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This map is preliminary, as it has not been reviewed to fully conform to editorial standards of the Minnesota Geological Survey.

PRELIMINARY BEDROCK GEOLOGIC MAP OF PART OF THE 2007 HAM LAKE FIRE AREA: Portions of Conners Island, Gillis Lake, Long Island Lake, and Munker Island 7.5-minute quadrangles, northeastern Minnesota, USA, and adjacent Ontario, Canada

Scale 1:24,000

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INTRODUCTION

This map describes bedrock geology along the Gunflint Trail in a part of the area burned during the Ham Lake forest fire in 2007. The map covers only a portion of the fire area because much of the burn lies in Canada, or within plutonic rocks that generally lack significant mappable variations. Only the southeastern corner of the map area was not burned—the burn extends to the north and east beyond the map sheet. The western edge of the map is coincident with the area of the 2006 Cavity Lake fire, which was mapped previously by Jirsa and Starns (2008).

The area transects Neoarchean, Paleoproterozoic, and Mesoproterozoic geology (Fig. 1). Archean greenstone-granite terrane of the Wawa subprovince of Superior Province is represented by a succession of metavolcanic rocks (ca 2700Ma), intruded by the Saganaga Tonalite (ca 2689 Ma). Some of the Archean geologic framework can be correlated in a general way with that across the U.S-Canadian border by Corfu and Stott (1998), and to the south and west (e.g., Jirsa and Miller, 2004). Diabasic dikes of imprecisely known age cut the Archean bedrock. The Archean rocks and diabase dikes are unconformably overlain by Paleoproterozoic sedimentary strata of the Animikie Group (ca 1870-1830 Ma), which includes the Gunflint Iron Formation. The stratigraphic top of iron-formation is marked by a major unconformity, and what is inferred to be ejecta from a meteorite impact that occurred near Sudbury Ontario, ca 1850 Ma. Remnants of an ejecta blanket from the impact have recently been identified in Ontario (Addison and others, 2005), Michigan (Cannon and others, 2010; Pufahl and others, 2007), and Minnesota (Jirsa, 2010). Mesoproterozoic rifting is manifest in hypabyssal dikes and sills of the Logan intrusions (ca 1115 Ma), and several phases of the Duluth Complex (ca 1100 Ma), emplaced into both Archean and Proterozoic rocks.

The geologic contacts depicted on this map are modified from those of Morey and others (1981). Only slight modifications were made for areas of the Duluth Complex and some parts of the basal contact of Animikie group strata. The major revisions from earlier mapping are within the Gunflint Iron Formation, Logan Intrusions, and in parts of the Archean bedrock.

STRUCTURE

Stratigraphic facing directions in Neoarchean supracrustal rocks, based on pillowed metabasalt flows, indicate that the sequence forms a northwest trending, steeply south-dipping and younging homocline. Much of the temporal distinction between various geological elements in the Archean rocks is based on regionally consistent fabrics that resulted from three major phases of deformation, denoted D_1, D_2, and D_3 (see Correlation of Map Units). All three deformation events are the result of N-S- to NW-SE-directed compression. Regionally, D_1 deformation is inferred to have folded, tilted, and thrust faulted large sections of the supracrustal rocks, but did not produce significant metamorphic mineral assemblages or cleavage and schistosity. The timing of D_1 deformation is bracketed between deposition of the volcanic and clastic rocks at about 2722 Ma (Peterson and others, 2001), and emplacement of the Saganaga Tonalite at about 2689 Ma (Corfu and Stott, 1998). The affects of D_2 deformation in this area include moderate to mild flattening of minerals and inclusions near the margins of the Saganaga Tonalite; and strong schistosity, metamorphism, folding of tonalite dikes, and flattening of pillow structures in the immediately adjacent supracrustal rocks. U-Pb dates of intrusions that bracket D_2 place the regional deformation and metamorphic event between about 2674 Ma and 2685 Ma (Boerboom and Zartman, 1993). D_3 deformation produced faults and shear zones. The distribution of outcrop (Fig. 2) clearly is related to these structures, as well as lithologic variations.

