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BEDROCK GEOLOGY OF LAKE VERMILION/SOUDAN UNDERGROUND MINE STATE PARK

by

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Precambrian Research Center Geology Field Camp**

Technical Report

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INTRODUCTION

Lake Vermilion/Soudan Underground Mine State Park possesses a rich cultural and natural history that is directly related to the bedrock geology in this part of Minnesota's Vermilion District. The bedrock geology comprises a complex record of Neoproterozoic-age (>2.5 billion years old) volcanic, sedimentary, hydrothermal, structural, and tectonic events associated with the Wawa-Abitibi Terrane within the southwestern part of the Superior Craton (Stott et al., 2007; Stott and Mueller, 2009; Lodge et al., 2013, 2015).

Considerable geological research has been conducted since the late 1990s to study the stratigraphy, hydrothermal alteration, structural geology, and economic geology in the Vermilion District (Lawler and Riihilouma, 1997; Hudak and Morton, 1999; Peterson and Jirsa, 1999; Hovis, 2001; Jirsa et al., 2001; Newkirk et al., 2001; Odette et al., 2001; Peterson, 2001, 2005; Peterson et al., 2001; Hudak et al., 2002a, 2002b, 2006, 2007, 2012; Hocker et al., 2003; Peterson and Patelke, 2003; Hoffman, 2007; Jansen et al., 2009; Lodge et al. 2013, 2015). As well, numerous geological field trips have been conducted in this region since the mid-2000s (Hudak et al., 2004, 2014; Jirsa et al., 2004, 2016; Larson and Mooers, 2009; Peterson and Patelke, 2004; Peterson et al., 2009a, 2009b). Although several regional scale geologic maps exist for regions encompassing, and in close proximity to, Lake Vermilion/Soudan Underground Mine State Park (Ojakangas et al., 1978; Sims and Southwick, 1980, 1985; Sims, 1985; Southwick, 1993; Peterson and Jirsa, 1999; Jirsa et al., 2001; Peterson and Patelke, 2003; Hudak et al., 2002b; Hoffman, 2007), no coherent, detailed (1:10,000 scale) geologic map exists for the region comprising Minnesota's newest state park.

Minnesota Department of Natural Resources Parks and Trails staff have partnered with the Precambrian Research Center (PRC) at the Natural Resources Research Institute (NRRI) at the University of Minnesota Duluth to conduct geologic mapping in Lake Vermilion/Soudan Underground Mine State Park since 2010. This partnership had two primary goals: 1) to offer a collaborative opportunity to train upper-level undergraduate and graduate university geology students effective and efficient methods to conduct geologic mapping in Precambrian terranes; and 2) through geologic mapping, gain a deeper understanding of the geological processes and events associated with the development of the Vermilion District within the context of the larger Wawa-Abitibi Terrane. This partnership has led to the development of a new geologic map for Lake Vermilion/Soudan Underground Mine State Park (Peterson et al., 2016) which this report describes.

PRC MAPPING PROJECTS IN LAKE VERMILION/SOUDAN UNDERGROUND MINE STATE PARKS

In 2010, two PRC capstone mapping projects (one in Soudan Underground Mine State Park under the direction of Dr. Dean Peterson of the PRC, the other in the western half of Lake Vermilion State Park under the direction of Dr. George Hudak of the PRC) were conducted under Minnesota Department of Natural Resources Special Permit 201051 (Figure 1). Three areas were mapped between August 1 and August 8, 2010, including:

- 1) The surficial bedrock geology encompassing the western one-half of Section 27, Township 62 North and Range 15W, and eastern two-thirds of Section 28, Township 62 North and Range 15 West. This mapping was completed by Dr. Dean Peterson and three PRC Field Camp students. Mapping was completed at 1:5,000 scale.
- 2) The underground bedrock geology encompassing the 27th Level West Drift within the former workings of the Soudan Mine. This area occurs in the subsurface at Soudan Underground Mine State Park in the west-central part of Section 27, Township 62 North and Range 15W, and east-central part of Section 28, Township 62 North and Range 15 West. This mapping was completed by Dr. Dean Peterson and three field camp students. Dr. George Hudak assisted in one evening of mapping with the students. Mapping was completed at 1:1,000 scale and compiled at 1:2,500 scale.
- 3) The surficial bedrock geology encompassing approximately the southern one-third of Section 14, Township 62 North and Range 15 West, the southern two-thirds of Section 15, Township 62 North and Range 15 West, the majority of Sections 22 and 23, Township 62 North and Range 15 West, and the northernmost parts of Sections 26 and 27, Township 62 North and Range 15 West. These areas comprise the northeastern part of Soudan Underground Mine State Park and the western part of Lake Vermilion State Park. Mapping in this area was completed by five PRC Field Camp students and Dr. George Hudak. Mapping was completed at 1:5,000 scale.

As a result of these efforts, two Precambrian Research Center Map Series geologic maps were produced and published in mid-August, 2010. These included:

- Vallowe, A. M., Thalhamer, E. J., Rhoades, D. L., and Peterson, D. M., 2010, Surface and Subsurface Geological Maps of the Soudan Underground Mine State Park, St. Louis County, Northeastern Minnesota: Precambrian Research Center Map Series, PRC/Map-2010-01, 1:2,500 and 1:5,000 scales (this map may be downloaded at the following website: <http://www.d.umn.edu/prc/fieldcamp/2010%20Field%20Camp/PRC-MAP-2010-01.pdf>).
- Radakovich, A. L., Parent, C. T., Partridge, M. E., Ritts, A. D., Pierce, R., and Hudak, G. J., 2010, Reconnaissance Bedrock Geological Map of the Northern Part of Soudan Underground Mine State Park and the Northwestern Part of Lake Vermilion State Park, St. Louis County, Minnesota: Precambrian Research Center Map Series, PRC/Map-2010-04, 1:5,000 scale (this map may be downloaded at the following website: <http://www.d.umn.edu/prc/fieldcamp/2010%20Field%20Camp/PRC-Map-2010-04.FNL.pdf>).

