NRRI/TR-2010/31

GEOLOGY AND SULFIDE CONTENT OF ARCHEAN ROCKS ALONG TWO PROPOSED HIGHWAY 169 RELOCATIONS TO THE NORTH OF SIXMILE LAKE, ST. LOUIS COUNTY, NORTHEASTERN MINNESOTA

By

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and
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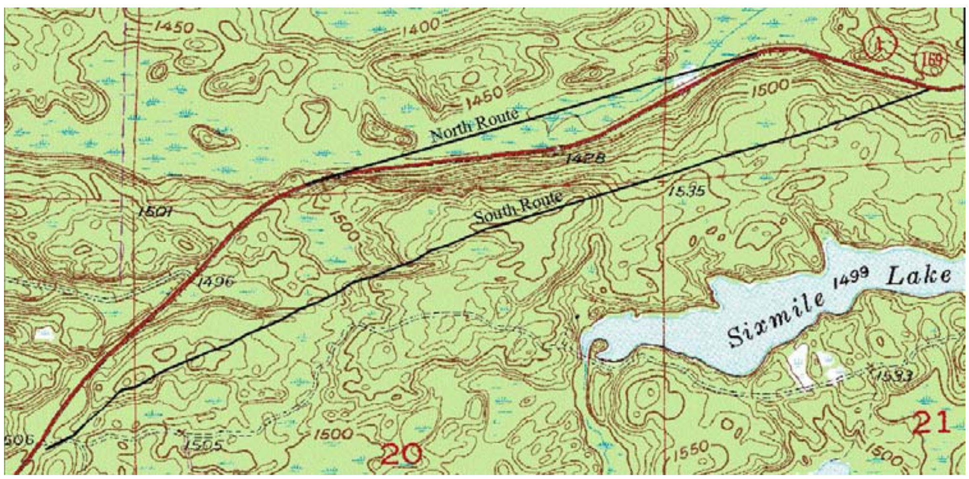

December 2010
Technical Report
NRRI/TR-2010/31

Funded by the Minnesota Department of Transportation
Project No. 1026-10416-20109 E009206578 (CF1)

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This publication is accessible from the home page of the Economic Geology Group of the Center for Applied Research and Technology Development at the Natural Resources Research Institute, University of Minnesota, Duluth (http://www.nrri.umn.edu/egg) as a PDF file readable with Adobe Acrobat 6.0.

Date of release: December 2010

Cover Photo Caption

Mn/DOT-proposed relocation routes for Minnesota Highway 169 to the north and northwest of Sixmile Lake, St. Louis County, MN (T.62N., R.14W.).

Recommended Citation

Severson, M.J., and Heine, J.J., 2010, Geology and Sulfide Content of Archean Rocks Along Two Proposed Highway 169 Relocations to the North of Sixmile Lake, St. Louis County, Northeastern Minnesota: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/TR-2010/31, 46 p.

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INTRODUCTION

Geologic mapping to the north of Sixmile Lake was initiated at the request of the Minnesota Department of Transportation (Mn/DOT) in response to concerns brought forth by local property owners regarding relocating a portion of Minnesota Highway 169. This relocation, referred to as the “South Route” (Fig. 1), was planned to both straighten out the highway and to position the road on top of a large hill, rather than at the base of the hill (north-facing slope) where the road is currently situated, to allow for more sunlight conditions in the winter to melt road ice and snow.

Property owners in the Sixmile Lake area believed that the waters of Sixmile Lake, which is a small spring-fed lake, would be affected by the proposed South Route. They cited the presence of sulfides in rocks along the relocation corridor and stated that these sulfides would be weathered from newly-made road cuts; thus, generating more acidic waters that could result in environmental harm. The property owners further referred to a 1970s-vintage map that mentions the presence of sulfides, and localized copper-staining, in rocks immediately north of Sixmile Lake. This map was produced by United States Steel Corporation (USS) in 1978 and is now on file at the Minnesota Department of Natural Resources (MDNR) office in Hibbing, MN. Other lines of evidence that were cited as further evidence that significant sulfides could be present in the rocks along the proposed South Route corridor included: 1. highly anomalous copper values in the lake sediments of Sixmile Lake (Meineke et al., 1976) are the highest in the state and may reflect additions from localized weathered bedrock (or from rocks in the overburden); and 2. potential volcanogenic massive sulfide (VMS) mineralization, and associated hydrothermal alteration patterns, have been described in the nearby Fivemile Lake area (Hudak et al., 2002) to the south of Sixmile Lake. However, the specific area along the South Route corridor has never been mapped in detail, and the amounts, types, and morphologies of sulfides present in the rock have never been documented.

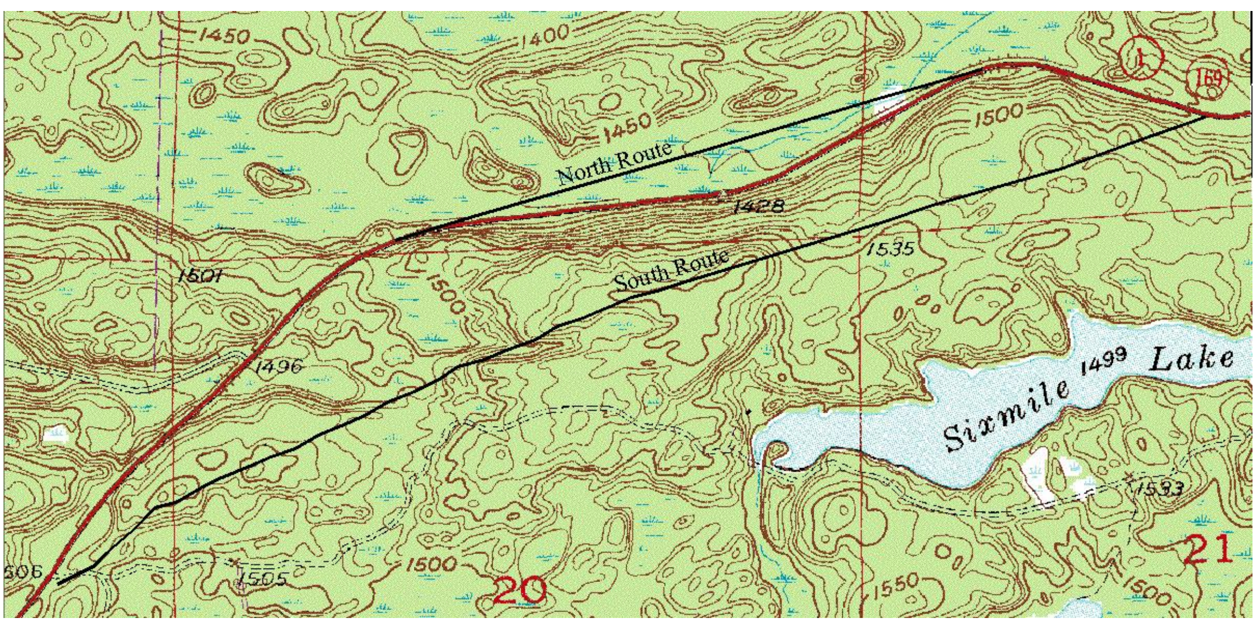

Figure 1. Mn/DOT-proposed relocation routes for Minnesota Highway 169 to the north and northwest of Sixmile Lake, St. Louis County, MN (T.62N., R.14W.).

Because of this environmental concern, Mn/DOT contracted with the Natural Resources Research Institute (NRRI) to map the geology in the vicinity of the proposed relocation, paying special attention to the amount of sulfides in the rock and their mode of occurrence. Mn/DOT also determined that a secondary/alternative route should be considered to the north of Highway 169 in the event that the original relocation along the South Route could not be constructed. They also contracted the NRRI to map the rocks along this secondary "North" route (also shown in Fig. 1).

Geologic mapping activities began on April 19, 2010, and continued intermittently until August 4, 2010. Prior to mapping activities, Mn/DOT personnel placed surveyed points (wooden laths at 100 foot spacings) along the centerline of the proposed highway relocation of the South Route. These surveyed points were used during mapping in that all outcrops within a minimum of 200 feet on either side of the centerline were mapped. In other words, all outcrops within a 400 foot-wide swath, with the highway in the center of the swath (as shown in Fig. 2), were mapped in the project area. In some instances, NRRI geologists mapped outcrops well to the north or south of this swath in order to project geologic units from outside areas into unexposed areas and to establish geologic continuity throughout the area. Mapping also took place along the North Route in a similar 400 foot wide-swath in the latter part of the summer. As this route generally follows an existing powerline, no surveyed points were established by Mn/DOT. The overall areas mapped during the summer of 2010 by the NRRI are shown in Figure 3.

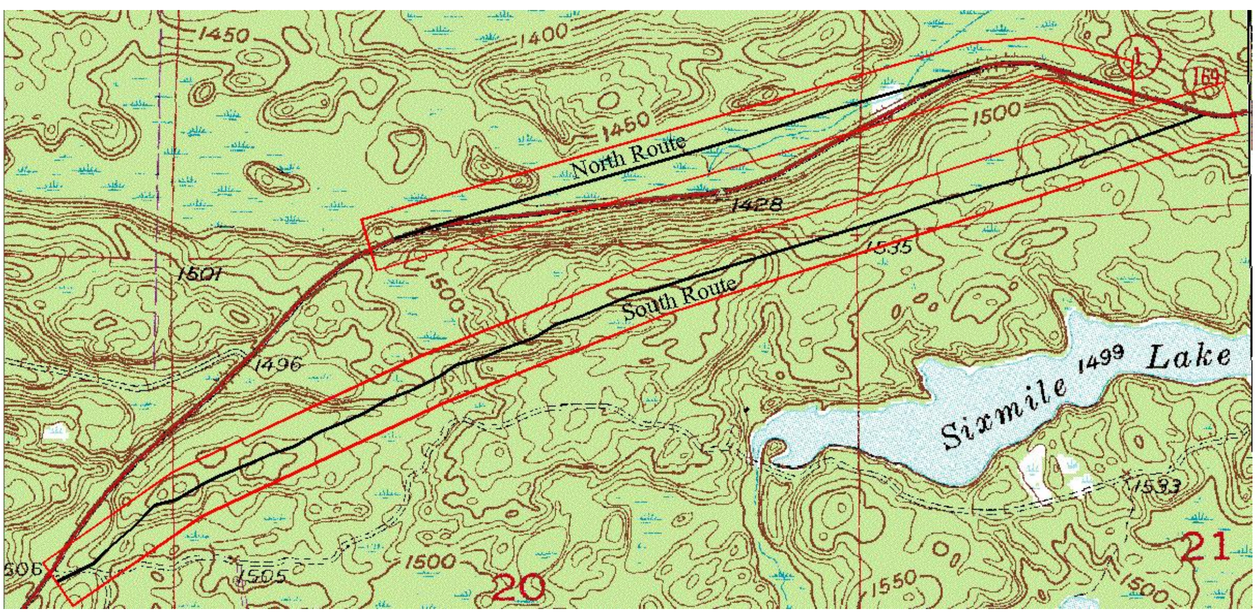

Figure 2. Proposed bands, outlined in red, where detailed mapping was to take place along both the South Route and North Route. Both of these bands are approximately 400 feet wide (200 feet to the north and south of the proposed centerlines for the two routes).

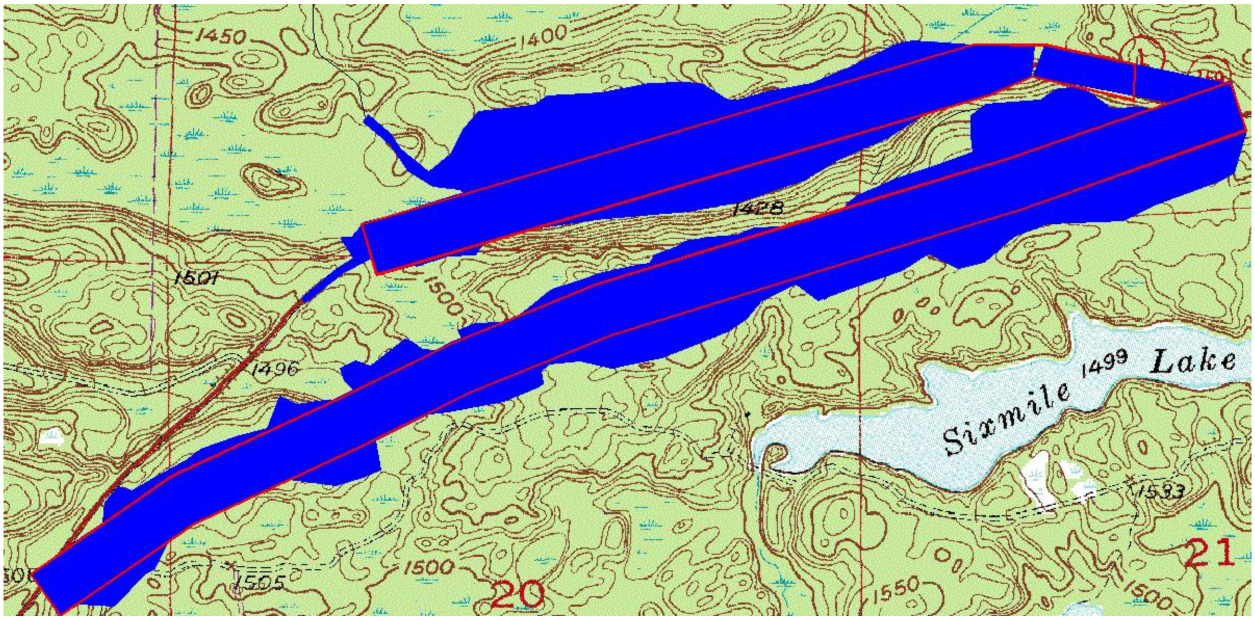

Figure 3. Actual areas where outcrop searches were conducted are shown (in blue) in relation to areas where proposed detailed geologic mapping was to take place (bands outlined in red).

