar stratigraphic position, located 2 miles to the east in the Fivemile Lake area, has a $^{207}Pb/^{206}Pb$ age of 2722.6 ± 0.9 Ma (Peterson et al., 2001).

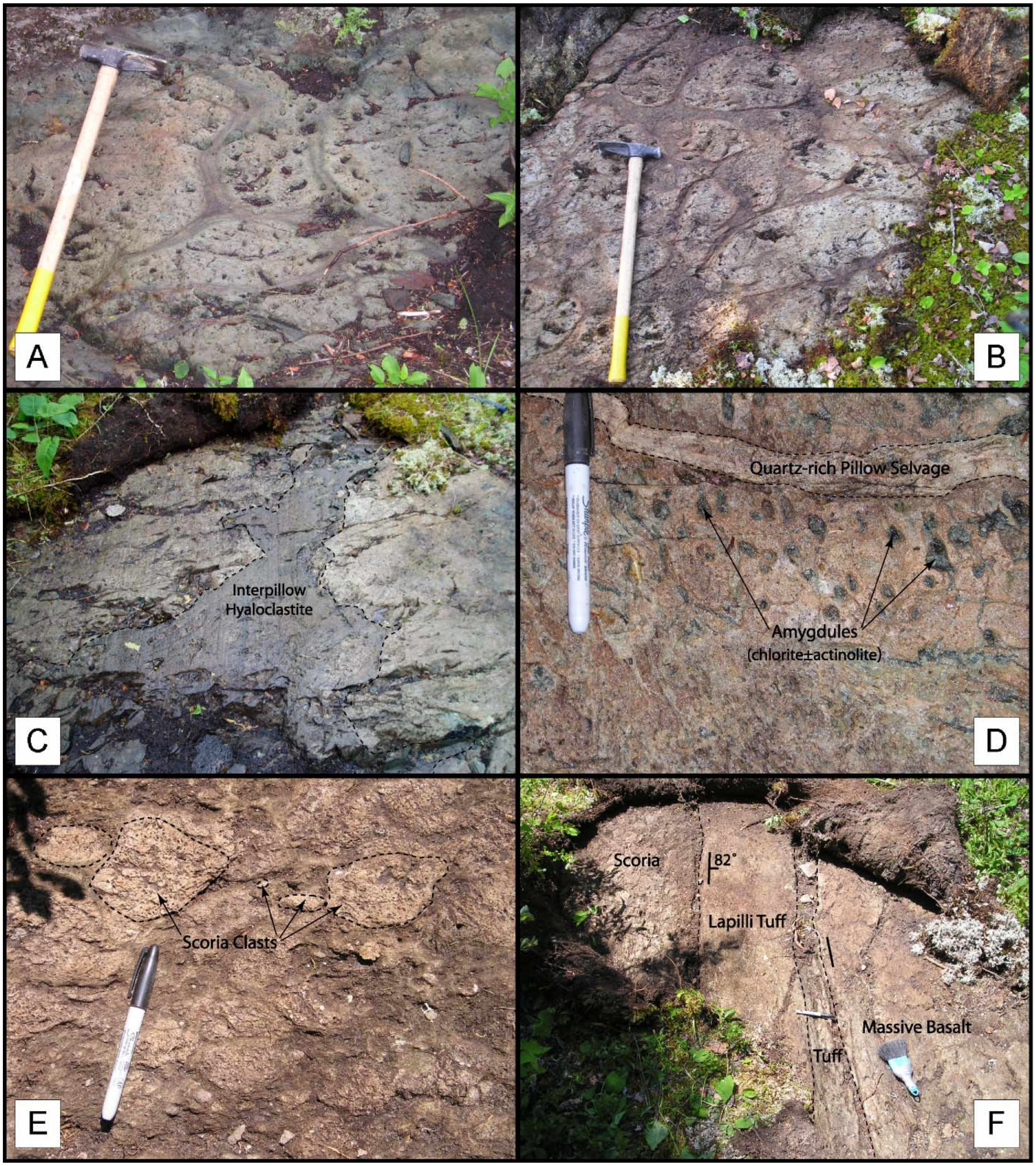

Figure 29. Outcrop photographs of mafic volcanic rocks of the Fivemile Lake sequence: A) typical vesicular pillow lava, outcrop OC-037 (hammer 68 cm for scale); B) quartz-albite altered pillow cores with ankerite-altered interpillow hyaloclastite in outcrop OC-564 (hammer 68 cm for scale); C) thick chloritic interpillow hyaloclastite zone in outcrop OC-273 (outcrop view approximately 3 m across); D) chlorite±actinolite amygdules in silicified pillowed andesite (14 cm marker for scale); E) scoria lapilli tuff deposit in outcrop OC-586 (14 cm marker for scale); and F) flow contact (from left to right) in outcrop OC-586, bedded scoria – lapilli tuff – fine-grained mafic tuff – basal zone of a massive basaltic lava flow (field of view ~3 m).

Figure 30. Outcrop photographs of felsic volcanic rocks from the Fivemile Lake sequence: A) massive rhyolite lava flow from outcrop OB-187; B) close-up photograph of massive rhyolite lava with sericitic cooling cracks from outcrop OC-286; C) flow top breccia of a massive rhyolitic lava flow overlain by basaltic scoria tuff, from outcrop OC-499; and D) rhyolitic tuff breccia from outcrop OC-276.

FM2c Felsic Heterolithic Breccia Deposits

Felsic to intermediate heterolithic (polymict) breccias of the FLS are composed of tan, rounded, siliceous pumice and/or scoria fragments set in a quartz-phyric, schistose chloritic matrix. Subrounded to subangular fragments range in size from 0.1 to 20 cm, and typically weather in positive relief (Fig. 31). The chloritic matrix wraps around the larger fragments, which are more rounded than small clasts. The wrapping matrix and curving chloritic patches can give impression of pillows or pillow selvedges in smaller outcrops. Amygdules in clasts are chlorite-filled, which weather in both positive and negative relief.

FM2d Felsic Monolithic Tuff-Breccia Deposits

Monolithic felsic fragmental rocks of the FLS are similar to massive rhyolitic lava flows [FM2a], except for ubiquitous angular clasts of rhyolite set in a fine-grained, siliceous tuffaceous matrix (Fig. 30).

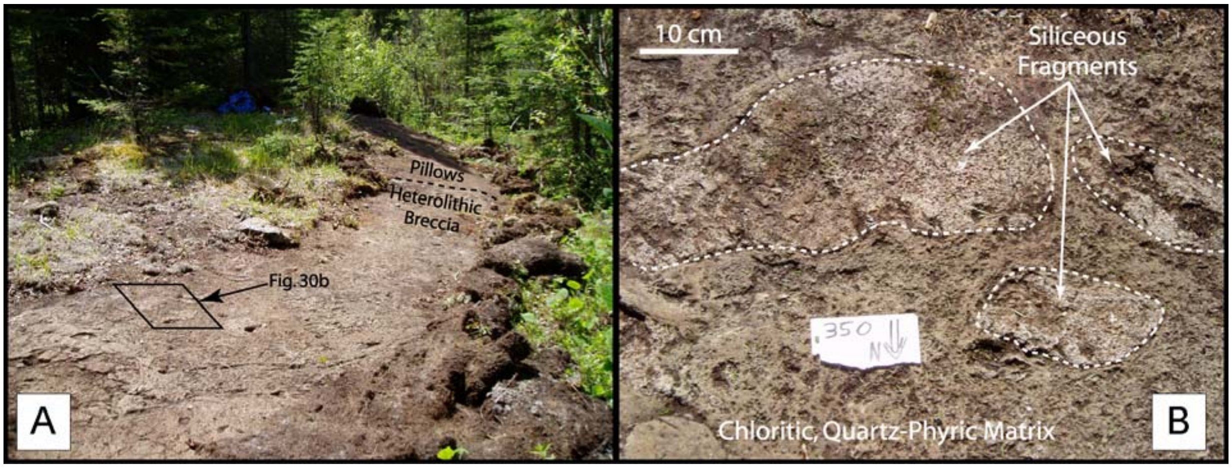

Figure 31. Outcrop photographs (OC-350) of felsic heterolithic breccia deposits in the Fivemile Lake sequence: A) outcrop view to the southwest showing the differential weathering of siliceous clasts and chloritic matrix (outcrop approximately 20 m long); and B) close-up of highly vesicular and siliceous clasts.

FM2e Felsic Tuff and Lapilli Tuff

Felsic tuffs consist of grey to tan, fine-grained, well-bedded, quartz-phyric, rhyolitic tuff and lapilli tuff. Lapilli fragments include rhyolitic lava and pumice up to 4 cm in length that are set in a highly siliceous, quartz-phyric recrystallized felsic ash matrix. These deposits occur as thin units (<3 m thick) stratigraphically overlying felsic lava flows.

FM4a Banded Iron-Formation

Banded iron-formation occurs as black and white, laminated to finely bedded, banded chert-magnetite iron-formation. The iron-formation generally occurs as rare, thin lenses (<3 m) interbedded with pillowed lava flows.

Soudan Mine 27th Level East Drift Mapping

The east drift of the 27th level of the Soudan Mine was mapped (Plate 2) as part of this project in order to: (1) evaluate the continuity of the geology exposed at the surface with that exposed at a depth of 710 m below the surface; and (2) understand the geologic and structural complexity of the drift (because the tentative construction plan for NUSEL begins with extension of the drift to the east). A team of three geologists (John Heine, Peter Jongewaard, and Mark Severson) mapped the East Drift - 27th level of the Soudan Mine over a period of four days. They mapped the bedrock exposed on the surface vertically above the drift prior to the underground mapping. Underground, one geologist made measurements of structural data (cleavage, lineation, and joint orientations) and described the rocks present. A second recorded observations and plotted them on the drift map. The third worked ahead of the others locating contacts between rock units and collecting representative samples. Locations in the mine were determined by tape and compass methods, with origin points based on recent surveying and the original mine drawings by Oliver Iron Mining Division of United States Steel Company. Structural data were measured using a field compass, and there was no deviation of the local magnetic field observed.

The drift essentially is parallel to the stratigraphic and structural grain of the rocks (E-W), and is located in the footwall of the Alaska massive-hematite ore body of the Soudan Mine. Many of the other levels in the mine are accessible, and future mapping of other levels would lead to a better understanding of the mine geology and structural history of the area. The geology of the 27th level east drift essentially mimics the rock units mapped on the surface south of the main iron-formation horizon in the Mine Trend shear zone, and includes chlorite schist, sericite-chlorite schist, sericite-quartz schist, banded iron-formation, and gabbro. Descriptions of the rock units mapped underground are presented in the following sections, and photographs are presented in Figure 32.

5e Chlorite Schist

Chlorite schist in the 27th level east drift is dark green, fine-grained, and strongly-foliated. The foliation in the rock varies in intensity from moderate to intense, and the unit commonly contains minor quartz and/or calcite veinlets. Chlorite schists generally contain trace amounts of disseminated pyrite, and typically are in gradational contact with chlorite-sericite schists. This unit correlates with map unit 5e (chlorite schist) on the surface (Plate 1).

5eb Chlorite-Sericite-Quartz Schist

Chlorite-sericite-quartz schist is dark greenish-yellow, fine-grained, and strongly to intensely foliated. These rocks commonly contain quartz and/or calcite stringers and veinlets oriented parallel to the foliation. Disseminated pyrite occurs in trace amounts, and the unit is locally stained dark red by hematite. Interlayered lenses and/or boudin-trails of chert and/or banded iron-formation occur locally. This unit correlates with map units 5eb (chlorite-sericite schist), 5be (sericite-chlorite schist), and 5,4 (Schist ‘n’ Bif) on the surface (Plate 1).

5b Sericite-Quartz Schist

Sericite-quartz schist is creamy-yellow, fine-grained, and strongly foliated and/or sheared. Unit may include minor chlorite, quartz phenocrysts, and thin chert lenses and/or boudins. The unit is locally strongly overprinted with deep-red hematite stain and foliation-parallel quartz veining. The sericite schists define the immediate footwall to the overlying jaspilite units and high-grade ore zones. The unit does not directly correlate with any rock unit recently mapped on the surface, but probably correlates with sericite schist zones noted on Oliver Iron Mining Company geologic maps of the mine pits.

4a Jaspilite

Jaspilite occurs as dark red and grey, fine-grained, thin- to thick-bedded chert-jasper-hematite +/- magnetite banded iron-formation. Bedding is typically contorted and convoluted, with brecciation, quartz veining, and segregations of white quartz and minor amounts of disseminated pyrite common. Massive steel-grey hematite is common as matrix in breccia zones, and minor coarse-grained specular hematite occurs locally. The unit correlates with map unit US4a (iron-formation) on the surface (Plate 1).

Gb Gabbro

Gabbro in the 27th level east drift is characteristically a dark green to black, fine- to medium-grained, equigranular and homogeneous intrusive rock consisting of chlorite-feldspar±quartz±calcite and trace amounts of pyrite. The unit is unique underground in that it is typically blocky-fractured, and contains quartz veining and stringers in brittle gash-veins. Unit may be strongly foliated along its margins adjacent to chloritic and sericitic schists, but generally only contains a weak east-west fabric. The unit is believed to be continuous with the gabbro body exposed on the surface in the central part of Section 27 (Gb on Plate 1).

Figure 32. Photographs in the Soudan Mine: A) cross-cut into an open stope on the 21st level; B) banded hematite and jasper, 25th level (Eastwing rock hammer handle for scale); C) rusty hydrous iron-oxide staining in chlorite schist, 27th level; D) copper staining (locally associated with groundwater seeps) on floor of the 12th level (field of view 3 m); E) drill hole (circa 1961) from a cross-cut into the gabbro on the 27th level east drift (field of view 3.5 m). The hole penetrated massive hematite ore of the Alaska ore body just north of the drift. Note the quartz gash veins and hematite-rich seep eminating out of the abandoned hole; and F) sericite-quartz schist covered with hematite soot, south wall of the 27th level east drift (field of view 3 m).

Structure

The local structural setting of the rocks in the field area is interpreted from the integration of the 2D bedrock geology map (Plate 1), analysis of numerous types of 3D planar and linear features measured in outcrop, and review and modification of ideas presented in previous structural investigations in the region (Hooper and Ojakangas, 1971; Hudleston, 1976; Hudleston et al., 1988; Jirsa et al., 1992; and Schultz-Ela and Hudleston, 1991). Structural features observed in the mapping area are largely related to D_2 dextral shearing and transposition. The field area lies on the north limb of the Tower-Soudan Anticline (Fig. 2), and field evidence for this earlier D_1 deformation of the rocks is largely the steep northerly dip and northerly facing direction of the rocks. The only D_1 structural elements mapped (besides the steep north dip of the strata) are distinct parasitic folds and layer-parallel shears interpreted as D_1 in the NE quarter of Section 27. Ideas on the specific timing of D_2 structural zones in the map area (as presented in the following sections) are based on the structural analysis by the authors, who believe the interpretations presented are compatible with both the local and regional structural history of the area.

Field Measurements

Approximately 2,000 structural measurements were recorded and georeferenced during the course of the recent field investigation. These measurements included the strike and dip of planar features, the trend and plunge of linear features, and written notes on kinematic sense of shear textures. Planar features measured included joints (1,022 measurements), foliation and fabric (596 measurements), bedding and pillow forms (91 measurements), veins (91measurements), and the orientation of shear bands (78 measurements). Measured linear features include the orientation of mineral lineation and intersecting planar features, e.g., multiple foliations or foliation-shear band intersections (62 measurements), and small-scale fold hinges (6 measurements). In addition, 32 measurements of glacial striations and grooves on polished bedrock surfaces (Fig. 5a) were taken.

The magnetic declination in the field area in 2003 is 0° 06' E, and no correction was made for this minimal amount of declination. Generally we had no problems with compass deviation caused by magnetic rocks, although we did not attempt a significant number of detailed structural measurements in the iron-formations. In the southeast corner of the map area (Section 25-36 boundary) the azimuth of a road (taken from georeferenced air photos) and the compass readings on the ground differed by as much as 13°. In this small area of outcrop, our measurements were adjusted and recorded in the field notes. In a few cases, azimuths were checked with sun observations.

Map Scale Generalization

Rock layering is generally steeply inclined and consists of original bedding, foliation, and localized shear bands. In addition, curvilinear domains of highly strained rocks (map units [5xxx]) commonly contain steep, east-dipping mineral lineations, intersections, and small-scale fold hinges. Over the project area, the generally steep layering and localized lineation of the rocks is best visualized on the stereographic projection presented in Figure 32. Although variable, the general strike and dip of foliation and fabric is quite strongly clustered at 275°/80°, while original bedding measurements vary locally from 240° to 300° with dips near vertical or very steep (>80°) to the north. Linear features within the map area generally plunge steeply east (Fig. 33), and are parallel to lineations and D_2 fold hinges (F_2) described by Hooper and Ojakangas (1971), Hudleston (1976), and Hudleston et al. (1988) in the thick greywacke-slate sequence of the Lake Vermilion Formation immediately west of the field area.

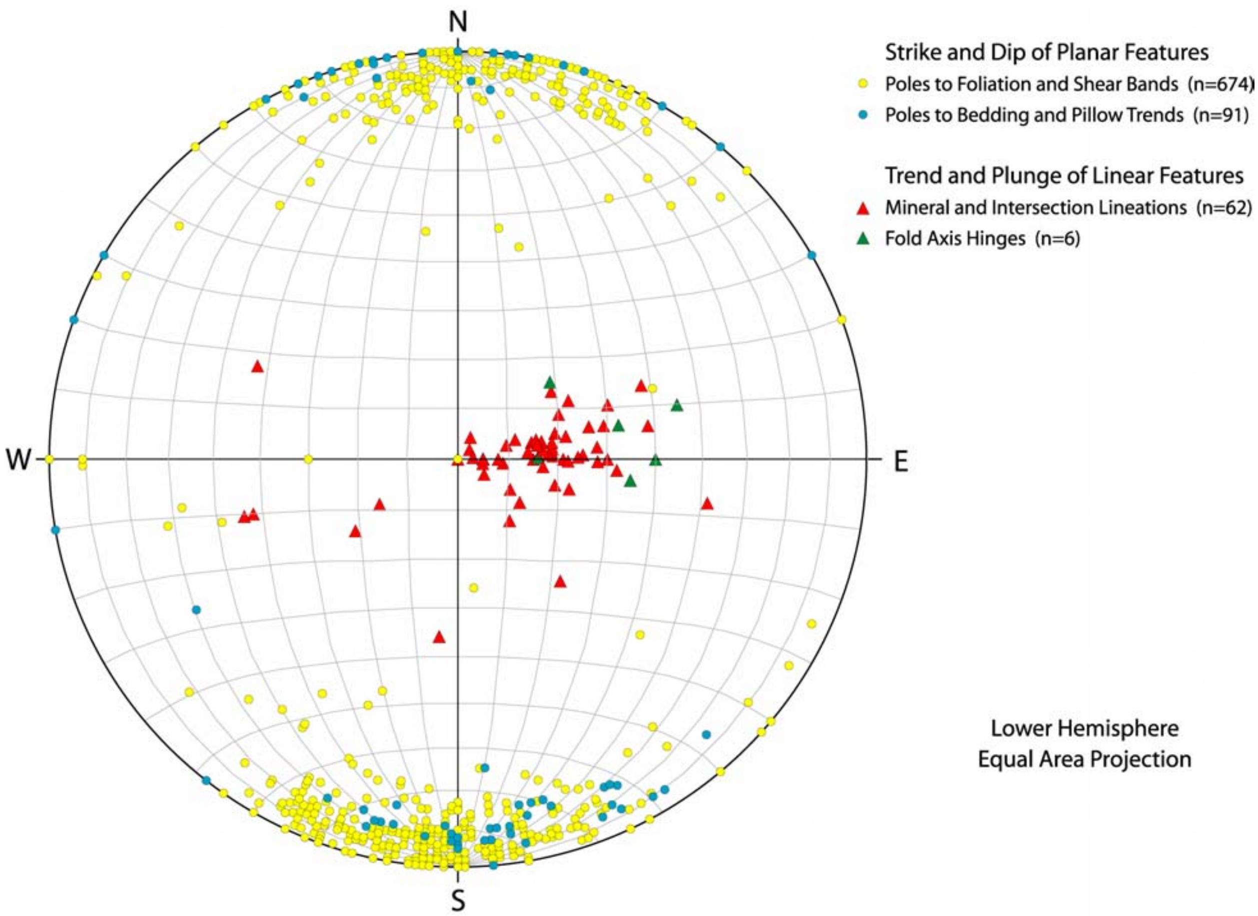

Figure 33. Stereonet projections of bedding, foliation, and lineation from throughout the field area.

Fracture surfaces consist of joints along which no appreciable displacement was observed, or thin quartz and/or carbonate veins (where perpendicular and/or parallel displacement along the original fracture has occurred). Many joints in the intrusive and volcanic rocks of the field area show "bleached" walls, which indicate movement of hydrothermal fluids along early-formed cooling surfaces. These bleached joints commonly contain a thin (<1 mm) chloritic zone at the center. The generation of joints and veins in the rocks undoubtedly occurred throughout the geologic history of the area, with major episodes of fracturing speculated to have occurred during: 1) cooling of igneous rocks; 2) inflation and subsidence of volcanic-intrusive sequences; 3) synchronous with D_1, D_2, and D_3 deformation; 4) unloading during >2.6 billion years of erosion; and 5) recent loading and isostatic rebound from repeated Pleistocene glaciations. Joint surfaces occur as systematic (Fig. 19a) and nonsystematic (Fig. 17b) sets, but appear to be oriented randomly throughout the field area (Fig. 34). A review of the data (Fig. 34, also provided as an ArcView shapefile on the accompanying cd-rom) shows a dearth of subhorizontal measurements. This paucity of low-angle measurements is likely a function of outcrop exposure, in that a majority of the outcrops are flat lying, leaving few spots where low angle joints can be distinguished from the outcrop surface.

Apart from strongly foliated rocks, all of the map units are rather competent, and one should not infer a relation between the number of joint measurements taken in a particular unit, or a particular area, with the overall bulk strength of these rocks.

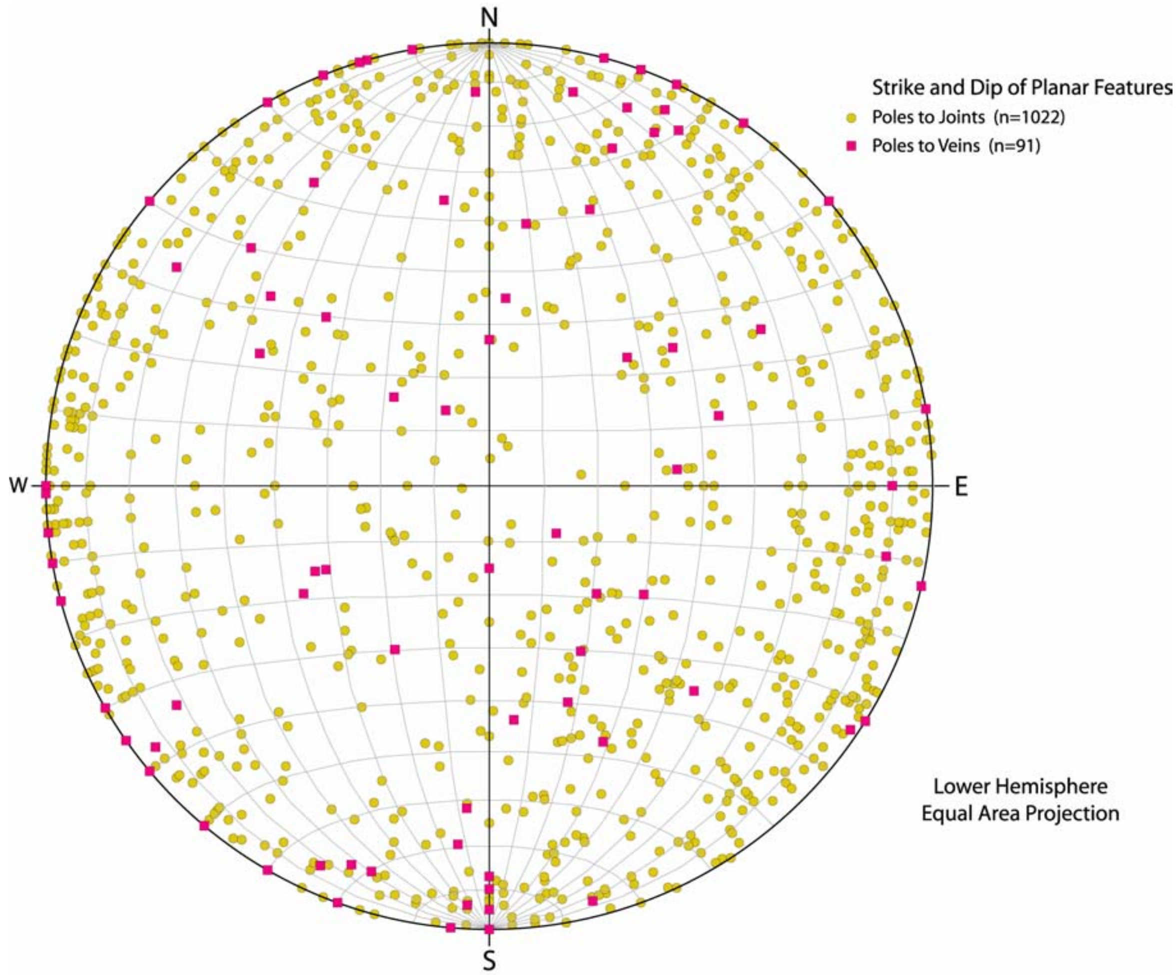

Figure 34. Stereonet projections of joints and veins from throughout the field area.