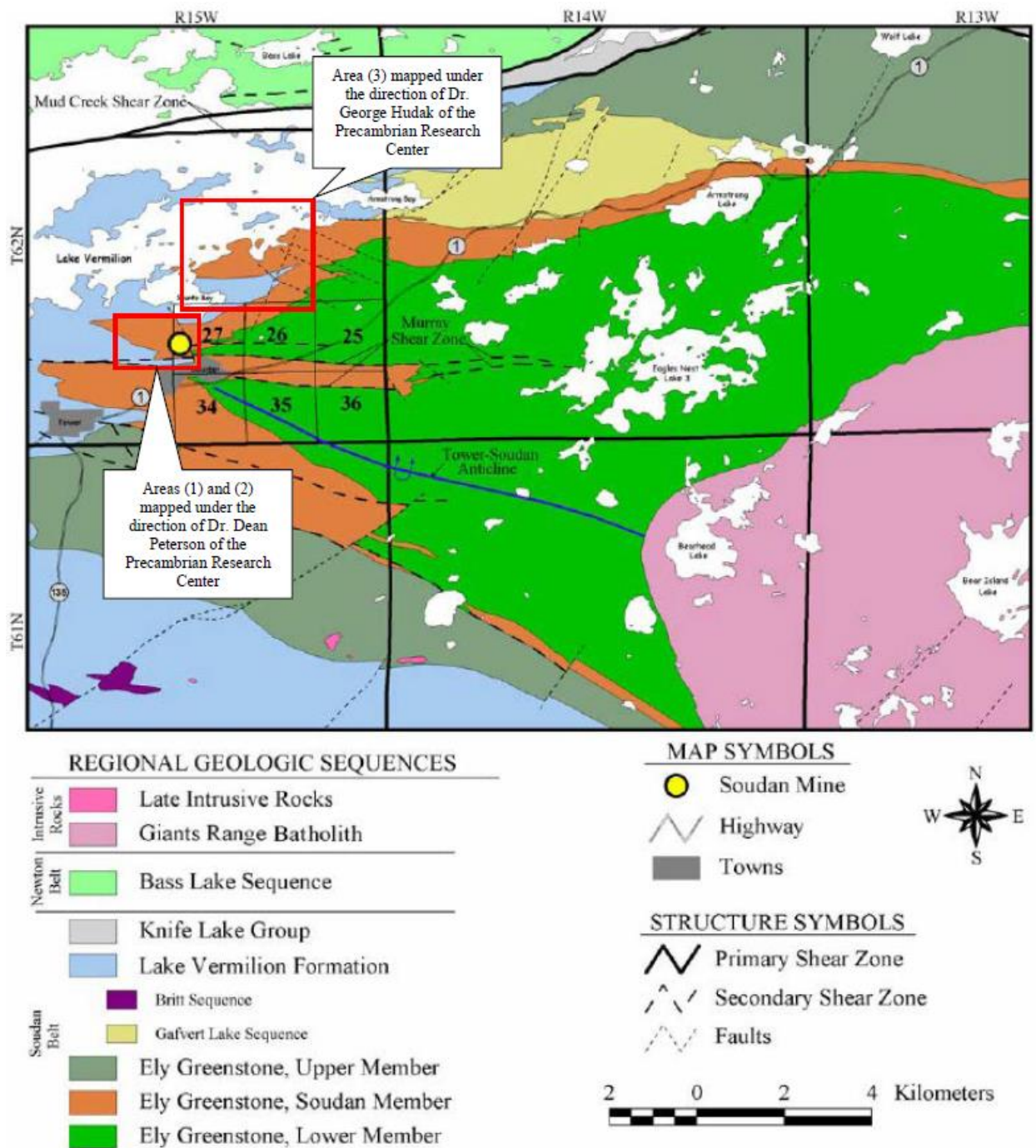


Figure 1. Locations of areas mapped during Capstone Project at Soudan Underground Mine State Park and Lake Vermilion State Park by PRC Faculty and Students, August, 2010. Refer to the “Methods” section of this document for detailed descriptions of Areas (1), (2), and (3). Map modified from Peterson and Patelke, 2003.

Geologic mapping performed in Soudan Underground Mine State Park and Lake Vermilion State Park by PRC faculty and students during the summers of 2011 and 2012 was completed under Minnesota Department of Natural Resources Special Permit No. 201252. Two areas were mapped (Figure 2), and included:

- 1) Surficial geologic mapping conducted between July 31 and August 6, 2011 in the northwestern part of Soudan Underground Mine State Park. The goal of this mapping project was to acquire detailed (1:5,000 scale) geologic data in the western part of Soudan Underground Mine State Park that to date had not been accomplished. The mapping area extended geologic mapping conducted in Soudan Underground Mine State Park that was conducted the previous year by Vallowe et al. (2010), and overlapped with mapping conducted previously by Peterson and Patelke (2003) and Radakovich et al. (2010). The purpose of the overlap was to allow geological interpretations in the overlapped areas to be reinterpreted from previous mapping endeavors to negate map area boundary effects. This same area was mapped between July 30 and August 4, 2012 to verify and enhance student mapping results from the previous year.
- 2) Surficial geologic mapping conducted between August 7 and August 13, 2011 in the eastern half of Lake Vermilion State Park. The purpose of this mapping was to complete the detailed (1:5,000) scale geologic map of Lake Vermilion State Park that was initiated by Radakovich et al. (2010). Geologic mapping conducted for this project overlapped with previous mapping by Peterson and Patelke (2003) and Radakovich et al. (2010) in an effort to complete a seamless map of Lake Vermilion State Park that was devoid of boundary effects resulting from several mapping campaigns.

As a result of these efforts, one Precambrian Research Center Map Series geologic map was produced and published in mid-August, 2011:

- Heim, N., Scott, H., Kilduff, R., Rahtz, C., Vial, A., Young, S., Mahr, C., and Hudak, 2012, Preliminary Bedrock Geology Map of the Eastern Part of Lake Vermilion State Park, St. Louis County, Northeastern Minnesota: Precambrian Research Center Map Series, PRC/Map-2011-01, 1:5,000 scale (this map may be downloaded at http://www.d.umn.edu/prc/fieldcamp/2011_Field_Camp/Vermilion_FINAL.pdf).