OUTCROP MAPPING TECHNIQUE

Outcrops were located along traverses that followed the terrain to topographical features where bedrock exposures would be most likely, e.g., knobs, ridges, and steep slopes. Search patterns, consisting of several parallel traverses, were also conducted in relatively flat areas, and several additional exposures were discovered in this manner. Over 530 outcrops, and around 45 shallow test pits and trenches (probably dug in the early 1900s), were found in this manner. Upon finding exposures, the procedure used to map the rocks was to:

1. obtain a UTM (Nad83 – Zone 15) location for the outcrop, using a hand-held Global Positioning System (GPS) unit, and sketch the outcrop on one of several field maps – each at a scale of 1 inch = 50 meters (1 inch = 80 feet) that incorporated topography (10 foot contour interval) from the appropriate 15 minute USGS quadrangle map;
2. make a sketch of the outcrop(s) on pre-printed outcrop sheets and geologically describe the unit(s) in the exposure, or series of exposures (scans of individual outcrop sheets are presented in Appendix A);
3. on the same pre-printed outcrop sheets, make note of additional lithologies, alteration styles, structural trends (measured with a sun compass along the South Route due to the abundance of magnetic iron-formation exposures), and sulfide contents and morphologies;
4. collect a sample, or series of samples, from each major outcrop and record the salient data on pre-printed sample sheets – both random samples and sulfide-bearing samples were collected depending on the presence, or absence, of sulfides and the variability of sulfide contents and morphologies in the exposures; and
5. digital photographs were taken of the general lithologic type(s) and individual sample sites (Appendix B).

During field work, all data regarding outcrop descriptions, sample descriptions, and photographs were entered into the following Excel Spreadsheets, respectively, that are included with this report and consist of the following:

- MnDOT_Sixmile_Outcrop_Data.xls (Appendix C);
- MnDOT_Sixmile_Sample_Data.xls (Appendix D); and
- MnDOT_Sixmile_Photo_Data.xls (Appendix E).

GENERAL GEOLOGY

The bedrock geology in the area is part of the Neoarchean (~2.7 billion years old) Vermilion Greenstone Belt that includes rocks of the: Lower member of the Ely Greenstone; Soudan Iron-formation member of the Ely Greenstone, and the Gafvert Lake volcaniclastic sequence of the Lake Vermilion Formation. The spatial distribution of these members is shown in Figure 4. These rocks have been folded in the Tower-Soudan Anticline and are now rotated to near-vertical with steep dips to the north in the area of interest. A second phase of deformation associated with regional metamorphism lead to the development of regional east-west-trending shear zones. Other common fault orientations in the area are in a northeast direction and are interpreted as syn-volcanic in origin. These faults were probably reactivated during the third phase of deformation. Each of the geologic units that were encountered during mapping for this investigation are briefly described below (starting with the oldest rocks/bottom of the stratigraphic pile and progressing upwards).

Soudan Iron-formation

The Soudan Iron-formation member overlies, and locally interfingers with, mafic volcanic rocks of the Lower Ely Greenstone member. The iron-formation is composed of thinly-laminated, magnetic chert (black to gray) with variable amounts of red jasper beds (Fig. 5). Lesser amounts of the mafic flows, tuffs, and sediments are present throughout the iron-formation. This package of rocks formed during a period of quiescence in volcanism at the end of the deposition of the Lower Ely Greenstone. In the area of interest, the iron-formation is 1,800 to 2,000 feet thick.

Bedding in the iron-formation is typically well-laminated and thin-bedded, with massive-bedded black chert more common near the top of the unit. Bedding is planar (2 mm to 2 cm thick) but in many areas is extremely folded. This folding (Fig. 5) is thought to be caused by soft sediment deformation (slumping) prior to lithification. The iron-formation is highly magnetic, making usage of a normal compass for structural measurements impossible and requiring the employment of a sun compass for the measurements. Near the top of the iron-formation, magnetite content decreases and the unit is composed of light-gray to black chert. Thin tuffaceous beds, probably correlative with the overlying Gafvert Lake volcaniclastic unit, are also common near the top of the iron-formation (Fig. 6).

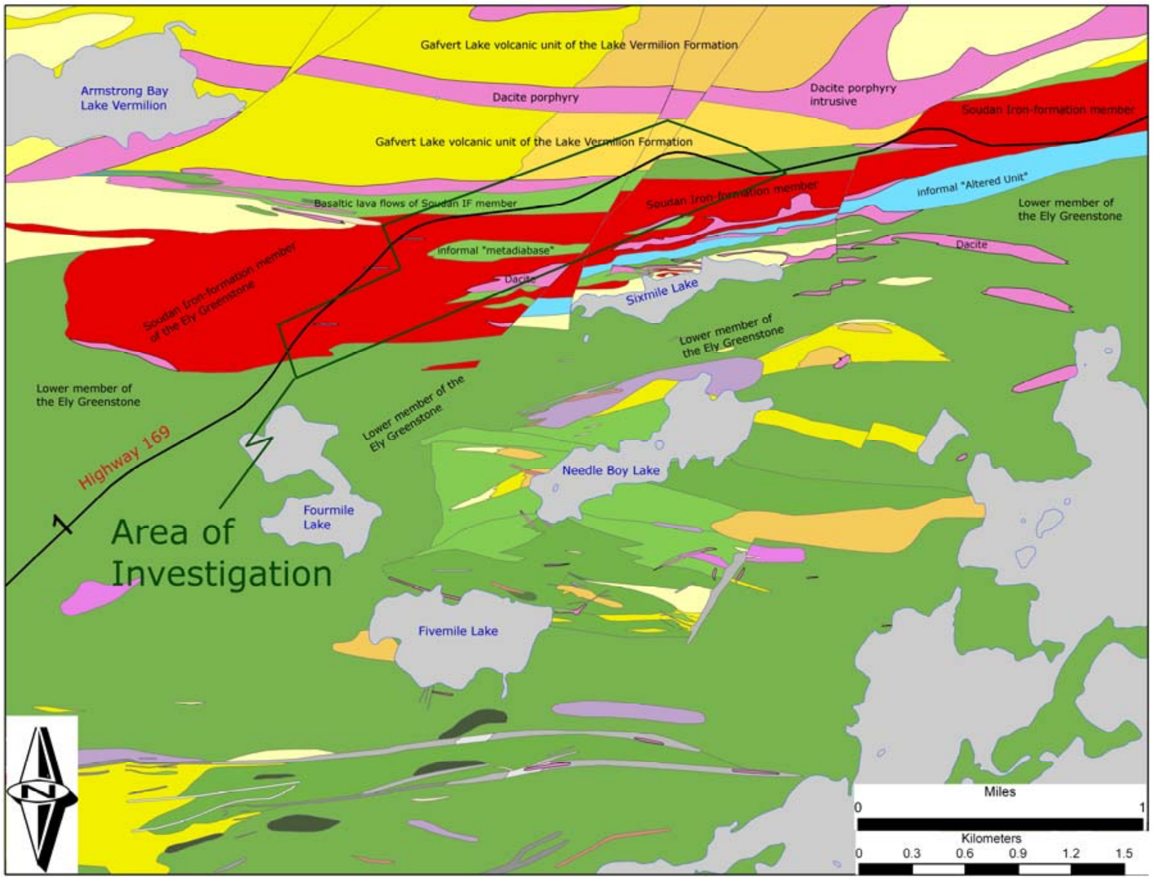

Figure 4. Regional geologic map of the western Vermilion District (modified from Peterson and Jirsa, 1999) showing the major geological formation names and outline of the area of this investigation.

Figure 5. Convoluted-bedded Soudan Iron-formation with white bedding-parallel quartz carbonate veins (OC-115: UTM = 565,160E; 5,299,470N).

Figure 6. Bedded tuffaceous units that are present as interfingering lenses near the top of the Soudan Iron-formation (OC-017B: UTM = 565,032E; 5,299,630N).

Altered Unit

Mafic sediments or reworked volcaniclastic/tuffaceous units (Fig. 7) are locally interbedded with the iron-formation, and these rocks are commonly 3 to 15 feet thick. These units have been historically referred to as the "altered unit" (ALT Unit) because of the dramatic colors the rock exhibits due to a superimposed moderate to strong alteration (Fig. 8). The alteration consists of epidotization (both green and pink epidote), sericitization, chloritization, and silicification with local garnet-rich zones. The Altered Unit consists of fine-grained sediments or tuff and bedding is highly variable in these outcrops, ranging from thin- to massive-bedded. In some areas the alteration is so intense it is difficult to determine the precursor rock type. Small lenses of highly-folded iron-formation are also common to the ALT Unit. Overall, outcrops of the ALT Unit usually contain higher than normal pyrite concentrations (0.5% to more than 2% by visual estimation) in the area of study. The ALT Unit near Sixmile Lake, to the south of the study area (Fig. 4), generally exhibits higher pyrite contents (plus widely-scattered, small copper-stained zones).

Figure 7. Sediments, or reworked volcaniclastics, and tuffs interbedded with Soudan Iron-formation (OTC-185: UTM = 564,310E; 5,299,207N).

Figure 8. Strong epidotization (both pink and green epidote) commonly exhibited by the Altered Unit (OC-004W: UTM = 565,169E; 5,299,569N).

Metadiabase

The metadiabase, spatially correlative with the Lower Ely Greenstone member, occurs as intrusive sills in the Soudan Iron-formation. These sills generally extend for several hundred feet along bedding trends and are thought to have served as feeder channels to the overlying mafic volcanic units exposed elsewhere in the Soudan Iron-formation (or even as feeders to the overlying Upper Ely Greenstone member). The metadiabase is characteristically plagioclase phyric with a felty texture, and varies from dark green to nearly black in color (Fig. 9). Contacts, where exposed, commonly have a chilled margin that has locally undergone some shearing as indicated by the presence of thin chlorite schist zones.

Dacite Porphyry

The dacite porphyry occurs as sills, and to a lesser extent as dikes, in the Soudan Iron-formation. These rocks are thought to be the feeders for the overlying Gafvert Lake volcaniclastic unit. The dacite (Fig. 10) is white to light green gray in color and contains conspicuous phenocrysts of feldspar (2 to 10%) and quartz "eyes" (3 to 6%), with lesser amounts of hornblende (1 to 2%). Xenoliths of iron-formation are common in these intrusive sills. For the most part, the dacite sills intrude all rock types; however, local dikes of metadiabase are seen to intrude the dacite, e.g., outcrop OC-012 in Figure 37.

Gafvert Lake volcaniclastic unit

The Gafvert Lake volcaniclastic unit is an informal subunit of the Lake Vermilion Formation and is best exposed in an area peripheral to Gafvert Lake. These rocks represent a period of explosive volcanism. In the area of this investigation, the rocks consist of a series of felsic tuffs and block-and-ash flows (Figs. 11 and 12). The fine-grained felsic tuffs are quartz- and feldspar-phyric and white to brown in color. The block-and-ash flows are characterized by rounded blocks of fine-grained tuff, iron-formation, dacite porphyry, basalt, and sulfide-rich clasts within a matrix that is similar to the felsic tuffs. Pumice is found in both types of volcanic rocks. Individual tuff and block-and-ash flows have not been mapped in detail so the thickness of these flows is not known.

Gray Basalt

The Gray Basalt is a thin unit within the Gafvert Lake volcaniclastic unit exposed along the North Route of this investigation. It is a fine-grained, light-grayish green mafic flow unit. Partial pillow rinds are present in one outcrop, and a few amygdules or vesicles were identified locally. These outcrops are on the north side of the current highway and the contacts between the underlying Soudan Iron-formation and the overlying Gafvert Lake volcaniclastic unit are not exposed. Most of the exposures of this rock type are heavily frost-heaved (Fig. 13), making it difficult to make structural measurements.

DIGITAL PRESENTATION OF GEOLOGIC MAP

During field work, and after field work was completed, all outcrop shapes and lithologic rock types were digitized into an AutoCAD™ drawing (Appendix F) with a topographic base (Soudan and Eagles Nest 15 minute quadrangles). The distribution of specific lithologic units in the outcrops was then used to generate a geologic map. Mapped geologic units from the 1978 USS map (Appendix G) were also added to the geologic map. In total, 31 various layers were constructed in the AutoCAD™ drawing file (6mile_geology_map_final.dwg) in Appendix F). A description of each of the 31 layers is provided in Appendix H).