Strain Patterns

Regional strain patterns in the Vermilion district vary from north to south in the belt (Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991). These patterns include flattening strains that occur to the north, near the present Vermilion Fault (which bounds the greenstone belt to the north), and constrictional strains to the south (Fig. 35). Schultz-Ela and Hudleston (1991) mathematically modeled the observed strain patterns as deformation paths that produced flattening strains (west plunging λ_1 axes) by dextral shear of the pre-existing constrictional strains (east plunging λ_1 axes). The linear E-W strain patterns and minor rotations about horizontal axes during the deformation, as described by Hudleston et al. (1988) and Schultz-Ela and Hudleston (1991), preclude early theories (Hooper and Ojakangas, 1971; and Hudleston, 1976) on the structural setting of the greenstone belt by infolding and shear off the flanks of rising granitic diapirs. An estimate of 50% north-south shortening across the belt is proposed by Schultz-Ela and Hudleston (1991), and their model favors the origin of the Vermilion district rocks at a convergent margin, most likely as a N-dipping subduction complex with shallow slab dip. The origin of the constrictional strains remains enigmatic.

The field area lies within the mixed zone of overlapping flattening and constrictional strains of Hudleston et al. (1988) and Schultz-Ela and Hudleston (1991). A detailed strain analysis of the rocks within the immediate field area is not in the scope of this project, nor have the authors the laboratory equipment or expertise to complete such a study. However, the recent detailed geological mapping completed for this project, as well as detailed mapping in the Bass Lake sequence south of the Vermilion Fault by the authors in 2002 (Peterson and Patelke, in prep), has confirmed the existence and patterns of strain defined by Hudleston et al. (1988) and Schultz-Ela and Hudleston (1991). In addition, the timing of strain described by Schultz-Ela and Hudleston (1991), with flattening strain formed by dextral shear of pre-existing constrictional strains, is used to interpret the local structural setting in the south-central portion of the map area. Photographs of structural features associated with flattening and constrictional strains in the study area are presented in Figure 36.

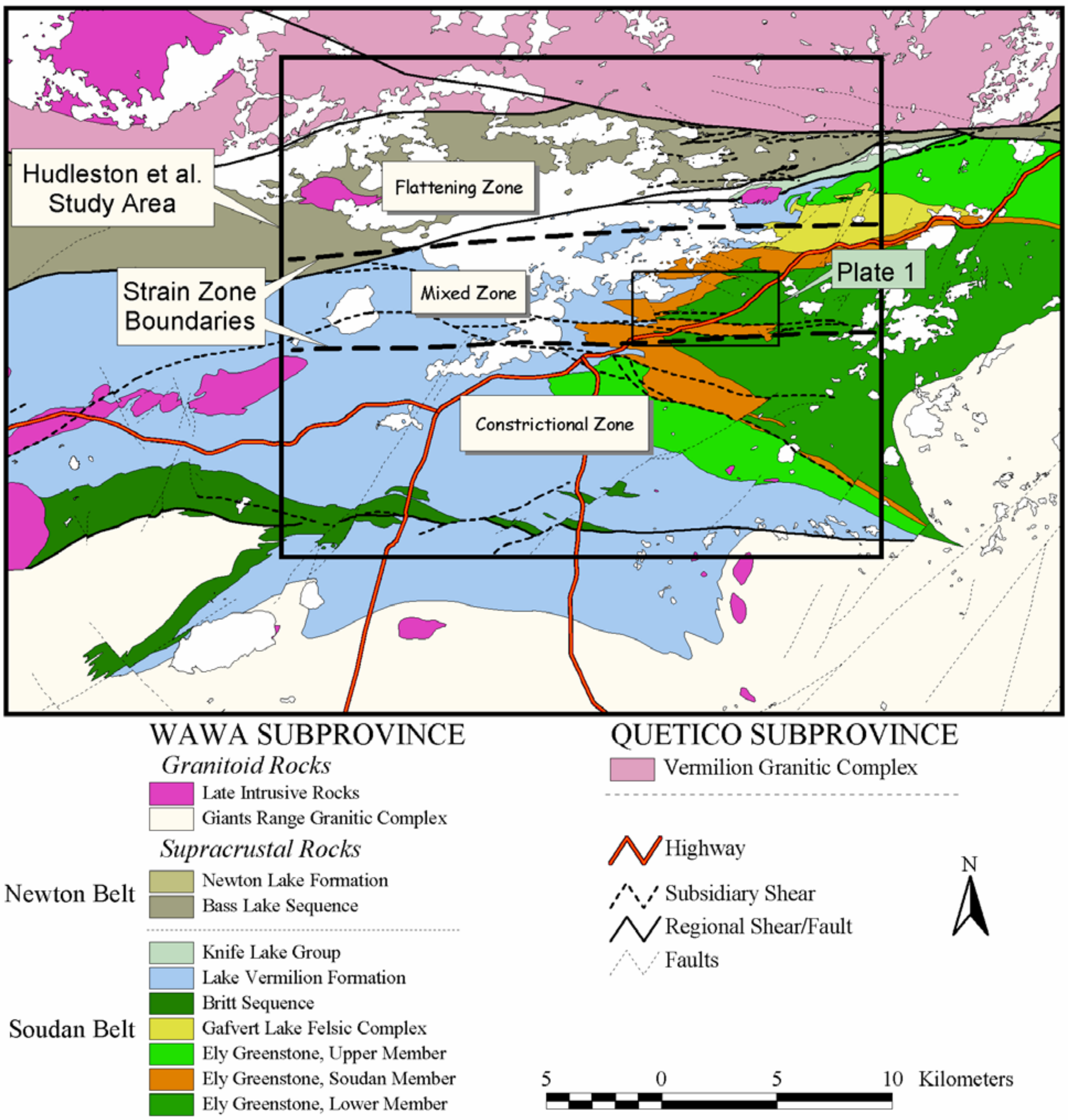

Figure 35. Strain symmetry map of Hudleston et al. (1988) superimposed on the simplified regional geologic map of Peterson (2001). The field area (see Plate 1) occurs in the "Mixed Zone" of Hudleston et al. (1988), with both flattening and constrictional strain symmetry.

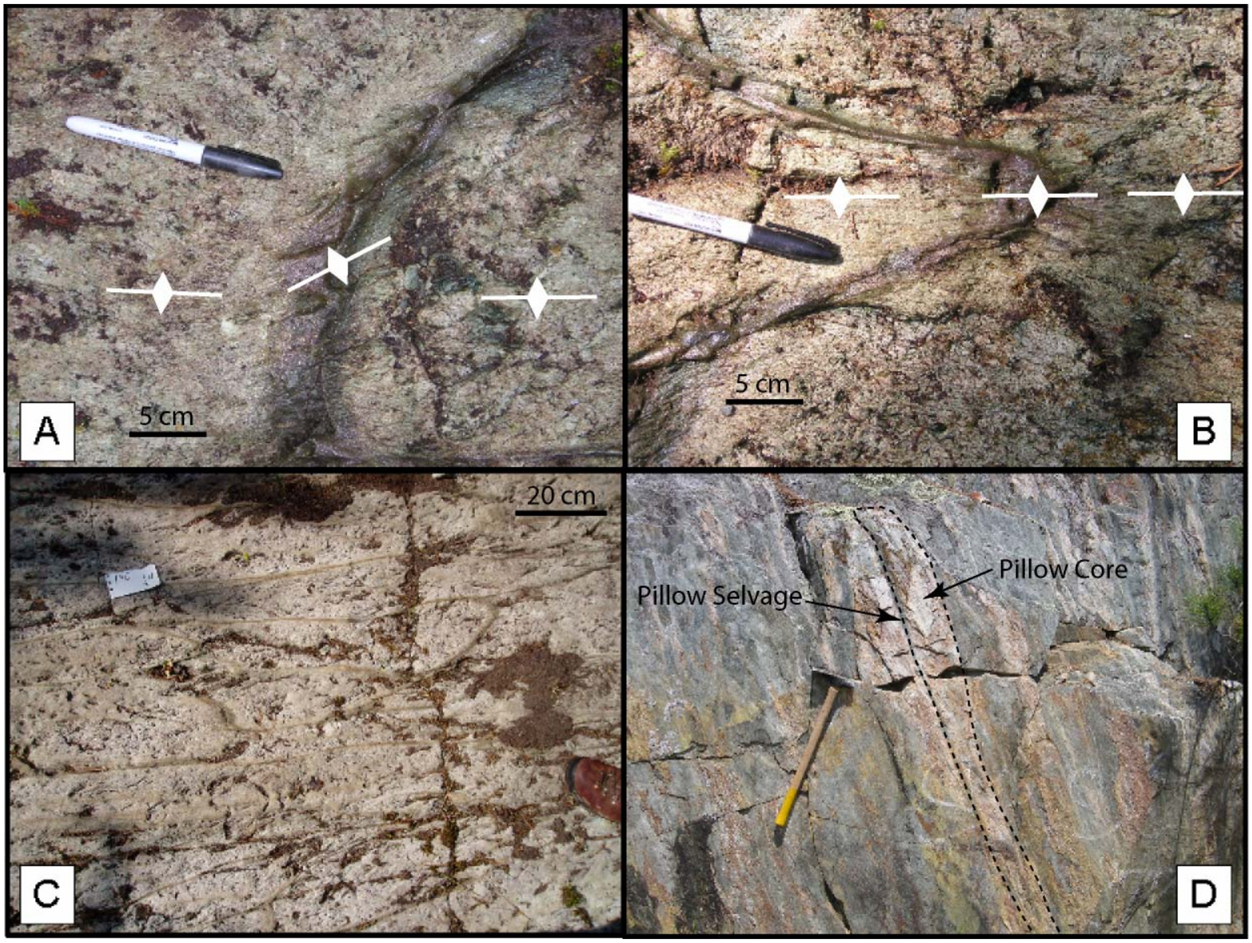

Figure 36. Outcrop photographs of structural features: A) pronounced foliation deflection across a pillowed andesite core-selvage boundary that is oriented nearly perpendicular to the regional east-west foliation, outcrop OC-582; B) lack of foliation deflection across a pillowed andesite core-selvage boundary oriented nearly parallel to the regional east-west foliation, outcrop OC-582; C) flattening strain pattern in a classic "stretched pillow" outcrop (OC-140); and D) constrictional strain revealed in highly lineated and rod-shaped pillow forms on the vertical face of outcrop OC-567 (rock hammer 68 cm for scale).

Local Structural Domains

The field area is divided into four main structural domains that include: 1) the Murray shear zone; 2) the Mine Trend shear zone; 3) the Linking Zone; and 4) the Collapsed Hinge Zone. These domains appear to be internally structurally coherent, and are separated from each other either by areas of undeformed rocks or discrete sheared boundaries. A location map of the local structural domains, with important and/or structurally revealing internal geologic units is presented in Figure 37.

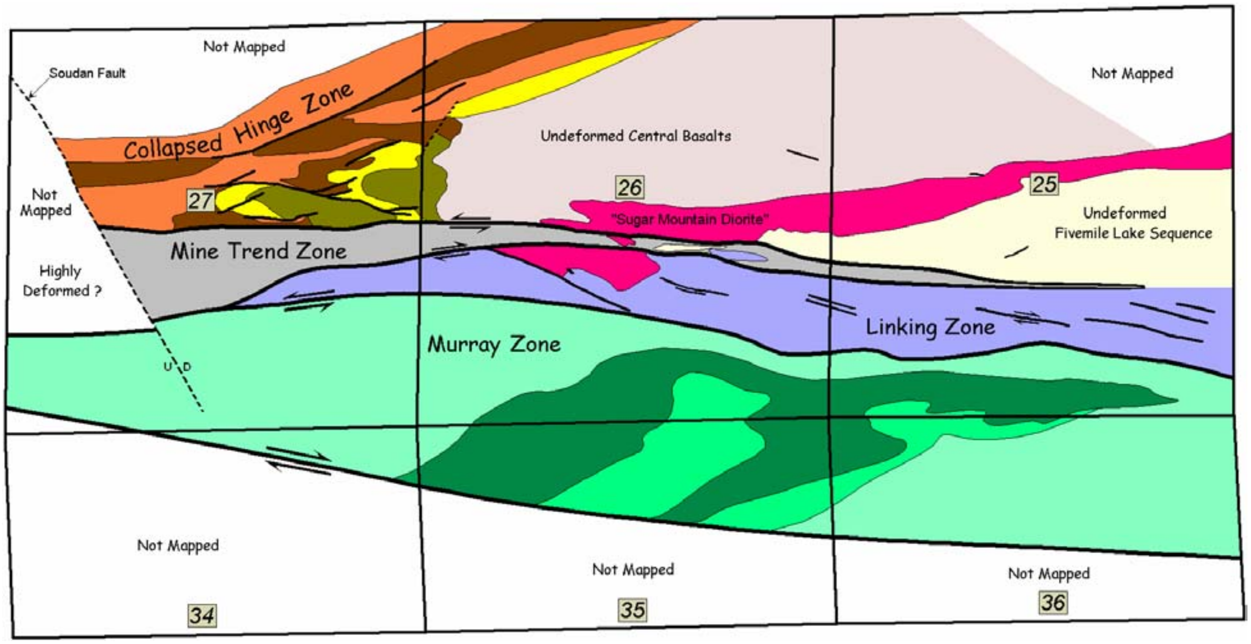

Figure 37. Structural domain map of Sections 25, 26, and 27; and the north half of Sections 34, 35, and 36. Geology simplified to display only structurally revealing lithologic units.

Murray Shear Zone

Undoubtedly the most striking structural feature in the immediate study area is the relative transposition of Upper Sequence rocks 3-5 km eastwards (Fig. 10) in the zone bounded by the northern and southern segments of the D_2 Murray shear zone (the Tower-Soudan shear zone of Hudleston et al., 1988). The overall geometry of this panel of rocks is similar to the geometry of "wedge-shaped shear zones" described in detail by Ramsey and Huber (1987). Our mapping and collection of structural data (Fig. 38) in the Murray shear zone panel is largely confined to a series of outcrops along the northern edge of the zone. Field observations of these outcrops indicate that the strain symmetry along this boundary is largely constrictional, with a dominant steeply east-dipping, elongate and rod-shaped structural fabric (Fig. 35d). Outcrop data have been integrated with previous mapping and compilation by Sims and Southwick (1980, 1985), Southwick (1993), Peterson and Jirsa (1999a), and Peterson (2001) to form the final bedrock geologic map of this area presented on Plate 1.

A stereonet projection of planar and linear structural features within the Murray panel is shown in Figure 37. The mean value of the strike and dip of planar features is 282°/82°, and the trend and plunge of linear features has a mean orientation of 87°/71°. The overall map-scale internal geometry of the Murray panel clearly shows dextral asymmetry, with a strong sigmoidal wrapping of iron-formation (Plate 1 and dark green unit on Figure 37) to the northeast.

Assuming that the relative timing of the regional strain symmetry described in Schultz-Ela and Hudleston (1991) is correct, then the constrictional strain features of the Murray shear zone indicate that this structure formed early during D_2 deformation. This timing may be further corroborated by the map-scale geometry of the northern segment of the Murray shear zone in Sections 25 and 26. In this area, the shear zone geometry could be simplified to consist of a series of right-stepping, en echelon segments, with possible dextral offsets of the Murray shear zone along minor shear zones of the "Linking Zone". Thus, the Murray shear zone may have formed prior to deformation within the Linking Zone. Further fieldwork is required to test this hypothesis.

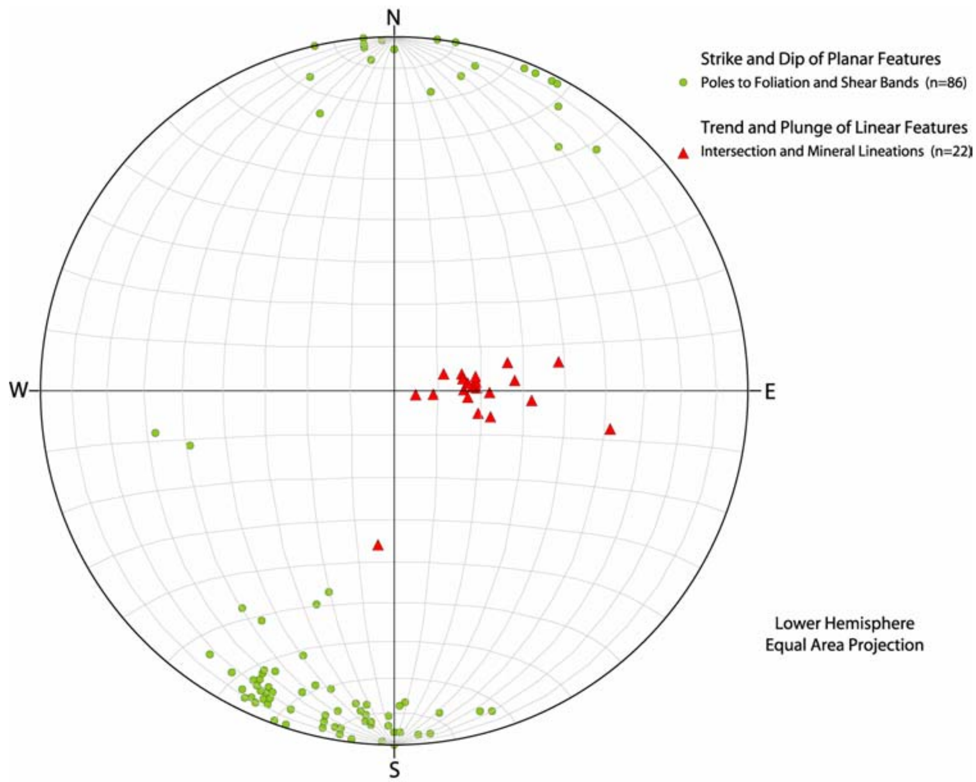

Figure 38. Stereonet projections of foliation, shear fabrics, and linear features from the Murray shear zone.

An estimate of the amount of displacement of the Upper Series rocks within the panel of rocks bounded by the Murray shear zone is given in Table 5. These values were calculated geometrically by using the average plunge of measured lineations (71°) and two measured lines of possible correlative stratigraphy offset by the bounding shear zones (Fig. 39). The calculated total displacement values (net slip) are quite large (up to 13.8 km, or 43,000 feet of net slip), but the displaced rocks would still fall within the range of depth generally associated with greenschist facies metamorphism.

Table 5. Calculated displacement along the Murray shear zone

	Calculated Displacement (Kilometers)		
Lineation Plunge	Strike Slip	Dip Slip	Net Slip
71°	4.5	13.1	13.8
71°	3.0	8.7	9.2

In the mid-1980s, Newmont Exploration discovered lode gold mineralization along the northern margin of the Murray shear zone in the eastern portion of the map area (Section 30 of Township 62 North, Range 14 West, Peterson and Jirsa, 1999b). Gold mineralization in this area, named the Murray prospect by Newmont, is associated with quartz-carbonate-pyrite-galena-tetrahedrite veins in strongly sheared and carbonatized rocks (Figs. 3, 12f, 13b). Newmont reported values up to 12.5 g/t gold during the course of their exploration. Numerous mineralized schists were mapped along strike to the west of the Murray prospect, but no precious metal assays were completed for this project.

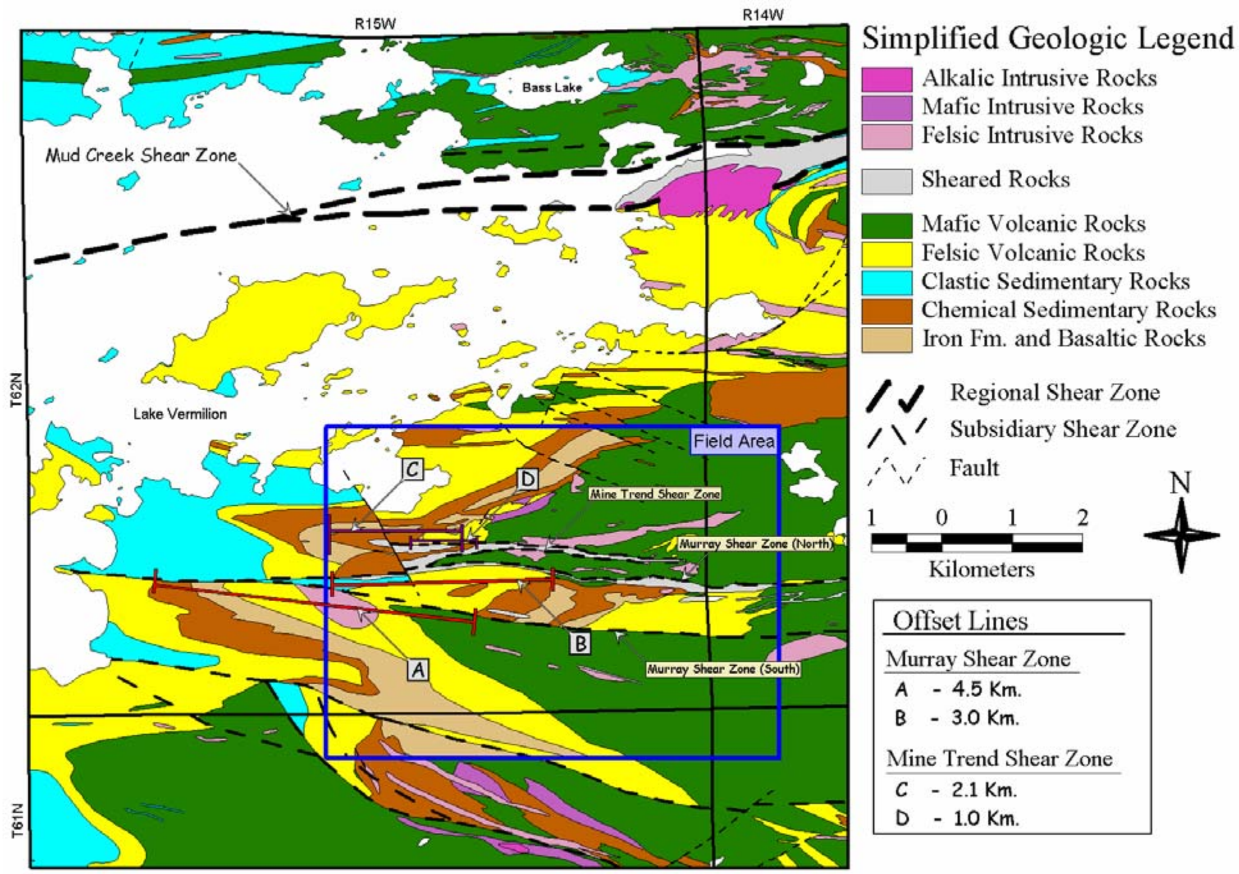

Figure 39. Simplified geologic map of Township 62 North, Range 15 West with offset lines linking possible correlative stratigraphy displaced to the east by the Murray and Mine Trend shear zones.

Mine Trend Shear Zone

The Mine Trend shear zone is a previously undescribed, east-trending and thinning, steeply north-dipping, curvilinear zone of highly deformed rocks that host the Alaska, 734, and 651 massive-hematite ore bodies (see Plate 2) of the Soudan Mine. As mapped, this shear zone extends 2.5 miles eastwards from the Soudan Fault in Section 27, through Section 26, to nearly the eastern edge of Section 25 (Fig. 37). The shear undoubtedly extends to the west, and likely hosts the majority of the Soudan Mine ore bodies west of the Soudan Fault. Detailed bedrock and underground geologic mapping, as well as integration of drill hole data from Oliver Mining, would be the first step in defining the western extension of this important structural zone. Although uncertain, we believe the origin of the massive hematite ore in the Soudan Mine is linked to highly oxidizing and/or acidic hydrothermal fluids synchronous with D_2 shearing of the Mine Trend shear zone.

In map view, the shear appears similar to the Murray shear zone, though smaller in scale, and can be interpreted as "wedge-shaped shear zone" (Ramsey and Huber, 1987). A relative eastward displacement of rocks within the shear zone is interpreted from kinematic indicators, which are largely sinistral on the north margin and dextral along the south margin of the shear zone. Stereonet projections of planar and linear structural features measured within the Mine Trend shear zone (including data from our mapping of the 27th level east drift of the Soudan Mine) are given in Figure 40. The mean value of the strike and dip of planar features exposed on the surface is 270°/84°, and the trend and plunge of east-dipping linear features is 81°/73°. The sweeping pattern of planar features exposed on the surface is the result of the curvilinear nature of the shear, which mimics a north facing, flattened and convex arc. The stereonet projection (Fig. 40) of underground data displays a more complex geometry of planar features (and to lesser extent linear features). This complexity is interpreted to be the result of local perturbations caused by the extreme competency contrast between iron-formation, schists, and the gabbroic body mapped along the 27th level east drift (Plate 2).