The results of the 2011 and 2012 mapping projects in Soudan Underground Mine State Park, and the 2011 capstone mapping project (Heim et al., 2011) in the eastern half of Lake Vermilion State Park, when combined with previous mapping projects in Soudan Underground Mine and Lake Vermilion State parks (Peterson and Patelke, 2003; Hoffman, 2007; Vallowe et al., 2010; Radakovich et al., 2010), had the desired effect that the entire areas of Soudan Underground Mine and Lake Vermilion state parks were geologically mapped at 1:5,000 scale.

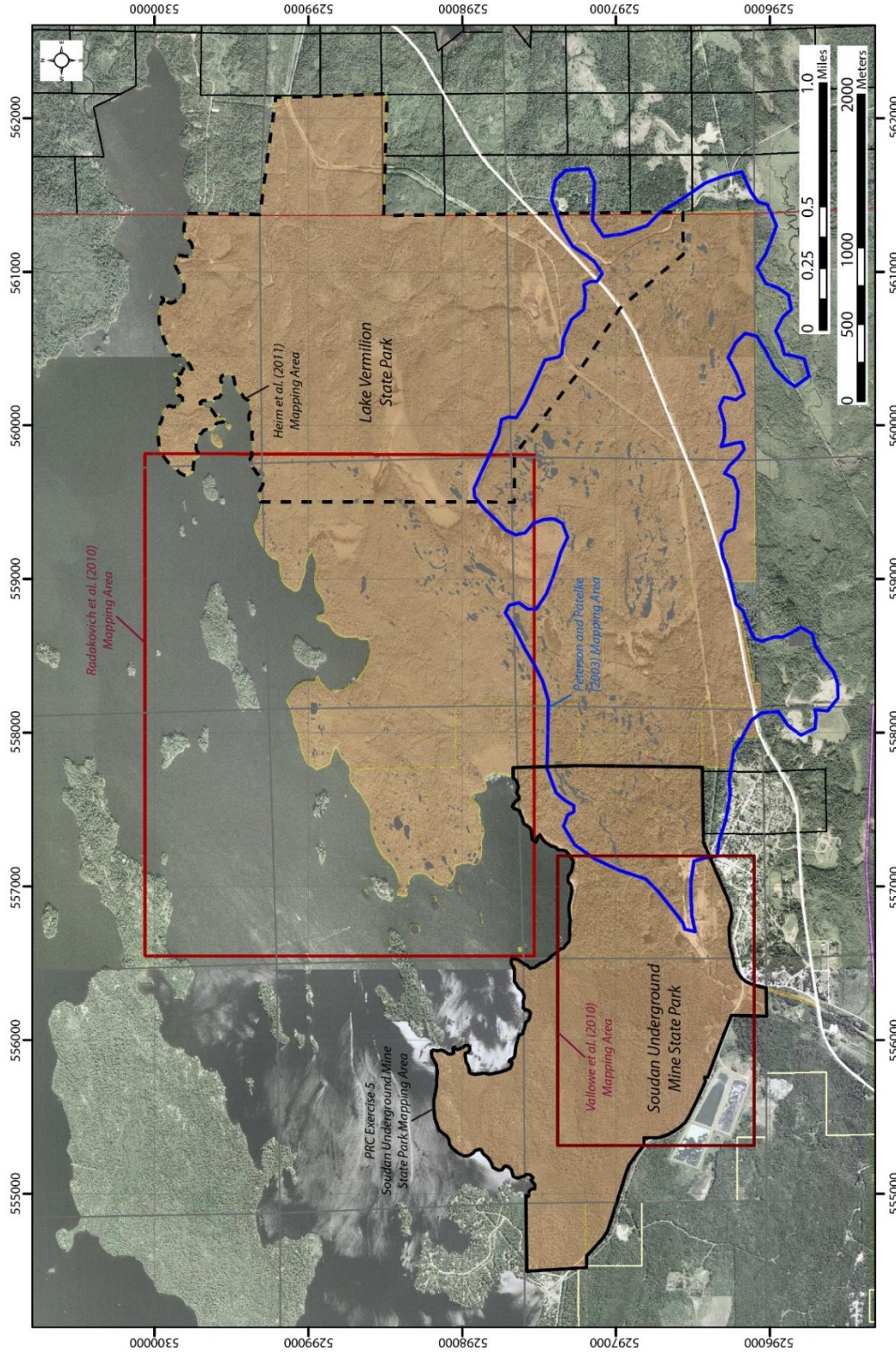


Figure 2. Air photo illustrating Soudan Underground Mine State Park, Lake Vermilion State Park, area of mapping conducted by Peterson and Patella (2003), areas of mapping conducted by Vallowe et al. (2010) in Soudan Underground Mine State Park, Radakovich et al. (2010) in the western half of Lake Vermilion State Park, Heim et al. (2011) in the eastern half of Lake Vermilion State Park, and the area in Soudan Underground Mine State Park mapped as Exercise 5 by PRC field camp students and faculty.

Between August 4 and August 10, 2013, a PRC capstone mapping project under the direction of PRC Faculty Member Dean Peterson (Baumgardner et al., 2013) was conducted in the vicinity of Gafvert Lake, located east of Lake Vermilion State Park. Mapping conducted for this capstone project overlapped with mapping conducted in the eastern half of Lake Vermilion State Park by Heim et al. (2011). This enabled development of a coherent geologic map extending from the western boundary of Soudan Underground Mine State Park east to the vicinity of Gafvert Lake, and allowed the geologic maps of Soudan Underground Mine State Park and Lake Vermilion State Park to merge seamlessly with the broader geology of the Vermilion District.

In summary, the geologic map of Lake Vermilion/Soudan Underground Mine State Park is a compilation of both regional scale geologic maps produced by the Minnesota Geological Survey and the U.S. Geological Survey (Ojakangas et al., 1978; Sims and Southwick, 1980, 1985; Sims, 1985; Southwick, 1993; Peterson and Jirsa, 1999; Jirsa et al., 2001), detailed geologic maps in Soudan Underground Mine State Park associated with the Deep Underground Science and Engineering Laboratory program (Peterson and Patelke, 2003; Hoffman, 2007), as well as detailed 1:5,000 scale geologic maps produced by PRC students and faculty (Vallowe et al., 2010; Radakovich et al., 2010; Heim et al., 2011; Baumgardner et al., 2013).