Figure 9. Metadiabase sill in the Soudan Iron-formation (outcrop OC-121: UTM = 565,045E; 5,299,390N).

Figure 10. Contact of a Dacite Porphyry sill in the Soudan Iron-formation (OC-129: UTM = 564,840E; 5,299,380N).

Figure 11. Basalt, pumice, and iron-formation clasts in a felsic block-and-ash flow of Gafvert Lake volcaniclastic unit. Typical exposure along logging road located well to the north of the North Route at UTM = 563,285E; 5,299,905N.

Figure 12. Close up of a block-and-ash flow unit of the Gafvert Lake volcaniclastic unit (OC-097A: UTM = 564,090E; 5,299,575N) exhibiting well-rounded clasts of tuff (light) and sub-rounded clasts of iron-formation (black).

Figure 13. Frost-heaved Gray Basalt unit within the Gafvert Lake volcaniclastic unit at OC-199 (UTM = 565,350E; 5,299,655N).

After the AutoCAD™ drawing file was completed, all of these layers were converted to shape files and incorporated into the GIS-format map included with this report (Appendix I). While all of these shape files can be downloaded and built as layers into ARC-based maps, a few of the types of maps generated in this manner are shown for illustrative purposes in the Figures 14 through 16.

SULFIDE CONTENT IN SPECIFIC ROCK TYPES AND AREAS

One of the goals of this project was to map out, and sample, sulfide-bearing zones and to visually estimate the total amount of sulfides present, by volume, within each outcrop and rock type. For the most part, the dominant sulfide is pyrite (FeS_2) with highly-localized trace amounts of chalcopyrite ($CuFeS_2$) that are often noted due to blue and green copper oxides that form on the outcrop surface. Whenever sufficient amounts of pyrite occur in a rock exposure, the pyrite can occur in a myriad of forms such as:

1. disseminated cubes (ranging from less than 0.2 mm and up to 2-3 mm, with occasional occurrences up to 1 cm) that occur in discontinuous patches, semi-continuous beds, and bedding parallel bands and lenses (Figs. 17 and 18);

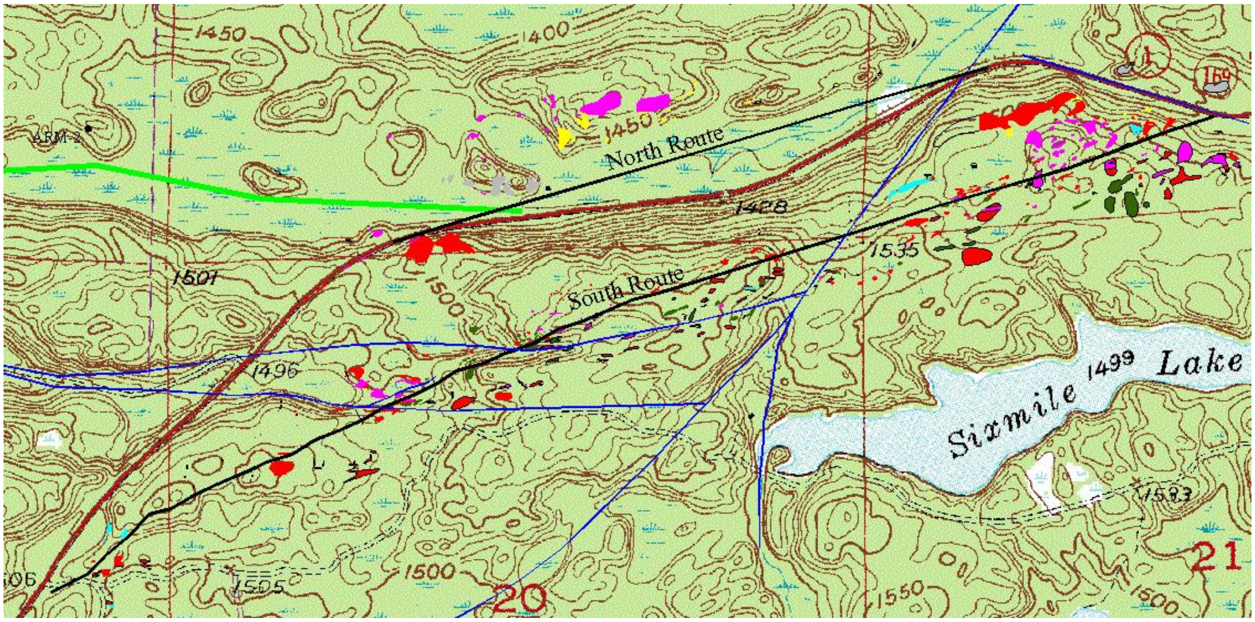

Figure 14. Distribution of outcrops that were mapped, and color-coded by rock type (see legend of Figure 15 for geologic unit designations), for this project during the summer of 2010. This map is produced when only the following shape files have been loaded and turned on: airborne-conductors, alt-unit, bif, dacite, faults (blue lines), gray-basalt, metadiabase, outcrop-shapes, proposed-road, Test_trenches_pits, and tuff.

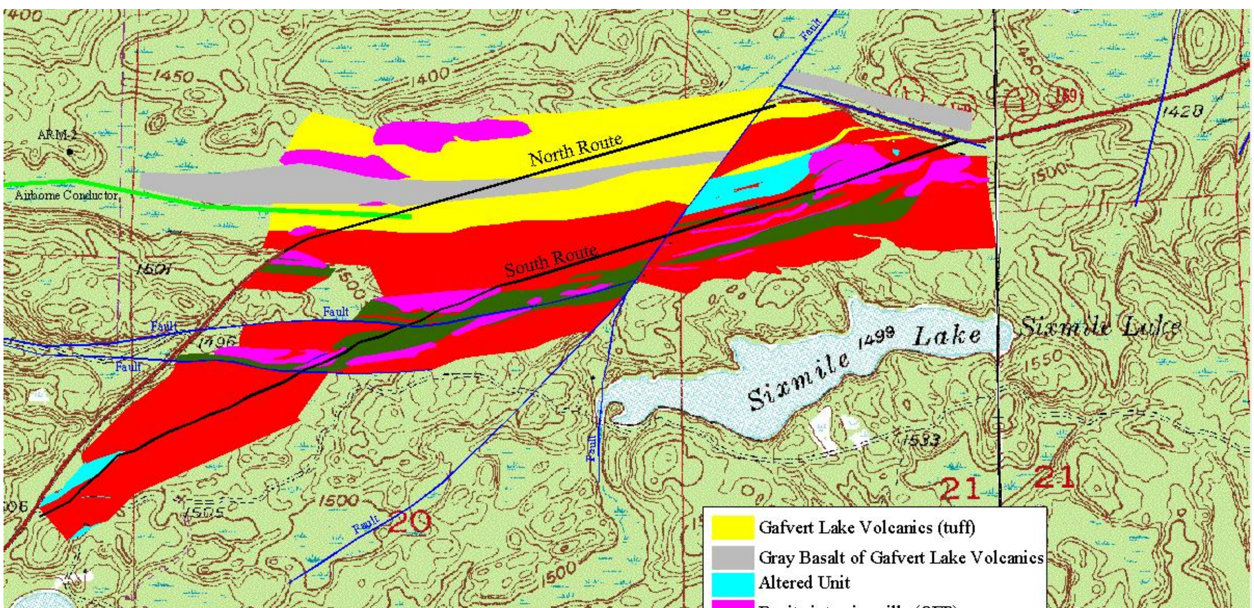

Figure 15. Geologic map of the project area as determined by the distribution of lithologies present in groups of outcrops. This map only shows the geology that was defined by mapping in 2010 and is produced when only the following shape files have been loaded and turned on: airborne-conductors, Big_alt, Big_BIF, Big_dacite, Big_gray_basalt, Big_metadiabse, Big_tuff, contact, faults, and proposed-road.

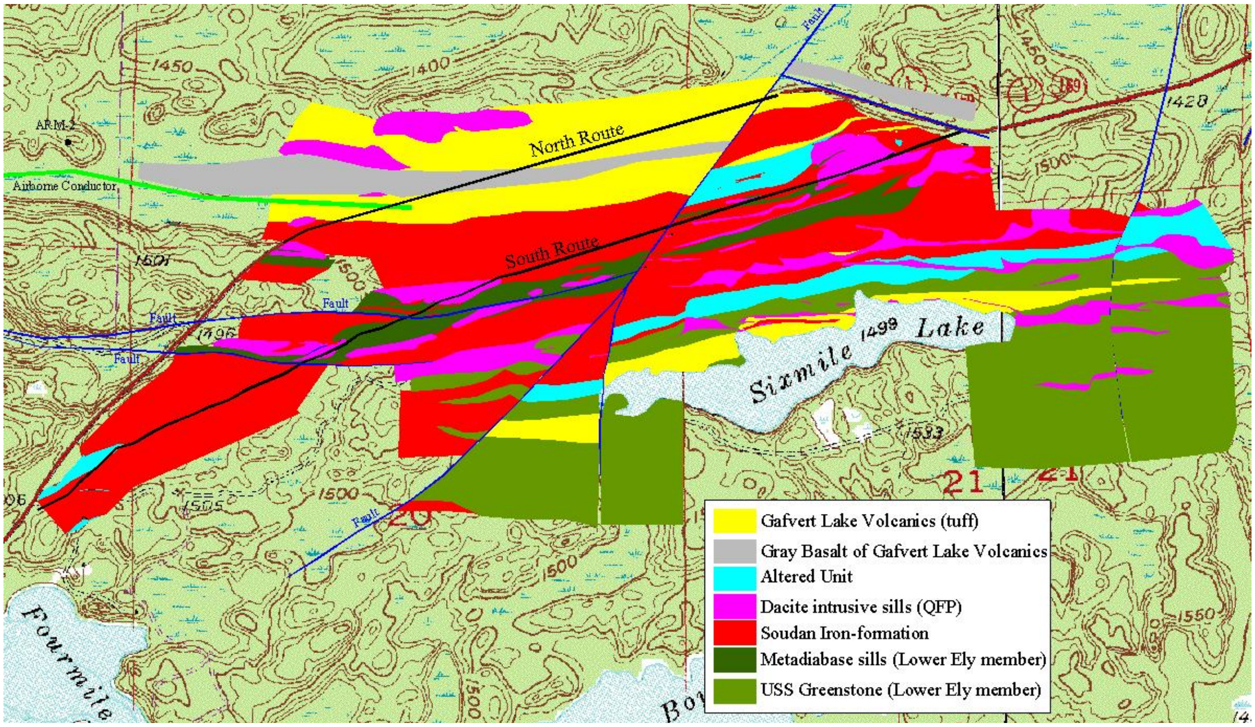

Figure 16. Geologic map in the vicinity of Sixmile Lake that shows both the geology as determined by the 2010 mapping, as well as, the geology as portrayed in the 1978 USS geologic map. This map is similar to Figure 15 in that the same shape files are included plus the following shape files: uss-alt-unit, uss-iron-fm, uss-faults, uss-grnstn, uss-tuff, and uss-qfp. Note that the southernmost cyan-colored Altered Unit was mapped by USS and was described as containing fairly consistent sulfides and local copper-staining.

2. syngenetic (formed while the rock was deposited) semi-massive pyrite beds up to several millimeters thick and occurring in several repetitive micro-beds over a collective thickness of up to one foot thick (Fig. 19) – this type can locally contain as much as 25% pyrite and is restricted to zones in the northern-most part of the Soudan Iron-formation and positioned well to the north of the South Route;
3. cross-cutting veins and veinlets that often exhibit some bifurcation (branch-outs and rejoining branches) that vary from 0.5 mm to 5 mm wide (Fig. 20) and very locally can contain up to 10% visually estimated sulfide;
4. discontinuous massive sulfide patches, up to a few inches across, that consist of medium- to coarse-grained cubic pyrite aggregates (Figs. 21 and 22) – these aggregates are most often seen in the metadiabase unit, and in some instances the iron-formation, in close proximity to faults;
5. discontinuous massive sulfide patches that are fine-grained and up to several centimeters across (Fig. 23) – most often seen in reworked tuffs and sediments of the Gafvert Lake volcaniclastic unit; and
6. weathered-out pyrite that is expressed by empty cubic voids (up to 6 mm across; Fig. 24) and is most often present in the iron-formation near fault zones (expressed by linear-trending valleys), but there are several exceptions.

Figure 17. Presentation of iron-staining associated with disseminated pyrite in a chert band near the top of the Soudan Iron-formation at sample site OC-304 (UTM = 563,391E; 5,299,329N) with visually estimated 3% pyrite. This sample site is just north of present Highway 169 and near the west end of the proposed North Route. Similar material is also present in nearby drill holes. Overall, this type of sulfide-bearing material is presumed to be locally present in portions of the wetlands beneath the proposed corridor for the North Route.