Much of the apparent complexity in the part of the map containing Paleoproterozoic strata and Logan Intrusions is a product of shallow dip, local faults and folds, and moderate to high topographic relief. Deformation associated with the Lookout Fault grades from a distinct fault structure on the west—where Paleoproterozoic iron-formation is folded and faulted against Archean rocks—to a shallowly eastward-plunging, sympathetic drape structure in the eastern part of the area dominated by higher stratigraphic levels of iron-formation and slate. The drape structure is manifest in a tight anticline-syncline pair, in which the shallow plunge and a progressive flattening of limbs occurs toward the southeast (Fig. 3). The depiction of the Mesoproterozoic Logan Intrusions differs significantly from the previous mapping (Morey and others, 1981), which implied the intrusions were folded. Additional field work indicates that the intrusions are semi-concordant with adjacent strata where dips are gently southeastward, but are markedly discordant where north dips occur along the limbs of the anticline-syncline pair. Although the sills generally mimic fold structures, the local discordance implies that much of the deformation associated with the Lookout Fault and related folding predated emplacement of Logan Intrusions.

MESOPROTEROZOIC

DULUTH COMPLEX

Igneous rocks formed during development of the Midcontinent Rift approximately 1.1 Ga. Unit descriptions and contacts are modified only slightly from Morey and others, 1981, and Costello and others, 2009.

Tuscarora intrusion—Troctolite cumulate forming the Layered series at the base of the Duluth Complex; normally polarized.

Mta **_Interlayered anorthositic gabbro and troctolite_**—Medium- to coarse-grained; interlayered on scale of centimeters to meters. Unit is considered transitional between lower augite troctolite to the north and anorthositic gabbro south of the map area.

Mtt **_Augite troctolite_**—Medium- to coarse-grained, except stratigraphically lower (northern) zone that grades to fine- to medium-grained. Modal layering is well developed and generally concordant with unit boundaries that dip gently to the south—typically more shallowly dipping than the subjacent Animikie Group strata. A sample just west of the map area gives an age of 1098.81±0.32 (Hoaglund and others, 2010).

Mtm **_Melatroctolite_**— Medium- to coarse-grained (Costello and others, 2009).

Mtg **_Heterogeneous basal unit_**—Taxitic, augite-poikilitic, olivine gabbro; fine- to medium-grained; locally contains hornfels inclusions of subjacent strata, and chalcopyrite, pyrrhotite, and minor pentlandite locally.

Mh **Hornfels**—Fine-grained, metamorphosed inclusions of volcanic (primarily basaltic) and sedimentary protolith in the Tuscarora Intrusion; derivation from the North Shore Volcanic Group is inferred.

Mpg **Poplar Lake intrusion**—Interlayered gabbroic cumulates, with minor amounts of troctolitic and anorthositic cumulates. Magnetic polarity is reversed. Analysis of a sample taken east of the map area provides an age of 1106.9±0.6 Ma (Paces and Miller, 1993).

LOGAN INTRUSIONS

Mlu, Mll, Mld

Diabase—Fine- to medium-grained sills and dikes emplaced into slate and mudstone of the Rove Formation and Gunflint Iron Formation; locally plagioclase-phyric to glomeroporphyritic, particularly at the top of sills and in the centers of dikes. Typically less than 10 m thick in map area, though sills as thick as 350 m are known farther to the east. Two semi-concordant, lithologically similar sills most influence this geologic depiction, and are distinguished separately: **Mlu** is the upper, **Mll** is the lower. The unit designation **Mld** is used for dikes and other sills of varied trend and thickness. Similar intrusions near Thunder Bay, Ontario yield an age of 1115±1 Ma (Heaman and Easton, 2005). Earlier mapping by Morey and others (1981) inferred lateral continuity of sills within folds of the enclosing iron-formation. Although some sills appear to have delaminated the Paleoproterozoic strata along fold structures, the current mapping has shown that the intrusions in many locations are discordant, lenticular, and locally terminate along irregularly-trending dikes.