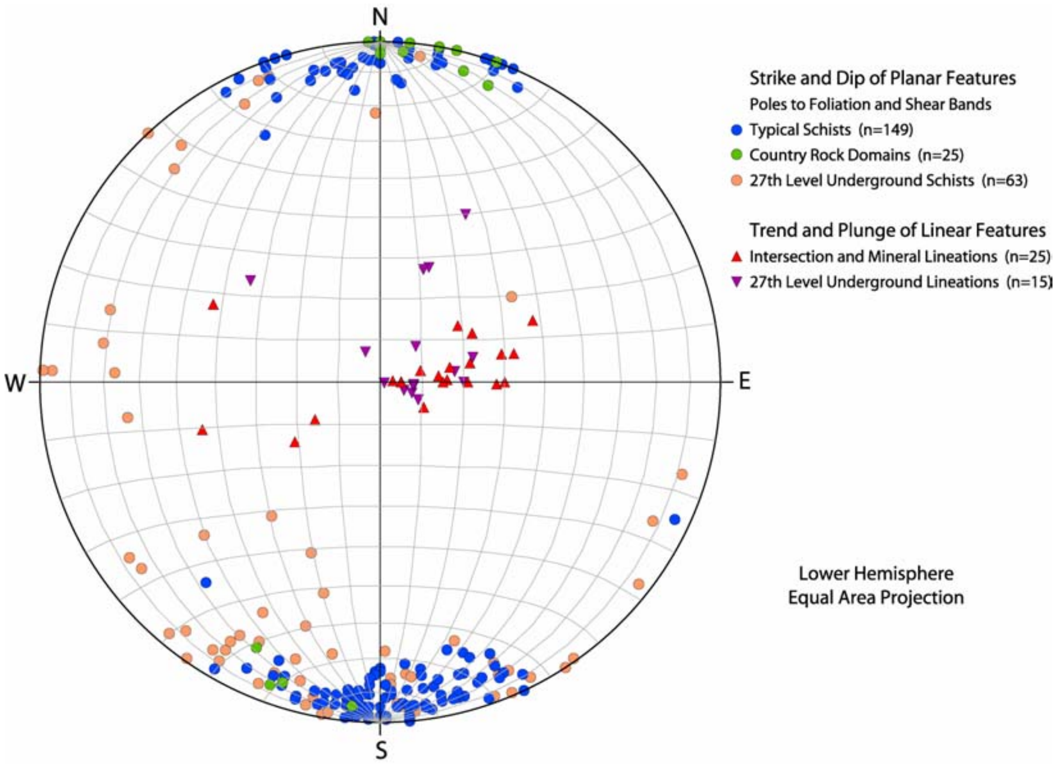

Figure 40. Stereonet projections of foliation, shear fabrics, and linear features from the Mine Trend shear zone.

Because the western extent of the Mine Trend shear zone is not yet defined, a calculated displacement along this structure is, at best, only tenuous. However, two possible solutions of displacement geometry for the Mine Trend shear zone are given in Table 6, with horizontal stratigraphic displacement vectors presented in Figure 39.

Table 6. Calculated displacement along the Mine Trend shear zone.

	Calculated Displacement (Kilometers)		
Lineation Plunge	Strike Slip	Dip Slip	Net Slip
72.6°	2.1	6.7	7.0
72.6°	1.0	3.2	3.3

The geology of the shear is well exposed in Section 27, and enables the discrimination of schistose domains into discrete mappable units (see Plate 1). To the east, the geological interpretation and structural setting of the shear is more tenuous. The shear zone transects the exposed western margin of the very competent "Sugar Mountain Diorite", and then thins, diverges, and incorporates country rock domains of the Fivemile Lake and Central Basalt sequences as it reconverges and trends eastward. The west-plunging linear features presented in Figure 40 occur where the shear zone thins as it crosses the diorite, but typical east-plunging lineations again occur to the east. A simplified three-dimensional geologic map/longitudinal section of the Mine Trend shear zone, with the trend and plunge of lineations measured on the surface, is presented in Figure 41. As can be seen in Figure 41, the measured west-plunging lineations all occur in the area where the shear transects the Sugar Mountain Diorite.

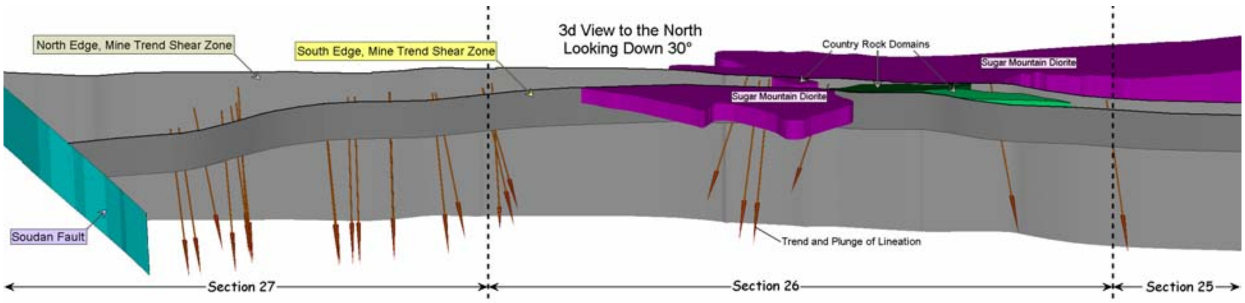

Figure 41. Simplified three-dimensional view to the north of the Mine Trend shear zone. Lineation arrows all have lengths of 500 meters, and thus the differential lengths displayed are the result of the geometry of lineation trend and plunge and the view plane. The southern edge of the Mine Trend shear zone surface and Sugar Mountain Diorite solid south of the Mine Trend shear zone are clipped at depth to display lineation arrows.

Linking Zone

A series of thin (<20 meters), ESE-trending, steeply inclined domains of sheared and highly foliated rocks of the Fivemile Lake sequence were discovered during the course of the detailed mapping in the area between the Mine Trend and north edge of the Murray shear zones (Fig. 37). This distinct structural domain has been informally named the "Linking Zone" for this report. Kinematic sense of shear textures observed in a number of outcrops of sheared rocks is dextral, and stereonet projections of planar and linear structural features measured within the Linking Zone are given in Figure 42. The mean value of the strike and dip of planar features exposed on the surface is 282°/83°, and the trend and plunge of east-dipping linear features is 85°/77°.

A structurally compatible solution for the origin of deformation associated with development of shears in the Linking Zone has been interpreted from: (1) the geometry of the shears in relation to the bounding shear zones; (2) timing of Vermilion district strain symmetry defined by Hudleston et al. (1988) and Schultz-Ela and Hudleston (1991); (3) review of classic structural geology publications (Riedel (1929), Tchalenko (1970), Ramsey and Huber (1987)); and (4) rigorous analysis of the finalized geology map of the field area (Plate 1). The Linking Zone shears appear to be directly related to the dextral sense of motion associated with the Mine Trend shear zone, and are interpreted to be secondary Riedel R shears developed south of the Mine Trend shear zone during Tchalenko's (1970) peak stage, in which resistance to shear is at a maximum. The peak stage may have developed while the Mine Trend shear was propagating through the very competent Sugar Mountain Diorite. To the north of the Mine Trend shear zone, geometrically compatible Riedel R structures were observed in the diorite in the form of small, linear WNW-trending zones of breccia. In addition, the geometry of the southern margin of the Linking Zone (the north edge of the Murray shear zone) could be interpreted to consist of a right stepping, en echelon array with linking shears offsetting the earlier Murray shear zone. The lack of outcrop data precluded the incorporation of this proposed right stepping, en echelon structural array onto the final geologic map (Plate 1). However, unlike the schists of the Mine Trend shear zone to the north, the mineralogy of the linking shears include ankeritic and pyritic schists similar to the Murray shear zone to the south, and thus the linking and Murray shears may truly have been linked during ascent of CO_2- and H_2S-rich hydrothermal fluids that deposited these minerals. A simplified model for the formation of the Linking Zone is given in Figure 43.

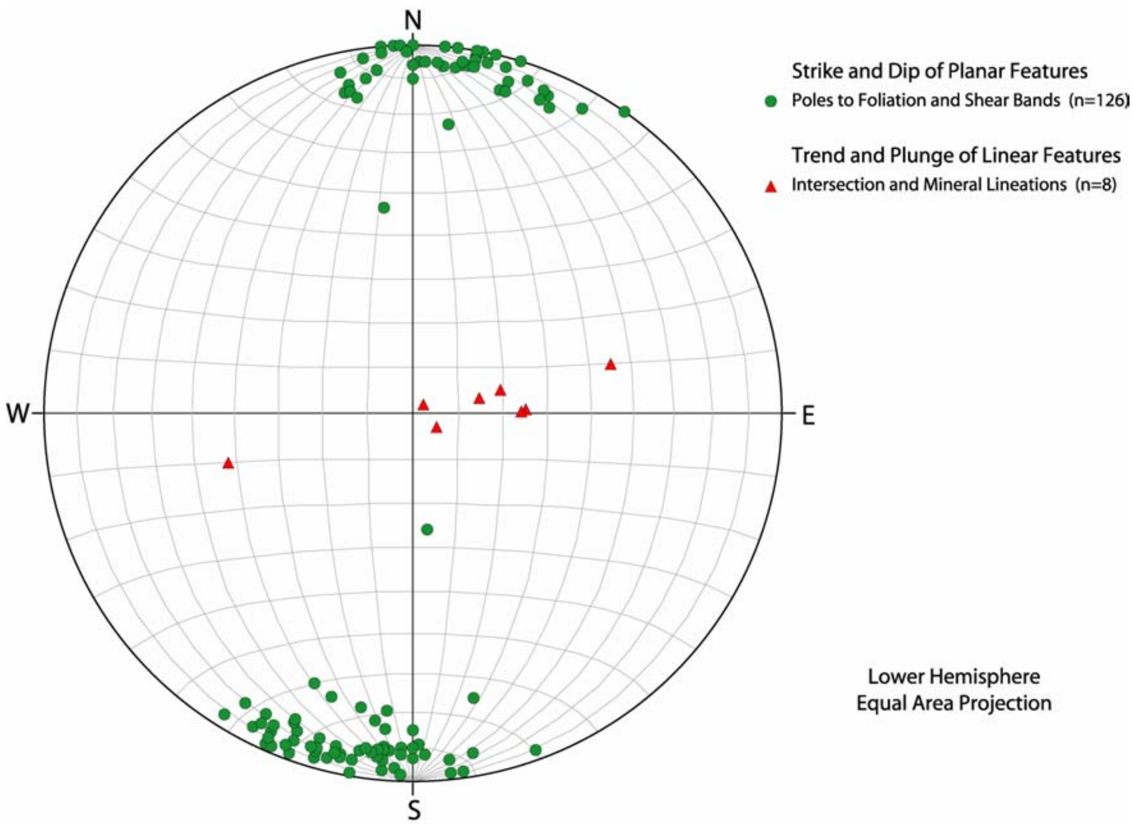

Figure 42. Stereonet projections of foliation, shear fabrics, and linear features from the Linking Zone.

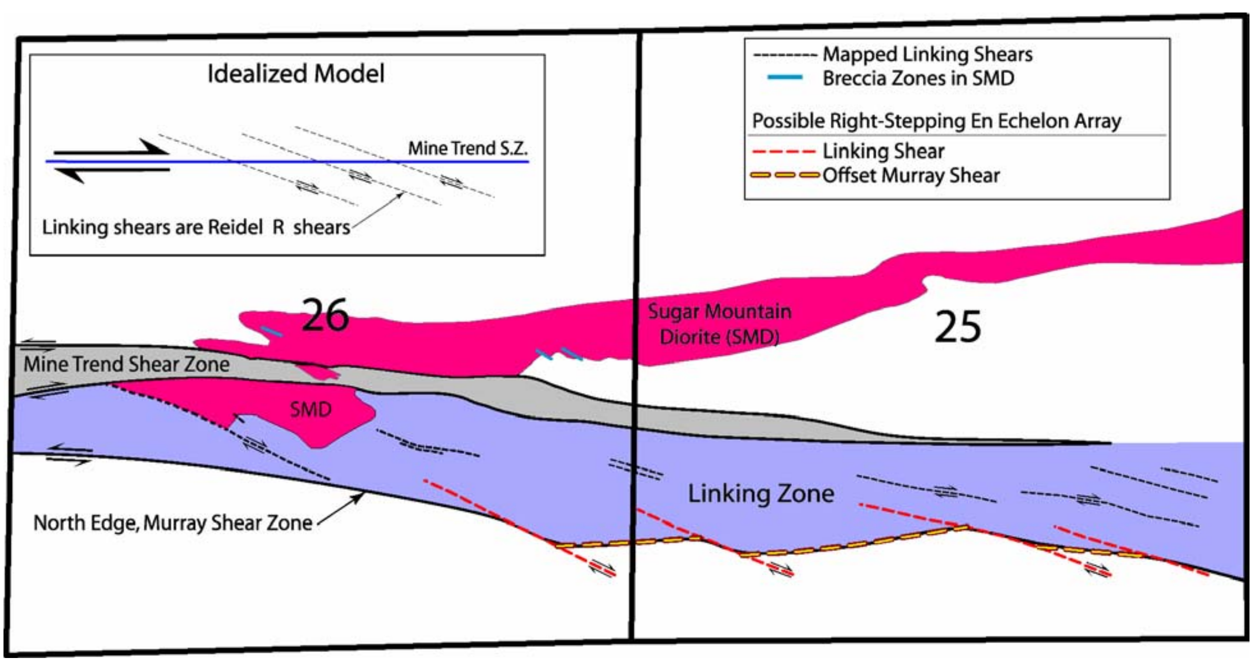

Figure 43. Idealized model for the formation of sheared domains in the Linking Zone.

Collapsed Hinge Zone

As defined for this report, the Collapsed Hinge Zone occurs in the northern half of Section 27 and the northwest quarter of Section 26 (Fig. 37). The geology of the "Collapsed Hinge Zone" is unique in the field area in that it is largely composed of a laterally continuous sequence of layered sedimentary rocks (Upper Sequence). Rock units include felsic tuff and epiclastic rocks, basaltic rocks (probably largely sedimentary rocks derived from basalt), and iron-formation. These layered rocks were originally deposited on a very thick sequence of basaltic rocks of the Lower Member of the Ely Greenstone (the Central Basalts of this study). Initial ideas on the structural setting of the rocks in the northeast quarter of Section 27 began while mapping, and were focused on the change in the strike of bedding of iron-formation horizons from ~245° in the northeast to 270° to the west. In addition, exceptional exposures of contorted, small-scale soft-sediment deformation features in iron-formation provided possible analogs for the larger-scale geometries. An annotated photograph of one of these exposures is given in Figure 44.

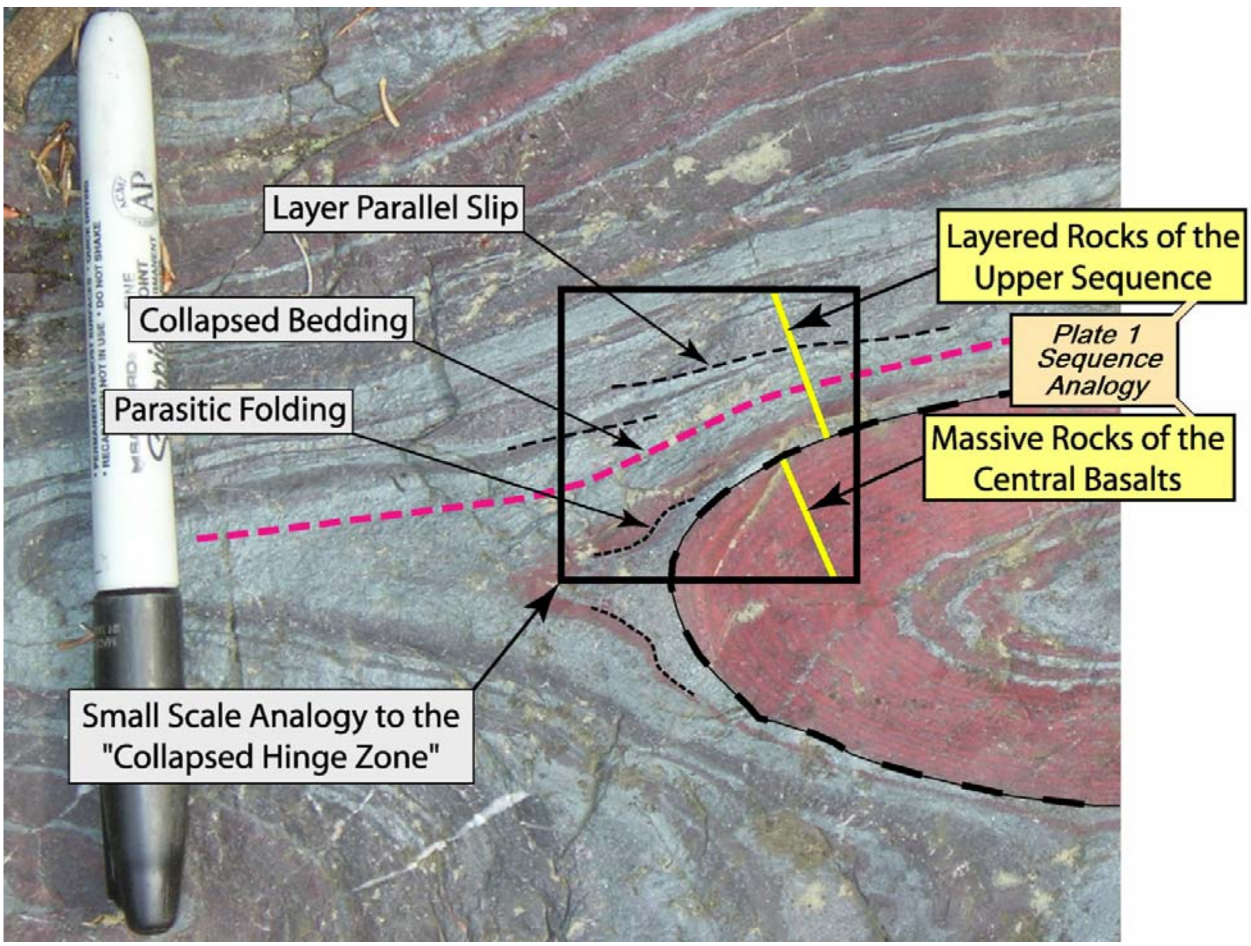

Figure 44. Outcrop photograph of small-scale deformation features in iron-formation that mimics the interpreted structural setting of the Collapsed Hinge Zone (see Figures 36, 38, and 45).

Stereonet projections of planar and linear structural features measured within the Collapsed Hinge Zone are given in Figure 45. The strikes of the steeply dipping planar features are dispersed compared to other domains and are attributed with the overall change in strike of layering from ~245° in the northeast to 270° to the west.

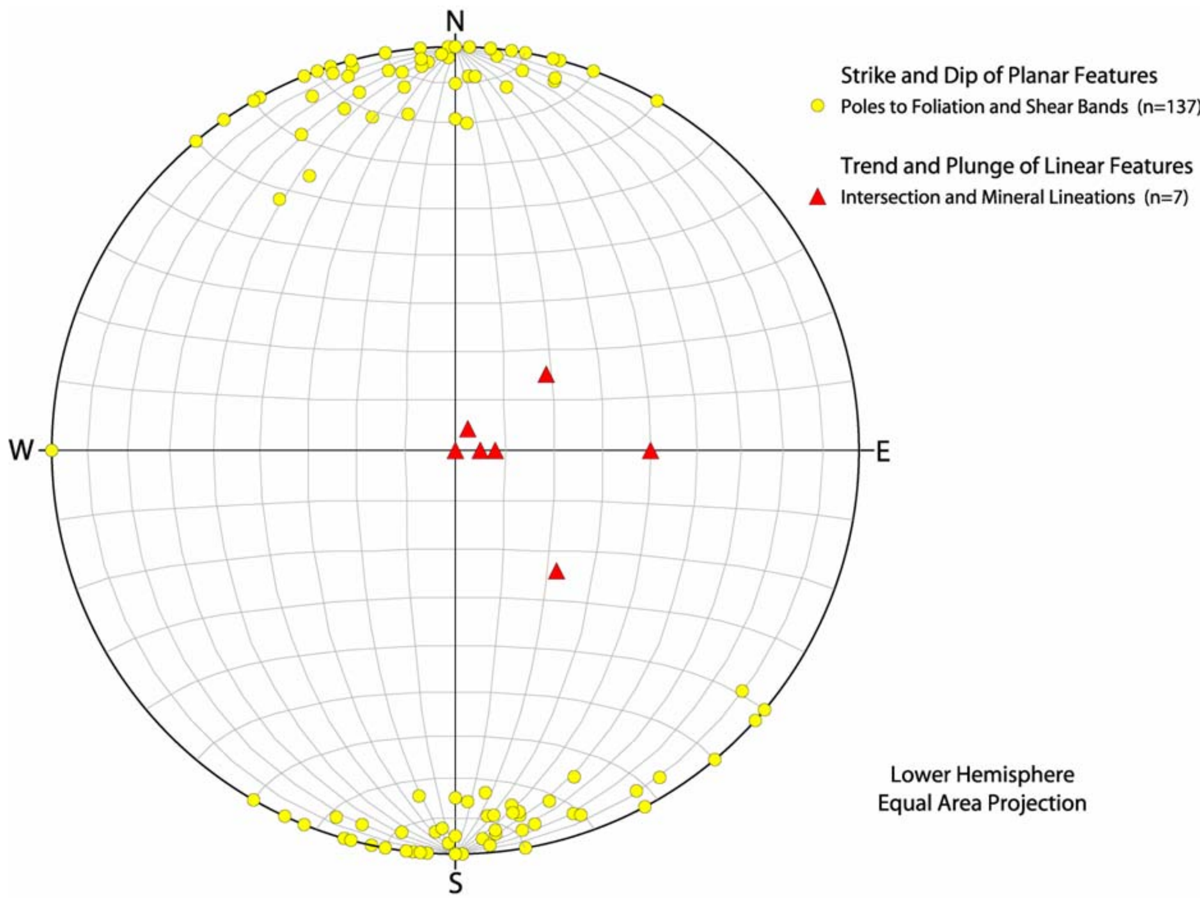

Figure 45. Stereonet projections of foliation, shear fabrics, and linear features from the Collapsed Hinge Zone.

In general, three main types of structural features were observed within the Collapsed Hinge Zone area, including: 1) northeast-striking shears that appear to generally follow original layering; 2) west-verging folds defined by felsic tuff and epiclastic rocks; and 3) east to east-southeast-striking, dextral shear zones. These distinct structural features are presented in map view in Figure 46. The structural setting of the Collapsed Hinge Zone is interpreted to be the result of localized D_2 dextral shear overprinting D_1 -related flexural slip folding and layer-parallel dislocation associated with the formation of the Tower-Soudan Anticline (Fig. 2). Distinct zones of layer-parallel flexural slip gave rise to the observed northeast-striking D_1 shears (which locally are observed to have sinistral sense of shear kinematics), which are dexturally offset by D_2 shear zones. The folded felsic tuffaceous and epiclastic rocks occur at the base of the Upper sequence in this zone (Fig. 46), and are interpreted to be S-shaped folds associated with the D_1 Tower-Soudan Anticline. Though poorly defined at present, the hinge lines and vergence of these folds are essentially parallel to the Tower-Soudan Anticline, and thus can be interpreted as parasitic folds to this major D_1 structure. The S-shape kinematics are also displayed in the overall collapsing of layering from ~245° in the northeast to 270° to the west. The parasitic folds are believed to have formed by localized layer parallel shortening resulting from the competency contrast between the massive footwall basalts of the Central Basalt sequence and the well-layered rocks of the Upper sequence. The east-southeast-striking D_2 shear zones are envisioned to have formed similar to the shears described in the Linking Zone, and can be interpreted as subsidiary Riedel R shears located on the north side of the Mine Trend shear zone.