METHODS

Geologic Mapping

Prior to all mapping exercises, 1:5,000 scale base maps comprising topographic data and an air photo base were constructed using ArcMap geographic information system (GIS) software. All base maps utilized North American Datum (NAD) 1983, Zone 15 North as a datum. For mapping completed in 2010 and 2011, topographic contour lines were manually digitized from U.S. Geological Survey topographic base maps in three dimensions using AutoCAD software. Two layers were constructed in AutoCAD, one layer being major topographic lines (e.g. 50-foot contours), and the other being minor topographic lines (10-foot contours). Digitized contour lines were exported from AutoCAD as .dxf files and converted into shapefiles using CAD2Shape software. Shapefiles from CAD2Shape software were imported into ArcMap as line feature layers. For mapping completing in 2013, topographic contours were extracted from Minnesota statewide lidar data downloaded from the Minnesota Geospatial Information Office website (<http://www.mngeo.state.mn.us/chouse/data.html>). This data was contoured at a two-foot contour interval and included as a line feature layer in ArcMap project files.

Areas geologically mapped within Lake Vermilion/Soudan Underground Mine State Park were accessed by hiking trails, unpaved roads, and paved roads already established in the Park, or by canoe where lake access was available and more convenient. Where roads and trails were not available, students accessed mapping areas by completing traverses (commonly north-south traverses given the generally east-west strike orientations of both lithological contacts and geological structures).

Students and faculty involved in geologic mapping acquired both topographic and geological information in pen on mylar overlays of the base maps, as well as in their field notes. Lithological units were labeled with standardized lithological unit codes (see Peterson and Patelke, 2003),

and each outcrop was colored with colored pencil, with distinctive colors corresponding to each of the lithological units mapped. Students and faculty collected the following information at each of their outcrop locations:

- Outcrop size and shape;
- Outcrop location (NAD 83 Zone 15 North UTM coordinates);
- Lithology (rock type including mineralogy, textures, distribution) and alteration (if present) information (e.g. synvolcanic and post-volcanic alteration features indicative of ancient hydrothermal systems);
- Geological structures (e.g. geological contacts and their orientations, fault zone/shear zone orientations and kinematic features); and
- If present, composition and concentration (in area percent) of mineralization present.

At the end of each field mapping campaign, students compiled their field data and produced 1:5,000 scale geologic maps, which included a geochronologically organized geological legend, descriptions of rock units mapped, and explanations of map symbols. As well, original mylar overlays of student and faculty field maps were archived for subsequent use to produce a final map of Lake Vermilion/Soudan Underground Mine State Park.

RESULTS

Geology

Regional Geology

Lake Vermilion/Soudan Underground Mine State Park contains a wide variety of Neoproterozoic age supracrustal and intrusive lithological units that are within the Wawa-Abitibi Terrane within the Superior Province of the Canadian Shield. In northeastern Minnesota, this terrane is subdivided based on stratigraphic units and structural settings into: 1) the Soudan Belt, to the south; and 2) the Newton Belt, to the north (Jirsa et al., 1992; Southwick et al., 1998). The boundary between these two contrasting regional structural panels can be traced across Minnesota and is known as the Leech Lake Structural Discontinuity (Jirsa et al., 1992). A simplified regional geologic map illustrating the distribution of the Soudan and Newton belts in northeastern Minnesota is presented in Figure 3. The Soudan belt contains large, broad folds of calc-alkaline and tholeiitic volcanic strata overlain by, and locally interdigitated with, sedimentary rocks of turbiditic origin. 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. Both the Soudan Belt and adjacent Newton Belt contain unconformable, Timiskaming-type sequences composed of calc-alkalic volcanic rocks, conglomerates, and finer grained sedimentary rocks. A description of the Newton Belt can be found in Hudak et al. (2014).