PALEOPROTEROZOIC

ANIMIKIE GROUP

Shallowly dipping, locally gently folded sequence of sedimentary strata including iron-formation, argillite, slate, and graywacke. The sequence rests unconformably on eroded and locally weathered Archean rocks, that have contributed detritus to lowermost strata. The iron-formation and overlying argillaceous strata lie within the contact metamorphic aureole of the Duluth Complex. Floran and Papike (1978) delineated irregularly northwest-striking metamorphic zones recognized on the basis of the dominant iron-silicate mineral present in iron-formation (Fig. 4). From least metamorphosed on the northeast, to most metamorphosed on the southwest, these indicator minerals are greenalite+minnesotaite, grunerite, hedenbergite, fayalite, and ferrohypersthene. Despite this metamorphism, sedimentary textures are well preserved in most outcrops. Metamorphic affects of the Duluth Complex on the Rove Formation are much less pronounced, except for very near the contact (Labotka and others, 1981). Metamorphism of both formations adjacent to the Logan Intrusions was minor.

Prf **Rove Formation**—Carbonaceous argillite to slate, and fine- to medium-grained graywacke; thinly bedded to laminated. Basal several meters of the formation are irregularly bedded, carbonate-rich, and locally conglomeratic. Metamorphosed near Duluth Complex to hornblende and pyroxene hornfels. Detrital zircons taken from lower parts of the formation in Ontario yielded ages of 1827±8 and 1836±5 (Addison and others, 2005). Detrital zircons higher in the stratigraphic section yield ages as young as 1777 Ma (Heaman and Easton, 2005), indicating some considerable hiatus separating the Rove from the underlying 1850 Ma Sudbury impact layer.

Gunflint Iron Formation

The Gunflint Iron Formation consists of interlayered “slaty” or mudstone strata, and “cherty” or granular siliceous strata. Although the two rock types are interlayered on all scales, some parts of the formation contain an abundance of one type over another. In the past, this led to subdivision of the Gunflint Iron Formation, and the correlative Biwabik Iron Formation on the Mesabi Iron Range, into members denoted lower cherty, lower slaty, upper cherty, and upper slaty (Wolff, 1917; Broderick, 1920). Although this terminology has some descriptive utility in the field, the subdivision employed here is based instead on a sedimentalogical model (after Pufahl and Fralick, 2000). In this model, the lower cherty and lower slaty members represent marine transgression, which was followed by a regression that deposited the lower part of the upper cherty member—the resulting sedimentary strata are collectively termed *lower sequence* here (unit **Pgl**). The upper part of the upper cherty represents a second transgression that continued through deposition of the thick upper slaty member, and is collectively termed the *upper sequence* here (unit **Pgu**). The contact between the two sequences is a diastem inferred to represent a period of maximum regression, and the initial second transgression is marked by intraformational conglomerate containing oncoliths, fragments of what appear to have been semi-lithified grainstone derived from the lower sequence, and both in-place and dislodged stromatolites. The uppermost strata of iron-formation (unit **Pgs**) is variably brecciated and/or chaotically folded, carbonate-bearing, and capped by granular ejecta from the ca. 1850 Ma Sudbury meteorite impact event (Krogh, 1984; Davis, 2008).

Pgs **Sudbury impact layer**— Brecciated and complexly deformed iron-formation as much as 10 m thick, overlain locally by less than 1 m of mesobreccia and granular ejecta. Both deformed (seismically shattered and chaotically folded) iron-formation and ejecta are inferred to be related to the Sudbury meteorite impact event (Jirsa, 2010). The macroscopically most apparent feature of ejecta is the presence of 0.1-1.0 cm, concentrically zoned spheres inferred to be accretionary lapilli. Microscopic evidence that this material has an impact origin includes rare occurrence of quartz fragments marked by planar deformation features—metamorphism presumably has obscured or obliterated other diagnostic attributes (e.g., French and Koeberl, 2010).