While mapping, special attention was paid to the amount of rust-colored, iron-staining that was present in the outcrops. In some cases, this staining was directly related to the amount of pyrite present in the outcrop and upon closer inspection, with a hand lense, anywhere from 0.25% to 5% was commonly noted. However, not all iron-staining was related to pyrite content. Rather, the staining was due to iron-oxide minerals (goethite and limonite) that are common to many of the iron-formation exposures and related to surficial oxidation of magnetite and hematite. In either event, the presence of iron-staining was always taken seriously, and stained zones were broken up with a rock hammer, closely examined with a hand lense to determine if sulfides were present, and sampled for future geochemical analyses. In some instances, iron-stained beds were present in glacially polished pavement outcrops of iron-formation that precluded sample collection. In two instances these types of outcrops were drilled with a hand-held coring unit and a 3-5 inch long core segment was obtained. At one drilled outcrop about 5% bedding-parallel pyrite bands could be seen in core obtained from a six-inch thick iron-stained band in iron-formation (Fig. 25); whereas, in the other instance (Fig. 26), no sulfides could be seen in core obtained from gossan-coated (goethite and limonite) iron-formation.

Figure 18. Iron-staining associated with a 1-2 foot thick sheared sericite-rich band in iron-formation near the top of the Soudan Iron-formation at sample site OC-303 (UTM = 563,506E; 5,299,303N). The amount of visually estimated sulfides is approximately 5%, but intense weathering of this horizon generates a “punky” rock that when broken with a hammer does not produce any fresh surfaces. This “punky” nature precludes exact determination of sulfide content, and in this case, a large sample piece (shown at the head of the hammer) was taken for geochemical analyses. This sample site, like the one shown in Figure 17, is also near the top of the Soudan Iron-formation and more of this type of material is presumed to be present beneath portions of the wetlands beneath the proposed North Route.

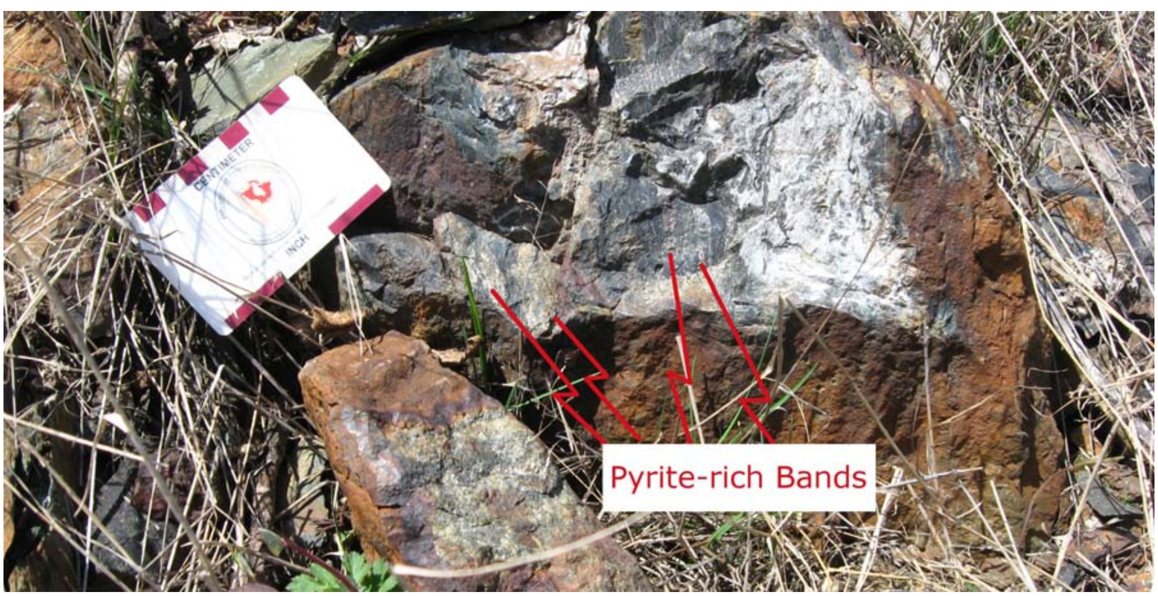

Figure 19. Syngenetic semi-massive pyrite bands (light-colored beds – some denoted by arrows) in a one foot wide zone near the top of the Soudan Iron-formation at sample site OC-17D (UTM = 565,026E; 5,299,629N). This sampled material is located well to the north of the proposed South Route. Note the well-developed iron-staining in the rock and sampled piece – both contain around 20-25% visually estimated pyrite.

Figure 20. Cross-cutting and bifurcating pyrite veins in Soudan Iron-formation (difficult to see in the photograph) from sample site OC-22SULF (old test pit; UTM = 564,021E; 5,299,467N) with 5% visually estimated pyrite in the large block (under the hammer) and in the sample collected from this site (second-largest block). Note that only trace amounts of pyrite are present in all of the other iron-formation pieces at this particular locality. Note also the overall lack of iron-staining in the block and sampled material. The test pit is located within 20 feet of the centerline of the proposed South Route.

Figure 21. Coarse-grained massive pyrite aggregates, with intense iron-stained halos and some localized copper-staining (not evident in photograph). These pyrite aggregates are present within the metadiabase unit at sample site OC-057A (UTM = 563,794E; 5,299,099N). This sampled material is located about 65 feet to the north of the centerline of the proposed South Route.

Figure 22. Coarse-grained massive pyrite aggregates, and intense iron-stained halos, associated with garnet-rich Soudan Iron-formation at sample site OC-49B (UTM = 563,781E; 5,299,102N). This sample contains approximately 15% visually estimated pyrite, and is located about 90 feet to the north of the centerline of the proposed South Route.

Figure 23. Discontinuous massive sulfide patches up to a few centimeters across in intensely sulfide-stained and moderately-sheared tuffaceous sediments of the Gafvert Lake volcaniclastic unit at sample site OC-091 (UTM = 563,413E; 5,299,586N). These rocks contain approximately 10% visually estimated pyrite and are located well to the north of the centerline of the proposed North Route (about 940 feet north). This outcrop was exposed in a relatively new borrow-pit along the edge of a major east-west trending swamp. The "swamp-edge" location of this exposure, and easily-weathered nature of the rock type, indicates that portions of the wetlands along the North Route corridor could be underlain by similar materials.

Figure 24. Weathered-out cubic pyrite pits associated with oxidized and iron-stained Soudan Iron-formation at sample site OC-067 (UTM = 564,070E; 5,299,197N) with approximately 5% pyrite pits (in the entire sample). This type of material locally occurs on the edge of some large iron-formation outcrops in close proximity to a linear valley that is presumed to represent a fault zone. Furthermore, it is difficult to visually estimate the amount of fresh pyrite present in the rock in that the rock breaks into lots of smaller pieces when hammered – each piece is similar to the large piece and only trace amounts of fresh pyrite can be observed. In these types of cases, large samples of similar-looking material were not broken apart and were sampled intact for possible geochemical analyses. This particular sample site is located 30 feet to the north of the centerline of the proposed North Route.

While the above descriptions and photographs give the impression that multiple rock exposures with high pyrite content occur throughout the project area, the opposite is more the norm – most exposures contain only trace to rare amounts of pyrite at best (trace amount is approximately equal to <0.2% pyrite). In fact, most of the pyrite-enriched zones occur as localized "anomalous sulfide zones" – each with a surface area varying from less than four square feet (e.g., a 2 x 2 foot zone) to upwards of 75 square feet (3 feet wide by 25 feet long) at a maximum. While the pyrite content in these areas can locally be as high as 5-10%, the overall average pyrite content for the entire zone averages about 1-2%, and even lower in many cases.

These pyrite-enriched "anomalous sulfide zones" can be extremely variable in size and lateral extent, and thus, they have been assigned to a unique layer (anom-sulf-zones) in the AutoCAD™ and ARCView maps included with this report. All outcrops that average more than 0.5% visually estimated pyrite overall have been assigned to this anom-sulf-zones layer. It should be reiterated these "anomalous sulfide zones" are very small in lateral extent, and they are not overly obvious on the geologic maps unless small-scaled areas are viewed in specific areas of the included maps.

Figure 25. Drilled portion of a five inch thick iron-stained band (reddish-brown colored band) in the iron-formation at sample site OC-70 (UTM = 563,205E; 5,298,781N). The band contains about 5% bedding-parallel pyrite that is evident as yellow stringers in the core piece. Several similar-looking pyrite-bearing bands (each less than eight inches thick) are present elsewhere in this same exposure of iron-formation (around 100 x 175 feet across), but these sulfide-bearing bands only account for about 5% of the entire outcrop. This particular sample site is located about 100 feet to the south of the centerline of the proposed South Route. Note that the pyrite in this particular outcrop is fresh/not oxidized within centimeters of the outcrop surface, as indicated by the fresh pyrite in the cored segment, due to almost complete encapsulation of the pyrite by silica in the cherty iron-formation.

Over 350 samples were collected during mapping from both sulfide-bearing rock exposures and typical sulfide-poor exposures. The volume of sulfides content in each sample was visually estimated by using charts (shown in Figure 27 – committed to memory) that depict the various percentages of dark grains in equal volume areas (white circles). In some rare cases, the sulfides may be too fine-grained to accurately estimate. In these cases, and for other samples with visible sulfides, rock samples that were collected during mapping could be geochemically analyzed to more accurately determine their sulfur contents.

During field mapping, it was noticed that specific rock types contain, on average, less pyrite than other rock types. These can be categorized as follows (starting with rocks with the least sulfide potential and progressing upward to rocks with the highest sulfide potential):

1. the Dacite Unit generally contains the least amounts of sulfides of all the rock types, except for highly-localized and very small internal areas (with ≤1% pyrite) and some scattered quartz veins (with up to 3% pyrite at best) that are ubiquitous to this rock type (note that most quartz veins do not contain pyrite);
2. the Metadiabase Unit generally contains only slightly elevated pyrite contents, except in zones peripheral to two east-west trending fault zones (discussed below);

Figure 26. Drilled portion of gossan-coated Soudan Iron-formation at sample site OC-030 (UTM = 563,131E; 5,298,800N). No sulfides were seen in the four-inch long cored segment obtained at this site. Note that bedding is vertical and can be seen on the right side of the photograph.

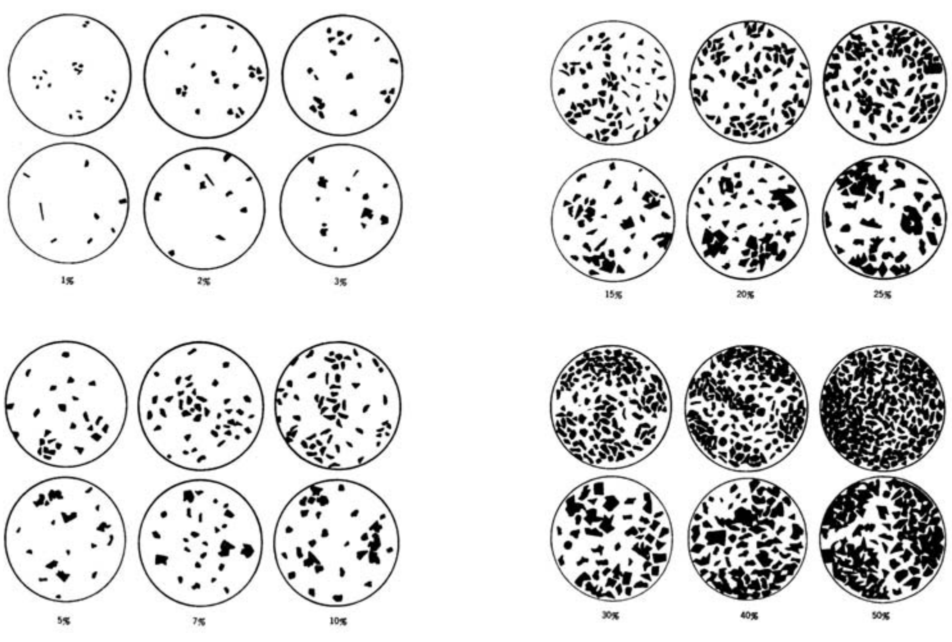

Figure 27. Charts for estimating percentage of minerals in rock (from Compton, 1962).

3. the Altered Unit generally contains only minor amounts of pyrite, but thick zones with up to 2% consistent pyrite contents (often very fine-grained and difficult to estimate) are common to some localities, and samples of this unit should be run for geochemistry – especially in areas where rock cuts will be made;
4. the iron-formation generally contains very little pyrite overall (<0.25% at best), **but** "anomalous sulfide zones" can be extremely common in localized areas that are suspected to be in close proximity to faults (outcrops adjacent to linear-trending valleys);
5. the upper-most northern-most portion of the Soudan Iron-formation contains several pyrite-rich horizons at many localities, and rock cuts should be avoided in this zone (nor are any planned at present); and
6. the most sulfides seen during mapping, and in drill core, are associated with the Gafvert Lake volcaniclastic unit. This type of material is suspected to be present beneath portions of the wetlands situated along the proposed North Route corridor.