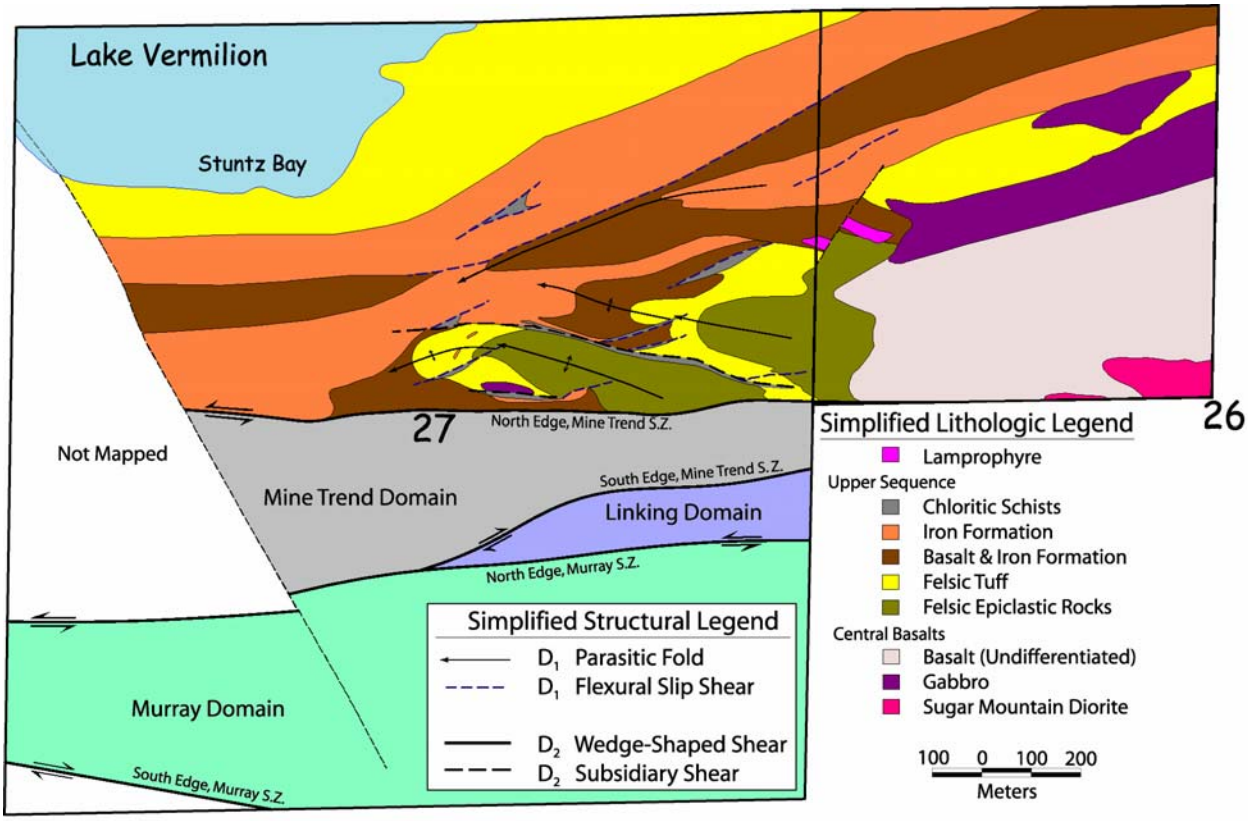

Figure 46. Interpreted structural setting of the Collapsed Hinge Zone, Section 27 and the NW quarter of Section 26.

Undeformed Zones

In the intervening areas between the four structural zones described in the preceding sections is a large eastward-widening, wedge-shaped domain of rocks that were essentially not effected by D_2 deformation. This zone occurs between the Collapsed Hinge Zone to the northwest and the Mine Trend shear zone to the south, and consists of the "undeformed Central Basalts", "Sugar Mountain Diorite", and "undeformed Fivemile Lake Sequence" area of Figure 37. In comparison to the four structural domains described in the previous sections, the lack of D_2 deformation observed in outcrops within this area is striking. Fine delicate volcanic textures (angular hyaloclastite fragments, pristine vesicles and amygdules, angular clasts in flow top breccias) are typically well preserved (Fig. 47), and the rocks generally illustrate no obvious schistosity or cleavage. However, very localized fabric is developed in some outcrops (especially in rocks of the Fivemile Lake sequence south of the Sugar Mountain Diorite), but as a general rule this fabric cannot be traced along strike into adjacent outcrops. It should be noted that strain associated with deformation in the previously described structural zones appears to gradationally dissipate over relatively short distances (<100 meters) along the margin of the undeformed rocks. The lack of D_2 deformation in this zone is attributed to three main factors: 1) the homogeneity and strength of the rocks (dominantly pillowed basalt) and location of the zone north of the hinge line of the D_1 Tower-Soudan Anticline (Fig. 2); 2) extensive early sub-seafloor quartz-epidote-garnet hydrothermal alteration; and 3) strain partitioning and deflection on regional and localized scales.

Figure 47. Preserved volcanic textures in the undeformed zone of the Central Basalt sequence: A) silicified pillowed basalt with preserved interpillow material composed of angular hyaloclastite fragments; and B) perlitic cracks preserved in devitrified hyaloclastite fragments (blurred US quarter for scale).

On a regional scale, the wedge-shaped zone of undeformed rocks occurs on the north limb of the Tower-Soudan Anticline; the axial trace of which strikes southeast away from the undeformed zone. Therefore, possible D_1 deformation features associated with the hinge of the fold should strike away from the rocks of the undeformed zone. Early sub-seafloor hydrothermal alteration mineral assemblages within the zones of undeformed rock include a moderate-temperature assemblage of albite-quartz-chlorite (spilitization) within the Fivemile Lake sequence, and a high-temperature assemblage of quartz-epidote-garnet within the Central Basalt sequence. The highly indurated rocks of the Sugar Mountain Diorite separate the volcanic sequences, and thus also separate these alteration mineral assemblages. The alteration empirically strengthens the rocks, sealing early-formed cooling joints, and filling primary void spaces via silicification. The strengthening is especially apparent in the quartz-epidote-garnet alteration of the Central Basalt sequence. The early alteration occurred prior to D_1 deformation that culminated in the formation of the Tower-Soudan Anticline. The enhanced competency of the altered rocks possibly partitioned strain away from the zone during D_1 and D_2 deformation.

Strain partitioning during D_2 deformation away from the zone of undeformed rocks is interpreted to have resulted from two main features: (1) The first feature is the relative large size (and thus large accommodated deformation) of the Murray shear zone, which undoubtedly is the largest D_2 feature in the mapped area. It is possible that the high competency of the hydrothermally altered rocks in the undeformed zone caused partitioning of D_2 strain into the zone now occupied by the Murray shear zone, and thus the large size of this shear zone is directly related to the undeformed rocks. (2) On a more localized scale, the highly indurated nature of the Sugar Mountain Diorite appears to have blocked the propagation of subsidiary Riedel structures associated with the Mine Trend shear zone to the north, into the undeformed rocks of the Central Basalt sequence. A summary diagram of features related to the lack of deformation in the undeformed zone is given in Figure 48.

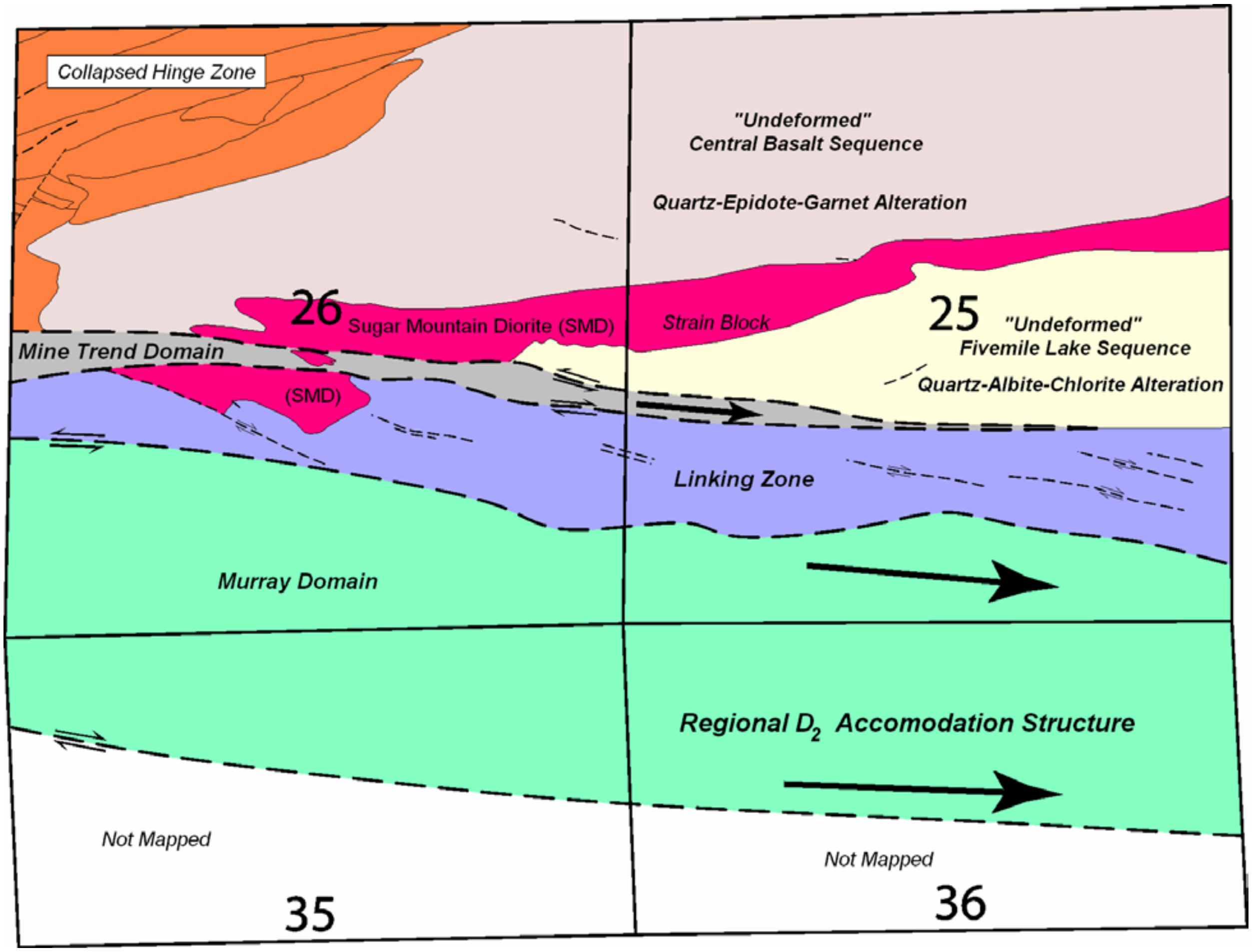

Figure 48. Summary diagram of geologic features associated with the lack of deformation within the undeformed zone.

Geologic History

Geological units exposed on the surface in the immediate Soudan Mine area include Neo-Archean rocks (~2.7 Ga), Pleistocene glacial deposits (~12.5 ka), and Recent (<10 ka) sediments. The timing of the stratigraphic and structural observations and interpretations described in the preceding sections of this report are integrated into the geological history outline presented below. The simplified geologic history is described from oldest observed and/or interpreted features to the youngest. In addition, the timing of other geological events known to exist in northern Minnesota, but not represented in the Soudan Mine area, is included.

1) Deposition of the Fivemile Lake Sequence (2722 Ma, Peterson et al., 2001)
    a. Shallow water, bi-modal volcanism (mid-level volcanic rocks of the Lower Ely Greenstone)
    b. Subsidence of the volcanic pile
    c. Spilitization of volcanic rocks
2) Deposition of the Central Basalt Sequence
    a. Deep water, tholeiitic basalt volcanism (upper volcanic rocks of the Lower Ely Greenstone)

    b. Intrusion of the Sugar Mountain Diorite (SMD) and north-trending associated dikes
    c. High temperature hydrothermal alteration of the Central Basalt sequence

3) Deposition of the Upper Sequence
    a. Stratigraphically continuous chemical (Soudan Iron Formation) and clastic sedimentation (basal units of the Lake Vermilion Formation)
    b. Final coalescing of SMD dikes into the Gd-Qfp map unit magma chamber
    c. Localized intrusion of Gabbroic sills
    d. Deep water clastic sedimentation with the deposition of the upper greywacke-slate sequences of the Lake Vermilion Formation (well exposed west of the field area)

4) D_1 Deformation
    a. Formation of the Tower Soudan Anticline
        i. Tilting of the rocks into their current north-facing, steeply inclined orientation
        ii. Parasitic folding and layer parallel slip in the Collapsed Hinge Zone

5) D_2 Deformation (2674 Ma to 2685 Ma, Boerboom and Zartman, 1993; Peterson et al., 2001)
    a. Dextral movement and juxtaposition of the Newton and Soudan belts (see page 4) along the crustal-scale Mud Creek Shear Zone (immediately north of the field area)
    b. Major eastward transposition of rocks within the Murray shear zone
        i. Localized intrusion of porphyritic felsic intrusions
    c. Eastward transposition of rocks within the Mine Trend shear zone
        i. Oxidizing and/or acidic hydrothermal fluid migration and development of the massive hematite ore bodies of the Soudan Mine
        ii. Subsidiary Riedel R shear development in the Collapsed Hinge Zone
        iii. Subsidiary Riedel R shear development in the Linking Zone
    d. Deep seated CO_2- and H_xS_y-rich hydrothermal fluid migration up the Murray shear zone
        i. Deposition of ankeritic carbonate within the Murray and Linking shear zones
        ii. Carbonitization of volcanic and intrusive rocks of the Fivemile Lake sequence in areas adjacent to the Murray and Linking shear zones.
        iii. Localized K^+ alteration and gold mineralization in ankerite-altered shear zones

6) Intrusion of Lamprophyric Rocks

7) D_3 Deformation
    a. Development of the Vermilion, Haley, and related faults resulting in the juxtaposition of the Wawa and Quetico Subprovinces of the Canadian Shield (~7 miles north of the field area)
    b. Formation of the NW-striking Soudan Fault and the NE-striking minor faults mapped in the field area.

8) Erosion (~2600 Ma to ~12.5 Ka)

a. Regional geologic events in northern Minnesota during this protracted period of erosion in the Soudan Mine area include:

    i. Intrusion of the Kenora-Kabetogama Dike Swarm (~2.1 Ga) immediately west of the field area

    ii. Paleoproterozoic Animikie Basin Sedimentation (~1.95 - 1.85 Ga), with the deposition of the Biwabik Iron Formation and related rocks south of the field area

    iii. Mesoproterozoic Mid Continent Rift (~1.1 Ga), subaerial flood basalts and intrusion of the Duluth Complex to the southeast of the field area

    iv. Intense weathering in the Cambrian

    v. Intense weathering in the Cretaceous

9) Pleistocene Glaciation (1.8 Ma – 10 Ka)

    a. Bedrock scouring of saprolite and weathered surfaces, subsidence ofby glacial loading

    b. Deposition of glacial deposits during final retreat of ice (13.5 – 10.5 Ka)

10) Recent (<10 Ka)

    a. Isostatic rebound of the crust

    b. Erosion and reworking of glacial deposits, organic sedimentation of lake basins

N U S E L S i t e S e l e c t i o n

The University of Minnesota's proposed design for the National Underground Science and Engineering Laboratory at the Soudan Mine includes several major features (Marshak et al., 2003). A major component of the proposed design is to provide world-class access to the existing Soudan Mine laboratories at 710 m and to new laboratories at depths of 1,450 m and 2,500 m. The access design is a combination of a circular, concrete-lined shaft, slashed to a diameter of 5 m, and a 1:7 decline with a cross-sectional area of 20 m laid out in a "racetrack" cross-section helix from the surface to the 2,500 m level. The shaft would provide quick access for personnel and "small" equipment (up to 3 m by 3 m by 10 m in height by 20 tonnes in weight), and would have a hoisting capacity for up to 5,000 tonnes per day in routine rock production. The decline will provide the initial access to depth, access for large and heavy instrumentation and production equipment, and serve as an emergency egress and access. The location of the new hoisting shaft would be tangent to the "race track" decline helix, and near the intersection of that helix with a connecting drift extended from the east drift of the 27th level (710 m) of the Soudan Mine. The shaft will have a shaft station at each point where it touches the decline helix, although only the stations at 710 m, 1,450 m (shaft and transfer station) and 2,500 m will be fully developed. The other shaft stations (at 350 m, 1,080 m, 1,800 m and 2,150 m) will be used only for raise boring, muck removal and emergency egress. Ventilation shafts will also be located at tangent points to the decline helix. The exact layout will be determined during preliminary engineering. The decline will have a cross-section of 20 m^2, beginning at the surface and extending downward to the 2,500 m level. The decline will drop ~350 m per revolution, thus requiring 7 revolutions to reach the lowest level. The conceptual design is that each revolution will be 2,450 m in length, with two straight sections of 685 m each and two 180° curved sections, each of length 540 m. The radius of curvature is 172 m. The cross-section of this layout is ~885 m, approximately east-west and ~345 m, approximately north-south. The area of the circumscribed rectangle is ~300,000 m^2 or ~75 acres. The conceptual design of the Soudan Mine NUSEL is presented in Figure 49.

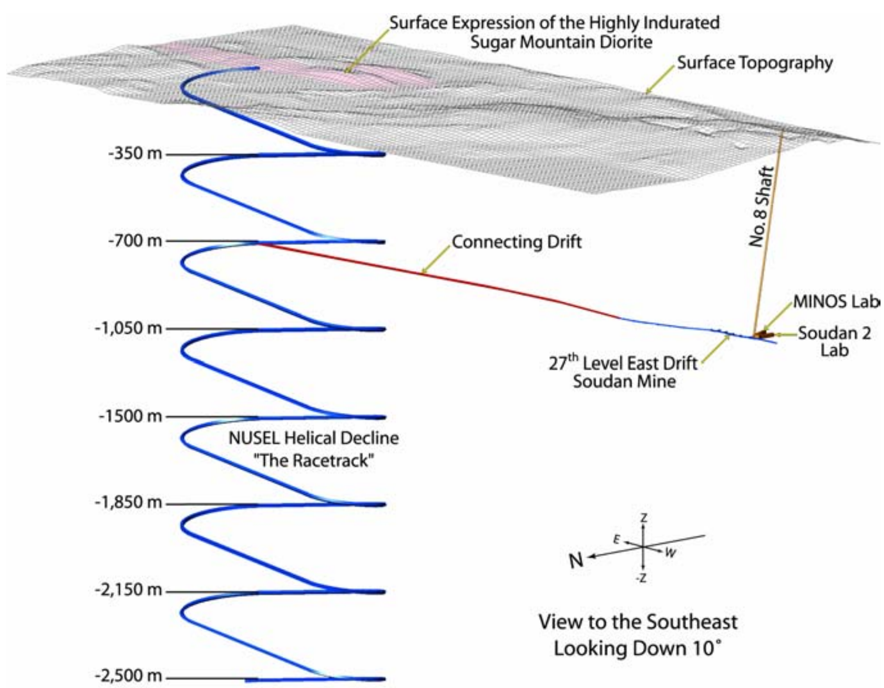

Figure 49. Simplified three-dimensional conceptual design of the proposed Soudan Mine NUSEL. Hoisting and ventilation shafts would be located adjacent to the helical decline, and the path of the connecting drift is idealized, i.e., drawn to connect with the decline at its starting elevation of 710 m below the surface.

The two central questions asked prior to the beginning of this project were: 1) Are the rocks east of the existing the underground laboratories at the Soudan Mine amendable for constructing a National Underground Science and Engineering Laboratory (NUSEL)?; and 2) Are there geological and structural features within and/or adjacent to these rocks that are required for a fully functional EarthLab? In short, the answers to both of these fundamental questions are yes. The suitability of the rocks for construction large caverns, as specified for NUSEL, is described below, and the geological and structural requirements needed for EarthLab are given in the following section of this report.

The geological criteria deemed most important for NUSEL construction include: 1) definition of a competent rock mass for excavation of large caverns at depths of 1,450 and 2,500 m; 2) minimizing the occurrence of major lithologic contacts (especially 3d surfaces between rock types with very different physical characteristics) that would be encountered during construction of shafts, drifts, and the helical decline; and 3) minimizing the occurrence of major structural features in the area proposed for construction of the helical decline. The area directly north of the Sugar Mountain Diorite, in the competent pillowed basalts of the Central Basalt sequence, appears to meet all of the criteria for construction of the helical decline, and large laboratories could probably be excavated out of the highly indurated Sugar Mountain Diorite. A simplified geological map depicting the vertical projection of the proposed location of the NUSEL facilities is presented in Figure 50.

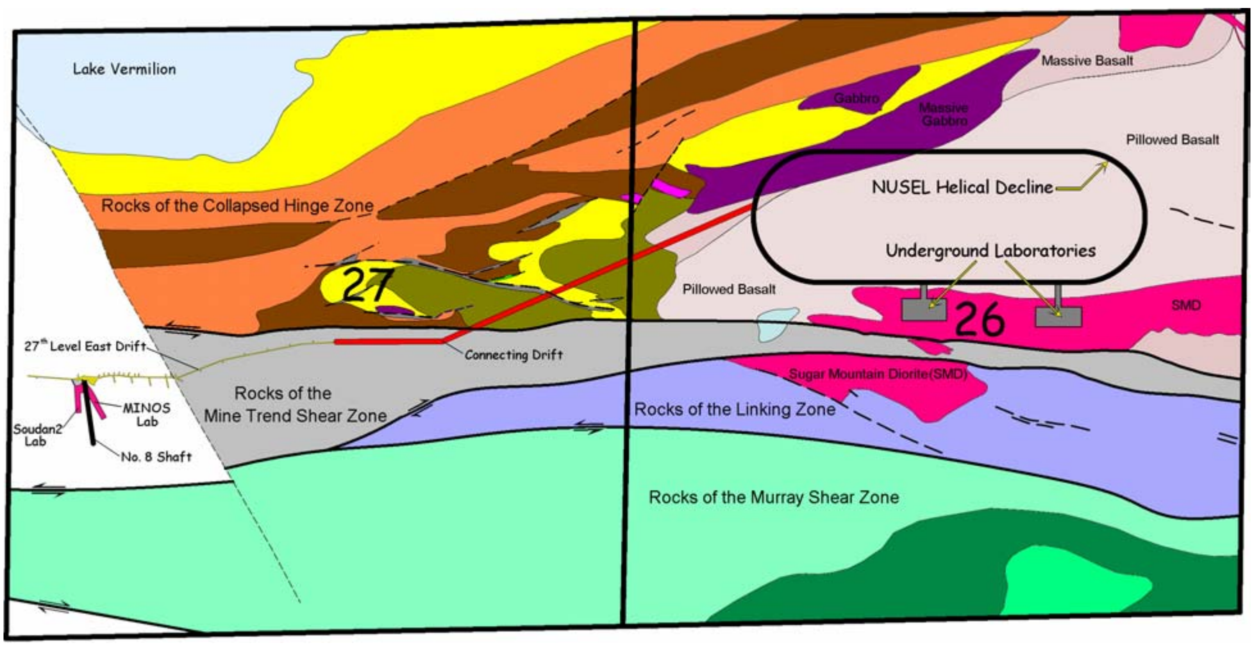

Figure 50. Simplified geologic map of Sections 26 and 27 with the vertical projection to the surface of the proposed location of the NUSEL helical decline and drift that connects to the eastern end of the 27th level (-710 m) workings of the Soudan Mine.

In the area of the proposed location of the NUSEL, i.e., north central portion of Section 26, two fundamental geological questions must be addressed that deal with the down-dip continuity of the geology mapped at the surface. These questions are:

1) What is the depth extent of the rocks of the Vermilion Greenstone Belt?
2) Is it reasonable to assume that the same rock units mapped on the surface occur at the depths envisioned (-2,500 m) for NUSEL laboratory construction?

Interpretation and modeling of gravity data in many greenstone belts have constrained the geology of these belts in the third dimension. Gravity studies in the volcanic-plutonic subprovinces of the Superior Province have largely focused on the shape and thickness of individual greenstone belts. Aside from the Abitibi greenstone belt, most gravity transects of greenstone belts show only a thin zone (2 to 6 km) of supracrustal rocks with comparatively flat bases. The large Abitibi greenstone belt varies from 3 to 12 km in depth extent by modeling by Gupta and Osmani (1990). Grant et al. (1965) determined the maximum thickness of the Red Lake greenstone belt of the Uchi subprovince to be no more than 4.7 km. Gupta and others (Gupta et al. 1982; Gupta and Wadge 1986) concluded from two-dimensional gravity modeling that the Red Lake greenstone belt averages 4 km and the Birch-Uchi greenstone belt 3.5 to 4 km in depth. Gravity modeling of the Sturgeon Lake greenstone belt of the Wabigoon subprovince by Dusanowskyj and West (1976) determined that belt extends to depths of approximately 3 km, and the base of the supracrustal rocks are broad and flat.

Detailed modeling of the depth extent of the Vermilion Greenstone Belt from gravity data has never been attempted for the Soudan Mine area, and thus the depth extent of the greenstone belt is unknown. However, the Minnesota Geological Survey (MGS) maintains active databases of gravity measurements and rock property data, and these data can be obtained on their Internet site (http://www.geo.umn.edu/mgs/rockprop.html). A pseudo three-dimensional Bouguer gravity anomaly map of the region around the Soudan Mine is presented in Figure 51. The gravity station data used to generate the map was obtained from the MGS web site, and the location of the proposed location of the Soudan Mine NUSEL lies along the red dotted line. The positive Bouguer gravity anomalies correlate well with known areas of dense rocks, which include basalt, iron-formation, and gabbroic rocks of the Duluth Complex.