Pgu **Gunflint Iron Formation-Upper sequence**—Siliceous grainstone and laminated chert; locally contains stromatolitic and intraclastic conglomerate at base of the sequence; which grades irregularly up-section to increasingly mudstone-rich; and typically parallel-laminated to wavy-bedded. Total thickness is approximately 45-55 m. Reworked volcaniclastic zircons from the upper sequence exposed in Ontario yielded a U-Pb age of 1878±1 (Fralick and others, 2002).

Pgl **Gunflint Iron Formation-Lower sequence**—Irregularly graded sequence recording marine transgression, followed by regression. It grades from conglomerate and sandstone at the base, unconformably overlying Neoarchean bedrock; to locally stromatolitic, siliceous grainstone; to interlayered, laminated to massive chert, to iron-rich mudstone, and finally to siliceous grainstone. Total thickness is approximately 50 m. The basal part of the sequence is marked by discontinuous conglomerate and minor fine- to medium-grained quartzofeldspathic sandstone that is typically thinner than 1 m. Conglomerate contains pebbles to small cobbles of quartz, Saganaga Tonalite, metabasalt, and diabase. Thicker sections of this facies exposed in Canada are known as the Kakabeka Conglomerate. The uppermost siliceous grainstone forms prominent ridges. It appears to have been partially lithified prior to deposition of, and contributed grainstone fragments to, the basal part of unit Pgu.

Mafic dikes

The dikes vary from 1-25 m thick and dip steeply. Relative age can be generally constrained as Paleoproterozoic by their emplacement into the Archean Saganaga Tonalite, and the presence of dike fragments locally in the basal Paleoproterozoic conglomerate of unit Pgl; however, more than one intrusive episode may be represented. An older age for lamprophyric dikes is possible, as similar compositions are present in some Neoarchean igneous rocks exposed to the west. Younger ages cannot be ruled out, as many dikes do not project to the Paleoproterozoic unconformity.

Pdd **Diabase**—Northwest- and east-northeast-trending dikes composed of diabase to ferrodiorite; locally scantly plagioclase-phyric; locally composite.

Pdl **Lamprophyre**—Northwest- trending dikes composed of lamprophyre. Petrographic and analytical work on one such dike by O'Brien (1982) indicates the dike is camptonite—defined by calcic amphibole, titanbiotite, and titanaugite phenocrysts in a plagioclase-rich groundmass.

Pdu **Aeromagnetic anomalies inferred to be mafic dikes**—Northeast and northwest- trending, positive magnetic anomalies.

NEOARCHEAN

Ast **Saganaga Tonalite-main phase**—Light gray, massive to trachytoid-foliated, medium to coarse-grained tonalite, having plagioclase in much greater abundance than microcline. Large quartz phenocrysts, or "eyes," as much as 1 cm in diameter are characteristic of this phase that makes up 90% of the intrusion. Quartz eyes are polycrystalline aggregates, in which each crystal has a different cystallographic orientation. Quartz also occurs interstitial to subhedral plagioclase (An_{20-28}). Small amounts of microcline occur as antiperthitic exsolution in plagioclase, as rims on plagioclase, and as small interstitial grains. Hornblende is the dominant ferromagnesian mineral, together with minor amounts of augite, biotite, epidote, and chlorite. Based on limited geochemical analysis, the tonalite and associated rocks can be classified as part of the sanukitoid suite (Jirsa and Weiblen, 2007). A pronounced foliation and mineral lineation is manifest in parallel aligned minerals and autoliths that more or less mimics the contact with adjacent metavolcanic rocks. Except for exposures very near the contact, this fabric appears to be largely magmatic. A U-Pb date of 2689±1 Ma was acquired from exposures in Canada (Corfu and Stott 1998).