SPATIAL DISTRIBUTION OF "ANOMALOUS SULFIDE ZONES"

This section of the report is a review of many of the "anomalous sulfide zones" (>0.5% visually-estimated pyrite) and their spatial placement relative to geologic units and structural elements. It would be next-to-impossible to describe every "anomalous sulfide zone" identified during field work in this report. That being said, the spreadsheets that accompany this report list the visually estimated sulfide contents of each outcrop, and their locations are shown on the accompanying GIS-based map and AutoCAD™ map. The following "anomalous sulfide zones" review is based on the observations recorded in those spreadsheets and is accompanied by various maps that depict some of the "anomalous sulfide zones" relative to the geology. This review starts at the western end of the South Route (Figs. 28 and 29) and progresses toward the east end of the South Route (Figs. 34, 35, and 36). "Anomalous sulfide zones" along the proposed North Route corridor are also discussed (Figs. 38 through 43).

As can be seen in Figure 29, there are relatively minor "anomalous sulfide zones," and relatively few outcrops, at the western end of the South Route. Areas of concern are: 1) pyrite-rich zone in the iron-formation at OC-132; 2) small patch with pyrite in altered mafic unit at OC-34; and 3) weakly-folded pyrite-bearing bands in the iron-formation at OC-070. In the first two examples, the zones with pyrite are small overall and could not be traced into other nearby outcrops. At site OC-070, the pyrite-bearing bands (with up to 5% pyrite in the drilled sample – see Fig. 25) account for only 5% of the exposure, and the pyrite has not been weathered/oxidized due to silica encapsulation. This situation is also the case for pyrite-bearing zones at the south end of OC-030.

No "anomalous sulfide zones" are present along the South Route to the immediate east of Figure 29 until outcrops are encountered in the area shown in Figures 30 and 31. In this area, both the iron-formation and metadiabase unit contain several "anomalous sulfide zones" that locally may contain up to 15% pyrite as massive pyrite aggregates (see Fig. 31 for more detail). The preponderance of "anomalous sulfide zones" in both rock types within this area is probably related to addition of sulfides from the two east-west trending faults. In Figure 31, note the strong topographic control (steep EW-trending ridges and valleys that define the faults) and the proximity of the "anomalous sulfide zones" to the faults.

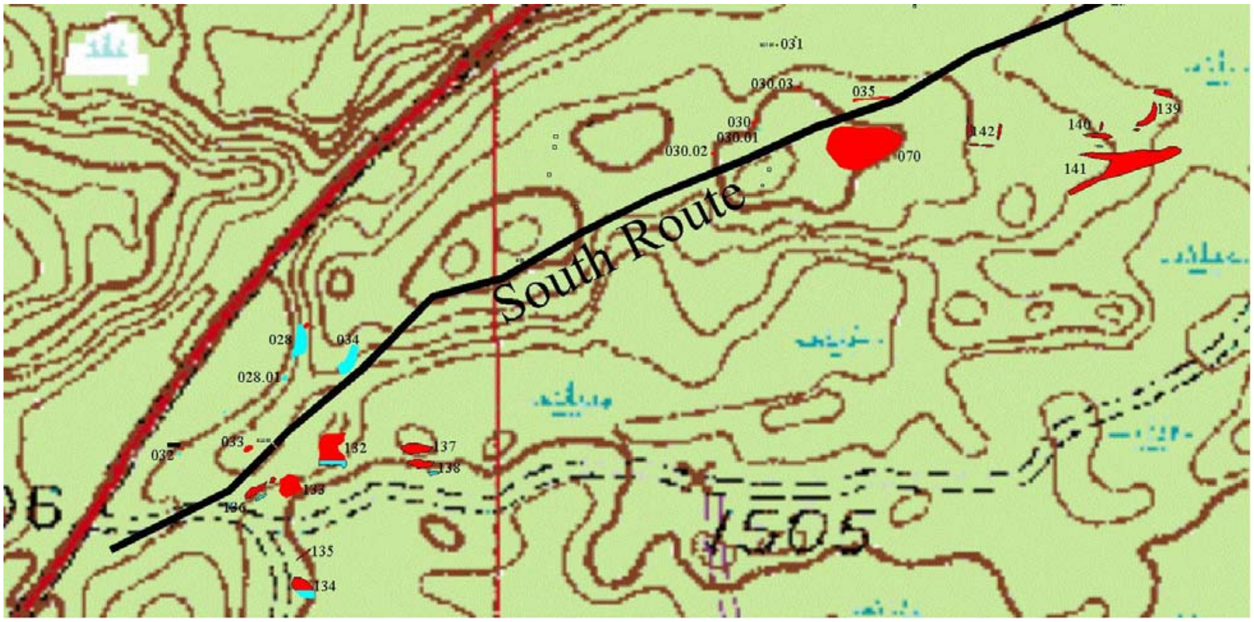

Figure 28. Map of outcrops at the west end of the South Route. Red-colored outcrops are Soudan Iron-formation and cyan-colored outcrops are the Altered Unit (presumably altered tuffaceous sediments to the south of the South Route and altered mafic volcanics to the north of the South Route). Compare with the location of "anomalous sulfide zones" shown in Figure 29.

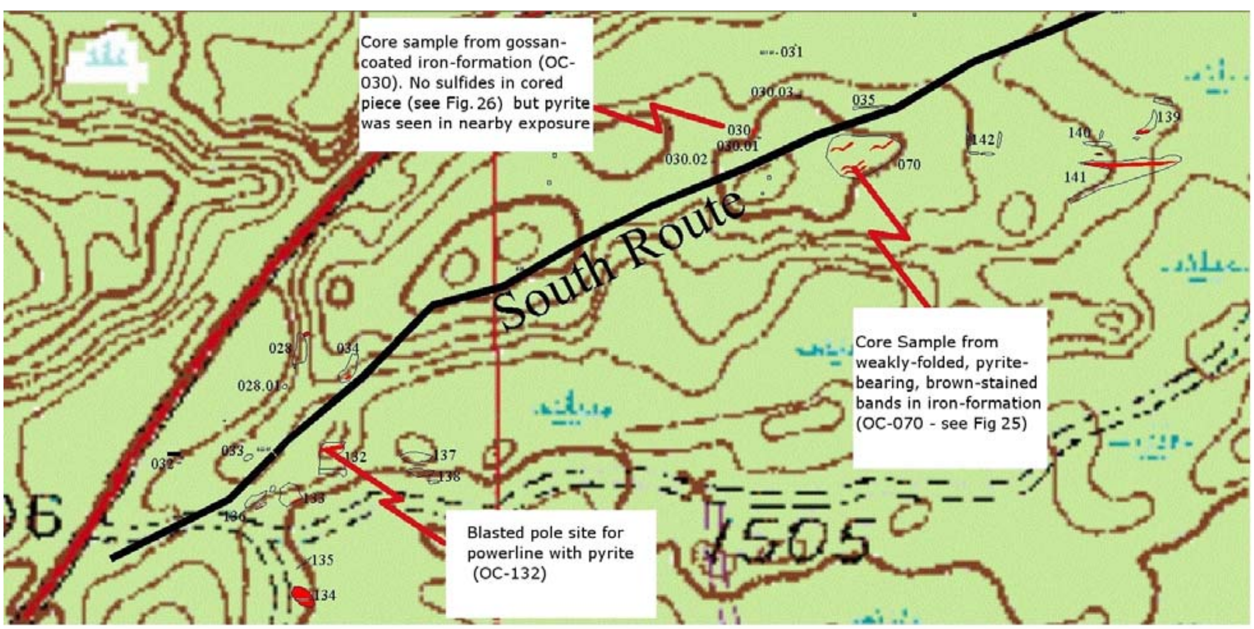

Figure 29. Spatial distribution of "anomalous sulfide zones" (shown in red) at the west end of the South Route.

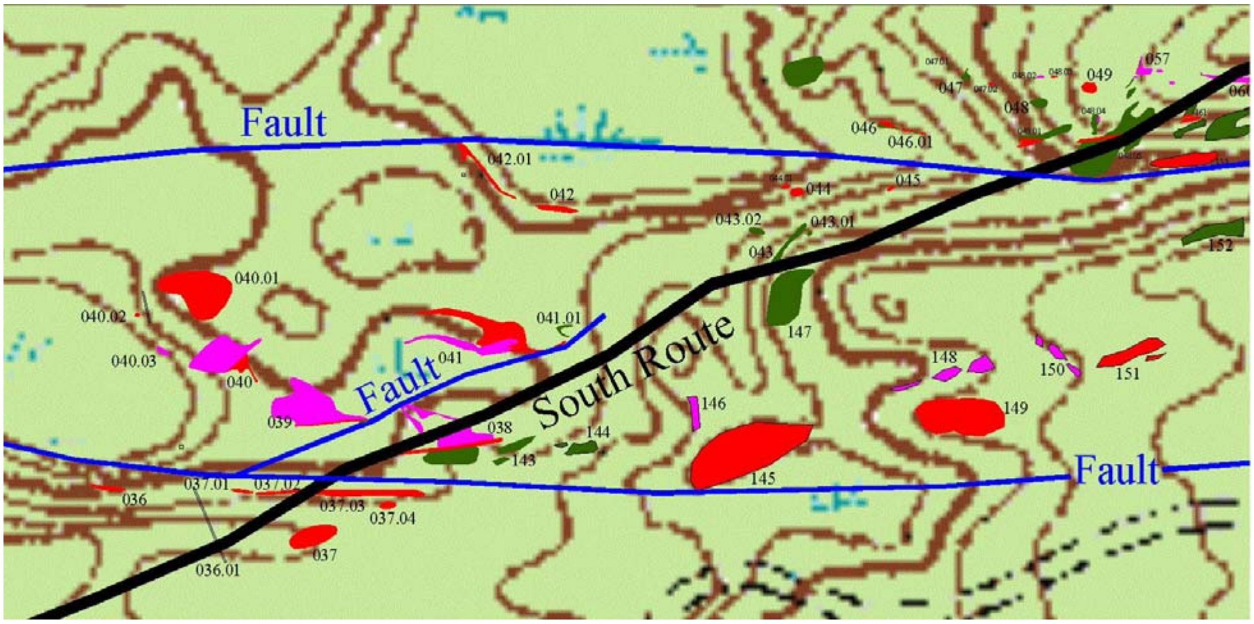

Figure 30. Map of outcrops near the west end of the South Route. Red-colored outcrops are Soudan Iron-formation, magenta-colored outcrops are Dacite, and olive-colored outcrops are the Metadiabase Unit. Note the two east-west trending faults (blue lines) that are defined by linear-trending topographic highs and lows. As can be seen in Figure 31, most of the "anomalous sulfide zones" in this area occur in close proximity to these two faults.

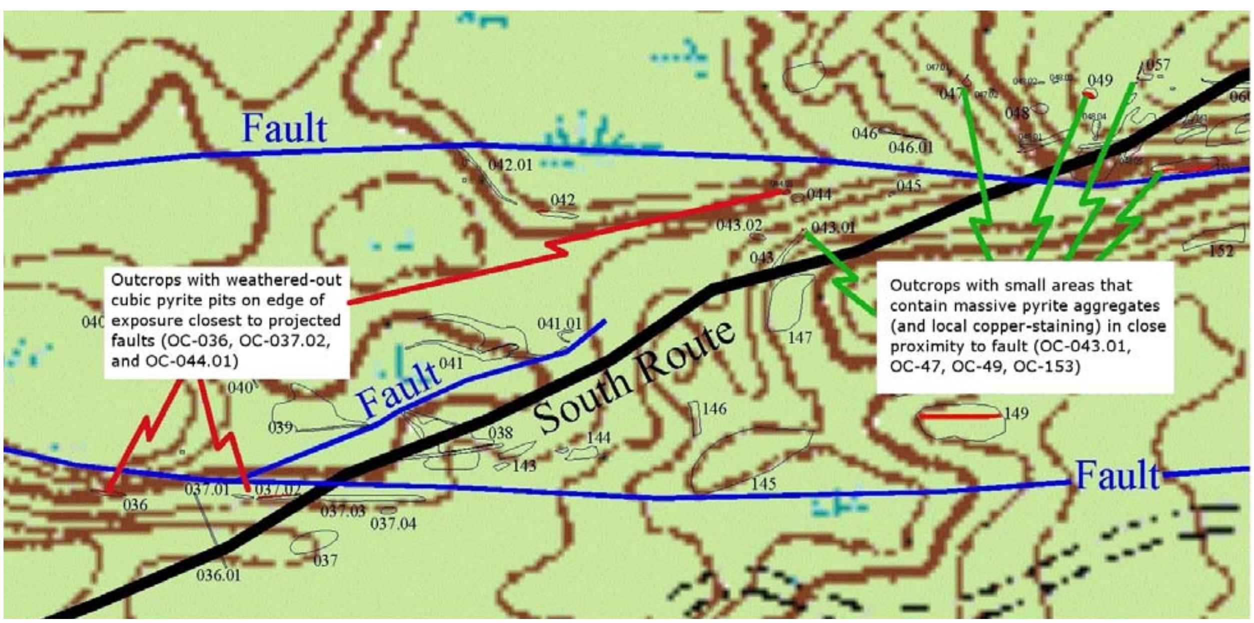

Figure 31. Spatial distribution of "anomalous sulfide zones" (shown in red) in close proximity to two EW-trending faults (near the west end of the South Route).