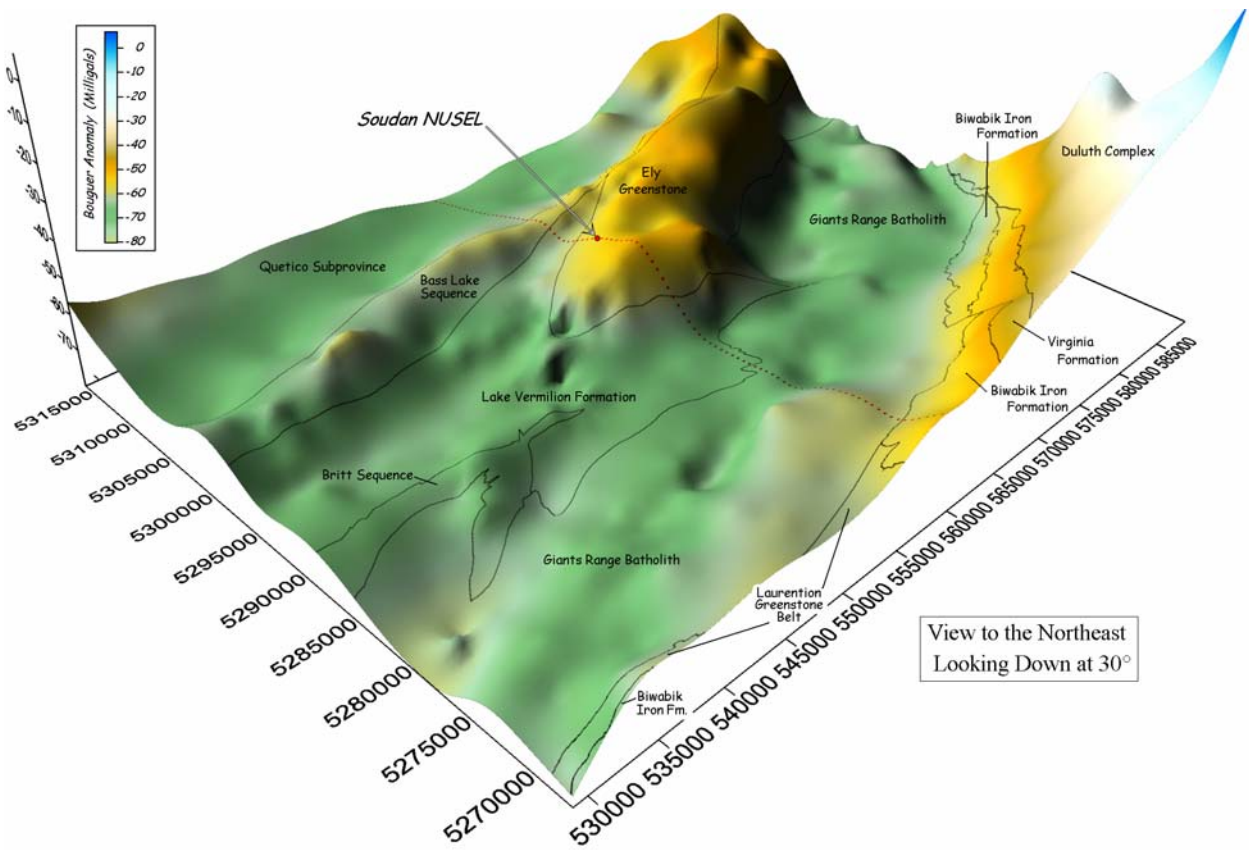

Figure 51. Three-dimensional Bouguer gravity anomaly map of the region around the Soudan Mine. The x and y grid values are UTM Nad83 easting and northing coordinates, in meters.

A south-north Bouguer gravity profile (the red-dotted line on Fig. 50) through the proposed location of the Soudan Mine NUSEL is given in Figure 52. The positive Bouguer anomaly associated with the Ely Greenstone is 17.25 milligals. Density measurements for rocks of the Ely Greenstone and Giants Range batholith in the region enclosed in Figure 50 were obtained from the MGS web site. The mean density of rocks of the Ely Greenstone is 2.854 g/cm^3 and the Giants Range batholith is 2.716 g/cm^3, and the density contrast is 0.138 g/cm^3. These data have been used to estimate the minimum depth extent of the Ely Greenstone using the Bouguer Infinite Slab Equation, which is:

$$\text{Slab Thickness}_{(\text{Ft.})} = \text{Bouguer Anomaly}_{(\text{milligals})} / (0.01276) \times (\text{density contrast}_{(\text{g/cm3})})$$

The calculated minimum depth extent of the Ely Greenstone along the profile line is 9,800 feet (2.98 km.). The true depth extent is probably twice this value (because the Ely Greenstone is not an infinite slab), on the order of 6 kilometers (Val Chandler, MGS geophysicist, pers. comm., 2003). Therefore, the depth extent of the supracrustal rocks of the Vermilion Greenstone Belt is similar to other greenstone belts located in the Superior Province of Canada, and is more than adequate for the construction of the Soudan Mine NUSEL.

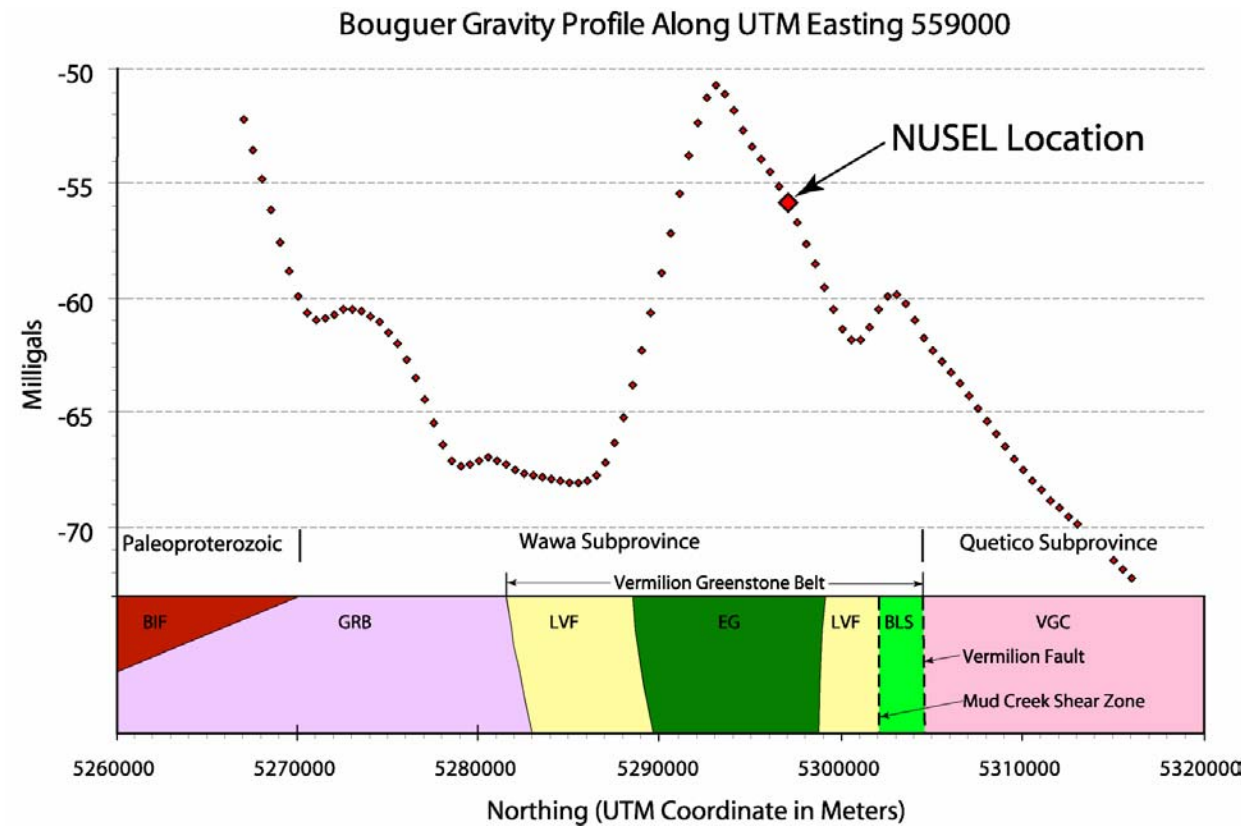

Figure 52. Bouguer gravity anomaly profile through the proposed Soudan Mine NUSEL. Abbreviations of rock units keyed to the Figure 51. View to the west, and the cross-sectional geology idealized.

The answer to question #2 {Is it reasonable to assume that the same rock units mapped on the surface occur at the depths envisioned (-2,500 m) for NUSEL laboratory construction?} is more tenuous. Without deep drilling, the continuity of individual geological units mapped on the surface down to depths of –2,500 m is unknown at the present time. However, reasonable assumptions can be made that are compatible with stratigraphic and structural framework outlined in previous sections of this report. These assumptions are based on four principal facts:

1) The geology within the eastern portion of the Soudan Mine, as mapped on the 27th level (Plate 2, 710 m depth), is essentially a continuous sequence from that mapped on the surface (Plate 1).
2) The stratigraphic continuity of the Ely Greenstone (Lower, Soudan Iron Formation, and Upper members) can be traced on the surface around the Tower Soudan Anticline for >50 km (a portion of this continuity can be visualized in Figure 2).
3) Intrusive rocks similar in shape (sill-like) and stratigraphic position (separating interpreted shallow water and deep water pillowed flows) with the Sugar Mountain Diorite occur essentially continuously on strike to the east for >7 km.
4) Alteration mineral assemblages observed in the Central Basalt sequence (quartz-epidote-garnet) have been mapped in similar stratigraphic position for approximately 20 km to the east.

Taken together, it seems reasonable that one can apply the concept of the Principal of Superposition and a modified version of Walthers Law (volcanic stratigraphy rather than sedimentary stratigraphy) to infer that the geology mapped at the surface in the Soudan Mine area does continue down dip to great depths. In fact, it seems unreasonable to assume otherwise at the present time and state of knowledge. Therefore, it is believed by the authors that the unique geological features mapped within the area selected for the location of the Soudan Mine NUSEL (homogeneous and competent Central Basalts, and the highly indurated nature of the Sugar Mountain Diorite) do continue at depth past the limits of the conceptual design for the facility (-2,500 m). Three-dimensional views of the area selected as the best site for the Soudan Mine NUSEL are presented in Plate 3.

Soudan's Compatibility with EarthLab

The June 2003 National Science Foundation publication "EarthLab, A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation" (McPherson et al., 2003) outlines the scientific themes that would be best studied in a controlled underground setting. The goal of EarthLab is to study complex geologic processes *in situ* with 3D access for continuous observations and controlled experiments. One of the main requirements for EarthLab is a very large, instrumented rock volume and access to great depths. At Soudan, the volume of rock that can be reasonably be accessed for EarthLab research in a Soudan Mine NUSEL is approximately 30 km^3, and this volume only includes the portion of the Soudan Mine to the east of the No. 8 shaft. This volume was calculated from a three-dimensional integration of the conceptual design of the Soudan Mine NUSEL, i.e., helical decline, connecting drift, and hoisting and ventilation shafts, with research and drilling plans documented in the EarthLab document (McPherson et al., 2003). A simplified model of this volume is presented in Figure 53.

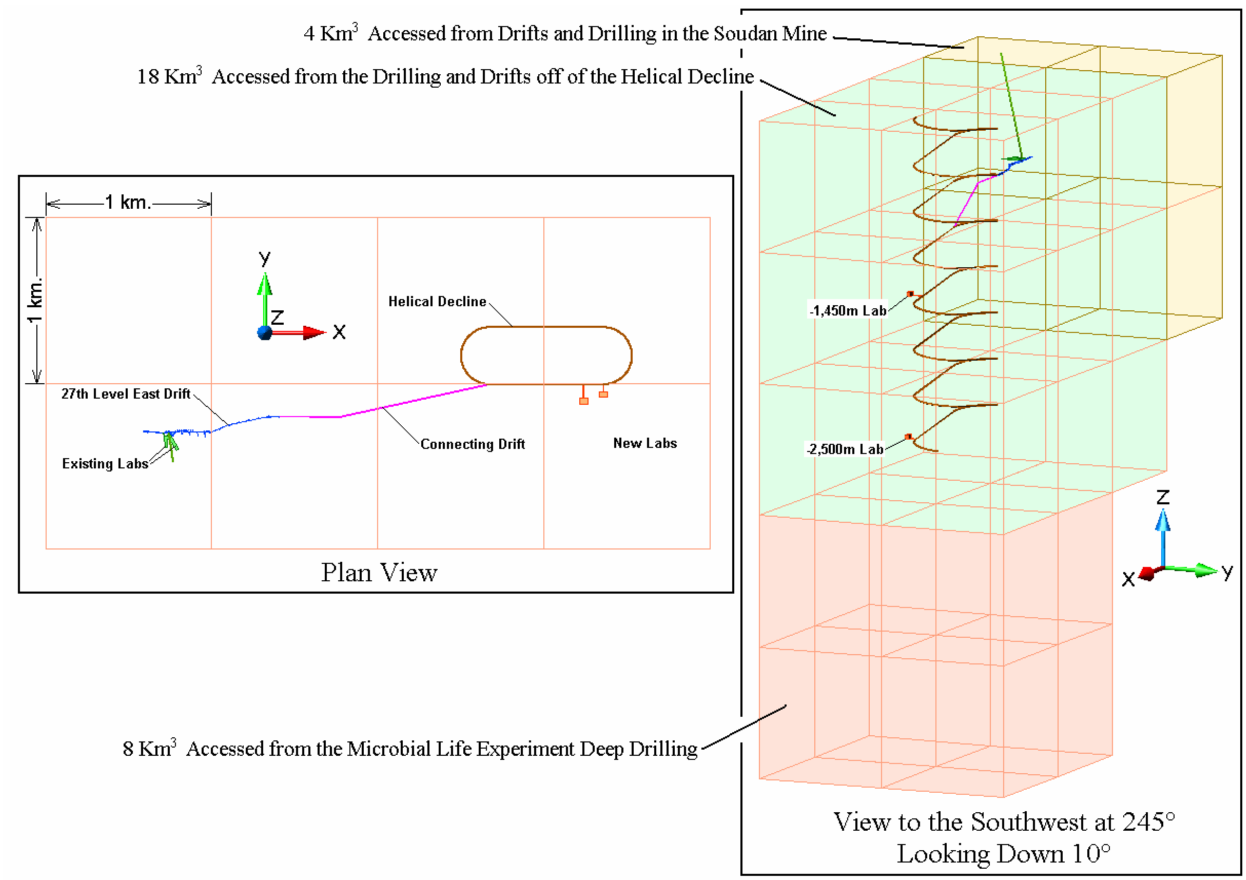

Figure 53. Simplified schematic three-dimensional and plan view images of the volumes of rock accessible from the conceptual design of the Soudan Mine NUSEL and EarthLab.

A fully integrated EarthLab concept fits very well within the proposed Soudan Mine NUSEL for a number of reasons, both practical and scientific. Practical considerations include the extensive previous and current mining in the region, with required mining support infrastructure already in place, and not dependent on

EarthLab or NUSEL for its existence. Drilling companies already operate in the area, and have the ability to drill to the depths required. The required electric power needs of the facilities are readily available, and large amounts of fresh water are available for pump storage testing. A mining familiar and friendly culture exists in the region, and a mining-related workforce is available. The acid producing potential of the rocks within the proposed location of the facilities appears small (possible acid mine drainage problems can be minimized), and the permitting process for such a project in Minnesota is reasonable.

Although the original EarthLab concept was directly linked with the Homestake Mine NUSEL proposal, the major research initiatives of EarthLab appear portable, and could be fully developed (with only minor modifications) at a Soudan Mine NUSEL. As outlined in the EarthLab document (McPherson et al., 2003), the scientific selection criteria for the EarthLab site are based on the existence of a diverse chemical and physical environment, which are not unique to the Black Hills of South Dakota, i.e., Homestake. These criteria include:

1) A variety of hydrological environments, including highly permeable, near-surface materials vs. deeper, low-permeability crystalline rocks.
2) A variety in groundwater compositions, such as high vs. low salinity, pH, and dissolved gas compositions.
3) A variety of structural environments, especially density and orientation of faults and fractures.
4) A variety of geochemical environments, especially in concentration of reduced minerals (sulfides) vs. oxidized minerals (hematite).

In the simplest sense, the geology of the Soudan Mine area could be broken down into the two hydrological environments required for EarthLab. These environments include the highly permeable, unconsolidated Pleistocene glacial deposits unconformably overlying the low-permeability crystalline bedrock of Neo-Archean age. At present, the composition of groundwater in the shallow and deep hydrological environment of the Soudan Mine area is poorly understood. However, groundwater studies in the Canadian Shield have documented the widespread occurrence of a three-component mixture of modern and Pleistocene meteoric recharge waters and a ubiquitous Na-Ca-Cl brine of equivocal origin, e.g., Frape and Fritz, 1987; Douglas et al., 2000. The components are defined by significant differences in major-element and stable-isotope geochemistry. The brine component generally dominates at depths below one kilometer, whereas anomalously shallow occurrences of high-salinity Na-Ca-Cl groundwater are common in the Lake Superior region, e.g., Douglas et al., 2000; Swenson et al., 2002. The depth-dependence of pore-fluid chemistry may be a signature of Pleistocene glaciation (Clark et al., 2000; Swenson et al., 2002).

The structural setting of the area proposed for hosting the Soudan Mine NUSEL (as described in detail in previous sections of this report) includes five major structural environments. These environments include the Murray shear zone, Mine Trend shear zone, Linking Zone, Collapsed Hinge Zone, and the areas of essentially undeformed rocks. Although the location of the Soudan Mine NUSEL (as envisioned in the conceptual design) would largely be located in undeformed rocks, the close proximity to the four remaining structural environments minimizes the cost of drilling and drifting into these structural settings (see Plate 3).

Based on generalized mapped lithology and mineralogy, each of the five structural environments should have unique bulk geochemistry. High-temperature sub-seafloor alteration of the undeformed Central Basalt sequence converted the basaltic rocks to a variable mineral assemblage of quartz-epidote-garnet, and by analogy to similar rocks mapped to the east (Peterson, 2001; Hudak et al., in press), the alteration included a concomitant leaching of base metals (Cu-Zn). The pillowed andesites of the Fivemile Lake sequence were ubiquitously spilitized during moderate-temperature sub-seafloor alteration. The massive hematite ore bodies of the Soudan Mine are hosted in the sheared rocks of the Mine Trend shear zone. In addition, hematite occurs in the schists hosting ore, and is by far the major oxide species in the iron-formations of the Upper Sequence (map unit US4a) in the Collapsed Hinge Zone. Sheared rocks along the Murray and Linking shear zones are commonly ankeritic and pyritic, and have all of the attributes of shear zones associated with mesothermal lode-gold mineralization.

The scientific themes of EarthLab are: microbial life at depth, the hydrologic cycle, rock fracture and fluid flow, rock-water chemistry, deep seismic studies, and geophysical imaging. The following sections of this report outline the scientific compatibility of the area proposed for construction of the Soudan Mine NUSEL with the scientific themes of EarthLab.

Microbial Life at Depth

The microbial life at depth initiative is well described in the EarthLab document (McPherson et al., 2003), and much of the biological science aspects fall outside of the realm of knowledge of the authors. However, the proposed Soudan Mine NUSEL appears to have all of the requirements to develop a fully integrated Ultradeep Underground Observatory to study microbial life at depth. These features are provided in the following list.

1) The geology of the proposed Soudan Mine NUSEL appears highly favorable for the construction of laboratory space at a depth of 2,500 m, and deep underground drilling to crustal depths of 4.0 to 4.5 km is possible.

2) The Soudan Mine NUSEL would largely be new construction at great depths. Therefore, the crustal hydrological environment studied in the microbial life at depth initiative would be pristine.

3) A varied suite of structural environments exists in the area. Each of these environments has distinct lithological (and thus geochemical) settings, and the influence of these varied crustal environments on subsurface microbial communities could be studied.

4) The deep hydrological environment of the Soudan Mine NUSEL area will undoubtedly show evidence of the recent advance and retreat of numerous Pleistocene continental ice sheets. The effects of these recent glacial episodes on subsurface microbial communities are unknown, but may have important implications for subsequent investigations of life on other planetary bodies, e.g. Mars.

Hydrologic Cycle

The proposed location of the Soudan Mine NUSEL leads to numerous opportunities to study various aspects of both the shallow and deep portions of the hydrological cycle. Soudan is in an area of moderate precipitation (~28 inches or 71 cm/yr), snowfall averages 280 cm/yr (110 in/yr), and snow cover typically lasts from early November to late April. Overlying cover ranges from bare rock at surface to many varieties of glacially derived surficial deposits and landforms (see Figures 6,7,8 and 9), such as: unsorted glacial tills deposited on scoured bedrock; coarsening upwards deltaic sand and gravel deposits; a sinuous ridge of sorted sand and gravel associated with a subglacial fluvial system (esker); a boulder-rich and sandy terminal moraine (the Vermilion Moraine); proglacial lacustrine deposits; and Holocene organic-rich deposits. The southeastern edge of Lake Vermilion (49,110 acres in size) is located <1/2 mi. north of the Soudan Mine (~3/4 mi. WNW of the proposed location of the Soudan Mine NUSEL), and may contribute to the groundwater system, though the low flow of water into the Soudan mine would suggest minimal input from this surficial water body.

The construction and full instrumentation of the proposed Soudan Mine NUSEL could revolutionize the field of fluid flow and transport at depth for a number of reasons. First and foremost is the ability to study these features in a pristine, three-dimensional setting, as outlined in the conceptual design of the Soudan Mine NUSEL. In addition, the structural setting of the area has been defined in previous sections of this report, and includes features with very large amounts of displacement, e.g., ~13 km of net slip along the Murray shear zone. The study of possible penetration of shallow groundwater to great depths along these distinct steeply inclined structural zones offers great opportunities for research. The ice margin of the Laurentide ice sheet was positioned directly over the proposed location of the Soudan Mine NUSEL at ~12.5 ka, as evidenced by the location of the Vermilion Moraine. The study of natural pumping of glacial melt waters deep into the local hydrologic environment, along structural zones, has possible great implications for regional water resource management throughout the Midwest, and could be used as a proxy for delineation of the Pleistocene record of climate.

Rock Fracture and Fluid Flow

As outlined by McPherson et al. (2003), the geomechanical priorities of EarthLab are to: 1) Determine the state of present-day stress and stress history in a large rock mass; 2) Study the origins of a three-dimensional fracture system; and 3) Complete active experiments underground to study the coupling of thermal, hydrological, mechanical, chemical, and biological (or THMCB) processes on fracture development and fluid flow. A necessary requirement to complete the study of these geomechanical priorities is *in situ* measurements throughout a large volume of rock at depth in a tectonically quiet environment. The geologic and structural setting of the Soudan Mine NUSEL, as well as the conceptual design of this proposed facility, appears perfectly suited to host such a research initiative.

In addition, over 1,000 measurements of the orientation of joint and vein surfaces have taken from outcrop exposures in the Soudan Mine mapping area. This dataset could be greatly expanded with additional fieldwork, and would form a detailed baseline of fracture orientations for rock masses studied underground. Rose diagrams of the strike of fractures (joints and brittle veins) measured directly over the proposed location of the Soudan Mine NUSEL helical decline, and directly over and north of the east drift of the 27th level of the Soudan Mine, are given in Figure 54.

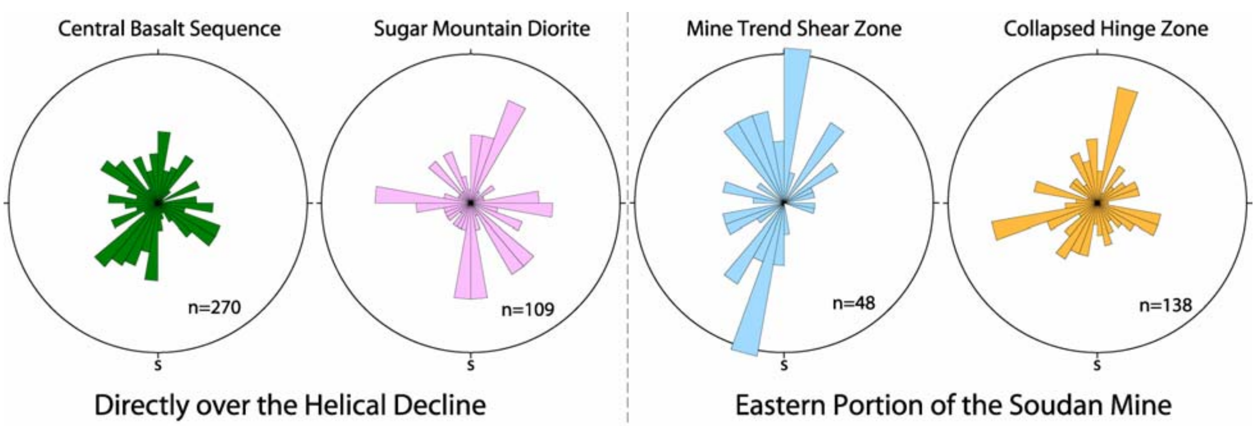

Figure 54. Rose diagrams of the strike of fractures observed over the areas proposed for underground construction of the Soudan Mine NUSEL.

Rock-Water Chemistry

The EarthLab rock-water chemistry initiative will allow study of active rock-water interaction at many scales in both space and time. The opportunity to observe (see Fig. 32) and study these interactions in an underground setting, at various stages and scales, will greatly enhance our understanding of these important processes. The three main themes of the rock-water chemistry initiative are acid mine drainage, underground waste storage, and the origin of mineral deposits. The geologic and structural setting of the Soudan Mine NUSEL, as well as the conceptual design of this proposed facility, appears perfectly suited to host such a research initiative. In that the authors are economic geologists, specific features associated with the rock-water chemical reactions relating to the origin of mineral deposits are especially interesting. Therefore, the specific features associated with the hydrothermal origin of volcanogenic massive sulfide deposits (VMS), mesothermal lode-gold deposits, and massive hematite deposits are outlined in the following sections of this report.