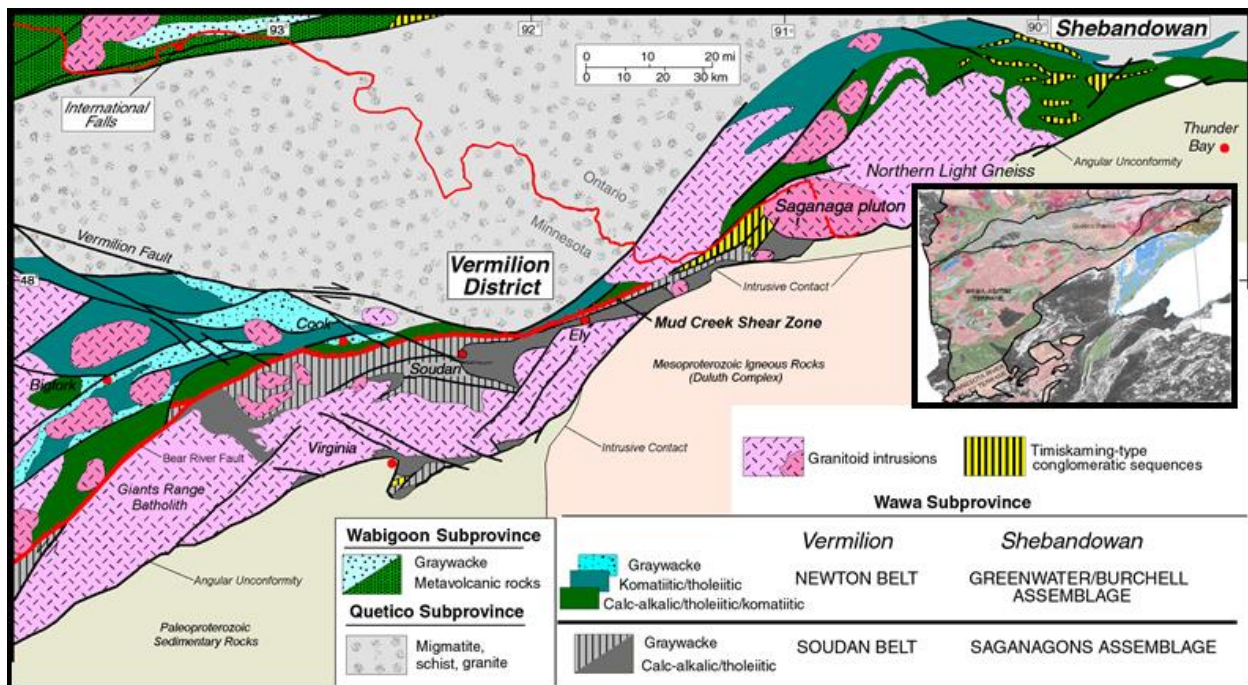


Figure 3. Simplified correlation map of Neoproterozoic assemblages in Minnesota and northwestern Ontario (after Peterson et al., 2001). Inset map illustrates location of the Wawa-Abitibi Terrane in Minnesota and northwestern Ontario (Stott et al., 2007). The Leach Lake structural discontinuity is illustrated in red. The red star symbols indicate location of Lake Vermilion/Soudan Underground Mine State Park.

Lithostratigraphic units in the western Vermilion district (Table 1) include: (1) the Lower member, Soudan Iron-Formation member, and Upper member (Upper Ely) of the Ely Greenstone Formation, 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, 1999) and the Newton Lake Formation 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. Contacts between the different units are typically conformable, although considerable overlap in time and space is documented between volcanic and sedimentary sequences (Southwick, 1993). Rocks within Lake Vermilion/Soudan Underground Mine State Park comprise the Lower member of the Ely Greenstone Formation, the Soudan Iron-Formation member of the Ely Greenstone Formation, the Upper member of the Ely Greenstone Formation, and the Lake Vermilion Formation of the Soudan Belt.

Table 1. Lithostratigraphic units within the western Vermilion District (modified after Peterson and Jirsa, 1999; Peterson et al., 2009a; Hudak et al., 2012).

Intrusive Rocks	
Late Intrusions	Plutons and stocks of syenite, monzonite, diorite, and lamprophyre. A U-Pb zircon age date of a non-foliated feldspar porphyry intrusion in the Newton belt is 2683 ± 1.4 Ma (Peterson et al., 2001).
Vermilion Granitic Complex	Granite, schist, amphibolite, and schist-rich migmatite
Giants Range Batholith	Granite, granodiorite, monzodiorite, and schist-rich migmatite
Supracrustal Rocks	
Newton Belt	
Newton Lake Formation	Tholeiitic and komatiitic basalt lava flows, intrusions, and clastic strata
Bass Lake Sequence	Tholeiitic basalt lava flows, iron-formation, and felsic porphyries
Soudan Belt	
Knife Lake Group	Graywacke, slate, conglomerate, and sheared equivalents
Lake Vermilion Formation	Graywacke, slate, dacitic tuff, minor conglomerate. Detrital zircons from planar bedded, normal-graded resedimented volcanoclastic rocks have U-Pb age dates of 2680-2690 Ma (Lodge et al., 2013)
<i>Gafvert Lake Sequence</i>	Dacitic to rhyodacitic tuff, lapilli-tuff, tuff-breccia, and iron-formation. Basal dacite tuff-breccia deposits in Lake Vermilion State Park have U-Pb age date of 2689.7 ± 0.8 Ma (Lodge et al., 2013)
<i>Britt Sequence</i>	Tholeiitic basalt lava flows
Upper Member – Ely Greenstone	Tholeiitic basalt lava flows and iron-formation
Soudan Member – Ely Greenstone	Oxide-facies iron formation with intercollated basalt lava flows and felsic volcanoclastic rocks
Lower Member – Ely Greenstone	Calc-alkaline and tholeiitic basalt-rhyolite lava flows, tuffs, epiclastic rocks, and minor iron-formation
<i>Central Basalt Sequence</i>	Calc-alkaline to tholeiitic sparsely amygdaloidal basalt and minor basaltic andesite lava flows with MORB-like or back arc basin-like chemical affinities within 100-200 meters of the overlying Soudan Member iron-formation; FII- and FIIIa-type felsic volcanic and volcanoclastic rocks
<i>Fivemile Lake Sequence</i>	Calc-alkaline to transitional moderately to highly vesicular basalt and andesite lava flows and volcanoclastic rocks with arc-like chemical affinities: FI-, FII-, and FIV-type felsic volcanic and volcanoclastic rocks. Rhyolite dome at near Fivemile Lake has U-Pb age date of 2722.6 ± 0.9 Ma (Peterson et al., 2001). Epithermal-like zinc stringer mineralization is present near Fivemile Lake (Hudak et al., 2002a).

Geochronological information for the rocks in the Vermilion District is sparse. A rhyolite lava dome located immediately east of Fivemile Lake in the Lower member of the Ely Greenstone Formation has a U-Pb zircon age date of 2722 ± 0.9 Ma (Peterson et al., 2001). A U-Pb zircon date of 2689.7 ± 0.8 Ma has been obtained by Lodge et al. (2013) for a Gafvert Lake Sequence dacitic tuff breccia that occurs approximately 2 meters north of the contact with the Soudan Iron-Formation member of the Ely Greenstone Formation. This sample occurs in Lake Vermilion/Soudan Underground Mine State Park (Hudak et al., 2014; Peterson et al., 2016). Lodge et al. (2013) also obtained detrital zircon dates of 2680-2690 Ma from greywackes that comprise the Lake Vermilion formation west of Tower, Minnesota. This date confirms the source of the detritus in the Lake Vermilion Formation was derived locally from the volcanoclastic rocks that comprise the Gafvert Lake Sequence. Jirsa et al. (2012) obtained a U-Pb age of 2690.7 ± 0.6 Ma for synvolcanic intrusions that cross-cut volcanoclastic rocks that comprise the Knife Lake Group. The upper part of the Knife Lake Group includes conglomerates which contain clasts derived from the Saganaga Tonalite, which has been dated by Driese et al. (2011) at 2690.83 ± 0.26 Ma. As well, Peterson et al. (2001) dated a non-foliated feldspar porphyry intruded into Newton Belt strata at $2683.1 \pm 1/-4$ Ma, a date that provides a minimum age for the regional D_2 deformation event that is described below. A map illustrating the distribution of geochronological samples in the Vermilion District can be found in Hudak et al. (2014).