Asb **Saganaga Tonalite-border phase**—Gray to pink, moderately to strongly foliated, locally modally layered, medium- to coarse-grained, quartz-bearing hornblende diorite to granodiorite, generally lacking large quartz "eyes." Autoliths of dioritic and quartz dioritic phases are common and trend parallel to foliation; xenoliths of greenstone are rare. Diffuse-bounded and irregularly distributed zones of similar polyphase rock occur elsewhere in the intrusion, but are not mapped separately. Aplite and pegmatite dikes are locally abundant, as are dikes of more mafic, hornblende-bearing dioritic phases. Apophosial dikes of granodiorite emplaced into adjacent volcanic rocks were moderately folded and cataclasically deformed during D2.

Amv **Metabasalt and hypabyssal sills and dikes of metagabbro, metapyroxenite to metaperidotite**—Moderately foliated, locally modally layered, steeply dipping. Textures of flows include variolitic, pillowed, massive, and locally autobrecciated. Stratigraphic facing is consistently southward. Inferred hypabyssal intrusions are marked by clot-textures of relict pyroxene oikocrysts and local relict spinifex textures pseudomorphed by amphibole. Metamorphic grade varies from amphibolite near the Saganaga Tonalite, to greenschist. The unit is mapped as Paulsen Lake sequence immediately to the west (Jirsa and Starns, 2008), and is geochemically identical with and inferred to be equivalent to the Newton Lake Formation (Vervoort, 1987). An age of ca. 2718-2722 Ma can be generally inferred from U-Pb dates of lithologically identical strata in adjacent terranes to the northeast (Greenwater Assemblage of Corfu and Stott, 1998).

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MAP SYMBOLS

Geologic contact—Approximately located. In areas lacking outcrop (see below), the positions of contacts are only slightly modified from previous mapping (Morey and others, 1981).

Fault—Approximately located. Faults in Paleoproterozoic and Mesoproterozoic rocks typically are dip-slip; letters indicate relative vertical displacement; up (U), down (D). Faults shown in the Neoarchean rocks are largely inferred from geophysical and topographic maps, and have both dip-slip and strike-slip displacement; arrows and letters show sense of relative displacement where it has been determined.

Trajectory of aeromagnetic anomaly inferred to be mafic dike

Surface trace of folds in Paleoproterozoic and Mesoproterozoic rocks—Dip is steep and plunge is shallow eastward, as shown by arrowheads; anticline, syncline.

Strike and dip of bedding in Paleoproterozoic rocks—Inclined.

Strike and dip of unconformity in Paleoproterozoic rocks—Marks the contact between deformed (brecciated and chaotically folded) iron-formation and overlying layered ejecta in the Sudbury impact layer (unit Pgs); inclined.

Strike and dip of mafic dikes—Units Pdl and Pdd.

Strike and dip of igneous foliation—Established primarily from magmatic segregations of plagioclase phenocrysts in Mesoproterozoic intrusions, and from modal layering and orientation of autoliths in Neoarchean Saganaga Tonalite; inclined, vertical.

Strike and dip of bedding in Neoarchean rocks—Established from trends of pillowed and autobrecciated zones; stratigraphic younging direction indicated by ball and bar; inclined, vertical.

Strike and dip of cleavage and schistosity in Neoarchean rocks—Inferred to be related to D2 deformation; inclined, vertical.

Outcrop—Bedrock exposure; typically areas of multiple, scattered exposures visited or viewed by author. Outlines inferred largely from post-fire air photograph imagery (Minnesota Geospacial Information Office).

Inferred outcrop—Shown in areas of recent forest fires based solely on post-fire air photography. Note that some areas with sparse outcrop may be the product of less intense burning, rather than variations in rock competence.

M-46 structure location—Center-point of structure symbol on map by Morey and others, 1981.

Line of cross-section—A through E.