Deep Seismic Observatory

The proposed Soudan Mine NUSEL appears to be essentially a perfect fit for the development of the EarthLab deep seismic observatory. This perfect fit is composed of two main components, which include both regional (located in the center of the North American continent) and local (northeast of the actively mined Mesabi Iron Range of northern Minnesota) features. Soudan is located essentially in the center of North America, far from any major source of natural seismic noise (the nearest ocean is the Atlantic, approximately 1,700 km to the east). The nearest source of major cultural noise is located ~330 km to the south (Minneapolis-St. Paul, population of ~2,500,000), and the much smaller city of Duluth (population of ~85,000) is 130 km to the south. The bedrock of the Soudan Mine area is part of the crystalline cratonic core of North America (the Canadian Shield), and therefore should have much less attenuation of propagating seismic waves then tectonically active areas, such as the western United States. These regional features of the Soudan Mine area provide enormous potential for recording seismic signals with fidelity rarely, if ever, previously achieved.

On a more local scale, the five operating open pit iron mines on the Mesabi Range (~25 km to ~100 km south and southwest from the Soudan Mine) have relativley large blasts approximately once a week. These blasts typically are designed to fracture 500,000 to 1,000,000 tons of rock in the open pits. The integration of the exact timing of these blasts (which can be envisioned as huge sources of "free seismic energy") with the deep seismic observatory could prove to be invaluable in the study of the earth's structure, as well as developing a geophysical picture across the Giants Range batholith and the Ely Greenstone.

Geophysical Imaging

The EarthLab geophysical imaging initiative deals largely with the needed ability to image fractures, and characterize their length, width, and aperture by geophysical techniques. Such research would have a large societal impact, and would be important to research on groundwater flow, oil and gas recovery, hazardous waste containment, carbon sequestration, and as habitats for subsurface microbial life. In addition, the ability to ground truth geophysical data by direct observation of imaged features in an underground setting would greatly enhance the perceived reliability of such techniques by the oil and gas, mining, mineral exploration, and hydrogeologic industries. The geophysical imaging component of EarthLab is highly portable, and could be uniquely designed for any EarthLab site, based on the local geology of the site selected.

Two other cultural features of the Soudan Mine NUSEL and EarthLab site may be very important for research on geophysical techniques. There are no obvious obstacles, e.g. small private land tracts, for completing large geophysical surveys on the surface above the proposed EarthLab site of a Soudan Mine NUSEL. In addition, the 34.5kv power line (Minnesota Power's, Tower-Ely line #2) that crosses just south of the proposed site could be used as a "free source" of electromagnetic energy for geophysical investigations in the area.

Outstanding Geologic Research Opportunities

The geology of the Soudan Mine area offers numerous outstanding geological research opportunities that fall at the margins or outside of the specific earth science initiatives outlined for EarthLab. The geologic and structural setting of the rocks within and adjacent to the proposed Soudan Mine NUSEL provides a unique opportunity for advances in several areas of earth science. Foremost among these opportunities is research on the origin of three major Neo-Archean ore deposit types. The three deposit types, which are known to (or may) occur in the area include: 1) mesothermal lode-gold deposits; 2) volcanogenic massive sulfide deposits; and 3) high-grade iron deposits within Algoma-type iron-formation (such as those historically mined at the Soudan Mine). Additional outstanding research topics, as briefly described at the end of this section of the report, include the opportunity to:

1) Conduct detailed studies of the genetic evolution and temporal development of an Archean volcanic arc.
2) Conduct detailed studies of Archean tectonic architecture.
3) Conduct detailed studies of Pleistocene hydrogeology and continental ice-margin dynamics.
4) Conduct detailed studies of crystalline bedrock permeability from the initial deep geotechnical and development holes drilled prior to the construction of a Soudan Mine NUSEL.

Brief descriptions of these research opportunities are described in the following sections of this report.

Structural Control on Lode Gold Mineralization

Mesothermal lode-gold deposits are a major source of the world's gold production, and are the most prolific gold source other than the ores of the Witwatersrand basin, South Africa. Over the last 25 years, considerable progress has been made on the origin of mesothermal lode gold deposits (see Groves et al., 2000, 2003; Robert et al., 1991; and references therein). These studies have characterized many features unique to this class of ore deposit, and have highlighted many critical features of these deposits that are yet unresolved. In general, the deposits form during compressional or transpressional deformation at convergent plate margins in accretionary or collisional orogens. They form over a large crustal-depth range (2 to 20 km) from deep-seated, low-salinity H_2O-$CO_2 \pm CH_4 \pm N_2$ ore fluids, with Au transported as thio-complexes, e.g., Au(HS). Regional structures provide the main control on distribution of lode gold deposits and mining camps. In many terranes, first-order faults or shear zones appear to have controlled regional fluid flow, with greatest ore-fluid fluxes in, and adjacent to, subsidiary faults, shear zones, and/or large folds. Highly competent and/or chemically reactive rocks are the most common hosts to the larger deposits.

Gold deposition occurs late during the evolutionary history of the host terranes, normally within D_3 or D_4 in a D_1-D_4 deformation sequence. Absolute ages of mineralization support their late-kinematic timing, and, in general, suggest that deposits formed diachronously towards the end of the evolutionary history of hosting orogens (Groves et al., 2000). The late timing of lode-gold deposits is critical to geology-based exploration methodologies, and hence mineral potential evaluations for these deposits. The late timing is critical because of the present structural geometry of: (1) the deposits; (2) the mining camps; and (3) the enclosing geologic terranes, are essentially all similar to the structural geometry during gold mineralization. Therefore, geological maps and cross-sections can be used to simulate the physical conditions that existed at the time of ore deposition.

Detailed studies at a Soudan Mine NUSEL and EarthLab could be instrumental in understanding the most important geological feature of mesothermal lode-gold deposits, which is the structural geometry of various classes of subsidiary structures. In the Vermilion Greenstone Belt, lode-gold mineralization is found in subsidiary shear structures related to the crustal-scale Mud Creek Shear Zone (MCSZ) (Peterson, 2001), immediately north of the Soudan Mine (Fig. 2). Gold mineralization is known to exist along the northern segment of the Murray shear zone (Fig. 12f), which is a large subsidiary structure related to a compressional jog of the MCSZ (Peterson, 2001). As described in previous sections of this report, the Mine Trend and Linking Zone shears immediately north of the Murray shear zone may be interpreted as higher-order D_2 subsidiary structures. Drifting and drilling to the south of the proposed Soudan Mine NUSEL would allow unprecedented access to a structural setting analogous to major gold camps within the Canadian Shield, e.g., Timmins, Val D'Or. The knowledge gained from understanding the connecting geometry of these structural zones could be applied to other districts, and could have a large impact on exploration techniques for such deposits worldwide. In addition, detailed studies aimed at identifying these structures geophysically could prove to be a virtual panacea for the mineral industry, especially in targeting drill holes in areas of potential mesothermal lode-gold mineralization.

Hydrothermal Alteration of Subaqueous Volcanic Rocks

(Submitted with Dr. George Hudak, Geology Department, University of Wisconsin Oshkosh)

The composition and distribution of hydrothermal alteration mineral assemblages in the Fivemile Lake and Central Basalt sequences of the Vermilion district is similar to that described in major lava-flow dominated volcanogenic massive sulfide (VMS) mining districts worldwide, e.g., the Noranda Camp, Quebec; Morton and Franklin., 1987; Franklin, 1996; Gibson et al., 1999; Hudak and Morton, 1999; Peterson, 2001; Hudak et al., 2002, 2003. Given the results of recent studies (Peterson, 2001; Odette et al., 2001; Hocker et al., 2003; Hudak et al., 2002, 2003), one of the most perplexing questions plaguing economic geologists is why economically significant VMS deposits have not been discovered in the Vermilion District. Two small massive sulfide deposits that are not economic to mine have been discovered at the Eagles Nest Prospect and the Skeleton Lake Prospect, located 5-15 km from the proposed NUSEL and EarthLab sites. Additionally, stringer zinc ± copper mineralization has been documented at the Fivemile Lake Prospect, located approximately 5km from the proposed NUSEL and EarthLab sites.

A regional study combining detailed field mapping (1:5000 scale), petrographic studies, lithogeochemical analysis and evaluations, complimented by subsequent mineral chemistry studies and stable isotope (oxygen and hydrogen) evaluations, would not only further refine our regional-scale understanding of the composition, distribution, paragenesis, and processes associated with the genesis of the hydrothermal alteration mineral assemblages in the Vermilion district, but would further enhance our understanding of the potential for discovering VMS deposits in this ancient volcanic greenstone belt. Results of such a study could significantly enhance the effectiveness of mineral exploration programs not only in the Vermilion district (which could have a substantial economic effect on northern Minnesota), but worldwide (for example, enhance mineral exploration programs in third-world developing countries).

A genetic model for the formation of VMS deposits and associated hydrothermal alteration zones, as recently presented by Franklin et al. (1998), requires convective metalliferous hydrothermal fluid generation in the sub-seafloor environment via heating of down-welling seawater and leaching of metals from the volcanic and sedimentary sub-strata (Fig. 55). The size of convective hydrothermal system is a function of the abundance of heat in the upper two kilometers of the sub-seafloor crust (Franklin, 1996; Franklin et al., 1998). The introduction of shallow hypabyssal synvolcanic intrusions into the seafloor may vigorously enhance the dynamics of the convective hydrothermal cell. On reaching a critical reaction temperature of ~ 350°C (sustained acid pH) in convective systems, metals are leached from the rocks into the hydrothermal fluid via primary mineral breakdown by calcium metasomatism, silicification, and hydrolysis reactions (Seyfried et al., 1999). In basalt-dominated systems such as that in the Soudan Mine area, leaching-related alteration of mafic "source" zones (lower semi-conformable alteration) forms a mineral assemblage composed of albite-epidote-actinolite-quartz. These zones are variably metal-depleted, and are characterized by patchy silicification and epidotization associated with areas metasomatically enriched in silica and calcium. Odette et al. (2001) and Hudak et al. (in prep.) have all shown that metal-depleted semi-conformable quartz + epidote ± actinolite ± albite ± chlorite alteration mineral assemblages in the Fivemile Lake area display these geochemical trends.

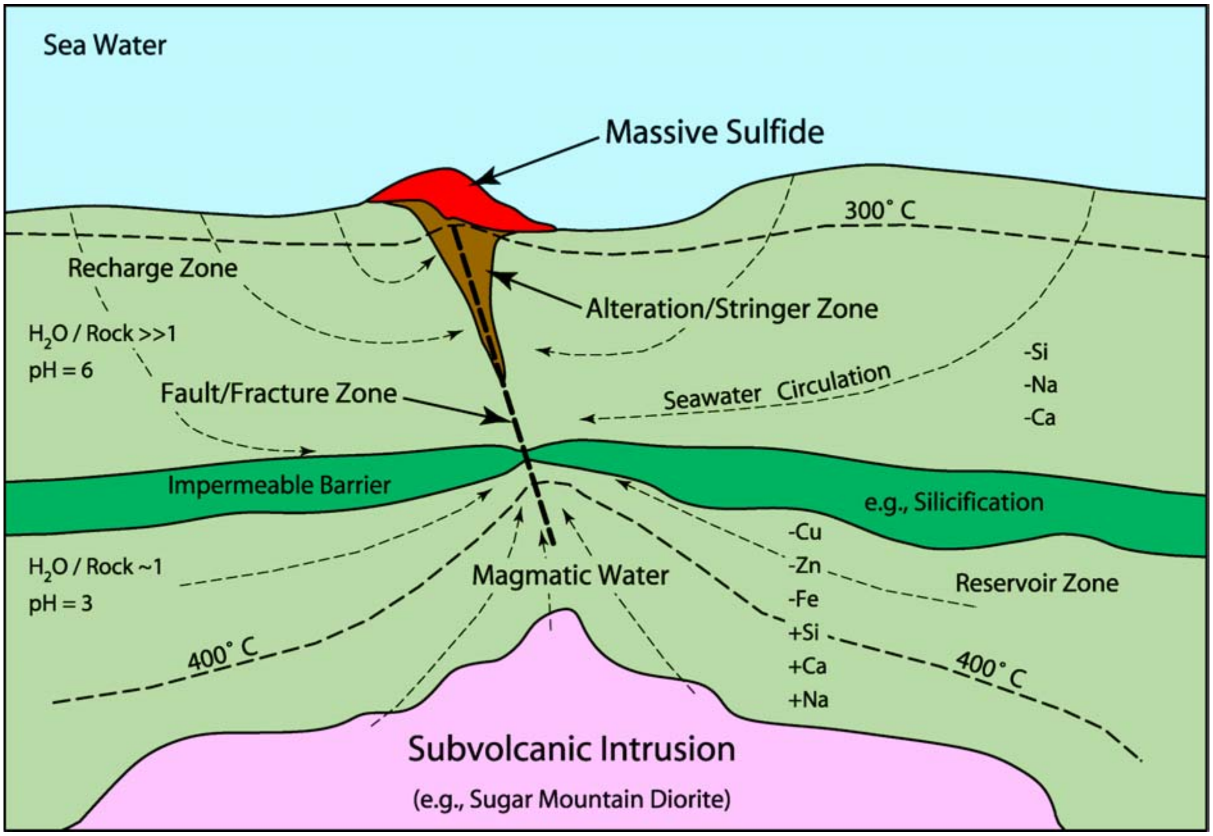

Figure 55. Simplified model of a convective hydrothermal system associated with the formation of VMS deposits.

In lava flow-dominated settings such as the Vermilion district, regionally confined discordant "pipe-like", and more regionally extensive "semi-conformable" alteration zones are present. The pipe-like alteration zones are closely associated with zones of cross-stratal permeability, e.g., synvolcanic fault zones; Morton and Franklin, 1987, and are characterized by well-defined, vertically extensive alteration zones containing anomalous abundances of sericite, chlorite (both Fe- and Mg-rich varieties), quartz, pyrite, and locally, pyrrhotite, and chalcopyrite. Semi-conformable alteration zones extend for several kilometers to tens of kilometers in the rocks stratigraphically beneath and adjacent to VMS mineralized horizons (Santaguida et al., 2002a,b). In mafic-dominated volcanic environments, such alteration typically is associated with regional zones of spilitization (an alteration assemblage composed of albite + quartz + Mg-rich chlorite ± sericite), silicification (quartz ± albite), and epidote-quartz alteration (epidote + quartz ± actinolite ± carbonate) (Morton et al., 1997; Gibson et al., 1999; Santaguida et al., 2002a,b). Regional semi-conformable zones in felsic rocks are found in extensive zones of spilitization, silicification, and sericitization (sericite + quartz ± Mg-rich chlorite) (Gibson et al., 1999).

Both discordant and semiconformable alteration zones have been discovered in the Vermilion district, and have been described by Hudak and Morton (1999), Peterson (2001), Odette et al. (2001), Hudak et al. (2002, 2003). As regional semi-conformable alterations zones are commonly poorly exposed in ancient environments, the well-exposed rocks of the Vermilion district offer geologists an opportunity to further study Archean regional sub-seafloor hydrothermal alteration from mineralogical, chemical, and isotopic perspectives. Pipe-like alteration zones that have been mapped up-section have, to date, not led to the discovery of economically significant VMS deposits despite the fact that the mineralogy (Hudak et al., 2002) and chemical compositions of the alteration minerals (Hocker et al., 2003) in these zones are consistent with that found in areas hosting major VMS mining districts (Hannington et al., 2002). Further alteration mineral assemblage and alteration mineral chemistry studies will enable an enhanced understanding of the hydrothermal systems in the Vermilion district, will shed significant light on the economic potential for VMS deposits in the belt, and may enhance the efficiency of VMS mineral exploration programs in other ancient volcanic belts worldwide.

Water depth controls aspects of associated VMS deposit composition (metal ratios) and alteration assemblages. The hydrothermal alteration study would be completed in cooperation with, and compliment, detailed volcanological studies in the Vermilion district which would evaluate physical features of the volcanic environments present (such as water depth, locations of synvolcanic fault zones, locations of synvolcanic intrusive rocks as described above). Volcanic settings associated with nascent ocean-dominated arcs and back-arcs settings (such as during the Neo-Archean deposition of the Central Basalt sequence in the Soudan Mine area) tend to be of low relief and deeply submerged (usually >1500 m) shield volcanoes or elongate rifts. However, recent research in the South Pacific Ocean has shown that these volcanic arcs may locally contain significant relief that may transform into the shallow water (Wright et al., 2002) or even subaerial realm. Field evidence from the current study and previous studies (Peterson, 2001; Hudak et al., 2003, 2003) indicates that both shallow and deep subaqueous environments were present in the Vermilion district, as represented by the Fivemile Lake and Central Basalt sequences. Such environments are not only associated with base-metal VMS deposits, but may also contain precious metal-rich, e.g. gold, silver, VMS deposits (Sillitoe et al., 1996; Hannington et al., 1999). Thus, the Vermilion district, and in particular, the rocks within a few kilometers of the proposed Soudan Mine NUSEL and EarthLab, would be ideal to investigate the relationships between water depth, composition, and distribution of hydrothermal alteration mineral assemblages, and associated metallic mineralization.

The rocks of the Soudan Mine area form a portion of an ancient sub-seafloor hydrothermal system that has a documented strike length of >20 kilometers (Peterson, 2001). It is well recognized that studies of ancient, land-based hydrothermal systems have shed significant light on the processes associated with modern seafloor hydrothermal systems (Franklin, 1996; Gibson et al., 1999). The Neo-Archean rocks in the vicinity of the proposed Soudan Mine NUSEL and EarthLab have been tilted to near vertical attitudes during D_1 deformation, and detailed mapping of surficial outcrops, mine workings, and drill core will produce a regional three-dimensional model of an ancient sub-seafloor hydrothermal system A detailed three-dimensional study of the hydrothermal alteration of the volcanic rocks in a Soudan Mine NUSEL and EarthLab setting would greatly compliment the worldwide research initiatives currently studying ancient VMS deposits (Large and Blundell, 2000; Allen et al., 2000) as well as modern seafloor hydrothermal systems (Herzig and Hannington, 1995, 2000) at a fraction of the cost necessary to conduct such regional studies in the modern seafloor environment.

In addition to the aforementioned VMS ore deposit research, the study of the alteration in the ancient rocks in the Vermilion district may compliment current research on Earth system heat transfer (Sclater, 1981; Stein and Stein, 1994), ocean chemistry at active hydrothermal vent sites on the seafloor (Edmond et al., 1979; Edmonds and Edmond, 1995), and deep-sea vent community ecosystems. Previous studies in the banded iron formations in the Vermilion district have indicated the presence of fossil life forms (LaBerge, 1973). Thus, detailed study of geologic features preserved in the rocks around the proposed Soudan NUSEL could be critical to further understanding the dynamic nature of the oceanic crust, and the possible origins of life on Earth.

Origin of Massive Hematite from Algoma-Type Iron Formation

The importance of iron cannot be underestimated in today's society, and has been used by humans for over 3,000 years. Most iron ores mined today comprise the iron oxide minerals magnetite, Fe_3O_4 (72% Fe); hematite, Fe_2O_3 (70% Fe); goethite, $Fe_2O_{3(s)} * H_2O$, (63% Fe); and limonite, a mixture of hydrated iron oxides (up to 60% Fe). The world's most important iron ore resources occur in iron-rich sedimentary rocks (20% - 40% Fe) known as banded iron-formations (BIFs), which occur on all continents and are almost exclusively of Precambrian age. In many iron-mining districts, e.g., the Mesabi Range of northern Minnesota, the BIFs are mined as iron ore with the iron content concentrated into pellets (~65% Fe) in large on site facilities. In other districts, e.g., the historic Vermilion Range of the Soudan Mine area; Hamersley District, Western Australia, the BIFs are the source rocks for large, natural high-grade concentrations of iron that typically occur as bodies of massive hematite and/or hematite-goethite with >60% Fe.

The origin of these important natural concentrations of iron minerals remains highly debated. The Fe atoms in hematite are all Fe^{3+}, whereas in magnetite they are comprised of two Fe^{3+} and one Fe^{2+} atoms. Therefore, the transformations of magnetite to hematite, or hematite to magnetite, in Fe-conservative systems is always a redox reaction, with the Fe^{2+} atoms in magnetite oxidized to Fe^{3+} atoms, or the Fe^{3+} atoms in hematite reduced to Fe^{2+} atoms, by reactions such as:

$$2Fe_3O_{4(mt)} + 1/2O_{2(g)} \rightarrow 3Fe_2O_{3(hm)} \quad (1)$$

and

$$3Fe_2O_{3(hm)} + H_{2(g)} \rightarrow 2Fe_3O_{4(mt)} + H_2O \quad (2)$$

In the past, the study of the transformation of magnetite to hematite (1) and conversely hematite to magnetite (2) in natural systems has largely focused on these reactions, which require either an oxidizing or reducing agent and an occurrence under specific redox environments. Since virtually all of the known concentrations of high-grade iron ores are hematite-dominant, the exploration for such deposits has concentrated on supergene enrichment of magnetite-rich BIFs. In this model, magnetite-rich BIFs are uplifted and subjected to weathering under oxygenated conditions to form goethite-rich ores; and are subsequently buried and metamorphosed to hematite-rich ores (Morris, 1985). Problems with this model have recently been discussed by Ohmoto (2003) for the Tom Price Mine of the Hamersley district, and are applicable to the origin of the massive hematite ores of the Soudan Mine. Ohmoto (2003) has proposed an alternative mechanism for the transformation of magnetite-rich iron-formations to massive hematite ores by the acid-base reaction:

$$Fe_3O_{4(mt)} + 2H^+ \leftrightarrow Fe_2O_{3(hm)} + Fe^{2+} + H_2O \quad (3)$$

Similar to most acid-base reactions, reaction (3) would be most efficient at high temperatures, and such hydrothermal fluids are capable of leaching silica as well as Fe^{2+} from magnetite. In addition, the conversion of magnetite to hematite by reaction (3) produces a volume decrease of 32%, greatly increasing permeability of the rocks, which would facilitate further water-rock reactions and enhance conversion of banded chert-magnetite to massive hematite.

The Soudan Mine offers a perfect opportunity to complete fully integrated research on the origin of the massive hematite ores. The integrated research could include the structural control; fluid state (redox vs. acid-base reactions); fluid temperature; and timing of the formation of the iron ores of the Soudan Mine. Because of the importance of iron on the world's economy, the implication of such research may have great societal impact. The development of a new genetic ore deposit model for massive hematite ores from typical low-grade banded iron-formation may be especially important for third-world countries. The development of local iron and steel industries in these countries could be a catalyst for economic growth and the improvement in the standard of living of the residents.

Genetic Evolution and Temporal Development of an Archean Volcanic Arc

(*Submitted by Dr. George Hudak, Geology Department, University of Wisconsin Oshkosh)*

Earth scientists understand that it is essential to study ancient volcanic sequences in order to understand the genetic processes and developmental dynamics of modern volcanic systems (Cas and Wright, 1987; Gibson et al., 1999; Lafrance et al., 2000; Mueller et al., 2000; Hudak et al., in press). Archean volcanic rocks in the Vermilion district, in which the proposed NUSEL and EarthLab sites are hosted, are well exposed relative to most areas in the Canadian Shield. These rocks have experienced relatively low-grade greenschist facies metamorphism and only localized intense structural deformation, and contain exceptionally well-preserved volcanic and sedimentary textures, as well as stratigraphic sequences (Jirsa et al., 2001; Peterson, 2001; Hudak et al., 2002). The steeply dipping structural orientation of the rocks in the vicinity of the NUSEL and EarthLab also allow detailed mapping of essentially a geological cross-section that exhibits the temporal and spatial development of the volcanic sequence, and permits it to be displayed and evaluated. The presence of well-preserved exploration diamond drill core at the Minnesota Department of Natural Resources Hibbing Core Repository, as well as new drill core and underground exposures associated with the proposed NUSEL facility, will provide additional geological data which will allow completions of three dimensional facies reconstructions. Such detailed stratigraphic information, over geological sections up to several kilometers long, are rarely observed in modern or ancient volcanic sequences. Thus, rocks in the Vermilion district offer an exciting opportunity to evaluate the genetic evolution and temporal development of an Archean volcanic arc.

Although our knowledge of the Vermilion Greenstone Belt is relatively good at the regional scale (Green and Schulz, 1977; Schulz, 1980; Schulz, 1982; Sims and Southwick, 1985; Southwick, 1993; Southwick et al., 1998; Peterson and Jirsa, 1999a), our understanding of the detailed genetic aspects of the belts architecture, stratigraphic evolution, and temporal development are lacking. A series of small, relatively detailed studies around VMS and gold prospects (Hudak and Morton, 1999; Newkirk et al., 2001; Peterson et al., 2001; Hudak et al., 2002, 2003; Peterson and Patelke, in prep.) have shown that detailed volcanic facies mapping and volcanic reconstructions, lithogeochemical evaluations of igneous, metamorphic, and tectonic processes, geochronology, and recognition of both synvolcanic and post-volcanic structures are possible in this region given the excellent preservation of the rocks.