The structural geology of the Vermilion District has been well described by Peterson et al. (2009) and Hudak et al. (2014). Three major regional deformation events are recorded in the Neoproterozoic rocks of the Vermilion District:

- 1) The earliest deformation event (D_1) resulted in broad, locally recumbent folds within the Soudan belt and several major fault zones throughout the region. A large, map-scale structure related to D_1 deformation in the western Vermilion District is the Tower-Soudan Anticline, a west-plunging anticline within which the axis plunge changes orientation along strike from nearly vertical in basalts to shallow NE plunging in the sedimentary rocks to the west of Lake Vermilion/Soudan Underground Mine State Park. Axial-planar cleavage associated with this D_1 fold typically has not been observed, although Bauer (1985), Hooper and Ojakangas (1971), Hudleston (1976), and Jirsa et al. (1992) have described early cleavage (S_1) locally. 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 sedimentary sequences in local fault-bounded basins occurred late in D_1 deformation (Jirsa, 2000).
- 2) The second deformation event (D_2) is associated with synchronous regional metamorphism, and resulted in the development of foliation and structures having primarily a dextral asymmetry. D_2 in the Vermilion District is constrained to 2674 to 2685 Ma (Boerboom and Zartman, 1993), and between about 2680 and 2685 Ma in the Shebandowan Belt (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 temporally relate other structural, intrusive, and deformation events in the region. Most shearing appears to have occurred relatively late in the D_2 event based on relationships between the S_2 fabric

and shear structures. Major shearing that produced the Mine Trend, Mud Creek, and Murray Shear Zone has been attributed to the late stages of D_2 dextral transpression (Peterson and Patelke, 2003; Thompson, 2015).

- 3) The third deformation event (D_3) is associated with the juxtaposition of the Wawa-Abitibi and Quetico terranes (Peterson and Patelke, 2003). Structures associated with D_3 include abundant NE- and NW-trending faults that dissect the stratigraphic assemblages. These 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.

Geology of Lake Vermilion/Soudan Underground Mine State Park

Introduction

As indicated above, rocks within Lake Vermilion/Soudan Underground Mine State Park comprise the Lower member of the Ely Greenstone Formation, the Soudan Iron-Formation member of the Ely Greenstone Formation, the Upper member of the Ely Greenstone Formation, and the Lake Vermilion Formation of the Soudan Belt (Hudak et al., 2014). For the purposes of the new geologic map of Lake Vermilion/Soudan Underground Mine State Park (Peterson et al., 2016), map units are based on rock type and have not been subdivided into lithostratigraphic members and/or formations. Supracrustal rocks include mafic volcanic rocks, felsic volcanic rocks, clastic sedimentary rocks, and chemical sedimentary rocks. Fragmental volcanic rocks (volcaniclastic rocks) have been classified utilizing the nomenclature of Fisher (1961, 1966). Bedding nomenclature has been classified using the nomenclature of McPhie et al. (1993). Intrusive rocks have been subdivided into mafic intrusive rocks and felsic intrusive rocks. Rocks generated by structural deformation are called sheared rocks, and include a variety of schistose rocks named on the basis of their major mineralogy.

Supracrustal Rocks

Supracrustal rocks in Lake Vermilion/Soudan Underground Mine State Park have been classified into four major types (Peterson et al., 2016):

- 1) Mafic volcanic rocks;
- 2) Felsic Volcanic Rocks;
- 3) Clastic Sedimentary Rocks; and
- 4) Chemical Sedimentary Rocks.

Mafic volcanic rocks have been subdivided on the basis of lithological characteristics into the following types:

- Mafic Volcanic Rocks, Undivided (map symbol Amvu) – Undivided mafic volcanic rocks that comprise green gray to green massive basalt, pillow basalt, basalt tuff, bedded scoria tuff and lapilli tuff, and foliated basalt rocks.

- Massive Basalt (map symbol Amvm) – Green to dark green, aphyric to sparsely plagioclase-phyric basalt.
- Pillow Basalt (map symbol Amvp) – Variable from light blueish green to dark green, aphyric to sparsely plagioclase-phyric, sparsely- to moderately amygdaloidal pillowed lava flows that display bun, mattress, and lobe morphologies using the pillow lava classification of Dimroth et al., (1978).
- Basalt Tuff (map symbol Amvt) – Green, massive to bedded, aphyric to sparsely plagioclase-phyric tuff.
- Bedded Scoria Tuff and Lapilli Tuff (map symbol Amvs) – Green, thin- to very thick-bedded, poorly-sorted, typically poorly-graded tuff and lapilli tuff containing up to 65% <1-20cm scoria lapilli.
- Foliated Basaltic Rocks (map symbol Amvf) – Green, fine-grained, moderately to strongly foliated basalt comprising anastomosing bands of chlorite-rich phyllite separating domains of less deformed basalt.

Felsic volcanic rocks have been subdivided on the basis of lithological characteristics into the following types:

- Epiclastic Felsic Sedimentary Rocks (map symbol Afve) – Light gray to brownish gray polymict volcanoclastic matrix-supported conglomerates and sandstones containing clasts of felsic volcanic and volcanic strata, oxide facies iron formation, and chert-rich iron formation.
- Laminated Felsic Tuff (map symbol Afvtl) – White to dark gray, laminated to very thinly bedded, aphyric to sparsely quartz- ± plagioclase-phyric dacite to rhyolite tuff.
- Felsic Tuff Breccia (map symbol Afvtb) – Light gray, very thickly bedded to massive, matrix-supported quartz- and plagioclase-phyric polymict dacite to rhyodacite tuff breccia containing 10-20% 1-10 cm quartz and plagioclase-phyric coherent dacite lapilli and blocks, 5-7% lens-shaped quartz- and plagioclase-phyric pumice lapilli up to 3 cm in diameter, 1% light- to dark-gray chert lapilli up to 3 cm in diameter, and 1-3% 0.5-5.0cm diameter black to dark gray to red magnetite-rich, hematite-rich, or jasper-rich banded iron formation lapilli.
- Massive Felsic Lava Flows (map symbol Afvm) – Light gray to greenish gray, fine-grained, massive, aphyric to quartz-phyric rhyodacite to rhyolite lava flows.
- Felsic Tuff (map symbol Afvt) – Gray to tan, fine-grained, aphyric to quartz ± plagioclase-phyric rhyodacite to rhyolite tuff.