Figures 32 and 33 display the geology, and spatial distribution of "anomalous sulfide zones," along the central portion of the proposed South Route corridor. As can be seen in the figures, there are numerous outcrops of Soudan Iron-formation in this area that contain late-stage/epigenetic vein pyrite in excess of 1%, e.g. outcrop OC-082. These sulfide-bearing exposures generally occur in close proximity to faults (both EW-trending and NE-trending).

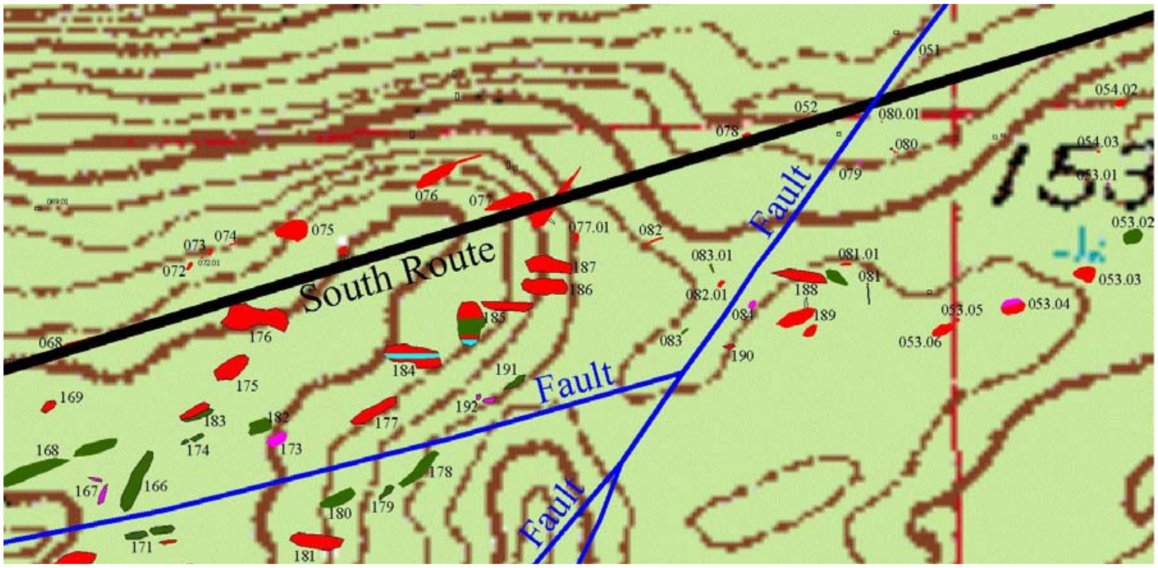

Figure 32. Map of outcrops near the central portion of the South Route. Red-colored outcrops are Soudan Iron-formation, magenta-colored outcrops are Dacite, olive-colored outcrops are the Metadiabase Unit, and the cyan-colored outcrops are the Altered Unit. Note the interconnected faults (blue lines) that are defined by linear-trending topographic highs and lows. As can be seen in Figure 33, most of the "anomalous sulfide zones" in this area occur in close proximity to these faults.

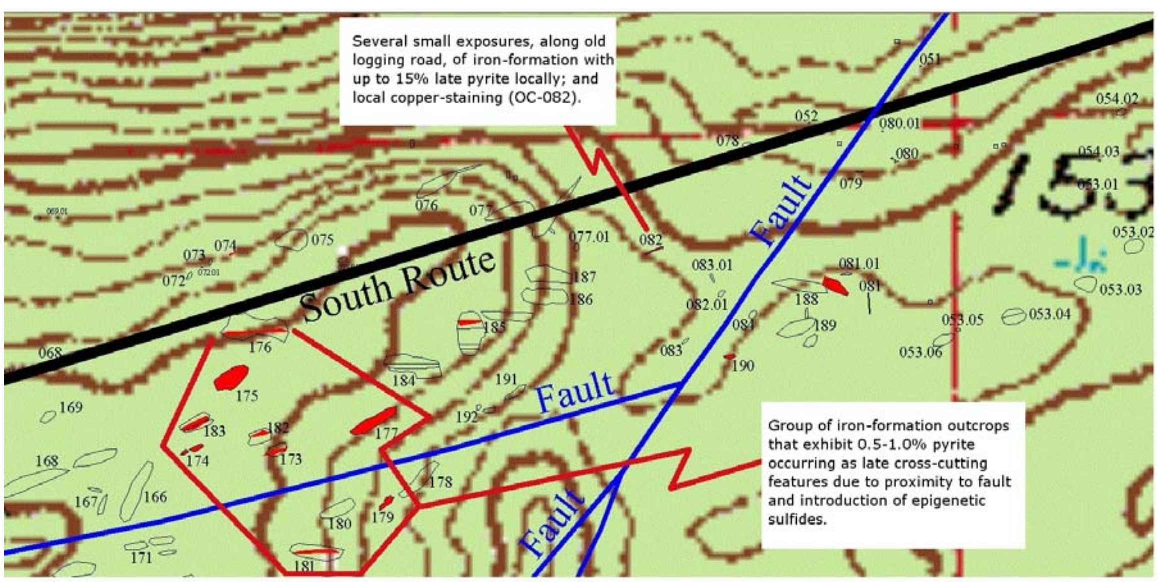

Figure 33. Spatial distribution of "anomalous sulfide zones" (in red) near the central portion of the South Route. Additional pyrite-bearing exposures are probably present in the poorly-exposed area along the NE-trending fault.

The easternmost portion of the South Route corridor is an area where considerable road cuts will be made during construction as the proposed road descends down a steep slope and merges with the current Highway 169 location. The geology and distribution of "anomalous sulfide zones" are portrayed in Figures 34 through 36. Most of this area is underlain by a large dacitic intrusion (Fig. 35), as defined by abundant exposures (Fig. 34), that generally contains less than trace amounts of pyrite, except in highly localized areas associated with: one 5 inch thick quartz vein (OC-011); a late metadiabase dike (OC-012; Fig. 37); and two gradational patches (< 2 x 2 feet across) with 0.5% disseminated pyrite (northwest end of OC-019). In addition to the dacite, there are abundant iron-formation outcrops in this area, and these outcrops also contain only rare to trace amounts of pyrite. In a few extremely localized spots (< 2 x 3 feet across), the iron-formation contains up to a few percent pyrite, e.g. OC-20.01, OC-21, and the southwest tip of OC-003. The geologic entity with the highest percentage of pyrite in this area is the Altered Unit that is exposed at OC-004W. This unit contains in excess of 1% very fine-grained pyrite in the entire outcrop area. Several samples were collected from this exposure for future geochemical analyses, if needed.

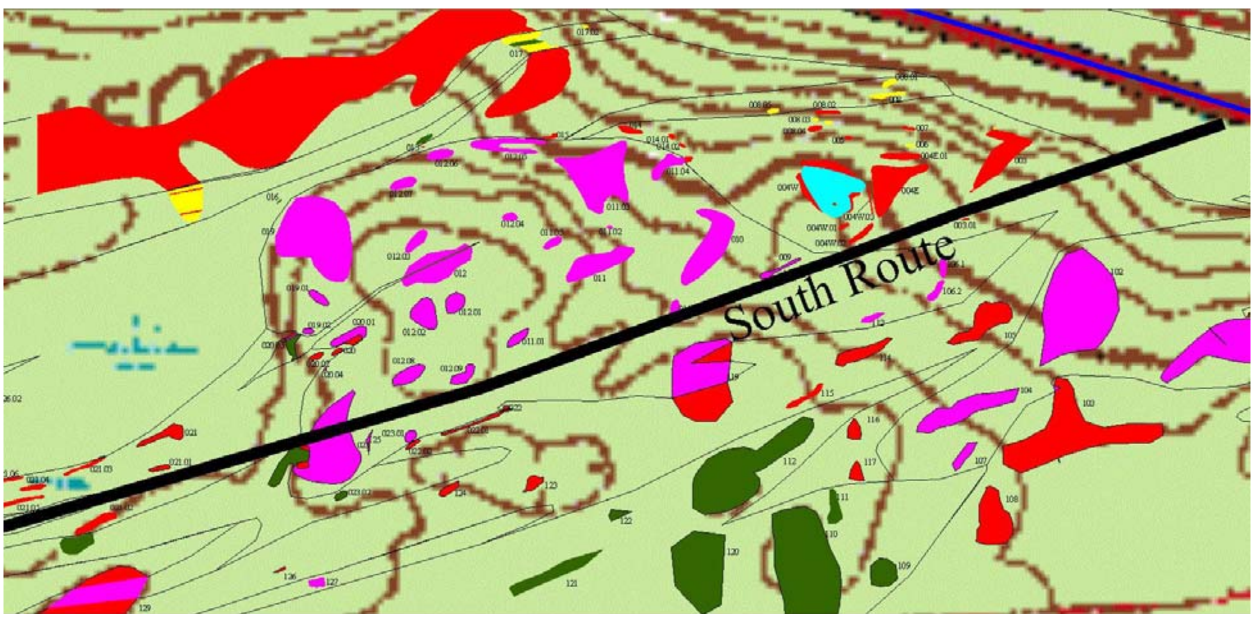

Figure 34. Map of outcrops at the eastern end of the proposed South Route. Red-colored outcrops are iron-formation, magenta-colored outcrops are dacite, olive-colored outcrops are the metadiabase unit, cyan-colored exposures are the Altered Unit, and yellow-colored outcrops are bedded tuffaceous units. Contacts between mapped units are also displayed (compare with geologic map of Fig 35).

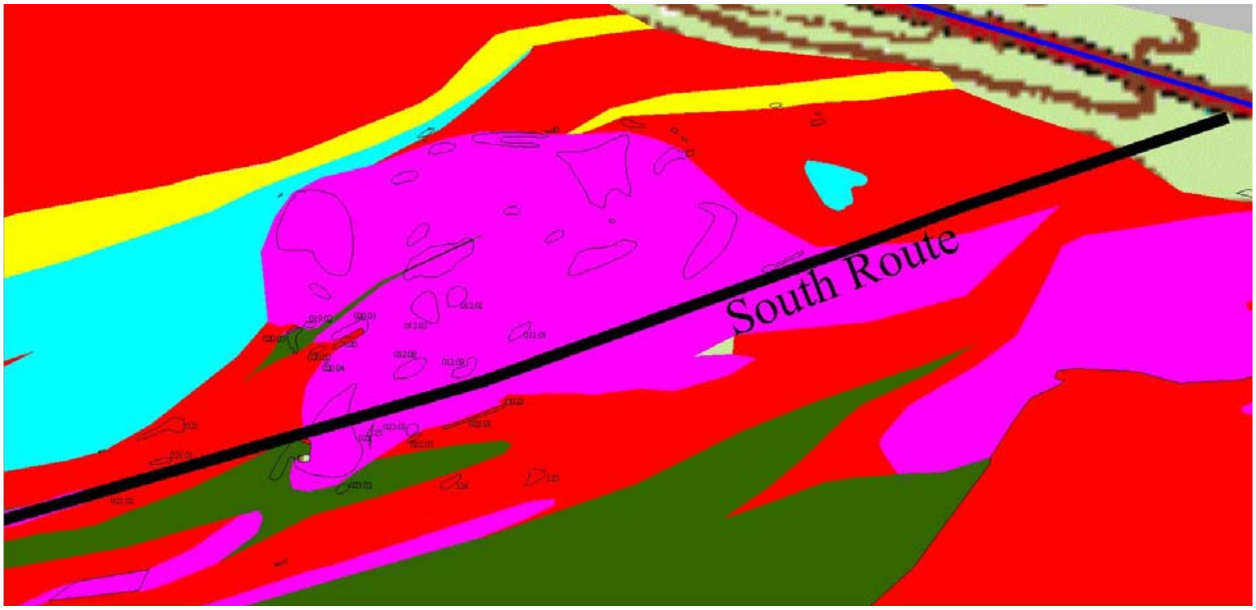

Figure 35. Geologic map of the eastern portion of the South Route showing major geologic units. Color scheme the same as in Figure 34. Note the restricted position of a plug of the Altered Unit (cyan-colored) in the upper right portion of this figure. This unit consistently contains >1% pyrite.