The purpose of our proposed work would be to better understand the detailed genetic evolution of the Vermilion Greenstone Belt. The work should be completed by a multidisciplinary team involving experts on the regional geology, volcanology, stratigraphy, geochemistry, igneous and metamorphic petrology, sedimentary petrology, economic geology, geophysics, and geochronology from both academia and government. A substantial contribution to the work can also be made via undergraduate and graduate students via honors theses, masters theses, and doctoral dissertations. Three major investigative components involving extensive field and laboratory research are included in our work.

The first of these components will comprise detailed field mapping, diamond drill core logging, petrographic studies, and lithogeochemical studies of volcanic and sedimentary facies in the belt to better understand and reconstruct the physical environment(s), tectonic environment, and metallogenesis in the Archean crust in this region of the Wawa subprovince. Detailed volcanic facies mapping in Precambrian terranes such as that performed by Gibson (1989), Mueller et al. (1994), Allen et al. (1996a,b), Dostal and Mueller (1996), and Morton et al. (1999) will be completed to determine the volcanic stratigraphy of the belt, and identify the volcanic facies and volcanic architecture of the region. The apparent presence of both shallow water and deep water volcanic rocks in the belt (Peterson et al., 2001, Hudak et al., 2002) will allow the physical features of rocks forming in various subaqueous environments, which continues to be a highly controversial subject (Burnham, 1983; Cas, 1992; Gibson et al., 1999; Wohletz, 2002), to be further evaluated and criteria for their identification further constrained. Petrographic and lithogeochemical studies will be used to better evaluate the volcanic textures present, as well as the mineralogical and chemical compositions of the rocks present. Once the stratigraphic relationships are established, geochronological studies will be used to determine the temporal relationships of the various strata in the belt. At the present time, neither the stratigraphy nor the amount of time needed for belt architecture is well constrained in this part of the Wawa Greenstone Belt.

The second of these studies will include detailed field mapping, petrographic studies, and lithogeochemical studies to evaluate synvolcanic intrusive rocks, their genetic relationships with the regional volcanic strata, and the associated mineralization. Several synvolcanic intrusive units have been identified in the

Vermilion District by Peterson (2001), Hudak et al. (2002, 2003), and Peterson and Patelke (2003 this study). Synvolcanic intrusions and their associated volcanic rocks (lava flows and tuffs) typically have unusual petrochemical trends (Campbell et al., 1982; Lesher, 1986; Galley et al., 2000; Galley, 2002, Galley, 2003) that are attributed to volcanic tectonic environment, rapid heat loss from the intrusion to the convective hydrothermal system, interaction of the intrusion with cold seawater, and/or assimilation by the intrusion of adjacent hydrated country rocks. At the present time, the relationships between the supracrustal and hypabyssal rocks in the Vermilion district, as well as their geochemical and temporal characteristics and relationships, are poorly understood.

The third study associated with our proposed work would encompass a detailed field, petrographic, and lithogeochemical investigation of the banded iron-formations in the Soudan Member of the Lower Ely Greenstone. The genesis of Archean Algoma-type iron formations, and their apparent relationships to base-metal volcanic-associated massive sulfide mineralization, continues to be controversial (Dimroth, 1986; Kimberly, 1989; Chown et al., 2000). Detailed field mapping should be able to identify the onset of hydrothermal activity responsible for the genesis of these deposits, and coupled with the volcanic facies mapping described above, should be able to identify the environment or environments of deposition associated with iron-rich mineralization. Felsic tuff horizons within the iron-formation may contain important geochronological information that would shed light on the period of time necessary to deposit the extensive section of BIF present in the Vermilion District. Once the stratigraphic and environmental aspects of the Soudan Member have been established, they will provide an important foundation upon which ancient microfossil studies, e.g., Cloud and Licari (1968), LaBerge (1973), could be attempted.

The proposed work would compliment the numerous studies of Archean Greenstone belts that have been conducted in the Canadian Shield of Canada. Research designed to improve the knowledge of the stratigraphy, volcanology, geochronology, geochemistry, igneous petrology, metamorphic petrology, metallogeny, structural geology, and tectonic setting of the Archean Vermilion district would greatly improve our understanding of the southwestern portion of the Wawa subprovince, and would dramatically improve our understanding of Archean crustal architecture, rates of Archean crustal genesis, Archean tectonic processes, and Archean metallogeny. Such information could be used to better understand both modern and ancient volcanic arc sequences, Archean tectonic processes, volcanic hazards, and extraterrestrial bodies. In addition, this work could shed significant light on difficult aspects of Archean volcanism and sedimentation, in particular, establishing new techniques to evaluate water depth in ancient subaqueous rocks that lack fossils. The study should also shed light on the current controversies surrounding Archean volcanic processes and Archean tectonics, e.g., Hamilton (1998) and references therein, as well as the development of life on the early earth. Detailed stratigraphic studies would also build the foundation upon which subsequent state-of-the-art geophysical research could be performed. The work may also eventually assist mineral exploration, and potential mining development, in the Vermilion district, which would have a major economic impact on Minnesota.

Archean Tectonic Architecture of the Southern Laurentian Margin

(Submitted by Dr. John Goodge, Dept. of Geological Sciences, University of Minnesota Duluth)

The proposed Soudan Mine NUSEL site is situated at the southern margin of the Archean Laurentian craton. Along with some of the oldest rocks in North America exposed in the Minnesota River Valley to the southwest, the southern Superior Province in northeastern Minnesota represents an upturned section of crust formed during one of the most critical periods of crustal evolution in Earth history (2.7-2.6 Ga). Exposed here are a number of volcanic, sedimentary and plutonic units that record juvenile crust production and subsequent involvement in deformation and sedimentation as a result of plate-margin tectonic events. The area is also situated near the tectonic boundary separating the Archean Superior Province basement, from deformed sedimentary and volcanic rocks of the Paleoproterozoic Penokean Orogen, regarded as one of the oldest accretionary belts developed along the southward-migrating paleomargin of North America.

Several extant problems hinder progress toward a viable, coherent tectonic model for development of this Archean crustal section: (1) much of the geology is poorly exposed at the surface, due to glacial erosion, cover by drift, and dense vegetation; (2) a precise chronology of events is not well known, in part because many of the rock types were not amenable to techniques available at the time of important regional geologic studies in the past; and (3) some recent structural studies have been conducted in the region, but much of the area remains poorly understood in terms of structural history and relation to mineral deposition. Several factors make it possible to now conduct a comprehensive, detailed study of the structural and tectonic history of the region. The gaps in exposed basement geology are minimized by wide-coverage, high-resolution aeromagnetic data (Hittleman et al., 1990) and by numerous drill cores. New techniques in geochronological analysis make it possible to recover timing constraints from smaller samples and a wider variety of minerals, and established methods in isotope geochemistry provide opportunities to discriminate age provinces and petrogenetic mechanisms. Since the advent of modern methods in kinematic analysis, it is possible to evaluate strain patterns on a macroscopic scale and interpret rock displacements from fabric asymmetry on a microscopic scale, as indicated above in this report. Development of the NUSEL would provide a tremendous opportunity to integrate subsurface geology with surface geologic mapping, geophysical imaging, geochronological data, drill hole samples, hydrologic data, and ore-body geometry in order to establish a comprehensive 4D (3D space + time) model for development of this geologically classical area.

A new program of geological research in the Soudan Mine area will address a variety of problems that relate to the broad tectonic architecture of Archean crust in the Superior province, including: (1) What is the origin of the protoliths in the different rock assemblages? In what tectonic environment did they form? What do these tectonic assemblages tell us about development of the southern margin of the Superior province? (2) What is the origin and tectonic setting of granitic rocks from the Giants Range batholith? Do they represent a subduction-arc, collisional, intra-plate or other type of magmatism? (3) In what tectonic setting did the pre-2.6 Ga deformations occur? How much crustal shortening is represented? How are they related kinematically and temporally? If transpressional, what does this tell us about development of ancient plate margins and large-scale displacement? (4) What effects, if any, did the Penokean orogeny have on crystalline basement of the Superior province? (5) How is gold mineralization related to deformation? and (6) What is the relation between volcanism, sedimentation and mineralization? How well does a VMS model for mineralization work to explain these Archean occurrences?

The overall approach to address these problems will involve integration of surface geological, subsurface geological, geophysical, and geochemical tools. This multi-disciplinary approach will likely involve researchers from a number of institutions, including the Natural Resources Research Institute, the University of Minnesota Duluth, the University of Wisconsin Oshkosh, the Minnesota Geological Survey, and other groups. Development of the Soudan Mine NUSEL will contribute to an increase in research activities, but these are expected to continue over a period of years and involve funded research and graduate theses. *Surface geological mapping* will continue across an expanded area in the manner described here for the recent field studies. Integrated with the mapping will be detailed *structural analysis* of deformation features, *petrologic study* of the rock assemblages, and further study of *ore deposits*. *Subsurface geological mapping* will continue in the existing drifts of the Soudan Mine, by targeting those areas thought to be most helpful in defining the spatial geometry of rock units and structures. Subsurface geological mapping will be conducted in detail in all new tunnels constructed for the NUSEL. The great depth of the NUSEL will permit measurement of *potential-field gradients* within this crustal section, providing a unique opportunity to combine actual subsurface measurements with surface or airborne data in order to construct well-constrained gravity and magnetic models. As needed, additional surface geophysical data will be collected to help constrain the 3D geometry of this Archean crustal section. A critical component of research will be a systematic program of *geochronological analysis* designed to address the timing of primary rock formation, as well as subsequent metamorphic, deformation, and mineralization events. The developing chronology will help to refine the regional tectonic history, but will also be relevant to general problems in Archean crustal evolution, accretionary development of the Superior province, and ore migration. All elements of the proposed geological research will provide a fundamental dataset that can be integrated with geoengineering, hydrogeological, and geobiological programs at the NUSEL.

Pleistocene Hydrogeology of the Superior Craton

(Submitted by Phil Larson, Dept. of Geological Sciences, University of Minnesota Duluth)

Recent years have seen an increasing amount of interest focused on the role the Laurentide ice sheet (LIS) played as a groundwater impelling mechanism. An ice sheet's surface is characterized by a steep topographic gradient near its margin. The hydraulic head of melt water at the base of a glacier is a function of the hydrostatic pressure induced by the overlying ice. Consequently, steep hydraulic gradients inducing deep flow in the underlying substrate are predicted near the glacier's margin. Most studies to date have focused on identifying and delineating the presence of "fossil" Pleistocene glacial melt water injected deep into aquifers in the glacier's substrate. Groundwater investigations conducted in conjunction with the proposed Soudan Mine NUSEL have the potential to address several additional aspects of Pleistocene glacially driven groundwater flow systems.

The extent to which glacially-driven dynamic groundwater flow perturbed normal (interglacial) flow systems in cratonic rocks is largely unknown. The depth of penetration of such flow systems has important policy implications, not least of which are the implications for the deep storage of toxic and radioactive wastes in cratonic rocks as has been proposed both in the US and internationally. Clark et al. (2000), and Douglas et al. (2000) describe the presence of relict Pleistocene glacial meltwater at depths of over 1600 m in their groundwater studies of the Con Mine, Yellowknife, Northwest Territories, Canada. They identified a fresh isotopically light ($\delta^{18}O$ –28‰) glacial meltwater end member mixed with modern meteoric recharge ($\delta^{18}O$ –18.9‰) and a Ca-Na-Cl brine. Pleistocene glacial meltwater was apparently driven to these depths under the influence of the steep hydraulic gradient near the margin of the LIS while it was located over the future Con Mine site. Modern hydraulic gradients induced by bedrock topography are apparently insufficient to induce flow deep enough to flush out the relict Pleistocene meltwater.

The bedrock groundwater system in the Soudan Mine area and the proposed NUSEL site likely contains all three elements of the system described at the Con Mine: (1) a shallow dynamic flow system containing modern meteoric recharge; (2) an intermediate layer containing fresh isotopically light glacial meltwater; and (3) a deep layer containing Ca-Na-Cl brines with salinities potentially as high as 324‰. Isotopically light ($\delta^{18}O$ –15.5‰) deep groundwater has been identified in the nearby North Shore Volcanic Group (Swenson et al., 2002). Dilute Ca-Na-Cl brine was documented in the Soudan Mine during construction of the Soudan II cavern (Stormoe, 1984 pers. comm. to CNA Associates). The persistence of this brine in mine waters 710 m deep in the Soudan Mine, despite decades of dewatering, suggests that brine of significantly higher concentration would be encountered during NUSEL construction. Construction of the proposed NUSEL offers an unprecedented opportunity to examine *in situ* the remnants of a Pleistocene glacially induced dynamic flow system. Collection of isotopic and elemental groundwater geochemical data will allow determination of both the depth to which the Pleistocene flow system penetrated and the extent to which it is preserved.

Relict Pleistocene meltwater preserved in deep bedrock aquifers in northern North America potentially record the isotopic composition of meltwater released from the LIS. The isotopic composition of glacial ice is a function of a number of variables dependent on the ice sheet geometry and climatic conditions under which it formed, including elevation and air temperature. Knowledge of the isotopic composition of meltwater from the LIS in turn provides an important constraint on models of ice sheet growth and decay. Estimates of the $\delta^{18}O$ value of glacial meltwater range from –18‰ in Iowa (Siegel and Mandle, 1984), -24.5‰ in the southern Lake Agassiz plain (Remenda et al., 1994), to –28‰ in the Northwest Territories (Clark et al., 2000). Closer to the Soudan Mine, meltwater $\delta^{18}O$ estimates range from –15.5‰ (Swenson et al., 2002) to –17‰ (Remenda et al., 1994). Collection of relict Pleistocene meltwater during NUSEL construction would allow determination of the isotopic composition of subglacial meltwater specifically from the LIS at ~13 ka, more accurate characterization of the range of LIS meltwater compositions, and a better understanding of the variability in meltwater compositions through space and time.

Crystalline Bedrock Permeability

(Submitted by Dr. John Swenson, Dept. of Geological Sciences, University of Minnesota Duluth)

The proposed Soudan Mine NUSEL offers numerous exciting and unique opportunities to study fluid and solute transport in fractured bedrock across a wide range (10^{-1} – 10^{12} m^3) of spatial scales. Many of these avenues for potential research are outlined in the EarthLab initiative. We focus here on potential hydrogeologic research projects that, in large part, require initiation and/or completion during the exploratory and construction phases of the facility. In particular, we plan to utilize a series of deep boreholes to characterize the spatial distribution of bedrock hydrogeologic properties, e.g., permeability, and to measure the distributions of pore-fluid properties in the current, quasi-equilibrium groundwater flow system. We also propose to use the deep boreholes to monitor the transient response of the groundwater flow system to construction of the Soudan Mine NUSEL. While our proposed work is largely "observational" in nature, it is ultimately designed to address the important issue of scale-dependence of hydraulic properties, notably permeability.

Permeability is the dominant control on groundwater flow systems and their ability to transport solutes and heat. The permeability of porous media appears to vary significantly with the scale of measurement and with depth (e.g., Bachu, 1988; Garven, 1989). For a specified fractured bedrock system, the mean *in situ* (wellbore scale 10^1-10^4 m^3) permeability is generally 10^3 times greater than the mean laboratory (core scale < 1 m^3) permeability; this trend apparently does not extend to larger scales, however, as mean *in situ* and regional-scale (>> 10^4 m^3) permeability values typically agree to within an order of magnitude, e.g., Brace, 1984. In general, laboratory, *in situ*, and regional scales of measurement do not overlap, particularly the *in situ* and regional scales, which are often separated by many orders of magnitude in the volume of material sampled. Comparatively little is known about how permeability varies between these somewhat discrete scales of measurement. Permeability in sedimentary basins decreases with burial depth, as the (general) increase in effective stress drives mechanical compaction and loss of porosity. Permeability in fractured crystalline rocks also appears to decrease with depth, though the relationship is less well established, e.g., Brace, (1984), Morrow et al., (1994).

The Soudan Mine NUSEL offers a unique opportunity to address the scale- and depth-dependence of fractured-bedrock permeability across a range of scales typically unavailable in a single study. We propose a two-phase plan to utilize initial deep boreholes to first analyze the bedrock hydraulic properties and pore-fluid chemistry and second to monitor the transient response to construction (dewatering) of the new laboratory. By piggybacking a hydrogeologic study atop a deep drilling project, we gain access to a large volume of fractured crystalline bedrock at minimal cost.

The first phase of our proposed work focuses on quantifying how permeability varies with scale of measurement (from core to *in situ* scale) and with depth (0 – 2.5 km depth). Nearly continuous core recovery from the boreholes will provide a large suite of bedrock samples. We will perform laboratory analyses to determine the core-scale permeability and how it varies with depth and lithology. After using downhole video to identify fracture zones and determine fracture density in the exploratory boreholes, we would conduct packer tests at various depths and over a range of "screened" (hydraulically isolated) intervals to quantify permeability as a function of both depth and a range of *in situ* scales, e.g., 10^1 – 10^4 m^3. Furthermore, with data from multiple boreholes, we can begin to address the variability in the scale- and depth-dependence of permeability.

As part of the first phase of our proposed work, we will also determine the spatial distribution of pore-fluid properties in the current (quasi-) equilibrium groundwater flow system. With each *in situ* permeability test, we will collect pore-fluid samples, and thus characterize the vertical variation in fluid chemistry, temperature, and density. Groundwater in North American shield settings is a three-component mixture of modern and Pleistocene meteoric recharge and a ubiquitous Na-Ca-Cl brine of equivocal origin, e.g., Frape and Fritz, (1987), Douglas et al., (2000). The components are defined by significant differences in major-element and stable-isotope geochemistry. On the Canadian Shield, the brine component generally dominates at depths below one kilometer, whereas anomalously shallow occurrences of high-salinity Na-Ca-Cl groundwater are common in the Lake Superior region (Douglas et al., 2000; Swenson et al., 2002). The depth-dependence of pore-fluid chemistry may be a signature of Pleistocene glaciation (Clark et al., 2000; Swenson et al., 2002). The spatial distribution of pore-fluid properties is an important initial condition for the second phase of our proposed research.

The second phase of our research involves using the construction and associated dewatering of the new laboratory as essentially a very large *in situ* test to determine bedrock hydraulic properties at the scale of 10^6 – 10^{12} m^3. Unlike a typical *in situ* (pump) test, in which the groundwater system is perturbed following completion of a borehole, dewatering of the helical decline, connecting drift, and shafts (Figures 49 and 53) will create large hydraulic gradients and, by extension, significantly perturb the groundwater flow system throughout the construction phase. Using reasonable values for bulk hydraulic diffusivity in fractured crystalline bedrock and a multi-year construction timeline, we predict that decline/shaft dewatering will affect the groundwater flow system on lateral length scales of several kilometers. A significant fraction of the transient groundwater response will occur during laboratory construction; failure to monitor the system during this phase will result in the loss of key hydrogeologic data. Our plan is to use the exploratory boreholes as deep monitoring wells to capture the transient response of the groundwater flow system to laboratory construction. By systematically repeating packer tests at specified time intervals, we can monitor how the spatial distribution of pore-fluid properties evolves during laboratory construction and after its completion. In particular, we will look for changes in water chemistry, with emphasis on salinity, stable-isotope concentrations, and the presence of short-lived radioisotopes suggestive of young, meteoric recharge. Changes in fluid pressure (hydraulic head) within the uncased boreholes will provide us with the depth-integrated hydrodynamic response to dewatering. In addition, the repeated packer tests provide a time series of the how *in situ* permeability responds to changes in effective stress produced by dewatering.

Hydrogeologic data obtained from both phases of our proposed research can be used to address a number of hypotheses; foremost among these is the scale- and depth-dependence of bedrock hydraulic properties, particularly permeability. Data derived from phase-one measurements will quantify permeability at the core and (a range of) *in situ* scales as a function of depth and, further, will establish the initial distribution of pore-fluid properties. We can use data from phase-two measurements, i.e., the transient response to dewatering, in inverse models of groundwater flow and solute transport to quantify the permeability (and dispersivity) at a scale intermediate between those that characterize “standard” *in situ* and regional studies. As such, this study may provide insight into the apparent transition to scale-*independence* in permeability between *in situ* and regional scales. A better understanding of the scale- and depth-dependence of permeability in fractured-bedrock in continental-shield settings has important scientific and societal implications for groundwater resource issues, geothermal energy, ore genesis, and hazardous (nuclear) waste disposal.

Geologic Studies During NUSEL Construction

As outlined by the Earth Science and Engineering Committee for the proposed National Underground Science and Engineering Laboratory, detailed knowledge of the geology of the area around the laboratory is a fundamental aspect of virtually all subsequent geological studies conducted at the site. For example, the study of deep groundwater circulation through the crystalline bedrock in the Soudan Mine area would be unequivocally tied to crustal-scale permeability, which is directly linked to the lithology and structural geology of the region around the laboratory. Much of the fundamental geologic information that will be used during the life of the laboratory is best collected during the construction of the site, when working faces of the proposed decline and shafts are open and can be directly related to the geologic information revealed in drill holes.

Detailed geological studies during the planning, construction, and operational phases of the proposed Soudan Mine NUSEL are needed for three major reasons: (1) Understanding the three-dimensional geologic setting of the area around the site, and using the information to construct the facility in the safest and most cost-effective manner; (2) Containment and mitigation of possible specific metaliferous groundwater seeps into the new workings; (3) Understanding the regional groundwater impact of NUSEL construction; and (4) Development of a detailed regional geological database of the lithology, alteration, structure, geochemistry, and rock properties of the bedrock, as well as surficial materials and near-surface waters. This database of geological information would be used as the basis of most future geological studies at the laboratory.

The following list includes the proposed geological studies that would be supervised and/or supported by the geologic staff of the Natural Resources Research Institute (NRRI), University of Minnesota-Duluth (UMD) during the construction phase (~6-year) of the underground laboratory. The work would be completed by the staff of the NRRI, as well as by personnel of the Minnesota Geological Survey, faculty and graduate students from the University of Minnesota Duluth and other American universities.

1) Completion of a detailed digital bedrock geologic map of the area (~ 10 mi^2). Summary reports and theses of the map area would include detailed studies of bedrock lithology, geochemistry, structural geology, volcanology, alteration mineralogy, and economic geology.
2) Completion of the digitization of all of the data from the Soudan Mine. These were excellent geologists, and once one grasps the terms they used, and has seen the rocks for themselves, these data can be invaluable.
3) Geological mapping of all accessible workings within the Soudan Iron Mine. Various levels are in good condition and have not been mapped in the last half-century.
4) Detailed geological and structural mapping of all openings (declines, shafts, caverns) created during site construction, and logging and archiving of all drill core generated.
5) Geological assistance to engineering and geotechnical firms contracted to develop NUSEL.
6) Geochemical studies of groundwater seeps encountered during construction. In addition, containment and mitigation plans for waters from environmentally hazardous seeps would be completed.
7) Creation of a 1:12,000 scale physical model of the geology of the Soudan Mine, Minos and Soudan 2 Laboratories, NUSEL, and EarthLab.
8) Completion of a detailed surficial Quaternary geology map of the area.
9) Installation of shallow and deep groundwater monitoring wells, as well as the collection, archiving, and study of the geohydrological data generated.

Bibliography

Allen, R.L., Lunstrom, I., Ripa, M., Seimeonov, A., and Christofferson, H., 1996a, Facies analysis of a 1.9 Ga, continental margin, back-arc felsic caldera province with diverse Zn-Pb-Ag-(Cu-Au) sulfide and Fe-oxide deposits, Bergslagen region, Sweden: Economic Geology, v. 91, p. 979-1,008.

Allen, R.L., Weihed, P., and Svenson, S.A., 1996b, Setting of Zn-Cu-Au-Ag massive sulfide ores in the evolution and facies architecture of a 1.9 Ga marine volcanic arc, Skellefte District, Sweden: Economic Geology, v. 91, p. 1,022-1,053.

Allen, R.L., Weihed, P., Blundell, D., Crawford, T., Davidson, G., Galley, A., Gibson, H. , Hannington, M., Herrington, R., Herzig, P., Large, R., Lentz, D., Maslennikov, V., McCutcheon, S., Peter, J., and Tornos, F., 2000, Global comparisons of volcanic-associated massive sulfide districts: *in* Blundell, D. J., Neubauer, F, and von Quadt, A., The timing and location of major ore deposits in an evolving orogen: Geological Society of London Special Publications, v. 204, p. 13-37.

Bachu, S., 1988, Analysis of heat transfer processes and geothermal pattern in the Alberta basin, Canada: Journal of Geophysical Research, v. 93, p. 7,767-7,781.

Bahcall, J., Barish, B., Calaprice, F., Conrad, J., Doe, P.J., Gaisser, T., Haxton, W., Lesko, K.T., Marshak, M., and Robinson, K., 2001, Underground Science: University of Washington Institute for Nuclear Theory report, 36 p.

Bauer, R.L., 1985, Correlation of early recumbent and younger upright folding across the boundary between an Archean gneiss belt and greenstone terrane, northeastern Minnesota: Geology, v. 13, p. 657-660.

Boerboom, T.J., and Zartman, R.E., 1993, Geology, geochemistry, and geochronology of the central Giants Range batholith, northeastern Minnesota: Canadian Journal of Earth Science, v. 30, p. 2,510-2,522.

Brace, W.F., 1984, Permeability of crystalline rocks: New in situ measurements: Journal of Geophysical Research: v. 89, p. 4,327-4,330.