Clastic sedimentary rocks have been subdivided on the basis of lithological characteristics into the following types:

- Greywacke-Slate (map symbol Ags) – Light gray, fine- to medium-grained, thin- to medium bedded greywacke containing up to 3% <1-2mm quartz- and plagioclase grains interbedded with dark gray, laminated to thin-bedded mudstone/slate.
- Graphitic Argillite (map symbol Aga) – Dark gray to black, laminated to thinly-bedded graphite-bearing argillite.

Chemical sedimentary rocks have been subdivided on the basis of lithological characteristics into the following types:

- Oxide-facies Iron Formation (map symbol Aifo) – Black (magnetite-rich), dark gray (magnetite and/or hematite-rich), red (jasper-rich), or gray (chert-rich) laminated to medium-bedded, planar bedded to chaotically soft sediment folded, banded oxide facies iron formation.
- Chert-rich Iron Formation (map symbol Aifc) – Light gray to black laminated to very thickly bedded chert locally interbedded with subordinate laminated to very thinly bedded oxide facies iron formation.

Intrusive Rocks

Intrusive rocks in Lake Vermilion/Soudan Underground Mine State Park have been classified into two major types (Peterson et al., 2016):

- 1) Mafic intrusive rocks; and
- 2) Felsic intrusive rocks.

Mafic intrusive rocks have been subdivided on the basis of lithological characteristics into the following types:

- Lamprophyre Intrusions (map symbol Aimp) – Enigmatic rocks comprising: 1) massive gray green intrusive rocks containing clast of scoria, chert and granite within a groundmass composed of up to 85% acicular amphibole; 2) black, fine-grained, massive hornblende-plagioclase rock containing up to 15% fine hornblende needles and local rounded granite blocks greater than 25 cm in diameter in a gray-black and red groundmass (Peterson and Patelke, 2003);
- Metagabbro Intrusions (map symbol Amgb) – Grayish-green to black-green, medium grained, massive to locally ophitic-textured, locally magnetic gabbro.

Felsic intrusive rocks have been subdivided on the basis of lithological characteristics into the following types:

- Diorite (map symbol Ad) – Gray to gray-green, fine- to medium-grained, plagioclase- and hornblende (actinolite)-bearing equigranular diorite.
- Granodiorite (map symbol Agd) – Whitish-pink to green gray, medium-grained, granodiorite and hornblende granodiorite which locally contains xenoliths of oxide facies banded iron formation, chert, felsic epiclastic rocks, and basaltic volcanic and volcanoclastic rocks.
- Feldspar Porphyry (map symbol Afp) – White to whitish-pink, medium-grained, holocrystalline dacite with 5-12% 1-4mm subhedral to euhedral tabular feldspar phenocrysts, and locally, 2-5% 1-3mm dark green actinolite pseudomorphs of hornblende (Radakovich et al., 2010).

- Quartz Feldspar Porphyry (map symbol Aqfp) – White to whitish-pink, light gray to pale green-gray porphyritic dacite to rhyodacite containing 20-25% 1-5mm diameter subhedral to euhedral tabular plagioclase phenocrysts, and 5-15% 1-3mm diameter subhedral to euhedral pale gray to gray blue quartz phenocrysts.

Sheared Rocks

Sheared rocks have been subdivided on the basis of lithological characteristics into the following types:

- Chlorite-dominant schist (map symbol Aszc) – Green to dark green very fine- fine grained chloritic phyllite and schist (Peterson and Patelke, 2003).
- Sericite-dominant schist (map symbol Aszs) – Pale yellow green to yellow gray, very fine- to fine-grained sericitic phyllite and schist (Peterson and Patelke, 2003).
- Fuchsite-dominant schist (map symbol Aszf) – Pale yellow green to yellow gray, very fine- to fine-grained sericitic phyllite containing up to 20% emerald green, disseminated porphyroblasts of green mica up to 5mm in length.
- BIF ‘n’ Schist (map symbol Aszb) – Interlayered phyllites and schists comprising green to dark green chlorite dominant schist, pale yellow to yellow gray sericite dominant schist, and lens-shaped zones of oxide facies iron formation that cannot be resolved into more specific schist and/or iron formation units at the map scale.

Geological Structures

Three distinctive types of fault zones have been identified within the bounds of Lake Vermilion/Soudan Underground Mine State Park. These include:

- Synvolcanic fault zones (D_0), which form at the time of the volcanism associated with the genesis of the volcanic rocks in the State Park, and which possess higher concentrations of synvolcanic hydrothermal alteration mineral assemblages proximal to the synvolcanic structures (see Hudak et al., 2014 for a detailed explanation of synvolcanic fault zones). Two potential synvolcanic fault zones have been described in the north-central part of the former Lake Vermilion State Park by Hudak et al. (2014);
- Shear zones (which are associated with the regional D_2 deformation described previously in this report), which are characterized by linear zones of sheared rocks such as chlorite-dominant schist, sericite-dominant schist, fuchsite-dominant schist, and BIF ‘n’ Schist. The Mine Trend and Murray shear zones (Peterson and Patelke, 2003; Peterson et al., 2016) are examples of D_2 -associated shear zones within the bounds of Lake Vermilion/Soudan Underground Mine State Park.
- Late faults which are characterized by brittle deformation and associated offset of adjacent lithological units. Within Lake Vermilion/Soudan Underground Mine State Park, these D_3 -associated structures are commonly expressed as northwest- to northeast-trending, minor displacement (generally less than one meter) brittle faults

that offset sedimentary bedding and / or contacts between adjacent lithological units. Excellent examples of D_3 -associated late faults can be observed on the “classic” outcrop of Soudan Iron Formation (NAD83 Zone 15N UTM location 557120E, 5296660N; Jirsa et al., 2004).