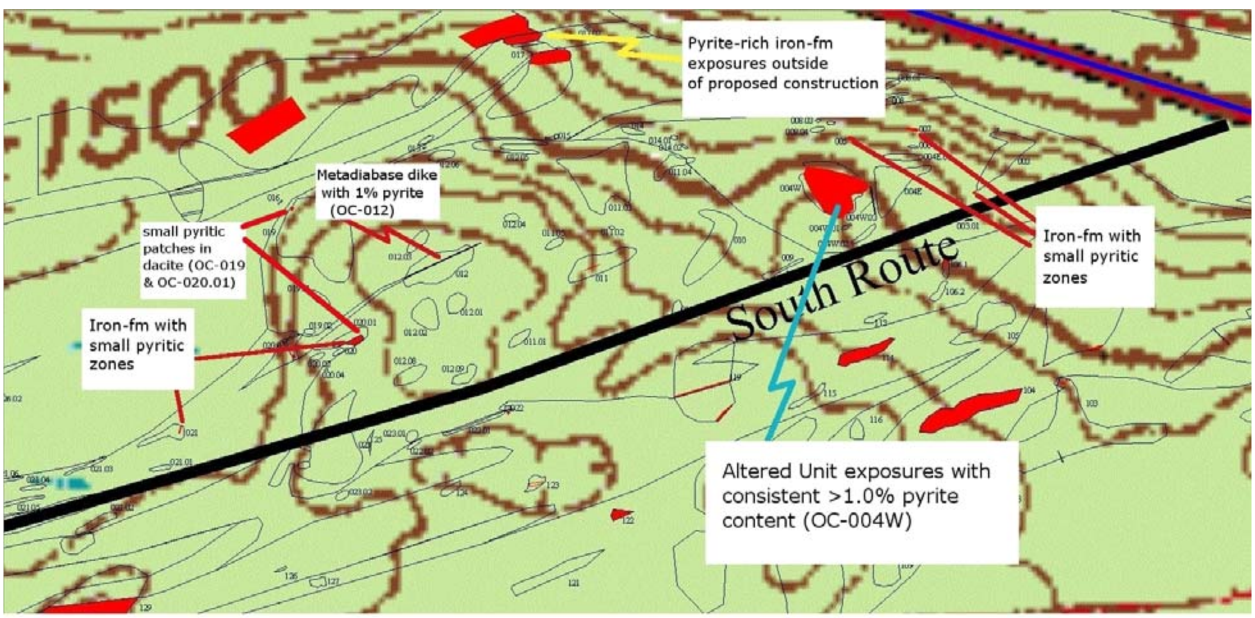

Figure 36. Spatial distribution of "anomalous sulfide zones" in the eastern portion of the South Route. The Altered Unit, which consistently contains >1% pyrite, is present in OC-004W. The large "anomalous sulfide zone" at the top of this figure represents areas where the top portion of the Soudan Iron-formation contains considerable syngenetic/bedded massive sulfide bands (<0.5 cm thick) and will not be disturbed during proposed road construction.

Figure 37. Pavement outcrop of dacite with NNE-trending metadiabase dike (OC-012, UTM = 564,985E; 5,299,584N). The dike contains about 1% pyrite in one sample that could be obtained from this exposure (toward the top of the photograph). Only rare amounts of sulfides were found in the dacite.

Rock exposures along the North Route are limited, and thus the amount of "anomalous sulfide zones" discovered during mapping are few in number. However, any discussion of rock types that are presumably present beneath the wetlands along the North Route needs to include information about rock types and sulfide contents present in drill holes that are located down strike of these wetlands. These drill holes (ARM-1, ARM-2, ARM-3, and V-1) are shown in Figure 38 relative to the trend of an airborne electromagnetic conductor (green line) whose detection was originally responsible for the drilling activity. Figure 39 shows the location of a pyrite-rich exposure (OC-091) and its probable continuation to the east beneath the wetlands that typify the North Route. The dominant rock type in the outcrops and drill holes associated with the North Route are volcanic rocks of the Gafvert Lake volcaniclastic unit. Exposures of this rock unit are typically iron-stained (Fig. 40) and almost always carry at least trace amounts of pyrite. The most pyrite seen in outcrops is typified by Figure 41 where a recent borrow-pit excavation (OC-091) exposed moderately sheared tuffaceous sediment with an estimated 10% pyrite.

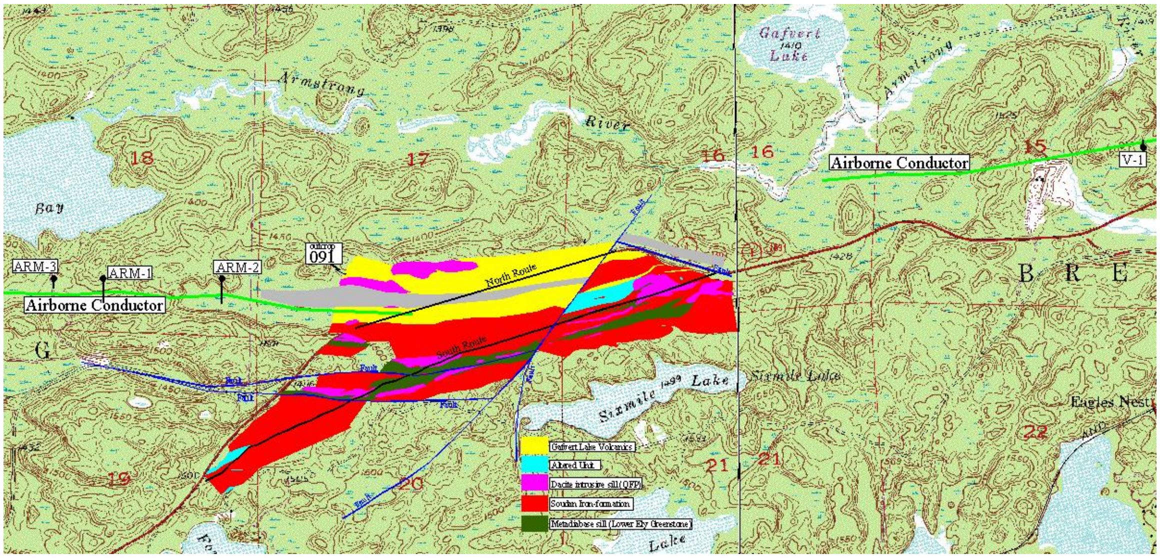

Figure 38. Location of four holes that were drilled into the "Armstrong Bay Conductor" (EW-trending green line on the left and right side of this figure). The holes include ARM-1, ARM-2, and ARM 3 on the left side of the figure; and V-1 on the very right side of the figure. Copies of the lithologic logs (by the exploration companies that drilled the holes and by the NRRI) are included in the appendices of this report. Geologic units on this map include: red = Soudan Iron-formation; green = Metadiabase of the Lower Ely greenstone; magenta = Dacite sills; yellow = Gafvert Lake volcaniclastic unit; and gray = Gray Basalt unit of the Gafvert Lake volcaniclastic unit.

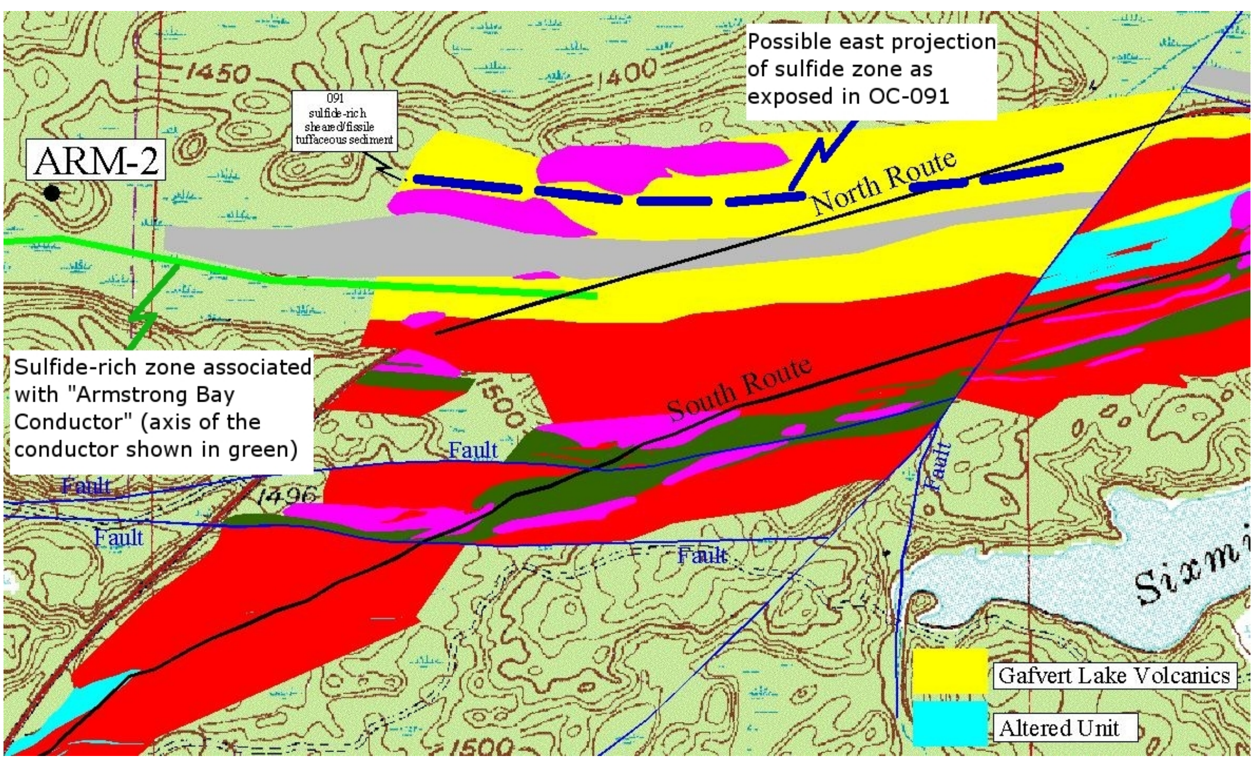

Figure 39. Location of pyrite rich Gafvert Lake volcaniclastic unit found in outcrop (OC-091) and its possible projection to the east beneath the proposed North Route corridor. A similar situation applies to sulfide-rich rocks intersected in drill holes and projected eastward along the trace of the "Armstrong Bay Conductor."

Figure 40. Typical exposure of Gafvert Lake volcaniclastic unit found in close proximity to the North Route. Note the brown iron-staining on the outcrop surface that is related to the presence of pyrite. Only 1% pyrite (which may include an undetermined amount of very fine-grained pyrite) was noted in this exposure (OC-093C; UTM = 563,872E; 5,299,552N). Numerous samples from this outcrop, and from similar-looking iron-stained Gafvert Lake volcaniclastics elsewhere, were collected for geochemical analysis for more accurate determination of the sulfur content.

In drill hole, the units of the Gafvert Lake unit are seen to contain considerable amounts of pyrite. Figure 42 is a correlation diagram of the rock types encountered in the four holes that were drilled into the "Armstrong Bay Conductor." The estimated sulfide contents of the rock units in the holes are also posted on this figure. As can be seen in Figure 42, the Gafvert Lake volcaniclastic units (yellow), graphitic argillite units (dark gray), and chert/iron-formation units (red) contain the highest amount of sulfides (dominantly pyrite) that range from trace amounts to 10% and generally average well above 2% for most of the intervals. Figure 43 is an example of a pyrite-bearing graphitic argillite that was intersected in drill hole V-1. If these types of bedrock materials, as illustrated in Figures 41 and 43, are uncovered during construction of the North Route, their potential to generate acidic waters, which would drain directly into nearby Lake Vermilion, would be profound.

Figure 41. Pyrite-rich Gafvert Lake volcaniclastic unit as exposed in a recent borrow-pit along a logging road to the north of the North Route (OC-091; UTM = 563,413E; 5,299,586N). Position of this outcrop in relation to the North Route is shown in Figure 30. Close-up photograph of this same exposure is presented in Figure 23. Note the highly broken-up nature of this outcrop that is probably characteristic of many bedrock exposures beneath the wetlands of the North Route corridor.