Burnham, C. W., 1983, Deep submarine pyroclastic eruptions: Economic Geology Monograph 5, p. 142-148.

Calaprice, F.P., Doe, P., Lesko, K. T., Marshak, M. L., Nelson, C., Peterson, D.L., Robinson, K.E., Wang, J., and Wilkerson, J.F., 2001, Report on the Technical Evaluation of Underground Laboratory Sites: University of Washington Institute for Nuclear Theory report, 40 p.

Campbell, I.H., Franklin, J.M., Gorton, M.P., Hart, T.R., and Scott, S.D., 1982, The role of synvolcanic sills in the generation of massive sulfide deposits: Economic Geology, v. 76, p. 2,248-2,253.

Cas, R.A.F., 1992, Submarine volcanism: eruption styles, products, and relevance to understanding the host rock successions to volcanic-hosted massive sulfide deposits: Economic Geology, v. 87, p. 511-541.

Cas, R.A.F., and Wright, J.V., 1987, Volcanic Successions: London, Allen and Unwin, 528 p.

Chown, E.H., N'dah, E., Mueller, W.U., 2000, The relation between iron-formation and low temperature hydrothermal alteration in an Archean volcanic environment: Precambrian Research, v. 101, p. 263-275.

Clark, I.D., Douglas, M., Raven, K, and Bottomley, D., 2000, Recharge and preservation of Laurentide glacial melt water in the Canadian Shield: Ground Water, v. 38, p. 735-742.

Clements, J.M., 1903, The Vermilion iron-bearing district of Minnesota: U.S. Geological Survey, Monograph 45, 463 p.

Cloud, P.E., and Licari, G.R., 1968, Microbiotas of the banded iron formations: Proceedings of the National Academy of Science, U.S.A., v. 61, 7p. 79-786.

Corfu, F., and Stott, G.M., 1998, Shebandowan greenstone belt, western Superior Province: U-Pb ages, tectonic implications, and correlations: Geological Society of America Bulletin, v. 110, p. 1,467-1,484.

Cushing, E.J., 1967, Late-Wisconsin pollen stratigraphy and the glacial sequence in Minnesota, *in* Cushing, E.J., and Wright, H.E., Jr., eds., Quaternary paleoecology: New Haven, Yale University Press, p. 59-88.

Dimroth, E., 1986, Depositional environments and tectonic settings of cherty iron formations of the Canadian Shield: Journal of the Geological Society of India, v. 28, p. 239-250.

Dostal, J., and Mueller, W.U., 1996, An Archean oceanic felsic dyke swarm in a nascent arc: the Hunter Mine Group, Abitibi Greenstone Belt, Canada: Journal of Volcanology and Geothermal Research, v. 72, p.37-57.

Dott, R.H., 1964, Wacke, greywacke and matrix – what approach to immature sandstone classification?: Journal of Sedimentary Petrology, v. 34, p. 625-632.

Douglas, M., Clark, I.D., Raven, K, and Bottomley, D., 2000, Groundwater mixing dynamics at a Canadian Shield mine: Journal of Hydrology, v. 235, p. 88-103.

Dusanowskyj, T.H., and West, G.F., 1976, A gravity study of the Sturgeon Lake area; Proceedings of the 1976 Geotraverse Conference, University of Toronto, p. 56-60.

Edmond, J.M., Measures, C., McDuff, R.E., Chan, L.H., Collier, R., Grant, B., Gordon, L.I., and Corliss, J.B., 1979, Ridge crest hydrothermal activity and the balances of the major and minor elements in the ocean: the Galapagos data: Earth and Planetary Science Letters, v. 46, p. 1-18.

Edmonds, H.N., and Edmond, J.M., 1995, A three-component mixing model for ridge-crest hydrothermal fluids: Earth and Planetary Science Letters, v. 134, p. 53-67.

Fisher, R.V., 1961, Proposed classification of volcaniclastic sediments and rocks: Geological Society of America Bulletin, v. 72, p. 1409-1414.

Fisher, R.V., 1966, Rocks composed of volcanic fragments, Earth Science Reviews, v. 1, p. 287-298.

Franklin, J.M., 1996, Volcanic-associated massive sulfide base metals, *in* Eckstrand, O.R., Sinclair, W.D., and Thorpe, R. I. eds., Geology of Canadian Mineral Deposit Types: Geological Survey of Canada, no. 8, p. 158-183.

Franklin, J.M., Hannington, M.D., Jonasson, I.R. and Barrie, C.T., 1998, Arc-Related Volcanogenic Massive Sulphide Deposits, *in* Metallogeny of Volcanic Arcs: British Columbia Geological Survey, Short Course Notes, Open File 1998-8, Section N.

Frape, S.K., and Fritz, P., 1987, Geochemical trends for groundwaters from the Canadian Shield, *in* Fritz, P., and Frape, S.K. eds., Saline water and gases in crystalline rocks: Geological Association of Canada Special Paper 33, p. 19-38.

Fries, M., 1962, Pollen profiles of late Pleistocene and recent sediments from Weber Lake, Minnesota: Ecology, v. 43, p. 295-308.

Galley, A., 2002, Characteristics of composite subvolcanic intrusive complexes associated with Precambrian VMS districts: *in* Galley, A., Bailes, A., Hannington, M., Holk, G., Katsube, J., Paquette, F., Paradis, S., Santaguida, F., and Taylor, B., eds., Database for Camiro Project 94E07: Interrelationships between subvolcanic intrusions, large-scale alteration, and VMS deposits: Geological Survey of Canada Open File Report 4431, p. 1-40.

Galley, A., 2003, Composite synvolcanic intrusions associated with Precambrian VMS-related hydrothermal systems: Mineralium Deposita, v. 38, p. 443-473.

Galley, A., van Breemen, O., and Franklin, J.M., 2000, The relationship between intrusion-hosted Cu-Mo mineralization and the VMS deposits of the Archean Sturgeon Lake mining camp, northwestern Ontario: Economic Geology, v. 95, p. 1543-1550.

Garven, G., 1989, A hydrogeologic model for the formation of giant oil sands deposits of the Western Canada sedimentary basin: American Journal of Science, v. 289, p. 105-166.

Gibson, H.L., 1989, The mine sequence of the Central Noranda Volcanic Complex: geology, alteration, massive sulfide deposits, and volcanological reconstruction: unpublished Ph. D. dissertation, Carleton University, Ottawa, Ontario, Canada, 800 p.

Gibson, H.L., Morton, R.L., and Hudak, G.J., 1999, Submarine volcanic processes, deposits, and environments favorable for the location of volcanic-associated massive sulfide deposits: Reviews in Economic Geology, v. 8, p.13-51.

Grant, F.S., Gross, W.H., and Chinnery, M.A., 1965, The shape and thickness of an Archean greenstone belt by gravity methods: Canadian Journal of Earth Science, v.2, p. 418-424.

Green, J.C., and Schulz, K.J., 1977, Iron-rich basaltic komatiites in the early Precambrian Vermilion District: Canadian Journal of Earth Sciences, v. 15, p. 857-859.

Groves, D.I., Goldfarb, R.J., Knox-Robinson, C.M., Ojala, J., Gardoll, S., Yun, G.Y., and Holyland, P., 2000, Late-kinematic timing of lode-gold deposits and significance for computer-based exploration techniques with emphasis on the Yilgarn Block, Western Australia: Ore Geology Reviews, v. 17, no. 1-2, p. 1-38.

Groves, D.I., Goldfarb, R.J., Robert, F., and Hart, C.J.R., 2003, Gold deposits in metamorphic belts: Overview of current understanding, outstanding problems, future research, and exploration significance: Economic Geology, v. 38, no. 1, p. 1-30.

Gupta, V.K, and Osmani, I.A., 1990, Regional gravity map of part of the Abitibi greenstone belt, Ontario, *in* Summary of Field Work and Other Activities 1990: Ontario Geological Survey, Miscellaneous Paper 151, p. 190-197.

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.

Gupta, V.K., Thurston, P.C., and Dusanowskyj, T.H., 1982, Constraints upon models of greenstone belt evolution by gravity modeling, Birch-Uchi greenstone belt, northern Ontario: Precambrian Research, v. 16, p. 233-255.

Hamilton, W.B., 1998, Archean magmatism and deformation were not the products of plate tectonics: Precambrian Research, v. 91, p. 143-179.

Hannington, M.D., Poulsen, K.H., Thompson, J.F.H., and Sillitoe, R.H., 1999, Volcanogenic gold in the massive sulfide environment: Reviews in Economic Geology, v. 8, p. 325-356.

Herzig, M., and Hannington, M. D., 1995, Polymetallic massive sulfides at the modern seafloor – a review: Ore Geology Reviews, v. 10, 95-115.

Herzig, M., and Hannington, M.D., 2000, Polymetallic massive sulfides and gold mineralization at mid-ocean ridges and in subduction-related environments, *in* Cronan, D.S., ed., Handbook of Marine Mineral Deposits, Boca Raton, Florida, CRC Press, p. 347-368.

Hittleman, A.M., Buhmann, R.W., Racey, S.D. and Chandler, V.W., 1990, Aeromagnetics Earth System data, Minnesota Region; National Oceanic and Atmospheric Administration, 2 data disks.

Hocker, S.M., Hudak, G.J., and Heine, J., 2003, Electron microprobe analysis of alteration mineralogy at the Archean Five Mile Lake volcanic-associated massive sulfide mineral prospect in the Vermilion District of NE Minnesota: Natural Resources Research Institute, University of Minnesota Duluth, Report of Investigation NRRI/RI-2003/17, 49 p.

Hooper, P., and Ojakangas, R., 1971, Multiple deformation in the Vermilion district, Minnesota: Canadian Journal of Earth Sciences, v. 8, p. 423-434.

Huber, J.K., 1987, A vegetational reconstruction from Big Rice lake, St. Louis County, Minnesota: Current Research in the Pleistocene, v. 4, p. 91-93.

Huber, J.K., 1992, An overview of the vegetational history of the Arrowhead Region, Northeastern Minnesota, *in* 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, p. 55-64.

Hudak, G.J., and Morton, R.L., 1999, Bedrock and glacial drift mapping for VMS and lode gold alteration in the Vermilion - Big Fork Greenstone Belt: Part A: Discussion of lithology, alteration, and geochemistry at the Five Mile Lake, Eagles Nest, and Quartz Hill Prospects: Minnesota Department of Natural Resources Project 326 Open File Report, 136 p.

Hudak, G.J., Heine, J., Newkirk, T., Hocker, S., and Hauck, S., 2003, Comparative geology, stratigraphy, and lithogeochemistry of the Needleboy Lake – Six Mile Lake area, Vermilion District, NE Minnesota: Natural Resources Research Institute, University of Minnesota Duluth, Report of Investigation, NRRI/RI-2003/18.

Hudak, G.J., Heine, J., Newkirk, T., Odette, J., and Hauck, S., 2002, Comparative geology, stratigraphy, and lithogeochemistry of the Five Mile Lake, Quartz Hill, and Skeleton Lake VMS occurrences, Vermilion District, NE Minnesota: Natural Resources Research Institute, University of Minnesota Duluth, Technical Report, NRRI/TR-2002/03, 390 p.

Hudak, G.J., Morton, R.L., Franklin, J.M., and Peterson, D.M., in press, Morphology, distribution, and estimated eruption volumes for intracaldera tuffs associated with volcanic-hosted massive sulfide deposits in the Archean Sturgeon Lake Caldera Complex, northwestern Ontario: American Geophysical Union Monograph on Subaqueous Explosive Volcanism.

Hudleston, P.J. 1976, Early deformational history of Archean rocks in the Vermilion district, northeastern Minnesota: Canadian Journal of Earth Sciences, v. 13, p. 579-592.

Hudleston, P.J., Schultz-Ela, D., and Southwick, D.L., 1988, Transpression in an Archean greenstone belt, northern Minnesota: Canadian Journal of Earth Sciences, v. 25, p. 1,060-1,068.

Jirsa, M.A., 2000, The Midway sequence: a Timiskaming-type pull-apart basin deposit in the western Wawa subprovince, Minnesota: Canadian Journal of Earth Science, v. 37. p. 1-15.

Jirsa, M.A., Boerboom, T.J., and Peterson, D.M., 2001 Bedrock geologic map of the Eagles Nest Quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey, Miscellaneous Map M-114, scale 1:24,000.

Jirsa, M.A., Southwick, D.L., and Boerboom, T.J., 1992, Structural evolution of Archean rocks in the western Wawa subprovince, Minnesota: Refolding of pre-cleavage nappes during D_2 transpression: Canadian Journal of earth Sciences, v. 29, p. 2,146-2,155.

Kimberly, M.M., 1989, Exhalative origins of iron formations: Ore Geology Reviews, v. 5, p. 13-145.

LaBerge, G.L., 1973, Possible biological origin of Precambrian iron formations: Economic Geology, v. 68, 1,098-1,109.

Lafrance, B., Mueller, W.U., Daigneault, R., and Dupras, N., 2000, Evolution of a submerged composite arc volcano: volcanology and geochemistry of the Normetal volcanic complex, Abitibi greenstone belt, Quebec, Canada: Precambrian Research, v. 101, p. 277-311.

Large, R., and Blundell, D., (eds.), 2000, Database on Global VMS Districts: GEODE (European Science Foundation) and Centre for Ore Deposits and Exploration Studies (University of Tasmania), 179 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.

Lesher, C.M., Goodwin, A.M., Campbell, I.H., and Gorton, M.P., 1986, Trace element geochemistry of ore-associated and barren felsic metavolcanic rocks in the Superior Province, Canada: Canadian Journal of Earth Sciences, v. 23, p. 222-237.

Marshak, M.L., Cushman, P.B., Heller, K., and Peterson, E.A., 2003, SOUDAN: A Proposal for a National Underground Science and Engineering Laboratory (NUSEL): National Science Foundation, submitted proposal, 146 p.

McPherson, B.J., and the EarthLab Steering Committee, 2003, EarthLab: A subterranean laboratory and observatory to study microbial life, fluid flow, and rock deformation: Geosciences Professional Services, Inc., 62 p.

Morey, G.B., Green, J.C., Ojakangas, R.W., and Sims, P.K., 1970, Stratigraphy of the Lower Precambrian rocks in the Vermilion district, northeastern Minnesota: Minnesota Geological Survey, Report of Investigations 14, 33 p.

Morris, R.C., 1985, Genesis of iron ore in banded iron-formation by supergene and supergene-metamorphic processes – a conceptual model, *in* Wolf, K.H., ed., Handbook of strata-bound and stratiform ore deposits: Amsterdam, Elsevier, v. 13, p. 73-235.

Morrow, C.A., Lockner, D., Hickman, S., Rusanov, M., and Rockel, T., 1994, Effects of lithology and depth on the permeability of core samples from the Kola and KTB drill holes: Journal of Geophysical Research, v. 99, p. 263-274.

Morton, R.L. and Franklin J.M., 1987, Two-fold classification of Archean volcanic-associated massive sulphide deposits: Economic Geology, v. 82, p. 1,057-1,063.

Morton, R.L., Hudak, G.J. and Franklin, J.M., 1999, Geology, south Sturgeon Lake area, Ontario: Geological Survey of Canada Open File Report 3642.

Mueller, W., Chown, E.H. , and Thurston, C., 2000, Processes in physical volcanology and volcaniclastic sedimentation: modern and ancient: Precambrian Research, v. 101, p. 81-85.

Mueller, W., Chown, E.H., and Potvin, R., 1994, Substorm wave base felsic hydroclastic deposits in the Archean Lac Vents volcanic complex, Abitibi belt, Canada: Journal of Volcanology and Geothermal Research, v. 60, p. 273-300.

Newkirk, T., Hudak, G.J., and Hauck, S.A., 2001, Preliminary lava flow morphology studies at the Five Mile Lake VMS prospect, Vermilion District, NE Minnesota: Implications for volcanic processes, volcanic paleoenvironments, and VMS exploration: Geological Society of America, Abstracts and Programs, v. 33, no. 6, p. A-398.

Odette, J.D., Hudak, G.J., Suszek, T., and Hauck, S.A., 2001, Preliminary investigation of hydrothermal alteration mineral assemblages and their relationship to VMS-style mineralization in the Five Mile Lake area of the Archean Vermilion Greenstone Belt, NE Minnesota: Geological Society of America Abstracts and Programs Volume 33, no. 6, p. A-420.

Ohmoto, H., 2003, Nonredox transformations of magnetite-hematite in hydrothermal systems: Economic Geology, v. 98, p. 157-166.

Peterson, D.M., 2001, Development of Archean lode-gold and massive sulfide deposit exploration models using geographic information system applications: Targeting mineral exploration in northeastern Minnesota from analysis of analog Canadian mining camps: Unpublished Ph.D. thesis, University of Minnesota, 503 p.

Peterson, D. M., and Jirsa, M.A., 1999a, Bedrock geologic map and mineral exploration data, western Vermilion district, St. Louis and Lake Counties, northeastern Minnesota: Minnesota Geological Survey, Miscellaneous Map M-98, scale 1:48,000.

Peterson, D.M., and Jirsa, M.A., 1999b, Lode gold and massive sulfide prospects in the Archean western Vermilion district: Minnesota Exploration Association, Minn. Exploration Conference, Field Trip Guidebook, 30 p.

Peterson, D.M., and Patelke, R.L., in prep, Neo-Archean gold mineralization in the Mud Creek Road area, Northern St. Louis County, Minnesota: Natural Resources Research Institute, University of Minnesota Duluth.

Peterson, D.M., Gallup, C., Jirsa, M.A., and Davis, D.W., 2001, Correlation of Archean assemblages across the U.S. - Canadian border; Phase I geochronology, abstract and oral presentation, Institute on Lake Superior Geology, 47th Annual Meeting, Thunder Bay, Ontario, v. 47.

Ramsay, J.G. and Huber, M.I., 1987, The Techniques of Modern Structural Geology, Volume 2: Folds and Faults: London, Academic Press Inc.

Remenda V. H., Cherry, J.A., and Edwards T.W.D., 1994, Isotopic composition of old ground water from Lake Agassiz: Implications for Late Pleistocene climate: Science, v. 266, p. 1,975-1,978.

Riedel, W., 1929, Zur Mechanik geolgischer Brucherscheinungen. Zentralbl: Mineral. Geol. Palaeontol., Reihe B, p. 354-368.

Robert, F., Sheahan, P.A., and Green, S.B., eds., 1991, Greenstone gold and crustal evolution: NUNA Conference Volume, Geological Association of Canada, Mineral Deposits Division, 251 p.

Santaguida, F., Gibson, H.L., Watkinson, D.H., and Hannington, M.D., 2002a, Part I: Semi-conformable epidote-quartz hydrothermal alteration in the central Noranda Complex, Canada: relationship to volcanic activity and VMS mineralization, *in* Galley, A., Bailes, A., Hannington, M., Holk, G., Katsube, J., Paquette, F., Paradis, S., Santaguida, F., and Taylor, B., eds., Database for Camiro Project 94E07: Interrelationships between subvolcanic intrusions, large-scale alteration, and VMS deposits: Geological Survey of Canada Open File Report 4431, p. 139-180.

Santaguida, F., Gibson, H.L., Watkinson, D.H., and Hannington, M.D., 2002a, Part II: Scaled metasomatic changes associated with epidote-quartz hydrothermal alteration in the Noranda Volcanic Complex, Quebec, *in* Galley, A., Bailes, A., Hannington, M., Holk, G., Katsube, J., Paquette, F., Paradis, S., Santaguida, F., and Taylor, B., (eds.), Database for Camiro Project 94E07: Interrelationships between subvolcanic intrusions, large-scale alteration, and VMS deposits: Geological Survey of Canada Open File Report 4431, p. 181-241.

Schultz-Ela, D.D., and Hudleston, P.J., 1991, Strain in an Archean greenstone belt of Minnesota: Tectonophysics, v. 190, p. 233-268.

Schulz, K.J., 1980, The magmatic evolution of the Vermilion greenstone belt, NE Minnesota: Precambrian Research, v. 11, p. 215-245.

Schulz, K.J., 1982, Magnesian basalts from the Archean terranes of Minnesota: *in* Arndt, N.T., and Nesbitt, E.G., eds., Komatiites: London, Allen and Unwin, p. 171-186.

Sclater, J.G., Parsons, B, and Jaupart, C., 1981, Oceans and continents: similarities and differences in the mechanisms of heat loss: Journal of Geophysical Research, v. 86, p, 11,522-11,535.

Seyfried, W.E. Jr., Ding, K., Berndt, M.E., and Chen, X., 1999, Experimental and theoretical controls on the composition of mid-ocean ridge hydrothermal fluids: Reviews in Economic Geology, v. 8, p. 181-200.

Siegel, D.I., and Mandle R.J., 1984, Isotopic evidence for glacial meltwater recharge to the Cambrian-Ordovician aquifer, north-central United States: Journal of Quaternary Research, v. 22, p. 328-335.

Sillitoe, R. H., Hannington, M. D., and Thompson, J. F. H., 1996, High sulfidation deposits in the volcanogenic massive sulfide environment: Economic Geology, v. 91, p. 204-212.

Sims, P.K., 1976, Early Precambrian tectonic-igneous evolution in the Vermilion district, northeastern Minnesota: Geological Society of America Bulletin, v. 87, p. 379-389.

Sims, P.K., and Morey, G.B., eds., 1972, Geology of Minnesota: A Centennial Volume: Minnesota Geological Survey, 632 p., 2 plates.

Sims, P.K., and Southwick, D.L., 1980, Geologic map of the Soudan quadrangle, St. Louis County, Minnesota: U.S. Geological Survey, Geologic Quadrangle Map GQ-1540, scale 1:24,000.

Sims, P.K., and Southwick, D.L., 1985, Geologic map of Archean rocks, western Vermilion district, northern Minnesota: U.S. Geological Survey, Miscellaneous Investigations Map I-1527, scale 1:48,000.

Southwick, D.L., Boerboom, T.J., and Jirsa, M.A., 1998, Geologic setting and descriptive geochemistry of Archean supracrustal and hypabyssal rocks, Soudan-Bigfork area, northern Minnesota: Implications for metallic mineral exploration: Minnesota Geological Survey, Report of Investigations 51, 69 p.

Southwick, D.L., compiler, 1993, Bedrock geologic map of the Soudan-Bigfork area, northern Minnesota: Minnesota Geological Survey, Miscellaneous Map M-79, scale 1:100,000.

Stein, C. A., and Stein, S., 1994, Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow: Journal of Geophysical Research, v. 99, p. 3,081-3,096.

Swenson, J.B., Larson, P.C., Person, M., Crawford, P.L., and Ripley, E.M., 2002, Continental glaciation as a groundwater-impelling mechanism: Pleistocene flushing of deep brines in the Lake Superior basin: Geological Association of Canada and Mineralogical Association of Canada Joint Annual Meeting, Saskatoon, Saskatchewan, May 27-29.

Tchalenko, J.S., 1970, Similarities between shear zones of different magnitudes: Geological Society of America Bulletin, v. 81, p. 1,625-1,640.

Wohletz, K., Water/magma interaction: some theory and experiments on peperite formation: Journal of Volcanology and Geothermal Research, v. 114, p. 19-35.

Wright, H.E., Jr., and Watts, W.A., 1969, with contributions by Jelgersma, S., Waddington, J.C.B., Oqawa, J., and Winter, T.C., Glacial and vegetation history of northeastern Minnesota: Minnesota Geological Survey, Special Publication Series SP-11, 59 p.

Wright, I.C., Stoffers, P., Hannington, M., de Ronde, C.E.J., Herzig, P., Smith, I.E.M., and Browne, R.L., 2002, Towed-camera investigations of shallow-intermediate water-depth submarine stratovolcanoes of the southern Kermadec Arc, New Zealand: Marine Geology, v. 185, p. 207-218.

Appendix 1 Digital GIS Data Files

ArcView® GIS datasets are given in the directory SM_NUSEL/ARCVIEW/SHAPEFILES on the CD-ROM enclosed in the back pocket of this report. These files include the entire geological and base map data required to recreate the map presented on Plate 1. ArcView® legend files (.avl) for the shapefiles are provided in the same directory. All of the data are georeferenced using the Universal Transverse Mercator (UTM) projection, using the North American Datum of 1983 (NAD83). A digital metadata file (SM_Metadata.doc) in Microsoft Word® format, that describes each of the ArcView datasets is provided in the directory SM_NUSEL/ARCVIEW/METADATA. Adobe Acrobat® pdf files of the three plates are provided in the directory SM_NUSEL/PLATES, and this report in the directory SM_NUSEL/REPORT.

Appendix 2 Digital Photographs

Digital outcrop photographs presented here as Appendix 2 are provided in the directory SM_NUSEL/PHOTOS on the CD-ROM enclosed in the back pocket of this report. These digital photographs are in “jpg” format. Most of the individual jpg files are named by outcrop number, usually with a short description included in the file name, e.g., OC-XXX-short-description.jpg, though some of the photographs are of general interest and have descriptive file names, but no outcrop numbers. The file descriptions reflect our nightly naming of units and rock types as the cameras were downloaded and files named. Some of these descriptions have been rectified to the final geological map (Plate 1) whereas others have not. Because unit names evolved and changed over the course of the project, it is best to consult the GIS outcrop database included with this report for detailed information about any outcrop photo.