Measurements of other planar (e.g. bedding orientation, orientations of geological contacts, foliation measurements) and linear (e.g. mineral lineations, glacial striations) geological structures were recorded during field mapping, and are included on the new geologic map (Peterson et al., 2016) of Lake Vermilion/Soudan Underground Mine State Park.

Geochronology

One felsic volcanic rock sample from the northwestern part (NAD83 Zone 15N UTM coordinates 558995E, 5298230N) of the former Lake Vermilion State Park was subjected to magmatic zircon geochronology analysis (Lodge et al., 2013). The sample, RL-11, comprises quartz- and feldspar-phyric dacite tuff breccia from the basal part of the Gavert Lake Sequence. The sample was taken approximately two meters north of the contact between the the Gavert Lake Sequence and the underlying Soudan member oxide facies iron formation. Geochronological analysis was conducted using thermal ion mass spectrometry (TIMS) at the Jack Saterly Geochronology Laboratory at the University of Toronto. This sample yielded a $^{207}\text{Pb} / ^{206}\text{Pb}$ age of 2689.7 ± 0.8 Ma, which led to the interpretation that the contact between the underlying Soudan Iron Formation member and the overlying Gavert Lake Sequence represents a disconformity (Lodge et al., 2013).

RATIONALE FOR GIS METHODOLOGY DEVELOPMENT

GIS development was completed in ArcMap 10. The map projection is Universal Transverse Mercator (UTM) North American Datum (NAD) Zone 15N.

Publicly available shapefiles for the State of Minnesota (available from the Minnesota Geospatial Information Office (www.mngeo.state.mn.us/chouse/data.html)) were utilized when available for construction of the geologic map of Lake Vermilion/Soudan Underground Mine State Park. Shapefiles related to infrastructure within Lake Vermilion/Soudan Underground Mine State Park were obtained from Sherry Watson, GIS Support Specialist, MN.IT Services, Minnesota Department of Natural Resources (see below). Shapefiles pertaining to the geology of Lake Vermilion/Soudan Underground Mine State Park were constructed using data obtained during field mapping in the park. Additional data related to roads, streams and lakes were derived by digitizing 2013 FSA air photos of the map area.

GEOGRAPHIC INFORMATION SYSTEM SHAPEFILES ASSOCIATED WITH THE MAP

The following ArcMap shapefiles have been utilized to construct the geologic map of Lake Vermilion/Soudan Underground Mine State Park (Peterson et al., 2016) for this project:

Publically Available Shapefiles from the Minnesota Geospatial Information Office

Publically available shapefiles obtained from the Minnesota Geospatial Information Office (www.mngeo.state.mn.us/chouse/data.html) were utilized in the construction of the geologic map of Lake Vermilion/Soudan Underground Mine State Park. These shapefiles primarily consisted of data related to political boundaries (e.g. townships, sections). Publically available shapefiles utilized in the construction of the geologic map of Lake Vermilion/Soudan Underground Mine State Park include:

- sections;
- state; and
- townships.

Shapefiles Obtained from Sherry Watson at the Minnesota Department of Natural Resources

The following shapefiles were obtained from Sherry Watson (GIS Support Specialist, MN.IT Services, Minnesota Department of Natural Resources) via email, and were utilized in construction of the new geologic map of Lake Vermilion/Soudan Underground Mine State Park:

- day_use_trails_final_design;
- gps_trail_inventory;
- hike_in_camping;
- historic_mining_pits;
- park_boundary;
- points_of_interest;
- prelim_campground_designs;
- proposed_camper_cabins;
- proposed_core_trail_extension;
- proposed_hiking_trails;
- roads_trails_developed;
- roads_trails_existing; and
- she_mesabi_trail_alignment_2014.

New Shapefiles Constructed for this Project by the NRRI

Geologic data (outcrop locations and attributes, geology contacts, geology polygons, structural measurements) obtained during the various mapping campaigns in the former Soudan Underground Mine State Park and former Lake Vermilion State Park were compiled for construction of the geologic map of Lake Vermilion/Soudan Underground Mine State Park.

Compilation of this data required NRRI personnel to develop new shapefiles for use in this geologic map. These include:

Point Layers

The following point layer was constructed by the NRRI using ArcMap10 for this project:

- NRRI_2016_Structure_Symbols (this point theme contains data for structure symbols displayed on the map).

Line Layers

The following line layers were constructed by the NRRI using ArcMap10 for this project:

- NRRI_2016_Faults (this line theme contains data for faults displayed on the map).
- NRRI_2016_Roads (this line theme contains data for roads located outside the boundaries of Lake Vermilion/Soudan Underground Mine State Park that were digitized from 2013 FSA air photos).
- NRRI_2016_Streams (this line theme contains data for streams in the map area that were digitized from 2013 FSA air photos).

Polygon Layers

The following polygon layers were constructed by the NRRI using ArcMap10 for this project:

- NRRI_2016_Geology (this polygon theme contains data for geology polygons that were interpreted from geologic mapping conducted by PRC students and faculty in Lake Vermilion/Soudan Underground Mine State Park between 2010 and 2013, as well as historic data from mapping performed by Peterson and Patelke (2003)).
- NRRI_2016_Outcrops (this polygon theme contains data for outcrop locations and geologic attributes, and was digitized from geologic mapping conducted by PRC students and faculty in Lake Vermilion/Soudan Underground Mine State Park between 2010 and 2013, as well as historic data from mapping performed by Peterson and Patelke, (2003)).
- NRRI_2016_Lakes (this polygon theme contains data for streams in the map area that were digitized from 2013 FSA air photos).
- NRRI_2016_Border (this polygon theme contains data for the boundary of the map area).

Image Layer

The following image layer was constructed by the NRRI using ArcMap10 for this project:

- NRRI_2016_DEM_Hillshade (this image theme was derived from the Arrowhead Region Block 2 and Block 5 3-meter Minnesota State LiDAR data utilizing Surfer 11 software).

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