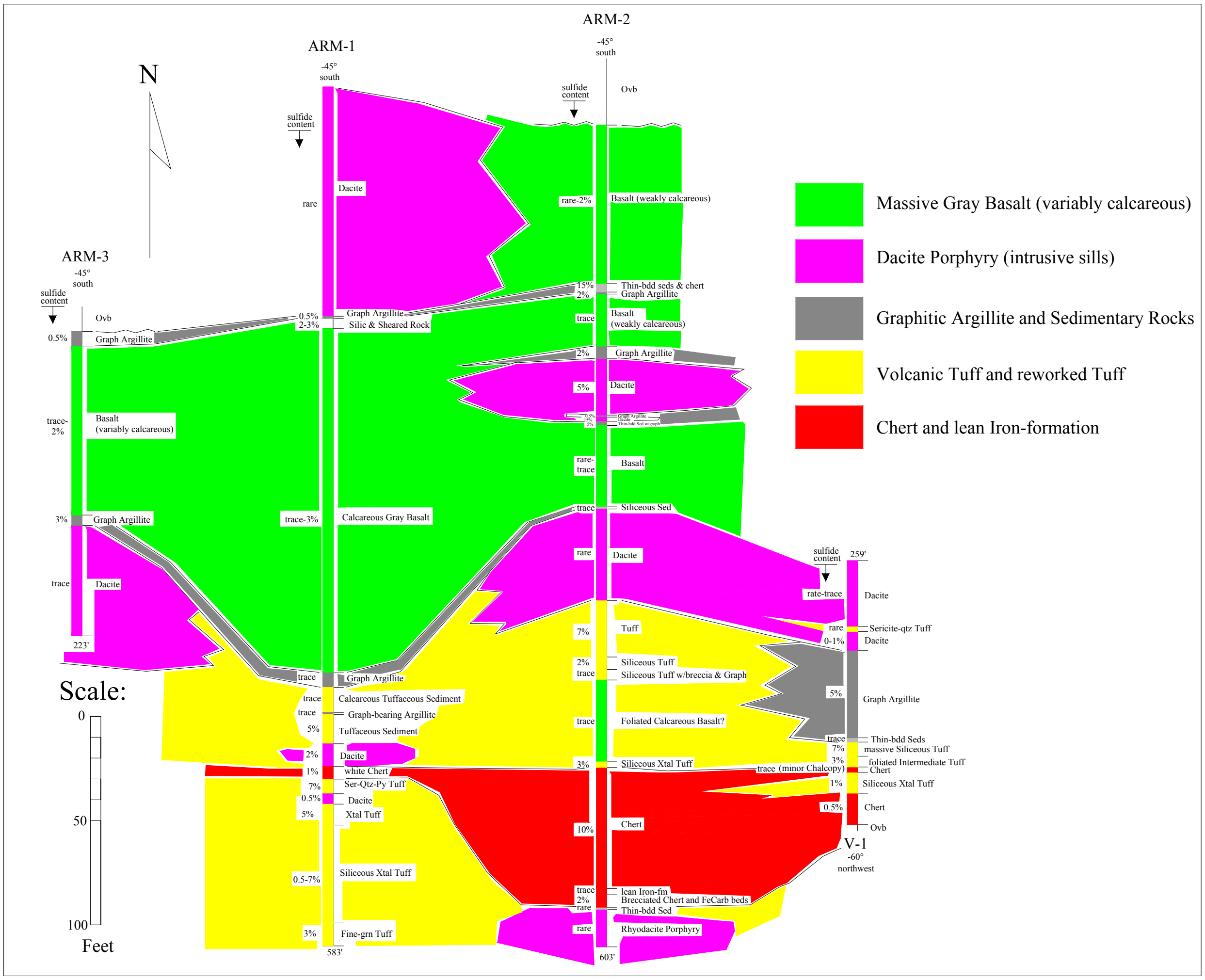

Figure 42. Correlation diagram of geologic units intersected in the four holes drilled into the "Armstrong Bay Conductor." The geologic units in these four holes are probably representative of covered bedrock exposures beneath the wetlands along portions of the proposed North Route corridor. These units occur in close proximity to the axis of the airborne conductor shown in Figures 38 and 39 (green line). Estimated sulfide contents are presented on the left side of each drill hole. Note the presence of graphitic argillite units (one of them, or all of them, are the cause of the electromagnetic conductor) and pyrite-bearing chert/iron-formation in these holes; these two units are not exposed anywhere along the proposed North Route but are presumed to be covered and present beneath the wetlands. Lithologic logs that describe the rock type and visually-estimated sulfide contents, prepared by the exploration company that drilled the holes in 1970, are presented in Appendix J. Lithologic logs for the same holes, prepared by the NRRI, are presented in Appendix K.

Figure 43. Drill core of a pyrite-bearing Graphitic Argillite unit, within the Gafvert Lake volcaniclastic unit, as intersected in drill hole V-1 at 145-164 feet. This unit is well-bedded (note the angle at which the core breaks), and contains bedding-parallel and cross-cutting quartz veins (white bands). Most of the pyrite is associated with the quartz veins, and it averages about 5% of the rock with localized high concentrations as high as 15% visually-estimated pyrite (note the red arrow).

CONCLUSIONS

Detailed mapping of rock exposures along one of the proposed Highway 169 relocation routes to the north of Sixmile Lake, the South Route, did not reveal the presence of any continuous geologic units with consistently high sulfide contents nor were any indications found to indicate the presence of volcanogenic massive sulfide (VMS) deposits. Rather, mapping revealed that there are only scattered outcrop occurrences with high sulfide contents – and these are present mostly in the iron-formation. These occurrences, referred to as "anomalous sulfide zones," are generally confined to portions of single outcrops and are generally restricted to very small areas (varying from less than two feet by two feet to less than three feet by 25 feet) with sulfide contents ranging from 0.5-5% pyrite. Many of the "anomalous sulfide zones" occur as isolated "islands" in a sea of pyrite-barren outcrops, except in the vicinity of fault zones. In these instances, the amount of "anomalous sulfide zones" show an increase in abundance near the faults, and some of these zones have higher sulfide contents than usual (up to 15% in some very small locales). Thus, any road cuts made during road construction along the South Route should take these faulted/pyrite-enriched zones into account.

While outcrops are not as abundant along the proposed North Route, geologic units intersected in drill holes, or traced down-strike from peripheral outcrops, indicate that sulfide-bearing units are probably more common to the North Route. In the first instance, several sulfide-rich units were found to be present in four core holes that were drilled into an electromagnetic conductor (the "Armstrong Bay Conductor") by mineral exploration companies. Conductive units in the drill holes include sulfide-rich graphitic argillite, sulfide-poor graphitic argillite, and pyritic iron-formation, as well as several other non-conductive but sulfide-bearing units. The trend of the geophysical conductor suggests that many of the sulfide-bearing units intersected in the drill holes are more than likely present beneath the wetlands at the west end of North Route. In the second instance, pyrite-rich tuffaceous sediments, found well to the north of the west end of the North Route, appear to trend eastward and could be present beneath the wetlands towards the east end of the North Route.

In conclusion, "anomalous sulfide zones" related to structural preparation and introduction along fault zones appears to be the main concern related to the South Route. Road cuts in these fault-related "anomalous sulfide zones" should take this type of occurrence into account. The main concern regarding the North Route is that rocks beneath the wetlands along this corridor appear to contain a much higher sulfide content based on trends of geologic units. If this route is chosen, care should be exercised to avoid disturbing the bedrock beneath the peat and till along the North Route.

This report concludes the mapping and sampling phase of the project. The second phase will consist of conducting sulfur analyses, by LECO, of all samples located in areas where roadcuts are planned. The results from this phase will be interpreted and released in an addendum report.

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Meineke, D.G., Vadis, M.K., and Klaysmat, A.W., 1976, Gyttja Lake Sediment Exploration Geochemical Survey of the eastern Lake Vermilion – Ely area, St. Louis and Lake Counties, Minnesota: MDNR report 73-3-1, 22 p., 11 plates.

Peterson, D.M. and Jirsa, M.A., 1999, Bedrock geological map and mineral exploration data, western Vermilion District, St. Louis and Lake counties, northeastern Minnesota: St. Paul, Minnesota Geological Survey Miscellaneous Map Series M-98.

APPENDIX A:

SCANNED OUTCROP SHEETS
(On DVD in back pocket of this report)

APPENDIX B:

ALL OUTCROP PHOTOGRAPHS
(On DVD in back pocket of this report)

APPENDIX C:

OUTCROP DESCRIPTION EXCEL FILE
MnDOT_Sixmile_Outcrop_Data.xls
(On DVD in back pocket of this report)

APPENDIX D:

SAMPLE DESCRIPTION EXCEL FILE
MnDOT_Sixmile_Sample_Data.xls
(On DVD in back pocket of this report)

APPENDIX E:

PHOTO DESCRIPTION EXCEL FILE
MnDOT_Sixmile_Photo_Data.xls
(On DVD in back pocket of this report)

APPENDIX F:

AutoCAD^{TM} MAP FILES
(On DVD in back pocket of this report – see Appendix H for description of various layers)

APPENDIX G:

SCAN OF SIXMILE LAKE GEOLOGY PREPARED IN 1978 FOR UNITED STATES STEEL CORPORATION (ORIGINALLY PREPARED AT 1 INCH = 200 FEET)

(On DVD in back pocket of this report)

APPENDIX H:

BRIEF DESCRIPTIONS OF LAYERS IN AutoCAD™ DRAWING AND SHAPE FILES IN ArcGIS MAP

Brief descriptions of the items portrayed as layers in the drawing file 6mile_geology_map_final.dwg (Appendix F) and as shape files in the ArcGIS map (Appendix I) are as follows:

1. airborne-conductors = green line marking the approximate center of an airborne electromagnetic conductor (the "Armstrong Bay Conductor") as defined by two surveys conducted for USS and the Hanna Mining Company in the 1960s (on file at the MDNR);
2. alt-unit = small cyan-colored polygons denoting individual outcrops of a unique altered unit, with bright pink- and green-colored epidote, first mapped by USS to the north of Sixmile Lake in 1978 and noted in this investigation;
2. alternate-route = a third proposed trend for the South Route, located within 100 feet to the north of the Mn/DOT-surveyed South Route, that would encounter very few rock exposures and possibly lesser sulfide-bearing zones;
3. anom-sulf-zones = line-work and red-colored polygons that denote sulfide-enriched exposures, or parts of exposures, that were encountered during mapping – sulfide content in these "anomalous zones" varied from 0.5% to 2% but locally was as high as 25%;
4. bif = small red-colored polygons denoting outcrops of banded iron-formation;
5. Big_alt = large cyan-colored polygons used as a map unit to denote areas with abundant outcrops of the altered unit on the geologic map;
6. Big_BIF = large red-colored polygons used as a map unit to denote areas with abundant outcrops of banded iron-formation (mostly correlative with the Soudan Iron-formation) on the geologic map;
7. Big_dacite = large magenta-colored polygons used as a map unit to denote areas with abundant outcrops of sill-like dacite bodies on the geologic map;
8. Big_Gafvert = large yellow-colored polygons used as a map unit to denote areas with abundant outcrops of felsic-intermediate tuffs and reworked tuffs/sediments (mostly correlated with the Gafvert Lake volcaniclastic unit) on the geologic map;
9. Big_gray_basalt = large gray-colored polygons used as a map unit to denote areas with outcrops of a poorly-pillowed gray basalt unit near the base of the Gafvert Lake Volcanics on the geologic map;
10. Big_metadiabase = large olive-colored polygons used as a map unit to denote areas with abundant outcrops of massive, metamorphosed, diabasic sills (mostly correlative with the Lower Ely Greenstone) on the geologic map;
11. contacts = polygon line-work used to define specific map units and hatched to form the Big_BIF, Big_dacite, Big_Gafvert, etc. polygons;
12. dacite = small magenta-colored polygons denoting individual outcrops of intrusive dacite sills (also often referred to as quartz-feldspar porphyries or QFPs);
13. drill-holes = small black dots denoting the locations of four drill holes (ARM-1, ARM-2, ARM-3, and V-1) that were cored by companies exploring for base metals in the 1970s to the northwest and northeast of Sixmile Lake;
14. faults = blue lines that define both NNW- and EW-trending fault zones;
15. gray-basalt = small gray-colored polygons denoting individual outcrops of a gray-colored basalt near the base of the Gafvert Lake volcaniclastic unit;
16. logging-roads = line-work that displays all dirt roads encountered and/or traversed during field work;
17. metadiabase = small olive-colored polygons that denote individual outcrops of intrusive metadiabase sills, correlative with the upper portion of the Lower Ely Greenstone;

18. MJS_traverses = line-work that displays actual traverses conducted by Mark Severson during outcrop searches;
19. outcrop-numbers = lists specific outcrop numbers used during mapping and sampling for each exposure or series of exposures;
20. outcrop-shapes = polygon line-work used to define specific outcrops and hatched to form the bif, dacite, metadiabase, etc. polygons;
21. proposed-road = trace of both the North Route and South Routes along their proposed centerlines;
22. Test_trenches_pits = outlines of test pits and shallow trenches that could have bottomed out in bedrock (now filled with a glacial till veneer) and were encountered during field work;
23. Till = line-work and brown-colored small polygons that denote individual exposures of till noted along the steep hillside to the immediate south of the current Highway 169 corridor;
24. tuff = small yellow-colored polygons that denote individual outcrops of tuffaceous rocks and tuffaceous sediments that are generally correlative with the Gafvert Lake volcaniclastic unit;
25. uss-alt-unit = line-work and cyan-colored polygons outlining USS-mapped areas with abundant outcrops of the "altered unit;"
26. uss-faults = blue lines mapped as faults by USS;
27. uss-iron-fm = line-work and red-colored polygons outlining USS-mapped areas with abundant outcrops of banded iron-formation;
28. uss-grnstn = line-work and olive-colored polygons outlining USS-mapped areas with abundant outcrops of mafic volcanic units (including an unknown amount of the metadiabase unit) correlative with the Lower Ely Greenstone;
29. USS-map = digital scan of the 1978 USS map of the Sixmile Lake area – note that this map was based on mapping along cut grid lines (400 feet apart and trending north-south) and thus the locations of individual outcrops do not always agree with GPS-located outcrops in some areas; and
30. uss-qfp = line-work and magenta-colored polygons outlining USS-mapped areas containing abundant outcrops of the dacite porphyry.

APPENDIX I:

ArcGIS MAP AND SHAPE FILES

NOTE: These files have not yet been finalized due to changes/additions that will be made during interpretation of geochemical results. The shape files will be submitted after anticipated geochemical results are received.

APPENDIX J:

SCANS OF COMPANY LOGS FOR DRILL HOLES:
ARM_1, ARM_2, and ARM_3
(On DVD in back pocket of this report)

APPENDIX K:

SCANS OF NRRI LOGS FOR DRILL HOLES:
ARM_1, ARM_2, ARM_3, and V_1
(On DVD in back pocket of this report)